An initial appraisal of ground probing radar for site investigation in Britain

by BRIAN W. DARRACOTT, PhD, BSc, MinstP, MIGeol, MBIM, FGS & MARK I. LAKE, MSc, BA, AMIGeol

GROUND PROBING RADAR refers to the technique of using an impulse radar system to study sub-surface soil and rock conditions. From initial applications some 20 years ago in the mapping of ice thickness from aircraft, the method has been developed to the extent that a number of systems now exist, with experience in such areas as the exploration for near-surface buried objects (pipes, cables and voids) and the general mapping of geological discontinuities. The technique has also been used in tunnels, mines and boreholes; for the mapping of permafrost; and in archaeological prospecting.

References 1 to 14 provide a representative background to this work, and describe some of the various systems. It is clear from this list that virtually all the experience to date has been in the United States. To our knowledge, only one earlier serious study of the use of ground probing radar has been made in the UK11, but this concentrated on system design, rather than applications.

In 1977, Wimpey Laboratories Ltd. became interested in the use of ground probing radar as a site investigation tool in the UK. Subsequently, in early 1978, one of the commercially available systems - manufactured by Geophysical Survey Systems Inc. (GSSI) of New Hampshire, USA — was imported into the UK by Fenning Environmental Products Limited (FEP). As suppliers of geophysical equipment, FEP had also recognised the potential usefulness of ground probing radar.

In view of the relative paucity of knowledge and experience in ground probing radar and its value in shallow sub-surface exploration, Wimpey Laboratories decided to conduct a series of trials of the GSSI system. Accordingly, the equipment was leased from FEP during the three-month period from November 1978 to January 1979 and used on a number of "typical" UK site investigation problems. This article describes the equipment used, the results of the tests, and points to some of the problems and limitations of use in the UK.

The GSSI system

The GSSI impulse radar system, fully described by Morey6, has been developed primarily as a shallow sub-surface exploration tool for engineering applications. The technique is sometimes known as electromagnetic sub-surface profiling, and can be considered as the electromagnetic equivalent of the single-trace acoustic profiling methods used for marine sub-bottom profiling. In practice, continuous profiling is carried out by towing a trolley-mounted antenna by hand, for short profiles (Fig. 1), or behind a vehicle. The antenna is connected via a 30m umbilical cable to the transceiver and recorders, which would usually be mounted in the rear of a van or estate car.

Fig. 2 shows the system in block diagram and functional form. The radar set operates from a 12V battery and draws about 1.5 amps. The radiated signal is a brief electromagnetic transient (3 nanoseconds) with a bandwidth of approximately 120MHz in the low VHF range (100MHz). The transmitter pulse repetition rate is 50kHz; peak power is 35 watts, and average power is 5.2 milliwatts. The signals are reflected from sub-surface interfaces and/or buried objects, and are received by the same antenna used for transmission. The receiving system electronics translates the repetitive received waveform, after amplification, to the audio frequency range by a time-domain sampling technique, whereby progressive amplitude samples are taken from each successive received waveform and used to reconstruct a waveform of similar shape having a much longer time base.

This reconstructed waveform is monitored on a small CRT and displayed in real-time on an EPC Laboratories graphic recorder. This recorder operates from a 110V power supply, drawing 15 amps, necessitating a small generator on site. Finally, the signals can be tape-recorded for later playback at optimum gain and sensitivity settings. A typical radar record obtained with this system is shown in Fig. 3. The chart paper can be calibrated in nanoseconds of time, and therefore also in terms of depth once the relation between the log of the range and the number of nanoseconds is known.

