

HKCI: TM 2

*Determination of Concrete Cover
and Distribution of Steel Rebar
by Surface Penetration Radar*



Test Method for Determination of Concrete Cover and Distribution of Steel Rebar by Surface Penetration Radar

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1. Scope

- 1.1 This test method covers the equipment, field procedures, interpretation of data, data processing and imaging methods for the nondestructive determination of concrete cover and spatial distribution of steel reinforcement within concrete and/or measurement of concrete element thickness using a Surface Penetration Radar (SPR) system.
- 1.2 SPR measurements as described in this method are used for reinforced concrete structures. The test surface may comprise many different materials such as concrete, mortars, screeds, tiles, etc.
- 1.3 The approach suggested in this method for using SPR is most commonly used, widely accepted, and well proven. However, other approaches or modifications to SPR that are technically sound may be substituted if technically verified and documented.
- 1.4 *This method does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. Specific hazard statements are given in Section 7.*
- 1.5 *This method does not purport to address every aspect of ground penetrating radar application. It is specially dedicated to concrete evaluation for practical purpose.*

2. Definitions

- 2.1 **Radar -**
RAdio Detection And Ranging
- 2.2 **Concrete cover -**
A distance between the test surface and the top of the steel reinforcement.
- 2.3 **Spatial distribution of steel reinforcement -**
A distribution showing the alignment and spacing (the centre to centre distance of adjacent steel reinforcements).
- 2.4 **Element thickness -**
A distance between the contact (test) surface and the concrete-air interface at the back of the element.
- 2.5 **Radargram -**
A two-dimensional intensity chart (produced by a SPR system) recording the magnitudes of reflections of the electromagnetic waves.
- 2.6 **Dielectric constant -**
A constant describing the ability of a material to store electric energy by separating opposite polarity charges in space [1]. The dielectric constant of a medium is generally considered as a constant value over a range of typical SPR frequencies, which is attributed to the velocity and attenuation plateau over the range, as shown in Figure 1. However, in certain case where very wet and porous media is studied, this constant may experience changes over the SPR frequency range [2, 3].
- 2.7 **Attenuation -**
The loss in electromagnetic wave energy from all possible sources, including condition currents, dielectric relaxation, and scattering, etc. [1,4].
- 2.8 **Depth of penetration -**
The maximum depth range a radar signal can penetrate in a given medium, be scattered by an electrical inhomogeneity, propagate back to the surface, be recorded by a receiver SPR antenna, and yield a voltage greater than then noise levels of the SPR unit [1].

2.9 Scattering -

The change in **direction of electromagnetic wave propagation** that occurs at a change in material properties over a **short distance** compared to a wavelength for an interval comparable to or greater than the radar wave's **wavelength** [1].

2.10 Dewow -

A frequently-used **temporal filter** for removing very low-frequency components from the SPR data. These components **may be due** to inductive phenomena or possible limitations posed on dynamic range of the instrument.

2.11 Background subtraction -

Acts as a **high-pass filter** or an average trace removal's tool. The former is similar to 'dewow' in Clause 2.10, and the latter allows surface weak signals to be visible in which these signals are often masked by the **transit pulse** (with transmitter reverberation and artifacts of time synchronous system).

2.12 Migration -

A **data processing method** used as a spatial deconvolution tool which reconstructs distribution of radar **reflectivity of the material under investigation**.

2.13 Hilbert transform -

A **data processing method** used for enveloping and converting a radar wavelet (with both positive and **negative polarities**) to a monopulse wavelet in positive polarity. This process eliminates the oscillating **nature of a radar wavelet** and shows the time resolution of the data.

2.14 Time-varying gain -

A **data processing method** used for magnifying received SPR signals (especially the reflections from the **reflectors**) based upon different gain functions. Two widely used gain functions are automatic gain control and **spherical** and exponential compensation (SEC) gain [5].

3. Principle

3.1 SPR involves the propagation of pulses of electromagnetic waves in concrete structures, and these waves are **reflected** when they encounter a material that have very different electrical properties (or dielectric constants) than concrete.

3.2 The **detection** of an object or interface between two different materials by SPR depends upon the partial **reflection of incident energy** at that interface. The intensity of the reflected energy, A , at that interface (or **boundary**), with respect to the intensity of the incident energy, A_0 , is related to the dielectric constants of the **two materials** according to the following formula:

$$\frac{A}{A_0} = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \quad (1)$$

where

ϵ_1 and ϵ_2 are the dielectric constants of materials 1 & 2, respectively.

3.3 The **abilities of the SPR system** to determine the concrete cover and spatial distribution of steel reinforcement **within concrete**, and measure concrete element thickness depend on the difference in dielectric constants between two electrically contrasting layers (i.e. between concrete and steel, or between **concrete and air**).

A sufficient **contrast** usually exists between concrete layers, concrete-steel reinforcement and concrete-air boundaries. **Such a contrast** may not always be sufficient if other materials are present above the interfaces or **spacing of reinforcement** is small (normally less than 50 mm).

3.4 Cover and **thickness determination** can be made using SPR technology if the propagation velocity of the electromagnetic **pulses in the studied concrete** is known. The dielectric constant of that material through which the **electromagnetic pulse** propagates mostly determines the propagation velocity of the electromagnetic **wave**. The relationship is governed by the following equation:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (2)$$

Where

v is the propagation velocity of electromagnetic waves through the material (in m/s);

c is the propagation velocity of electromagnetic waves in free space (3×10^8 m/s);

ϵ_r is the dielectric constant.

- 3.5 The dielectric constant of concrete depends primarily on moisture content of concrete [6]; and to certain extent, on aggregate types, cement sources, and cracks, etc.

NOTE Table 1 shows dielectric constants of different materials commonly found in this application.

