# EVALUATION OF GEOPHYSICAL SYSTEMS FOR REMOTE SENSING OF SUBSURFACE CAVITIES IN KANSAS

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The Federal Highway Administration and its contractors, in cooperation with the State Highway Commission of Kansas (now the Kansas Department of Transportation), completed a field program in Kansas during 1971 to evaluate field geophysical systems for detecting subsurface cavities. The geophysical systems included passive microwave radiometers, an impulse radar profiling instrument, and direct-current electrical resistivity. Verification borings were completed in 1972 after analysis of the field data. Field data and test borings are presented for 1 traverse line in Galena, Kansas, to characterize the research findings. Passive microwave radiometers are sensitive to soil moisture and often record the effects of surface drainage, groundwater seepage, and subtle topography. The penetration of microwaves into soils, however, is limited, and the microwave radiometers are not well suited for detecting subsurface cavities. The impulse radar profiling system produced a graphical output that closely approximated the subsurface soil, rock, water, and void interfaces. The depth of radar penetration was limited to 8 ft (2.4 m) because of the presence of moist, clay-rich soils. Electrical resistivity proved to be the most useful technique for delineating subsurface materials. Geoelectrical soundings are well suited for locating conductive and insulative layers, but, because of the principle of equivalence, they may be unable to distinguish a water-filled cavity from another conductive subsurface zone.

•SERIOUS problems are encountered in the construction and maintenance of highways in areas with subsurface openings. The ceiling rock over the opening may collapse under heavy construction equipment, and the completed highway will be susceptible to subsidence. Whether the openings result from solution of natural earth materials or various mining activities, detection of the openings during the planning stage of highway construction currently is largely an expensive hit-or-miss drilling procedure. The problem of detecting subsurface cavities, therefore, was included for study under Project 4E of the Federally Coordinated Program of Research and Development in Highway Transportation (FCP) being conducted by the Federal Highway Administration (FHWA). A coordinated research effort by the FHWA, FHWA contractors, and state highway and transportation departments was formulated to investigate aerial remote sensing and field geophysical systems for detecting subsurface openings. The first test area investigated was in Kansas. A cooperative effort between the Federal Highway Administration and the State Highway Commission of Kansas (now the Kansas Department of Transportation) took place in which both aerial remote sensing and field geophysical systems were evaluated. The results of the evaluation of both the aerial and geophysical systems are published in FHWA staff reports (1, 2). This paper describes the results obtained for one of the field test sites. Three geophysical systems were evaluated at this site.