In the following table, the waveforms are described briefly, and the conversion of the amplitude samples into a suitable display on the recorder is indicated in the form of the parameters and limitations of use in the UK.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity, (mho.m⁻¹)</th>
<th>Dielectric constant, Er</th>
<th>Attenuation, dB.m⁻¹</th>
<th>Velocity, cm.ns⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Fresh water</td>
<td>10⁻³</td>
<td>81</td>
<td>0.18</td>
<td>3.3</td>
</tr>
<tr>
<td>Sea water</td>
<td>4.0</td>
<td>81</td>
<td>0.33</td>
<td>3.3</td>
</tr>
<tr>
<td>Sandy soil, dry</td>
<td>1.5 x 10⁻⁴</td>
<td>3</td>
<td>0.14</td>
<td>17</td>
</tr>
<tr>
<td>Sandy soil, wet</td>
<td>7 x 10⁻³</td>
<td>25</td>
<td>2.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Clayey soil, dry</td>
<td>2.5 x 10⁻⁴</td>
<td>3</td>
<td>0.28</td>
<td>17</td>
</tr>
<tr>
<td>Clayey soil, wet</td>
<td>5 x 10⁻²</td>
<td>15</td>
<td>20</td>
<td>7.8</td>
</tr>
<tr>
<td>Granite, dry</td>
<td>10⁻³</td>
<td>5</td>
<td>10⁻¹</td>
<td>13</td>
</tr>
<tr>
<td>Granite, wet</td>
<td>10⁻³</td>
<td>7</td>
<td>0.6</td>
<td>11</td>
</tr>
<tr>
<td>Basalt, wet</td>
<td>10⁻³</td>
<td>8</td>
<td>5.6</td>
<td>11</td>
</tr>
<tr>
<td>Shale, wet</td>
<td>10⁻¹</td>
<td>7</td>
<td>45</td>
<td>11</td>
</tr>
<tr>
<td>Sandstone, wet</td>
<td>4 x 10⁻²</td>
<td>6</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>Limestone, wet</td>
<td>2.5 x 10⁻²</td>
<td>8</td>
<td>14</td>
<td>11</td>
</tr>
</tbody>
</table>

*Principal Geophysicist, Wimpey Laboratories Ltd. ‡Geophysicist, Wimpey Laboratories Ltd., now with Compagnie Générale de Géophysique.

Fig. 1. The GSSI system radar antenna being used to locate pipes buried beneath a road in Camberley, Surrey.
The relationship between travel-time and depth is known. Travel time is related to depth by the equation:

\[ V = \frac{2D}{T} \]

where \( D \) = depth to reflecting interface, \( T \) = elapsed time between transmitted and received pulse, and \( V \) = effective propagation velocity through the overlying material.

Also, \( V = \frac{C}{E_r} \)

where \( C \) = propagation velocity in free space (3 \( \times 10^8 \) m.s\(^{-1} \))

\( E_r \) = effective relative dielectric constant of the material.

Table 1 lists some "typical values" of velocity from commonly encountered materials. A useful average value of the velocity, \( V \), would be 8cm.ns\(^{-1} \). If the depth to a target or interface is known from other data, the velocity can be obtained, giving some indication of the moisture content of the soils.

**Factors affecting the use of radar**

The major factors that affect the performance of a ground probing radar system are:

(i) conductivity of the soil,

(ii) dielectric contrast between target and the soil,

(iii) the shape of the target and its orientation with respect to the radar antenna, and

(iv) density of scattering bodies within the soil that produce reflections similar to those from the target.

---

Fig. 2. Block diagram of the GSSI ground probing radar system (after Ref. 3)

Fig. 3. Radar record from a school playground, Edinburgh
Of these, the one that places the greatest limitations on the use of radar in engineering site investigation is the soil conductivity. The penetration depth of the radar energy is dependent upon the effective conductivity of the materials being probed, which, in turn, is primarily governed by the water content and the amount of salts in solution. Further, the effective conductivity value is also a function of temperature and density as well as the frequency of the electromagnetic waves being propagated. Table I shows the range of approximate attenuation factors likely to be encountered. It can be immediately seen that the least penetration is to be expected in saturated clayey materials or where any moisture is saline. In view of this, it is always wise to measure the conductivity of the soils (from a standard resistivity sounding) before a radar survey is carried out. The values of average maximum effective range in Table II can then be used to assess the applicability of the method.

The penetration of the radar energy could be increased by using a lower frequency, but this would have the unwarranted side-effect of reducing the resolution of the system.

UK test surveys
In view of the foregoing, it was clear that before the ground probing radar technique could be offered with confidence as a site investigation tool for general use, its applicability in the UK needed assessing.

The first real opportunity to do this arose in July 1978 when the GSSI radar system was used, alongside other methods, at a site in North Wales. Following an announcement of this work, many enquiries were received, concerning the application of the method to a range of different problems. Some of these enquiries were followed up during the period November 1978 to January 1979 and formed the basis of the present study.

From the outset it was decided not to rely on a “back-yard” evaluation, in which only a limited number of known situations would be covered, but to use real problems, encompassing as far as possible the range of typical targets, site and weather conditions that would be met in real life.