4. Significance and Use

- 4.1 This test method permits nondestructive determination of concrete cover, spatial distribution of reinforcement and concrete element thickness. As such, this test method is widely applicable as a concrete assessment technique [7].
- 4.2 Although this test method, under the right conditions, can be highly accurate, consistently reliable interpretation of the received SPR signals to determine concrete cover, spatial distribution of reinforcement and concrete element thickness can be performed only by an experienced data analyst. Such experience can be gained through use of the system and through training courses supplied by various equipment manufacturers or consulting companies. Alternatively, the operator may wish to use computer processing and visualization software to automatically track the concrete cover, spatial distribution of reinforcement and concrete element thickness, where applicable.

5. Measuring Apparatus

- 5.1 The apparatus normally consists of a transmitter and receiver antenna, a radar control unit, suitable data storage and display devices (as shown in Figure 2).

Antenna - used for transmitting and/or receiving electromagnetic waves. A single - dipole antenna can be used to both transmit and receive signals in the monostatic mode. The bi-static mode uses separate antennas for transmitting and receiving electromagnetic pulses [1]. The center frequency of antennas should normally range from 500 MHz to 2 GHz.

NOTE The selection of antenna frequency depends on the depth of penetration, spatial resolution, and system portability required for the study. The higher the center frequency of antennas, the shorter the penetration depth is; but the better the depth resolution is, and vice versa.

Radar control unit - used to control and synchronize signals to the transmitting and receiving electronics in the antennas. The synchronizing signals control the transmitter and sampling receiver electronics located in the antenna(s) in order to generate a sampled waveform of the reflected radar pulses. These waveforms may be filtered, amplified and are then transmitted along with timing signals to the display and recording devices [1].

Data storage device - used for data storage and the recorded data shall be recalled for subsequent analysis.

Data display unit - a radargram must be capable of being viewed on a suitable display unit (for example, an oscilloscope, a grey-level chart recorder, or a CRT monitor, or a personal computer with a data acquisition board) during and after the time of testing.

6. Personnel Qualifications

Personnel performing SPR measurements shall have adequate training, qualification & experience. The training course shall be recognized and approved by the Hong Kong Concrete Institute (HKCI).

7. Hazards

- 7.1 Warning the radar apparatus used in this test method is potentially a microwave radiation hazard. All personnel shall stand clear of the region directly under the antenna when the system is energized.
- 7.2 Electromagnetic emissions from the radar apparatus, if the system is improperly operated, could potentially interfere with commercial communications such as radio signals, especially if the antenna is not properly oriented toward the ground.
- 7.3 Take care to ensure that appropriate control measures are employed when operating the radar apparatus on roads, building exteriors and airports. Such measures are essential for the safety of system operators as well as that of the general traveling public.

8. On-site Calibration and Standardization

On-site calibration of equipment shall be performed in accordance with the calibration procedures in Appendix C.

9. Testing Procedures

- 9.1 *Planning the Survey* - Successful use of subsurface SPR measurements depends to a great extent on proper planning. Without careful and detailed planning, the SPR method may not yield data significant to interpret.

9.1.1 Objectives of the SPR Survey -

Planning and design of a SPR survey should be done with due consideration to the objectives of the survey and the characteristics of the site, because they will determine the equipment to be used, level of interpretation, and the level of effort and budget necessary to achieve the desired results. Factors that need to be considered include construction details, depth of investigation, geometry of the target, anticipated properties of the target and of the host material, topography, and access to the site. The presence of sources of noise (cultural) as well as operational constraints must also be considered. It is good practice to obtain as much of the relevant information as possible about the site prior to mobilization to the field, including data from any previous SPR data, covermeter data or as-built drawings.

- 9.1.2 The purpose of the radar survey may be for reconnaissance of subsurface conditions or detailed subsurface investigations. In reconnaissance surveys, the spacing between radar lines is large, few transects are used. In a detailed survey where the targets are expected to be small, the spacing between radar transects should be small. Elevations and locations of points along the radar lines should be accurately determined.

- 9.1.3 *Spacing between Survey Lines* - while there is no pre-defined minimum spacing between measurements on the surface of the concrete member, it is of little value to take two sets of measurements from virtually the same point. Conversely, measurements taken with very wide spacing may neither detect reinforcement that is continuous nor result in the appropriate accumulation of data for evaluation. The spacing shall therefore be consistent with the member being investigated and the intended end use of the measurements.

NOTE A spacing of 0.5 to 1.0 m has been found satisfactory for evaluation of bridge decks/slabs. Generally, larger spacing up to 5.0 m may be used for scans of longer duration (e.g. road evaluations) where the cover of individual steel reinforcement is less important than the maximum and minimum covers.

9.2 **Survey Lines** - Prepare survey lines with the following considerations:

