

GROUND-PENETRATING RADAR (GPR) SURVEY  
AT TELL HALIF, ISRAEL

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Introduction

Archaeologists are becoming increasingly aware of the advantages of using geophysical techniques for reconnaissance and pre-excavation surveys. These techniques are being used to facilitate excavation strategies, decrease field time and costs, and pinpoint the location of buried artifacts. Geophysical techniques compliment conventional methods of archaeological investigation. Compared with conventional methods, geophysical techniques are faster, provide greater areal coverage per unit time and cost, and are non-destructive. These techniques help to minimize the number of unsuccessful exploratory excavations and to reduce unnecessary or unproductive expenditures of time and effort.

Geophysical techniques used by archaeologists include electromagnetics (EM), ground-penetrating radar (GPR), magnetometer, and resistivity. Ground-penetrating radar (GPR) techniques have been used to locate buried artifacts in various areas of the world (Batey, 1987; Berg and Bruch,

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\* p 180 - 213. IN: M.E. Collins, G. Schellentrager, and W. E. Puckett (editors). Technical Proceeding of the Second International Symposium on Geotechnical Applications of Ground-Penetrating Radar. March 6-10, 1988; Gainesville, Florida.

1982; Bevan, 1977, 1984a and 1984b; Bevan and Kenyon, 1975; Bevan et al., 1984; Grossman, 1979; Kenyon, 1977; Parrington, 1979; Vaughan, 1986; Vickers and Dolphin, 1975; Vickers et al., 1976; and Weymouth and Bevan, 1983). These studies document the nondestructive efficiency of using GPR methods to pinpoint buried artifacts, facilitate excavation planning, and aid site interpretations.

The GPR field study at Tell Halif, Israel provided a unique opportunity to improve field procedures and develop search strategies and interpretative skills.

## Ground-Penetrating Radar

### Principles of Operation

Ground-penetrating radar is a broad band, impulse radar system that has been designed to penetrate earthen materials. Relatively high frequency (10 to 1000 MHz), short-duration pulses of electromagnetic energy are radiated into the ground from an antenna. When a pulse encounters an interface separating layers of differing dielectric properties, a portion of the pulse's energy is reflected back to the antenna. The radar's receiving unit samples and amplifies the reflected energy and converts it into the

audio frequency range. The processed reflected signals are displayed on a graphic recorder or recorded and stored on magnetic tape.

A continuous profile of the subsurface is developed on the graphic recorder as the antenna is towed along the ground surface. As electrosensitive paper moves under the revolving styli of the graphic recorder, images of subsurface features and conditions are "burned" onto the paper to create a graphic profile. Each scan of a stylus draws a line across the paper in the direction of increasing signal travel time (depth). The intensity of the image printed is dependent upon the amplitude of the reflected signal.

### Ground-penetrating Radar System

The GPR used at Tell Halif is the SIR (Subsurface Interface Radar) System-8 manufactured by Geophysical Survey Systems, Inc.<sup>1</sup>. The SIR System-8 consists of a control unit, a graphic recorder, a digital tape recorder, and a program control unit (microprocessor). The microprocessor did not significantly improve interpretations and was used with limited success. The system was powered by a 12-volt vehicular battery. A 60 meter transmission cable was used

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1. Trade names have been used to provide specific information. Their mention does not constitute endorsement.

to connect the control unit with the antenna. The antenna was hand-towed along survey lines at an average speed of 2.0 km h<sup>-1</sup>. Detailed techniques for using GPR in the field have been described by Morey (1974), and Shih and Doolittle (1984).

The 120 and 500 MHz antennas were used in this field study. The lower frequency 120 MHz antenna has greater powers of radiation, longer pulse widths, and emits signals that are less rapidly attenuated by earthen materials than the signals emitted from the higher frequency, 500 MHz antenna.

Each antenna has a fairly broad radiation pattern. Theoretically, the radar pattern is conical with the apex of the cone at the center of the antenna. The antennas have a 90 degree inclusive angle. Reflections from an interface are a composite of returns from within the area of radiation.