(i) Bagillt, Clwyd, North Wales

The specific aim at this particular site was to see if the ground probing radar could give any indications concerning the location of two suspected abandoned mine shafts. The site, measuring 100m x 50m, was oriented approximately south-west to north-east. The ground surface was generally undulating, sloping down to the north-east, and was covered by rough grass, nettles and thistles, and occasional old bricks. The site appeared to be well drained, although the work was conducted during the summer (July, 1978). A total of 35 lines of 40m length were traversed in a NW-SE direction. This represents a total of nearly 1.4km, which was accomplished in an afternoon, after initial setting up of the equipment.

Due to its low ground clearance, the antenna trolley required two people to pull it over the rough ground. The relatively short umbilical cable (30m) made it necessary to move the vehicle and recording apparatus every five or six lines. The records obtained were not clear, and proved difficult to interpret quantitatively: it was only possible to identify zones of different “character” and plot these on a plan of the site. These anomalous areas were all near-surface features. Subsequent trenching at the site to a depth of about 2m revealed a thin veneer of topsoil, covering either sandy clay or colliery fill. The sandy clay was associated with resistivity values of 100-200 ohm.m and the colliery fill with values of 250-500 ohm.m. The depth of penetration of the radar energy in the sandy clay was likely to be of the order of 2-3m.

The radar records showed no indication of the change from sandy clay to colliery fill, though there was some evidence that the anomalies previously noted represented areas of higher clay content within the sandy clay. The anomalies could also have been caused by locally higher moisture content. No indication of the two infilled shafts was seen, and in this respect the survey could not be regarded as successful.
Edinburgh

The objective here was to provide additional information on the location and extent of the radar signal beneath a school building. A number of trial lines were first run over a known buried sewer pipe, producing an identifiable diffraction pattern (see Fig. 5 for similar example). However, no buried object was noticed beneath the pipe. The calculated depth to the top of the pipe was 0.9m, which coincided well with the known depth of the pipe. This gave confidence to the depth calibration of the system, and it was decided to give a full depth of 10m, on the assumption of an average effective dielectric constant of 16 for the sub-surface materials.

The survey lines were carried out at accessible places in the grounds surrounding the school building. Those lines which crossed the asphalt area of the school playground produced good records with several strong reflectors apparent to a depth of 10m. The survey lines conducted elsewhere and the site produced records which showed only a limited depth of penetration of the radar signals of about 1m.

It was immediately evident from some of the lines that as the antenna passed from the asphalt to the grass fields that the penetration was greatly reduced (Figs. 3 & 4). This difference can be ascribed to the fact that the soil directly beneath the asphalt playground had been protected from surface rainwater and consequently had a much lower conductivity than the soil in the grass covered areas.

No cavities were indicated on the records, to a depth of about 10m. Since the cavities encountered by the boreholes drilled later were all at a depth greater than 10m it seems reasonable to conclude that the difference in radar penetration of the equipment been calibrated to allow reflectors to a depth of 15m to be recorded, then a response would have been seen for cavities occurring at depths between 10m and 15m — at least beneath the asphalt areas.

(iii) Marlborough, Wiltshire

Surveys for two different purposes were carried out here. In the first case, the radar system was used in an attempt to locate the sewerage beneath the A4 trunk road to the west of Marlborough. The services had earlier been located by another electromagnetic survey method carried out by Subtronic Ltd. Results from traverses across and along the road did not show any features which could clearly be identified as resulting from buried pipes or cables, and the survey cannot be regarded as a success.

A survey was also carried out on a site near the town. The object was to locate possible swallow holes and solution cavities below the floor of a dry valley cutting the Middle and Upper Chalk. This valley was believed to be filled to a depth of less than 2m with river gravel and alluvium and hence it was thought that the ground probing radar would be suited to the task. Very low penetration of energy was obtained in practice, and a subsequent trial survey showed the valley to be filled to a depth of 1.5m with clayey material; no reflections from the chalk, here at 1.7m, were recorded.

Penetration of the energy only increased when there was a layer within 0.5m of the surface. Hence at this site the radar seemed most useful for mapping the boundary between the chalk and the dry valley fill.

(iv) Woolwich, Kent

One aspect of the Thames Barrier works involves the strengthening of the existing sea wall. At Woolwich, where sheet piling will be used, concern had been expressed over the resistance to the installation of the sheet piling that may be presented by buried and polluted sedimentary deposits. At Fullers Wharf. This was built in 1934, at a depth of about 1.5m beneath the present riverside track. The fill and tip material probably overlie peat.