- 9.2.1 Lay out the survey lines in a straight line if possible.
 - 9.2.2 Place grid marks at equal intervals along the survey line using survey flags and tapes, measuring wheels, electronic measuring device, or other location systems.
 - 9.2.3 Note the distances so that data corrections can be made.
 - 9.2.4 The survey lines should be referred to a permanent object so the grid can be bench marked at a later date if necessary. A topographical survey may be carried out to correlate the survey lines with adjacent features.
- 9.3 Continuously traverse the radar antenna along each survey line using the odometer calibration settings method suggested by the manufacturer. The speed of the traverse will determine the number of data points per unit distance. For air-coupled antennas, the traverse speed is constrained only by the desired spacing of radar scans and the travel speed of the vehicle. For ground-coupled antennas, the traverse speed is controlled by the sampling frequency of the odometer signals in order to maintain stable ground contact and not to miss radar scans due to under-sampling of the odometer signals.
- 9.4 Identify the signal reflection associated with the test surface (normally concrete) using the display devices. If the survey is not clear, re-run test line. Record any parts of the trace that are not clear as 'data unclear'.
- 9.5 Perform the procedures of dielectric constant calibration according to one or more than one of the methods stated in Appendix C.
- 9.6 Identify the signal reflection associated with the steel reinforcements (if present) and the concrete-air interfaces (if present).
- 9.7 Determine the time interval, Δt , between these reflections (i.e. steel reinforcements and the concrete-air interfaces identified in Clause 9.5).
- 9.8 Determine the lateral distance Δl between adjacent signal reflections associated with the steel reinforcements as depicted in Figure 3. This distance can be made by either computer determination or manual printing and measurement using rulers or other instruments with a suitable accuracy.
- 9.9 Data Processing (optional) - Filtering of radar data during or after testing may be used to remove unwanted noise and correctly locate reflectors on the radargrams. Filtering processing tools may include, but not limited to, background subtraction, 'dewow', Hilbert transforms, migration, and time - varying gain. Figures 4 and 5 illustrate the performance of these filtering processing tools. Care must be taken when processing radar data because artifacts can be inadvertently introduced into the data.

10. Calculation and Expression of Results

- 10.1 Calculate the cover/element thickness, using the constant ϵ_r and the time interval Δt , (determined in clause 9.7) by the following equation (provided that the studied concrete is a low-pass material):

$$D = \frac{(\Delta t)(c)}{2\sqrt{\epsilon_r}} \quad (3)$$

Where:

D is the measured cover/element thickness (in mm);

Δt is the two-way pulse travel time between test surface and either top of reinforcement or back of test element under test (in ns);

c is the propagation velocity of electromagnetic waves in free space (3×10^8 m/s);

ϵ_r is dielectric constant of concrete calibrated with one or more of the methods stated in Appendix C.

- 10.2 Record the cover of all steel reinforcements to the nearest 1 mm and the thickness of the element to the nearest 5 mm.
- 10.3 The spacing of the steel reinforcements should be determined using the grid marks and the lateral distance Δl , and shall be recorded to the nearest 5 mm. Alternatively, the co-ordinates of each individually located steel reinforcements should be recorded for more precise measurement.
- 10.4 Diameters of steel reinforcements are not possible to be determined with the current method in this practice despite the signal spread is related to the reinforcement sizes.

11. Reporting

- 11.1 The following is a list of the key items that should be contained within most formal reports.
- 11.2 Report the following information:
 - Purpose and scope of the SPR survey
 - Date of survey and location of testx
 - Reference to this document
 - Limitations of the SPR survey (sources of noise, logistic constraints)
 - Assumptions made
 - Field approach used along with a description of the equipment and the data acquisition and display parameters, such as date of acquisition, gains, filters, antenna frequency, and geometry, etc.
 - Location of radar transects on a site map, directions of antenna motion along transects, orientation of antenna polarizations, distance from these transects to the adjacent features such as a wall
 - Corrections applied to field data and justification for their use
 - Measured results
 - Calibration methods for determination of relative dielectric constants of on-site materials
 - Software program(s) and steps for processing
 - Radargram(s) (an example as shown in Figure 3) showing the location(s) of steel reinforcements
 - Presentation of Data(optional and highly recommended)—Two-dimensional slice views at multi-Depths (an example as shown in Figure 6) and three-dimensional cube view (an example as shown in Figure 7) giving a whole picture of the orientation and alignment of the steel reinforcements embedded, other Anomalies and element thickness of a concrete structure.

12. Vertical Resolution

- 12.1 The resolution as described in this test method can be considered in two ways: (1) how small a change in depth can be determined by the SPR method and (2) how thin a layer can be detected by the SPR method.
- 12.2 The resolution of a SPR system is determined by the center frequency of the antenna. A typical system for this application usually has a resolution sufficient to determine a minimum cover of 25 mm with an accuracy of ± 5 mm, spacing of steel reinforcements with an accuracy of ± 5 mm, and measurement of concrete element thickness with an accuracy of ± 5 mm or 10 % whichever is greater. Improvements in the resolution of the system may be possible with additional data processing tools as described in Clause 9.9.
- 12.3 A better resolution can be obtained with high-frequency antennas (such as 2 GHz) comparing with low-frequency antenna (1 GHz) (see Table 2). However, high frequency signals result in a loss of the depth of penetration. In general, attenuation becomes significant with the centre frequency beyond 1 GHz due to the water relaxation effect, as shown in Figure 1.

13. Limitations

- 13.1 As the electromagnetic wave generated by a SPR system propagates through the test material and the wave is attenuated, dispersed and reflected at layer interfaces. At some depth, due to the wave attenuation and dispersion, the reflections at the layer interfaces cannot be detected by the SPR. This maximum penetration depth is a complex function of SPR system parameters such as transmitted power, receiver sensitivity, center frequency and bandwidth of the SPR system and signal processing, as well as the electromagnetic properties of the materials and environmental factors such as moisture content.
- 13.2 This test method may not be suitable for application to test surfaces which exhibit increased conductivity due to the increased attenuation of the electromagnetic signal. Examples of scenarios which may cause this are: extremely moist or wet (saturated) surfaces if free electrolytes are present and slag aggregate with high iron content [8]. Further details can be found in Ref. [9] - [10].