#### Factors Affecting the Radar's Performance

The performance of the GPR is highly site specific and soil dependent. The GPR does not perform equally well in all soils.

The maximum probing depth of the GPR is, to a large degree, determined by the electrical conductivity of soils. Soils having high conductivities rapidly dissipate the radar's energy and restrict its probing depth. The principal factors influencing the conductivity of soils are: (i) degree of water saturation, (ii) amount and type of salts in solution, and (iii) amount and type of clays.

Moisture content is the primary determiner of conductivity. Electromagnetic conductivity is essentially an electrolytic process that takes place through moisture filled pores. Tell Halif is in a xeric moisture regime (Soil Survey Staff, 1975). The average annual precipitation of 25 to 35 cm with a pronounced winter maximum. The survey was conducted during the dry month of July. However, in arid and semi-arid regions, small amounts of moisture can significantly increase the conductivity of soils and substantially attenuate the radar signals (Vickers et al., 1976). Signal attenuation is significantly increased in some soils (Jesch, 1978) when the moisture content is changed from 5 to 10 percent.

Electrical conductivity is directly related to the concentration of dissolved salts in the soil solution. In unirrigated areas, the concentration of dissolved salts in the soil profile and the probing depth of the GPR are influenced by parent material and climatic parameters.

Soils formed in sediments weathered from chalk, marl, and limestone, as at Tell Halif, generally contain more salts in solution than soils developed in felsic crystalline rocks. In general, most soluble salts are leached rapidly from soil profiles in humid regions. However, in semi-arid and arid regions, soluble salts of potassium and sodium and less soluble carbonates of calcium and magnesium accumulate in the soil profile; the depth of accumulation being a function of precipitation. The soils of Tell Halif are calcareous.

The electrical properties of many soils are strongly influenced by the amount and type of clay minerals present. At Tell Halif, moderately-fine textured (18-34 percent clay) soils have formed in residuum, colluvium, and fill materials overlying marl and limestone bedrock. Ions absorbed on clay particles can undergo exchange reaction with ions in the soil solution and thereby contribute to the electrical conductivity of soils. The concentration of ions in the soil solution is dependent upon the clay minerals present, the pH of the soil solution, the degree of water filled porosity, the nature of the ions in solution, and the relative proportion of ions on exchange sites. Smectitic and vermiculitic clays have higher cation exchange capacity (CEC) than kaolinitic and oxidic clays, and under similar soil moisture conditions, are more conductive.

At Tell Halif, unfavorable electromagnetic characteristics of soils, debris or fill material, and buried artifacts limit the radar's probing depth. The moderately deep (50 - 100 cm) and deep (>100 cm), moderately-fine textured, calcareous soils rapidly attenuated the radar energy and limited the penetration of the 120 MHz antenna to depths of 1.0 to 1.5 meters in most areas. In areas of shallow soils (<50 cm) overlying marl or limestone bedrock, attenuation was less severe and depths of 3 to 4 meters were achieved.

The earthen materials of Tell Halif rapidly attenuated the energy radiated from the 500 MHz antenna and restricted its penetration to depths of less than 50 cm. After limited field trials, use of the 500 MHz antenna was discontinued.

The depth of penetration is also limited by buried artifacts. Buried artifacts cause partial absorption, reflection, and scattering of the electromagnetic energy. The high clay content of mud brick walls and the calcareous nature of debris and fill materials absorbed and dissipated some of the radiated energy. Successive, closely spaced layers of fill, debris, and rubble cause partial reflection and scattering of the energy, thereby, further restricting the profiling depth.

In spite of these limitations, the GPR was successful at Tell Halif as a large number of artifacts were not deeply

buried and occurred within the effective profiling depth of the GPR. In most areas, the GPR provided sufficient resolution and penetration to detect artifacts within depths of 0.5 to 1.5 meters.