A ground probing radar survey was carried out in an attempt to locate the wharf or its remains. Traverses were made along the riverside track towning the antenna at walking pace. The records showed a pattern of modulated and low penetration of the signals. In the zones of low penetration (less than 1.5m) there was a distinctive response showing as a "white zone" on the record. Where there was greater penetration (up to 3m or more) the response was typical of that obtained from unsorted fill in other areas.

The conclusion was that the zones of low penetration are the old wharfs with the deckings probably intact, and the zones of higher penetration show the fill between the wharfs. The top of the wharfs seemed to be about 1m deep. This interpretation correlated very well with the suspected position of the wharf shown on a plan and in the engineer concerned with the project.

It is not clear why there was a poor signal return from beneath the presumed position of the wharfs. Either there was a total reflection from the saturated top layer of the old deck, possibly with an air-filled cavity immediately beneath, or, more likely, the zones beneath the wharfs are filled with a material of a higher clay content than the zones between the wharfs.

(v) Wickhamford, Worcs.

The object of this survey was to determine the depth to bedrock in the proposed extension of the Wolvercote Village. Earlier seismic refraction work carried out by the Department of Geological Sciences, University of Birmingham, showed the geology to be Lower Lias limestone overlain by lacustrine clays, up to 2m thick.

A number of traverses were run over short grass, others along asphalt paths. In all cases, the penetration was very limited, in spite of the fact that the water table was at a considerable depth. None of the records showed features typical of limestone bedrock; the only distinctive features could be correlated with small near-surface disturbances in the soil (e.g. over a buried manhole cover).

Resistivity measurements indicated an apparent resistivity of the clay of 25-300hm.m, which implies a penetration of only 1m. This example shows the importance of obtaining resistivity information before embarking on the radar survey.

(vi) Blue Bell Hill, Aylesford, Kent

Site investigation for a new bridge had revealed the presence of a 3m-thick layer of clay-with-flints overlaying the Upper Chalk, in three boreholes, but infilled solution features of up to a depth of 20m in two further boreholes. The estimated saving in cost of the proposed bridge piling was £20,000. Further ground probing radar surveys justified a further investigation, if it could be shown that the solution features do not extend beneath the proposed foundations.

Among other methods, a radar survey was carried out at this site. Although the existence of the clay-with-flints did not offer encouragement, it was, nevertheless, felt worthwhile trying, particularly since the limitations of the radar system were still being assessed. However, on all traverses, the penetration of signals was very low and nowhere was even the chalk surface reached.

(vii) London Docks Development

At the site of an old warehouse, a concrete raft, 2m deep and 2m thick, was thought to exist. Two boreholes over the supposed position of the raft showed about 0.9m of surface concrete and brickwork, over 2.7m of soft, moist fill and silt over 0.5m of grey clayey sandy silt, silt and an unknown thickness of brown-grey silty clay. The boreholes reached 9m without encountering any buried raft. A radar survey was carried out in an attempt to detect the raft (if it existed). The site conditions (very hard rubble) proved very difficult to work in. Penetration of the radar signals over the areas covered by surface concrete and surface fill was barely 2m and no significant reflections were noticed. It was concluded that the equipment was not adequate for finding buried structures, and in due course, the occupation of the site ceased. The survey was continued and extended whilst roadworks were in progress and for which the TRRL also had precise information about the locations of the various underground services (Fig. 1). Typical subsurface ground conditions were:

- 0 — 0.05m Antarctic
- 0.05 — 0.03m Gravel/sand sub-base
- 0.03 — 0.36m Organic matter
- 0.36 — 0.75m Brown and grey gravelly sand
- 0.75 — 1.10m Layer of flint
- 1.10m (no water table apparent)

The antennas were hand-carried across the street to give six wire-controlled traverses. The equipment controls were set such that penetrations of up to 2 or 3m would be recorded full-scale on the graphic recorder. Beneath the southerly lane of the street was a Post Office duct and beneath the northerly lane, a number of closely spaced pipes were known to exist. Records from all six traverses showed the classic parabolic diffractions to be expected from these materials. Fig. 5 shows, the single Post Office duct was clearly located, and accurately interpreted to be at a depth of 1.2m, whilst the closely spaced pipes on the north looking south, the ducts were closely located, but the individual pipes not resolved.