Table 1 Approximate dielectric constants of various materials [9]

Material	Relative Dielectric Constant ϵ_r
Air	1
Fresh Water	81
Wet Concrete	10-20
Dry Concrete	4-10
Steel	∞

Table 2 Vertical resolution limits (centimeters) for various antenna frequencies and relative dielectric constants (ϵ_r) based on $(\frac{1}{4})\lambda$ [1]

ϵ_r	1	5	10	15	25	80
Centre frequency of antenna (GHz)						
0.5	15.00	6.71	4.74	3.87	3.00	1.68
0.8	9.38	4.19	2.96	2.42	1.88	1.05
1	7.50	3.35	2.37	1.94	1.50	0.84
1.2	6.25	2.80	1.98	1.61	1.25	0.70
1.4	5.36	2.40	1.69	1.38	1.07	0.60
1.6	4.69	2.10	1.48	1.21	0.94	0.52
1.8	4.17	1.86	1.32	1.08	0.83	0.47
2.0	3.75	1.68	1.19	0.97	0.75	0.42

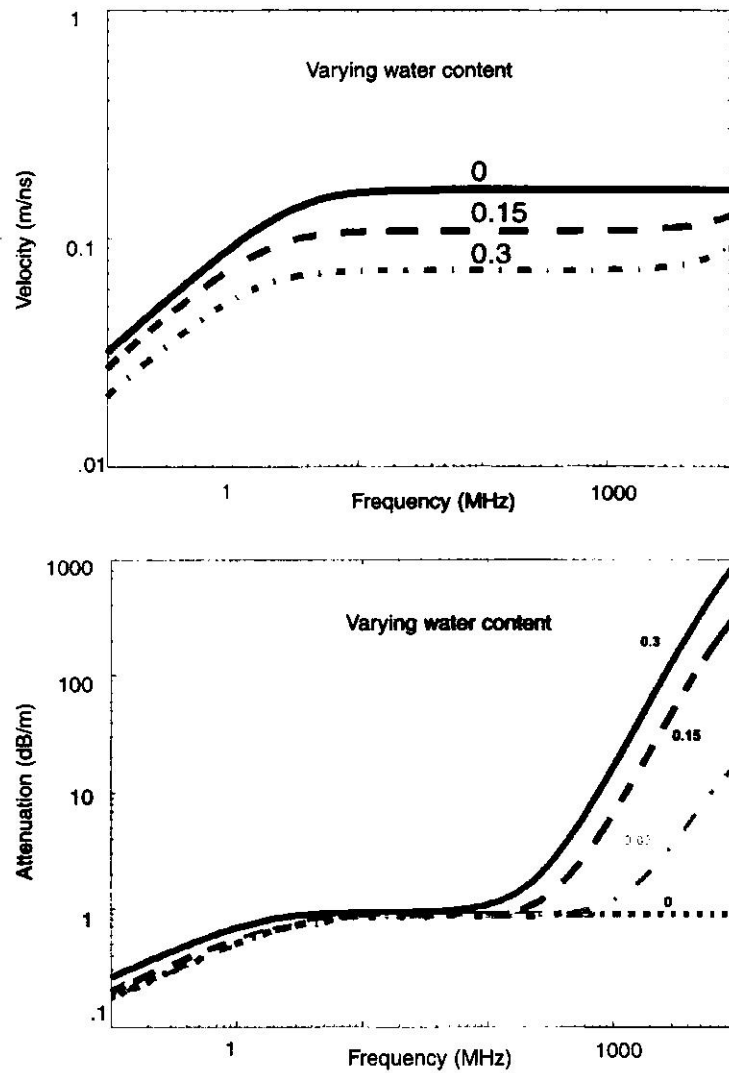


Figure 1 Velocity and attenuation plateau at different SPR frequencies [10]