### Interpreting the Graphic Profiles

Reliable interpretations are developed through experience. Interpretation of radar imagery is best accomplished in the field, through a joint effort of radar technicians and archaeologists, with some ground truth observations to verify the data.

All areas surveyed with the GPR were selected by field supervisors. Archaeologist familiar with the subsurface stratigraphy and history of the site provided invaluable information concerning the distribution and identity of subsurface images. Field supervisors directed the excavation of all ground truth observation sites used to verify the graphic imagery.

Interpretations should be made in the field to relate subsurface anomalies to surface features or expressions. Surface features, such as rock fragments, tree limbs, or metallic reflectors, can introduce unwanted background noise

on the radar profiles which if not properly identified, can lead to false conclusions. In Figure 1, overhanging tree limbs (C1) and utility lines (C2) produced undesired background noise on the graphic profile. These undesired images could be confused with or interpreted as subsurface layers.

Interpretations require a limited number of ground truth observations to correlate the radar imagery with observed features and to determine what features were and were not detected. During the course of this survey, nine exploratory pits were excavated to confirm the presence of buried artifacts and to improve interpretations.

The enclosed graphic profiles (Figures 1 to 3) are representative of traverse conducted in areas having verified subsurface features. They have been included in this report to clarify the interpretation process and to summarize some of limitations of radar surveys.

Figure 1 is a graphic profile from a GPR traverse conducted between excavated areas P5 and O5 in Site 301. The horizontal black lines labelled "A" are reflected images from the ground surface. These lines represent one interface, the air/soil interface. The dark bands represent positive and negative signal amplitudes. The intervening

white band is the zero or neutral crossing between the positive and negative signal amplitudes.

The next series of dark bands in Figure 1 (labelled "B") is a composite reflection from several closely spaced, surface and near surface features. These images overlap and are poorly resolved as a result of the low range and high gain settings used for this traverse. These superimposed images represent changes in surface roughness, soil texture, horizonation, density, organic matter content, coarse fragments, and/or moisture within the upper 40 to 50 cm of the soil profile.

Below surface and near surface images are images from subsurface interfaces. Interfaces are categorized as linear or point reflectors. Soil horizons, geologic strata, and layers of debris or fill having greater horizontal than vertical extent and generally broader than one meter are linear reflectors. When crossed with the antenna parallel with their long axis, foundation walls appear as linear reflectors. Linear reflectors appear as multiple, parallel bands on graphic profiles. In Figure 1, hard, indurated, artificial strata of clay (E), which provide a foundation for outer walls (D), appear as linear reflectors. Also, the false echoes from overhanging tree limbs (C1) and utility lines (C2) appear as linear reflectors.

Small objects, such as stones or boulders, buried artifacts or foundation walls (when crossed perpendicular to their long axis) having limited horizontal extent, will appear as point reflectors. Point reflectors produce hyperbolic patterns similar to the images designated by the letter "D" in Figure 1 and "A" in Figure 2. Hyperbolic patterns are caused by the antenna's conical radiation pattern. The antenna receives reflections before and after it passes over a subsurface anomaly. The hyperbolic patterns result from range changes as the antenna approaches, passes over, and goes beyond subsurface anomalies.

In Figure 1, the profiled depth is 2.85 meters. However, the effective depth of penetration is only 1.2 meters. Below this depth the radar energy has been so absorbed and dissipated that reflected images from subsurface anomalies are indistinct and partially or completely omitted from interpretations. The potential for errors of omission should be a major concern when determining the radar's effective depth of penetration. The examples published in the literature are mostly from areas in which the radar has performed exceptionally well. Often, it is uncertain whether many of the reported depths were consistently achieved and provided complete and interpretable imagery. Some reported depths may represent the lone and most significant exception to an otherwise more restricted trend in observable depths.