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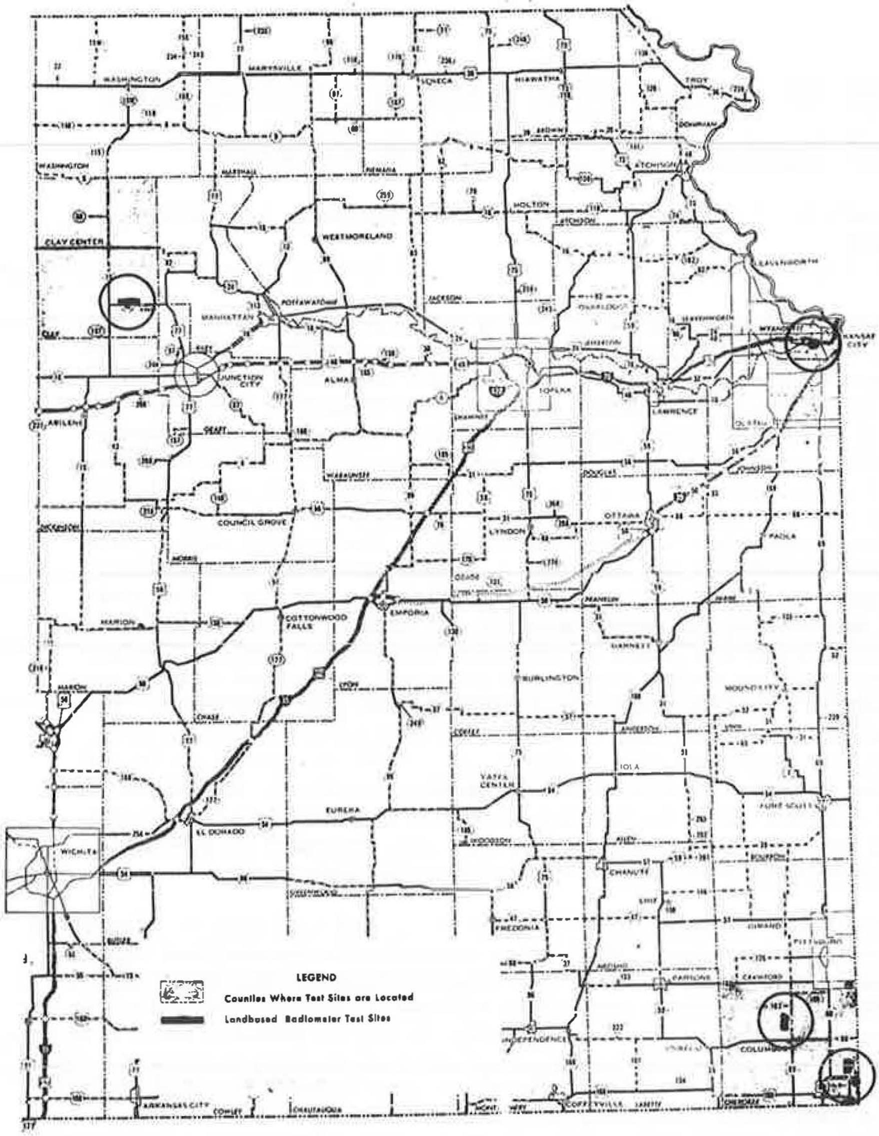
**Figure 1. Four field test sites in eastern Kansas.**




## FIELD PROGRAM

The State Highway Commission of Kansas suggested possible test sites in Kansas for the field program. Test sites and traverse lines were selected in July 1971 by the commission, FHWA personnel, representatives of the contractor, and their subcontractor. Figure 1 shows the 4 test sites in eastern Kansas: (a) shaft mines in a zone of lead and zinc mineralization in Galena, Kansas; (b) shaft mines in a coal seam near Scammon, Kansas; (c) subsurface solution of a limestone stratum in Clay County, Kansas; and (d) subsurface limestone mine in Kansas City, Kansas, that had been a test site during the initial aerial program.

The geophysical surveys were conducted in August 1971. Highway commission personnel surveyed and staked the traverse lines and obtained soil moisture, temperature, and density measurements at selected stations. Passive microwave surveys and impulse radar profiling surveys were performed. Electrical resistivity surveys were conducted during the field surveys. Each geophysical system was evaluated at the Galena and Scammon test sites; only microwave and limited resistivity data were acquired at the Clay County and Kansas City test sites. The geophysical surveys were analyzed by the investigators (3, 4) and a comparative analysis of the data was performed by FHWA staff. To verify the analysis of the data, FHWA directed the placement of borings over selected points at the Galena and Scammon test sites. The borings were accomplished in August and September 1972 by the highway commission.

This report presents the geophysical data for 1 survey line in Galena, Kansas. Galena lies in the tri-state zinc-lead district of Missouri, Oklahoma, and Kansas. Mississippian strata of limestone, chert, dolomite, and shale occupy nearly horizontal positions; sphalerite and galena are the principal ore minerals. Ore deposits are found only where structural deformation or solution and subsequent slumpage in the limestone strata created favorable premineralization reservoirs. Brichta and Ryan (5) conducted extensive electrical resistivity surveys in an area immediately north of Galena. Their work provides representative values for the resistivity of different geological formations. Cook and Van Nostrand (6) developed the theory for interpreting resistivity data over the shale-filled sinkholes in the tri-state area. Van Nostrand and Cook (7) included numerous examples comparing interpreted resistivity data from the tri-state area to borehole information by Brichta and Ryan (5).