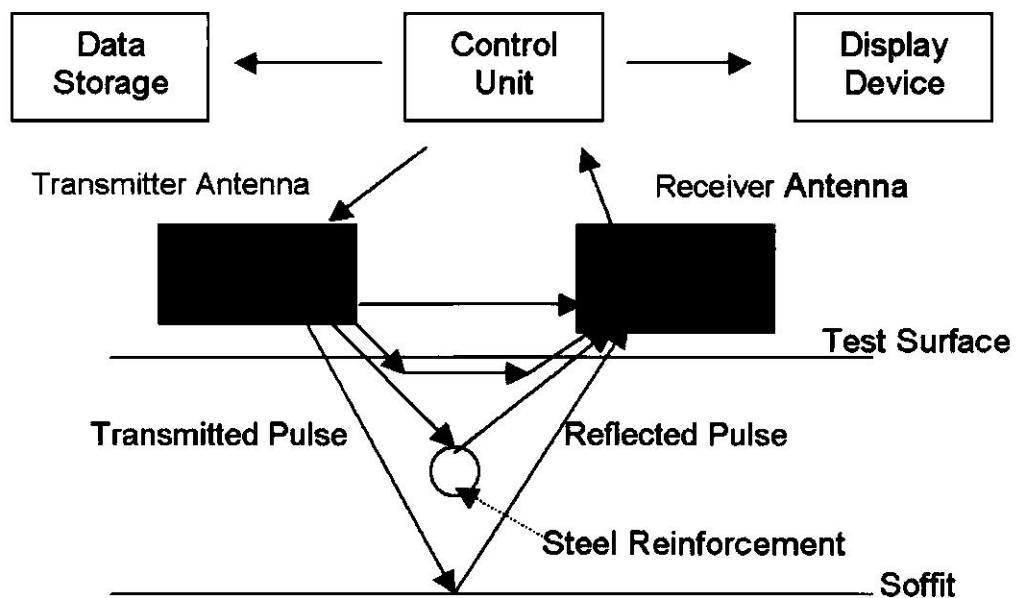


Figure 2 Schematic drawing showing the configuration of the typical SPR system

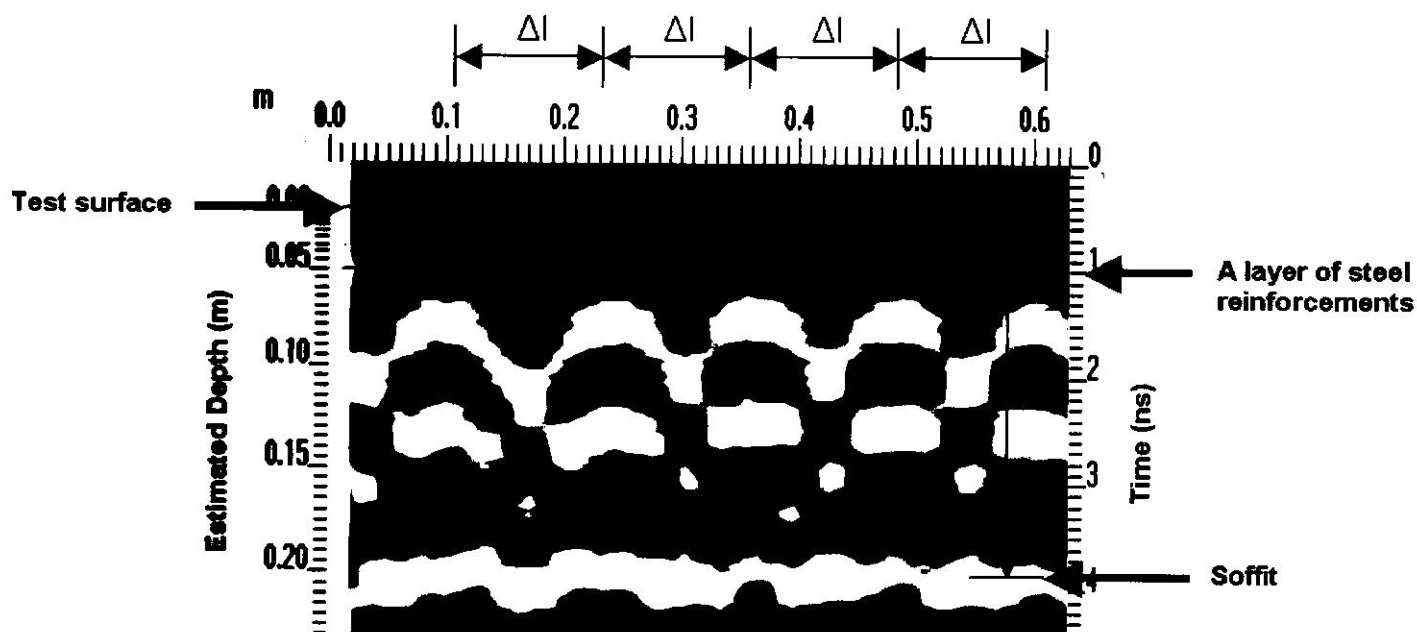


Figure 3 Two-dimensional radargram showing a layer of steel reinforcements embedded within concrete

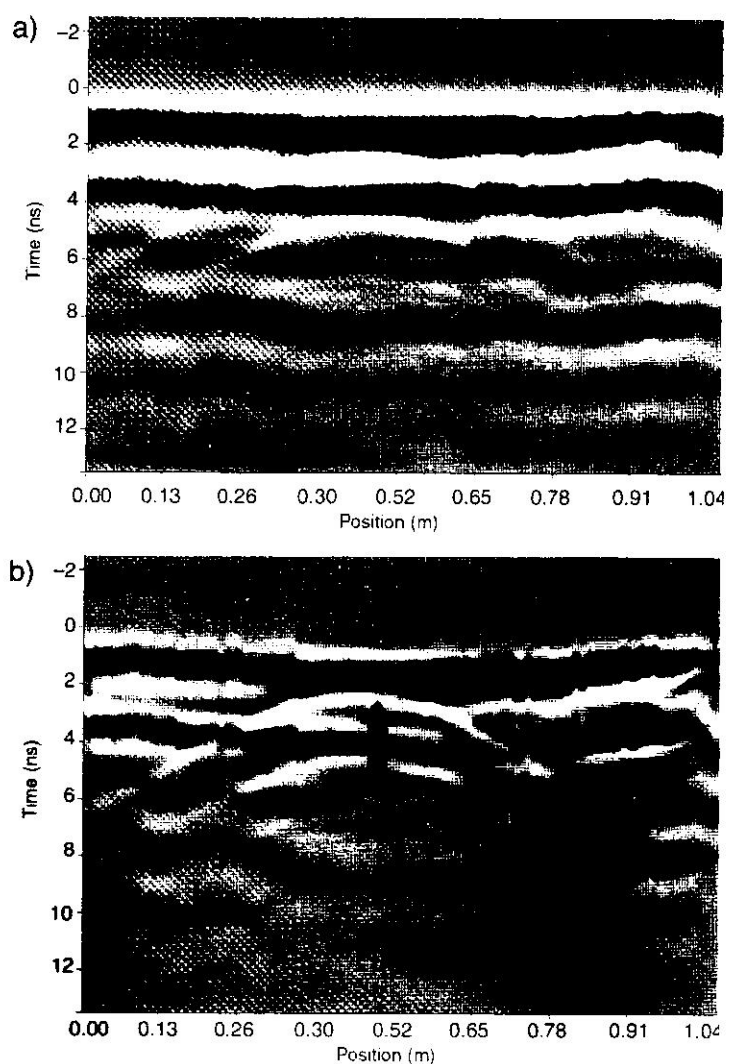


Figure 4 Radargram (a) before; and (b) after a data processing method called background subtraction [10]