Figure 2 is a graphic profile from the perimeter of the tell in Field IV. The graphic profile depicts and is representative of an area of high "cultural noise". Areas depicted with similar concentrations of subsurface anomalies represent prime sites for future archaeological investigations. The point reflector appearing in Figure 2 represents buried foundation walls and columns. In Figure 2, variations in the shape of the hyperbola are caused by variations in: (1) the angle at which the feature was crossed, (2) the speed of antenna advance across the top of the feature, (3) the velocity of pulse propagation, and (4) the size, shape, orientation, composition, and number of buried objects.

In Figure 2, a near surface metallic object produced a distinguishing hyperbolic image (A). When passed over with the antenna, metallic objects such as surveying pins or barbed wire cause excessive reverberations or "ringing" of the reflected signal. Signal reverberations produce repetitious, vertical patterns of similar images across the profile. Signal reverberations limit the ability of the radar to discriminate subadjacent anomalies.

While the GPR detects subsurface anomalies, it does not identify subsurface features. Unless sufficient ground-truth observations are made, few images can be correctly

identified with a high degree of confidence on radar profiles. With experience and sufficient ground truth observations many subsurface features can be identified by their unique graphic signatures.

The profile in Figure 3 is from a traverse conducted in Field I. The GPR was used at this site to predict the occurrence of artifacts prior to the removal of overlying strata within an excavation site. Subsurface features have been highlighted with a dark line. In this profile two foundation walls (A1 and A2) and three distinct layers of fill (B1 to B3) have been identified. The identity of these features was latter verified. The fill material consisted of layers of ashy detritus.

Each wall in Figure 3 has an identifiable graphic signature and is abruptly terminated by vertical breaks. Rubble and fill materials surrounding foundation walls can complicate the imagery and mask the presence of the walls. In many areas of the tell, it was difficult to isolate walls from rubble. Walls have been segmented by partial destruction and, where intact, are variable in expressions.

The graphic signatures appearing in Figure 3 are based on features which have been produced from unique site histories. Abrupt vertical breaks in the radar imagery are indicative of mans activities, and often, as in Figure 3,

separate zones of contrasting site histories. Note the difference in the imagery on either side of wall "A1". The graphic profile is more congested with subsurface reflection to the right of wall "A1" and reflects a different use, and perhaps, a more complicated history than areas occurring to the left of this wall.

Several layers are superimposed in the upper part of this profile. A large concentration of debris on the surface, "C", produced undesired background noise which interfered with other near surface images.

### Survey Procedures

One of the primary objectives of this study was to evaluate survey procedures for charting the location of buried artifacts within a tell. The most accepted and perhaps efficient method to chart the location of buried artifacts with the GPR is to establish a grid on the area to be surveyed. Generally, rectangular grids are preferred, though Bevan (1977), in a study of subsurface remnants of earthworks, describes traverses radiating outwards like spokes of a wheel from a fort. In addition, "wildcat" surveys have been used by some authors (Berg and Burch,

1982) to quickly locate small areas having large concentrations of buried artifacts within a larger area.

Grid spacing is dependent upon the purpose of the survey, available time, features being identified, local ground conditions, and desired detection probability. Bevan (1984b) has described three levels of surveying intensities based on the purpose of the investigation. These levels include: (1) locating an archaeological site, (2) defining site boundaries, and (3) charting internal features within a delineated site. The uniqueness and clarity of tells in the Israeli landscape has, in most places, simplified the scope of GPR surveys to charting the internal site features.

Grid spacing is a compromise between detection probability and available time or production rate. Generally, several grids of varying patterns and spacings are constructed within a defined area during the course of a survey. Often, in preliminary or pre-excavation reconnaissance surveys a large grid spacing is used to define the broad or general location of subsurface anomalies. Once the general location of anomalies has been defined, a smaller grid spacing is used. A smaller grid spacing provides more observation points and greater coverage, but, unless antenna positioning and position referencing are more rigidly maintained, does not necessarily insure greater precision. The more closely spaced grid pattern helps to pinpoint the location, define

the spatial extent, and perhaps resolve the identity of the subsurface anomalies.