An aerial mosaic of Galena (Figure 2) shows that much of the ground surface has been disturbed by mining operations, and fill material of either cobble-sized or finely crushed chert covers most of the field area. Survey lines Galena A and C were established where the ground surface was apparently undisturbed and covered by a minimal amount of fill material and vegetation. It would have been desirable for the survey to cross known subsurface openings, but published (8) and unpublished maps were insufficient for determining their exact location. Survey lines were selected to pass near open shafts and collapsed areas and thus hopefully over target subsurface openings. For example, the Galena A traverse (Figure 2) was selected to pass over mapped mine workings between stations 19+10 and 20+30. In addition, a large area of ceiling rock had collapsed adjacent to this survey line at station 19+65. The large collapsed area on Galena A is shown in Figure 3.

## GEOPHYSICAL SYSTEMS

### Passive Microwave Radiometers

Passive microwave radiometer measurements were obtained with a microwave field laboratory (Figure 4). Dually polarized radiometers with observational wavelengths of 21, 6.0, 2.2, and 0.81 cm are mounted on a hydraulically operated boom. Continuous microwave measurements were taken as the heavy field laboratory was driven forward and backward along each traverse line. Microwave profiles were obtained at 15, 30, and 45 deg above nadir for each traverse line. Aluminum foil strips were placed at discrete control stations to mark the radiometric data with respect to traverse position.

The energy received by a passive microwave radiometer, referred to as the brightness temperature, is the sum of energy emitted from the terrain surface plus the reflected sky energy. At microwave wavelengths, the differences between the radiometric brightness temperatures of various terrain surfaces are primarily the result of differences in their emittances, and variations in temperature are less important. For example, a smooth water surface has an emittance of 0.05 at 1.5 GHz and 0.3 at 70 GHz and will always appear very cold; soils and bedrock have emittances between 0.8 and 0.95 and will appear warm. The microwave brightness temperatures are dependent on the physical properties of the earth material, including moisture content; roughness of the surface at the observational wavelength due to microrelief, soil particles, or vegetative cover; and layering in the material. Compositional changes in a soil are of minor importance; only small effects are due to increased adsorption of water on clay particles.

The emission of microwaves from a smooth terrain surface without vegetative cover