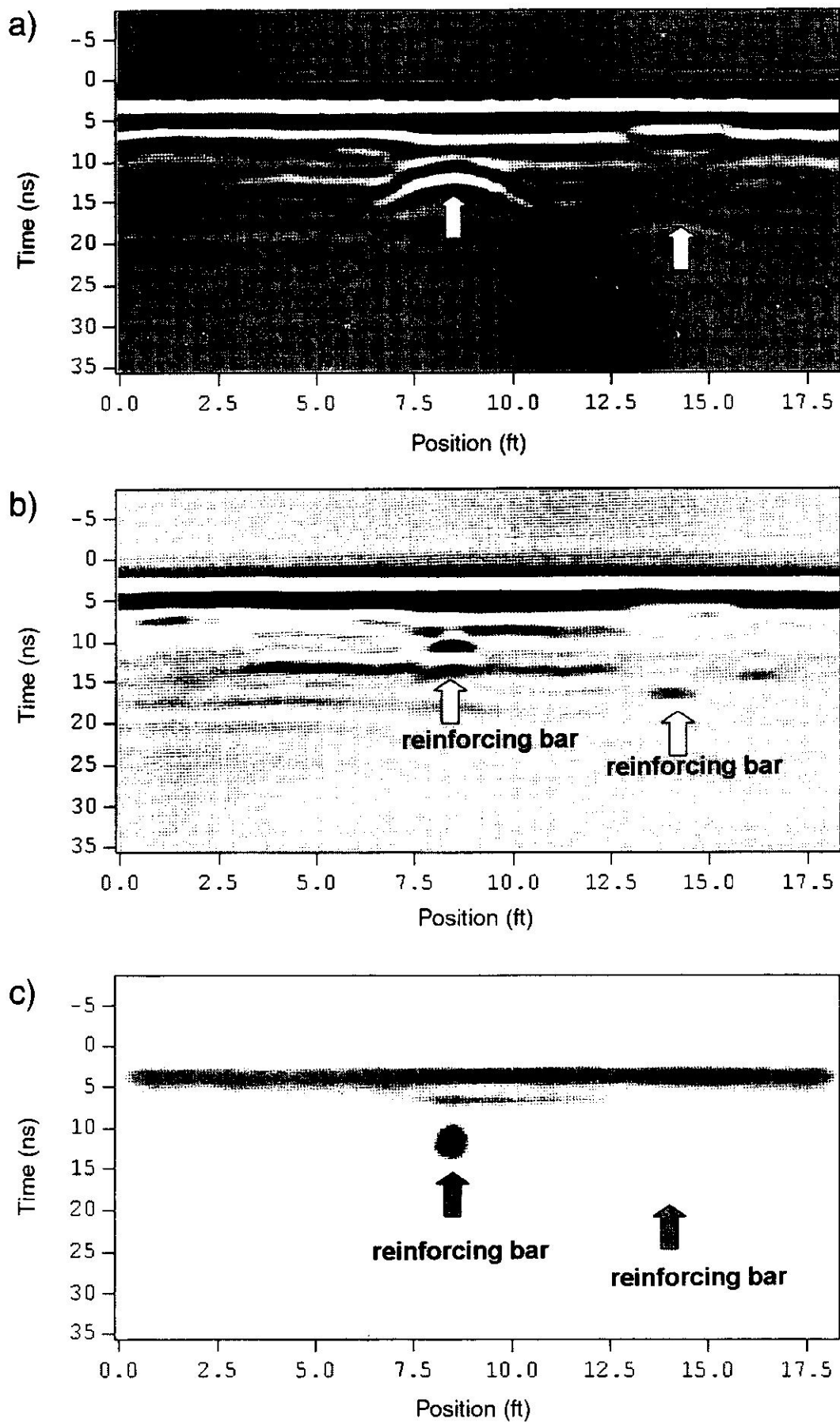


Figure 5 Radargram (a) without data processing method; (b) after Kirchhoff migration; and (c) after Hilbert transform [10]

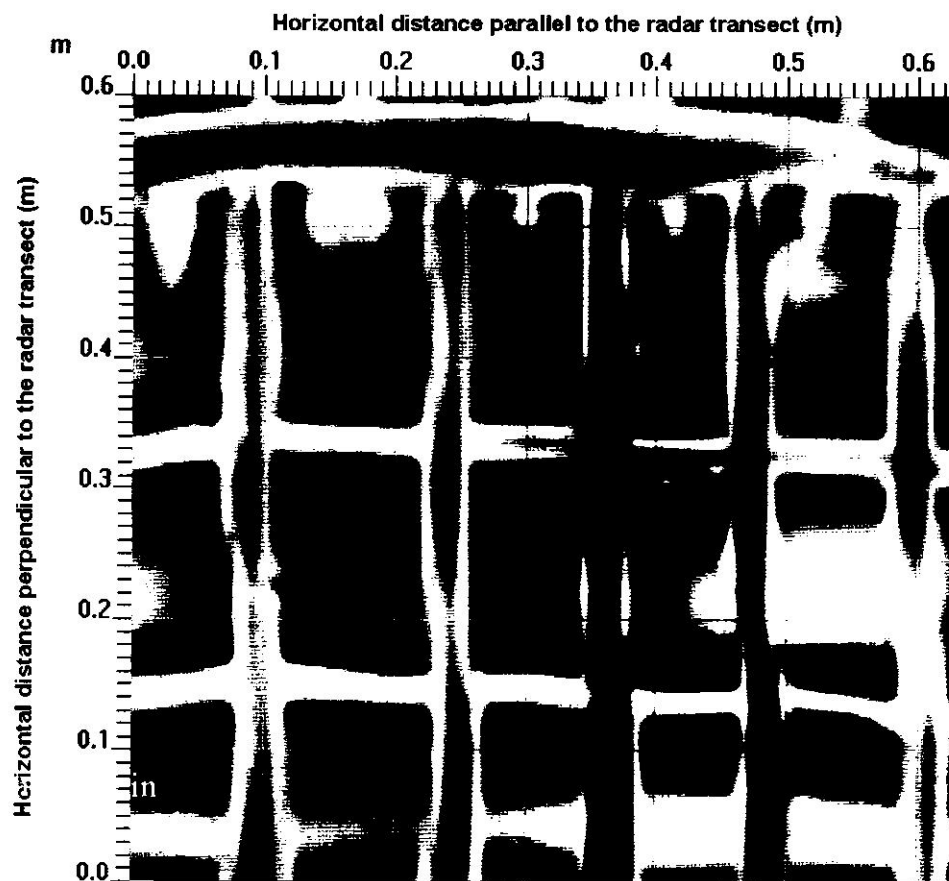


Figure 6 Two-dimensional slice view for radar signals collected at a depth from 50-75 mm beneath a concrete surface