The anticipated size of the buried artifacts being defined or located will dictate grid spacing. In relatively detailed surveys, grid spacings of 1 meter were used to detect grave sites (Vaughan, 1986), 1.5 to 3 meters to locate buried foundation walls (Bevan, 1979; Bevan et al., 1984; and Grossman, 1979), and 5 meters to define the general location of buried Indian ruins (Vickers et al., 1977). The 5 meter spacing, while satisfactory for defining areas with high concentrations of subsurface anomalies, is too coarse to relate anomalies with any degree of confidence (Vickers et al., 1977). Generally, in studies conducted in the area of the Mediterranean Sea, a 2 meter spacing has been preferred (Batey, 1987; and Fischer et al., 1980).

At many sites, local ground conditions will dictate the survey area as well as the grid spacing. Excessive slope, dense vegetation, irregular rock outcrops, and buildings will hinder or restrict GPR surveys. At Tell Halif, abrupt and precipitous slope breaks or excavation walls often defined the limits of the radar survey. Areas of trees, dense undergrowth, and barbed wire entanglements were generally avoided as these features impeded the movement of the radar antenna, ensnared the transmission cable, and introduced unwanted background noise.

Two reconnaissance surveys were conducted near Site 301 (Fig. 4) to assist the development of excavation strategies. One survey (survey lines A through F) was established to the north and northwest of Site 301 with survey lines spaced at irregular intervals, parallel with the slope. Reference points were marked at 2.5 meter intervals along each survey line. Survey lines varied in length from 20 to 26 meters.

A second survey area was established to the south of the excavated area at Site 301 (Figure 4). This survey area consisted of an irregularly shaped grid with a 5 meter spacing between each reference point. Survey lines varied in length from 10 to 26 meters.

After the completion of the radar survey, the graphic profiles were examined and annotated in the field. Symbols were used to make the master plot of the grid more interpretable. In Figure 4, only the most readily discernible subsurface anomalies occurring within the upper 1 to 1.5 meters of the soil profile are plotted. Poorly resolved or questionable subsurface features are not depicted on this master plot.

In Figure 4, the more southerly GPR survey area was plotted as having the greatest concentration of subsurface anomalies. The radar profiles disclosed the presence of

several buried walls and strata. One exploratory pit was opened along traverse H. This exposure provided ground truth observations which confirmed the presence of a buried structure (a hard indurated layer which was underlain by stones and pebbles; possibly a wall), and verified the reliability of interpretations.

Radar profiles from the northern GPR survey area revealed fewer subsurface anomalies; in part, a consequence of fewer and more widely spaced traverses. However, the survey did reveal a distribution of subsurface anomalies along the rim of the terrace. It is believed that these anomalies represent major walls and structures. One exploratory pit was dug on traverse line D to confirm the identity of a point object suspected to be a wall. A double row, mud brick interior wall was unearthed at this pit. While this observation confirmed the identity of a subsurface feature, more intensive surveying and further ground truth observations are needed to verify the occurrence of a major wall or the continuation of this wall.

It is generally assumed that linear features, such as buried wall foundations, are easily detected by conducting several parallel traverses with the GPR. According to Bevan (1984), reliable detection of a buried structure requires similar imagery on three to six transects. However, others (Vickers et al., 1976) have noted a "natural tendency" to assume the

occurrence of a linear object whenever radar images appear to align. At Tell Halif, foundation walls are not necessarily linear. The 5 meter spacing used at Site 301 was considered too broad to adequately define the continuation of buried cultural features or the presence of a major wall along this terrace.

A reconnaissance survey was conducted near Field I, on the summit of Tell Halif, in an area latter described as Field IV (Fig. 5). At this site, the presence of fortification walls and domestic structures were inferred from earlier investigations on a similar site (Field III), surface indications, and its location along the perimeter of the tell. A grid was established with a 2.5 meter spacing between reference points. Traverses were conducted along each of the thirty-one survey lines. Survey lines varied in length from 5 to 55 meters.