(ix) Stevenston, Ayrshire, Scotland

Following excavations in concrete at a chemical plant at Stevenston, there was evidence from core drilling that there were leaking, causing sand and fill below the concrete, and adjacent to pipes and gathering points, to be washed away, This could have led to collapse of the hard surface and possible damage to minor plant items.

Following discussions with the Site Engineer, a radar survey was carried out in an attempt to delineate the areal extent
of any of these cavities. The site was underlain by "strata of sand and peat; the sand layer, originally some 30-40ft thick, was consolidated to an average of 20ft using a vibro-compaction technique".

It was clear from the initial test traverses completed over the concrete that penetration of the radar signals to the zone of interest (i.e. less than 2m) would be no problem. Theoretical considerations suggested that a cavity would be associated with decreased signal penetration as the radar antenna is towed over it. This is due to the fact that the "problem" of transmitting the pulse from air to a solid medium is, in effect, "doubled-up".

However, at this site a possible cavity was detected as a zone of white on the records (see Fig. 6). This was unexpected, but seemed the only explanation, since other traverses over similar ground did not show the feature. A number of traverses in this area were carried out in order to delineate the "cavity". Similar features were observed, gradually vanishing as the survey proceeded from the initial spot. The suspected cavity was thus mapped out, and recorded for the Site Engineer.

Some months later, the plant owners drilled a number of 2in holes around the position of the suspected cavity, showing that a substantial cavity did indeed exist, though of greater extent than detected by the radar survey. The cavity was eventually backfilled with fly-ash.

In the light of experience, the discrepancy between the actual and suspected sizes of the cavity can certainly be attributed to inaccurate location by the interpretation of the radar records.

Conclusions

Although the technique of ground probing radar has been in use in the United States for some time now, it is still a relatively new method; experience of the use of the method in the UK is even more limited. There are situations where the technique appears to work well, i.e. in sandy soils; where groundwater is fresh; and in rocks; and there are also conditions where it does not work at all well, particularly in areas near-surface clays. As the test examples described above will show, this is a very serious limitation for its use in the UK. In view of this, it is regarded as most important to measure the conductivity of the soils at a site (by a simple shallow resistivity sounding) prior to embarking on a radar survey.

Like all geophysical methods, the data from the radar survey have to be interpreted in geological or engineering terms. This in turn calls for experience and skill on the part of the geophysicist, and, next to the conductivity limitation, it is this which will determine the success of a survey. Our study has also shown that the radar method would have a far greater use (soil conductivity permitting) in situations where one was searching for a known target (e.g. buried pipe, rock ledge, etc) rather than as a general reconnaissance tool, where just broad conclusions about sub-surface conditions are sought.

It was not our intention to make a critical evaluation of the GSSI system as such. However, certain design considerations which would be common to all field radars are important. The example of the survey at Camberley shows that although a single pipe can be detected quite easily (i.e. the technique is sensitive) the resolution was not adequate to distinguish the individual pipes. Similarly, it may be possible to detect the upper surface of a buried concrete slab, say, but not the lower surface. This is because the radar pulse length is of the same order of magnitude.

The resolution depends on the frequency of the signals and the pulse length. Certainly, GSSI do manufacture a range of antennae, with different operating centre frequencies ranging from 80MHz to 900MHz, but these are not readily available in the UK at the moment. In suggesting that a higher frequency will lead to better resolution, it must be remembered that the corollary is poorer signal penetration. Another practical point is the electromagnetic coupling of the antenna to the ground surface. This is affected by the compromise between mobility of the antenna and closeness to the ground. It is felt that this aspect and the choice of best operating frequencies could be useful areas for further research.

Digital processing of the radar data could also help enhance the usefulness of the technique, by, for example, removing unwanted multiple reflections from the received signals. Finally, although not strictly a GSSI system component, the EPC graphic recorder has a limited dynamic range of about 20dB and this may have led to a reduction in the usable information on the record.

In conclusion, there is no doubt that ground probing radar is a promising new method for site investigation. Provided the technique is used correctly, in the correct places, and the records interpreted carefully, it should have a useful role to play. The problems most amenable to solution by this technique would seem to be the search for buried objects such as pipes, sewers, old foundations, etc, and in the field of archaeological prospecting generally.

References

17. GSSI (no date): "Electromagnetic sub-surface profiling—Radar 'Eyes' for the scientist and engineer". GSSI Publications.