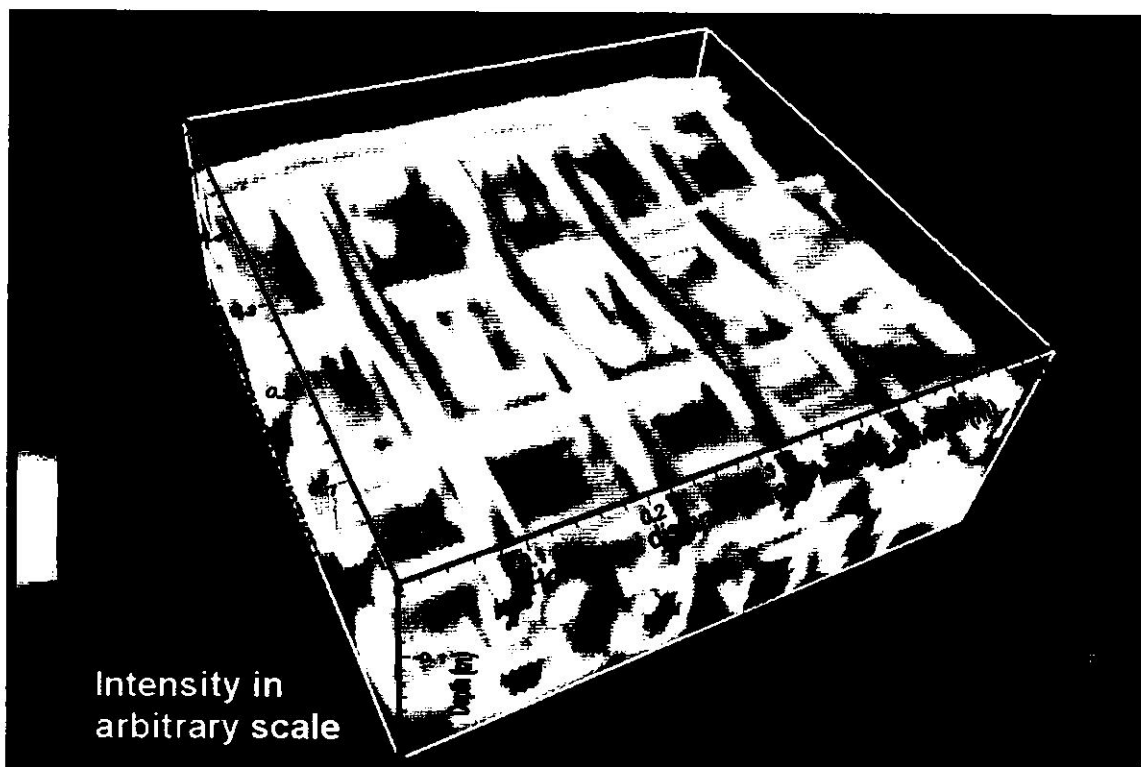


Figure 7 Three-dimensional cube view giving a whole picture of the orientation and alignment of steel reinforcements embedded within concrete (after background subtraction, 'dewow' filtering, migration and Hilbert transform)

Appendix A

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Appendix B

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Appendix C

On-site Calibration of Dielectric Constant of Concrete

C1 On-Site Calibration of Dielectric Constant

- C1.1 The dielectric constant, ϵ_r , for the concrete under the investigation must be estimated or determined. This dielectric constant is used to calculate the SPR wave velocity, which is then used to determine cover of reinforcement or thickness of concrete elements according to Equation C1.
- C1.2 Position the antenna over an area of known concrete element thickness and with absence of steel reinforcement and other anomalies (subject to prior information). Hold a metal plate at the surface of the concrete element, which is directly opposite to the antenna. Then, collect two waveforms (one with and another without the metal plate).
- C1.3 By comparing the two waveforms collected in Clause C1.2, measure the time interval in nanoseconds, Δt , between the surface reflection (or ground zero defined by the manufacturer) to the corresponding reflection from the other side of the element. It should be ensured that same polarity signals (preferably positive ones collected with the presence of the metal plate) are used for time interval determinations. This procedure may be carried out on-site for immediate calibration or off-site for post-calibration.
- C1.4 Calculate the dielectric constant, ϵ_r , for the concrete using the following equation:

$$\epsilon_r = \left[\frac{(c)(\Delta t)}{2D} \right]^2 \quad (C1)$$

where

c is the propagation velocity of electromagnetic waves in free space (3×10^8 m/s);

Δt is the two-way pulse travel time between test surface and either top of reinforcement or back of test element under test (in ns);

D is the measured cover/thickness of element (in mm).

- C1.5 The dielectric constant thus calculated can be used for all measurements made where the concrete appears identical to those in the calibration. If the materials change laterally according to visual inspection and/or subtle lateral differences in radargram, a new calibration would be necessary.
- C1.6 Record all machine calibration settings and try to maintain these settings for the whole survey. If any changes of settings are made then recalibration will be necessary as this could impact the test results.