The preliminary grid at Field IV defined the general location of subsurface anomalies and characterized their distribution. High concentrations of subsurface anomalies appear on graphic profiles from traverses conducted along the western perimeter of the tell. Along the perimeter, two areas of higher cultural noise were identified. The southeast portion of the survey area appears to be relative devoid of subsurface anomalies.

After plotting the distribution of subsurface anomalies detected in the preliminary survey, a more detailed survey was conducted in one area appearing to have a larger concentration of subsurface anomalies (Figure 5). The grid spacing of the detailed survey was 1 meter. This area adjoins the slope break which defines the outer perimeter of the tell. The 1 meter grid provided a more detailed picture of the area.

In Figure 5, the general distribution of subsurface anomalies appearing on the preliminary survey (2.5 meter spacing) and on the detailed survey (1 meter spacing) correspond. However, the detailed survey discerned more subsurface anomalies as a result of its more intense coverage. Also, some patterns do not appear to agree on the two plots. This is due to slight spatial discrepancies in the placement of survey lines, and imprecise antenna location and position referencing.

Radar surveys were successfully conducted within excavated areas of Field I (Figure 6 and 7) to provide archaeologists with a picture of the underlying strata and artifacts before they were encountered. For each of these surveys, the grid spacing was 1 meter. The intrenched excavation sites proved to be exceptionally tight quarters to operate the GPR. As the antenna approached the enclosing excavation walls, the

walls caused some interference and produced background noise which interfered with interpretations.

At Sites A9 and A10 in Field I, traverses varied in length from 2 to 5, providing 3 to 6, equally spaced (1 meter interval) traverses with the antenna. This spacing proved to be too wide for charting the location of buried foundation walls. Each traverse provides only one image of a wall. With the grid spacing used, images of a wall were spaced at one meter intervals. The presence of rock fragments and debris, which produced undesired point reflections, complicated the tracing of wall patterns within the excavation sites with the grid spacing used. In most areas, a closer, overlapping grid spacing would be desired to accurately anticipate the location of buried foundation walls.

In spite of these limitations, the GPR detected and accurately predicted the location of mud brick and stone walls, and layers of ashy detritus within areas A9 (Figure 6) and A10 (Figure 7) of Field I. Numerical values expressed in these figures are depths to the shallowest, buried subsurface layer detected with the GPR. These plots were developed from radar traverses conducted along all grid lines in Figure 6 and north-south grid lines in Figure 7.

Based on radar surveys at Tell Halif, the following grid spacings are recommended: 2.5 to 5 meter for reconnaissance surveys; 1.0 to 2.5 for general characterization of potential excavation sites; and < 1.0 meter for detailed mapping within an excavation site.

### Conclusions

The use of ground-penetrating radar for archaeological investigations is in an active stage of growth and development. This trend has been accelerated by the recent growth in its commercialization and by a growing familiarity with its potential uses. However, the use of GPR techniques has been limited because of (i) initial purchase costs, (ii) limited knowledge of performance in various media and geographic locations, (iii) rapid signal attenuation and depth restrictions in certain media, and (iv) results which are often dependent upon the skills and experience of the operator.

At Tell Halif, ground-penetrating radar has proven to be an effective reconnaissance tool for archaeological investigations. Ground-penetrating radar techniques can be successfully applied to tells in Israel. As more archaeologists become familiar with this geophysical technique, its use in Israel will undoubtedly increase.

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## List of Figures

- Figure 1. Radar Profile from Site 301.
- Figure 2. Radar Profile with numerous "point reflectors" from Field IV.
- Figure 3. Radar Profile of detritus layers and foundation walls at Site A9, Field I.
- Figure 4. Plot of radar traverses, Site 301.
- Figure 5. Plots of radar traverses, Field IV.
- Figure 6. Plot of radar traverses, Site A9, Field I.
- Figure 7. Plot of radar traverses, Site A10, Field I.