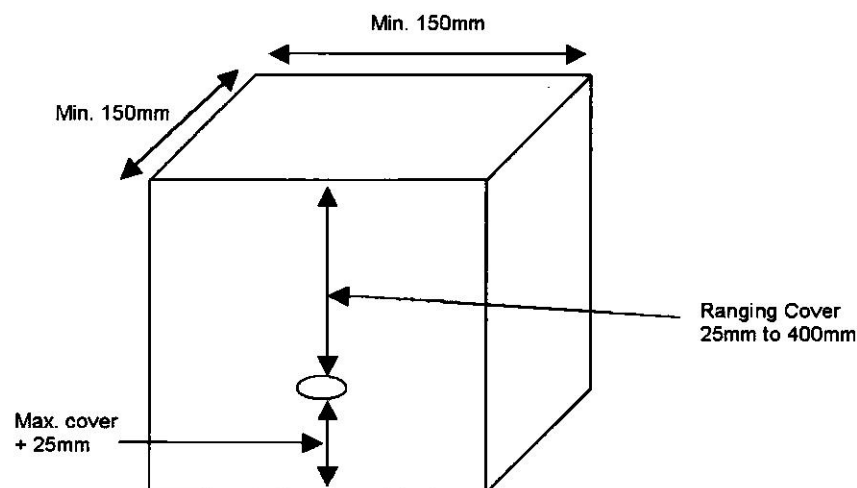


Figure C1 Schematic drawing of a control block for the calibration measurement

On-Site Surface Calibration of Dielectric Constant using Hyperbolic Geometry from point reflectors

Calibration with hyperbolic geometry of a steel reinforcement makes use of point reflectors such as pipes and steel reinforcements that result in a hyperbolic pattern on the radargram. Figure C2 illustrates a hyperbolic signature from a steel reinforcement. This information can be used to calibrate the surface dielectric constant when a distance along the ground (x) and two-way travel time ('a' and 'b') to an object, in Equation C2, are known. Both pieces of information are scaled from the data. It must also be cautious that the point object must orient perpendicularly to the radar transect, otherwise dielectric constant would be incorrectly estimated.

$$\epsilon_r = \left[\frac{1}{\left(\frac{1}{2b_1} \right) \left(\frac{x}{\sqrt{\left(\frac{b_1}{a} \right)^2 - 1}} \right)} \right]^2 \quad \text{Or} \quad \epsilon_r = \left[\frac{1}{\left(\frac{1}{2b_2} \right) \left(\frac{x}{\sqrt{\left(\frac{b_2}{a} \right)^2 - 1}} \right)} \right]^2 \quad (C2)$$

where

x is the distance along the concrete surface;

b₁ and b₂ are the two-way travel time or 'slant range' to steel reinforcement or buried pipe perpendicular to the radar transect;

a is the two-way travel time to pipe when antenna is directly over pipe;

ε_r is dielectric constant of concrete.

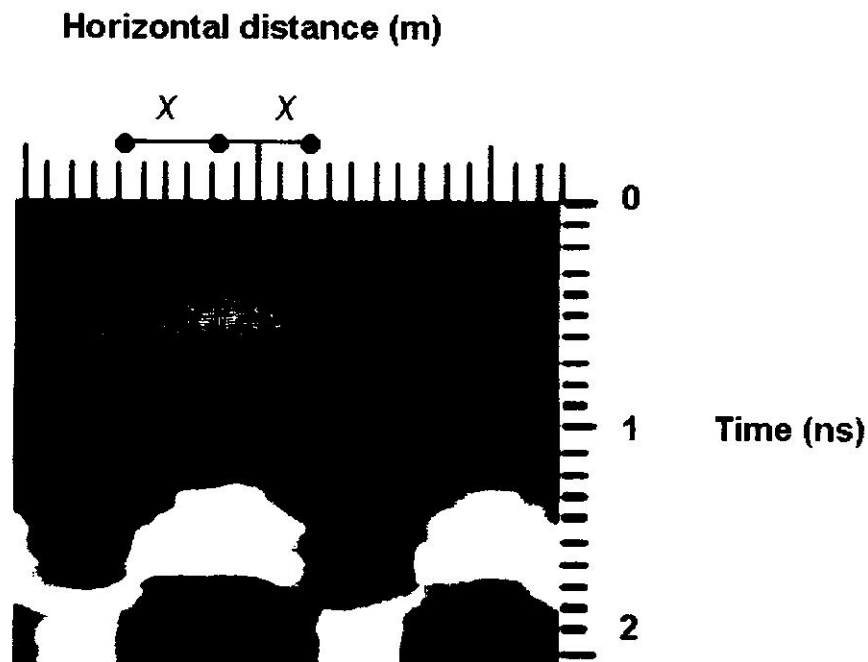


Figure C2 Partial radargram showing the reflection by a steel reinforcement perpendicular to radar transect

C3 'Best-guess' Estimates of Dielectric Constant

If it is impossible to perform the calibration procedures stated in Appendix C1 and C2 because of on-site physical constraint, then estimation of dielectric constant shall be made by an experienced operator based on known dielectric constants for given materials. If the latter is the case, this must be clearly stated in the report as this may have a significant effect on the accuracy of the test results. Typical dielectric constants of different materials are given in Table 1.

At least one of the calibration procedures (C1 or C2) should be carried out for a proper SPR survey. Procedure C3 ('best-guess') can only be used if on-site physical constraints make C1 or C2 not possible to carry out. However, it must also be realized that procedures C1 and C2 are subject to on-site variation of materials and differences of the SPR system. Therefore, the calibrated results represent a convenient use of average velocity estimation for practical purpose, but do not necessarily represent the true dielectric constant and velocity which may differ from place to place.