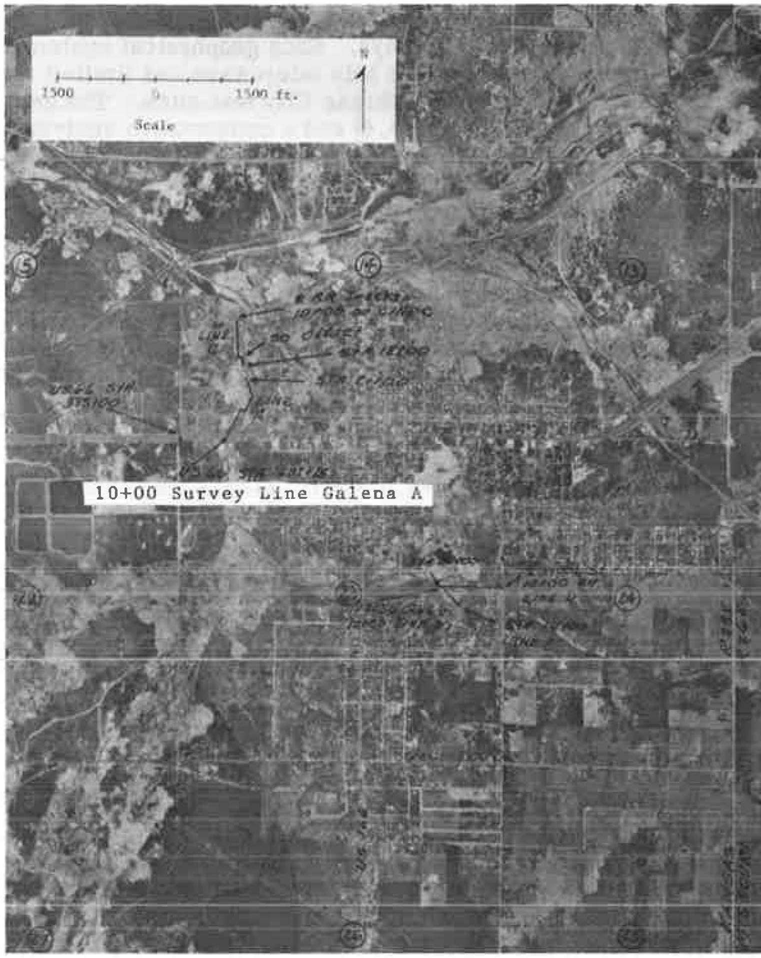



**Figure 2. Galena, Kansas, survey lines.**

**Figure 3. Collapsed ceiling rock over mine adjacent to survey line.**

is primarily determined by the material's dielectric constant. Lundien (9) studied the electromagnetic propagation constants of soils between 1.0 and 1.5 GHz—a spectral band that includes the 21-cm radiometer. A strong correlation was noted between the dielectric constant and the volumetric water constant of a soil. This relation is one that is nearly independent of type of soil. Soils have a relative dielectric constant of approximately 3 when oven dried, and this value increases uniformly with moisture content to approximately 81, which is the dielectric constant for water. This relationship between the volumetric water and the dielectric constant, which determines the surface emittance, enables one to map soil moisture content in terms of brightness temperatures. In addition, clays commonly have a higher volumetric water content than either sands or silts at the same capillary pressure; therefore, brightness temperatures may grossly delineate the texture of adjacent soil units. The depth of microwave penetration into soils is correspondingly very sensitive to increases in soil moisture content, and microwave penetration is severely limited in all but the driest natural conditions. Penetration is reduced further in clay soils because clays have higher loss tangents than other soils have at the same volumetric water content. In Galena, the effective penetration of the longest wavelength (21 cm) radiometer was probably always less than 3 ft (0.91 m).

Although the reflectance of a smooth surface is determined by electrical properties of the material, the reflectance will decrease as the surface becomes increasingly rough and each irregularity approaches the condition of a blackbody. A diffusely rough surface, such as vegetation, has microwave emittances near unity such that the recorded brightness temperatures are nearly independent of the observation angle and the actual physical properties of the earth materials.

As microwaves travel through a material, they are partially reflected whenever they encounter a change in dielectric constant or electrical resistivity. For a uniformly layered material, the subsurface reflections would combine with surface reflections to produce interference effects, depending on the thicknesses of the layers, their electrical properties, and the wavelength of the transmitted signal. However, because of the variability of soil properties and layer thicknesses, there will be no simple relation between the brightness temperature and the presence of a subsurface opening or even water table. Moreover, the penetration of microwaves is sufficiently limited in all natural earth materials that primary detection of a subsurface opening is probably impossible. The only physical basis for operating a microwave survey to detect subsurface openings is that soil moisture in the overburden may reflect the presence of an air- or water-filled opening.

## Impulse Radar Profiler

An impulse radar system, known as electromagnetic subsurface profiling (ESP), that can be considered as an electrical analogue to seismic reflection profiling has been developed (Figure 5). It can detect, record, and graphically display dielectric interfaces below the ground surface. The radar pulses are transmitted into the ground by a small transmitter-receiver sled that is towed across the ground at a velocity of 1 to 2 mph (1.6 to 3.2 km/h) by a 4-wheel-drive vehicle or by hand in rough terrain. The pulse is partially reflected as it encounters an interface of materials with different complex dielectric constants, and the reflected pulses from successive material interfaces add vectorially in the time domain to produce an analogue signal. The analogue signals are first recorded on magnetic tape at a sampling rate of 4 to 6 points/ft (13.2 to 19.8 points/m) of traverse line. The magnetic tape can be outputted on a graphical recorder in the field vehicle to enable field sampling of subsurface interfaces. The analogue tape can finally be computer processed to enhance or suppress reflections from interfaces at specific depths of interest.

## Electrical Resistivity

Constant depth resistivity traverses and geoelectrical sounding by means of the Wenner

Figure 4. Microwave field laboratory in Galena, Kansas.

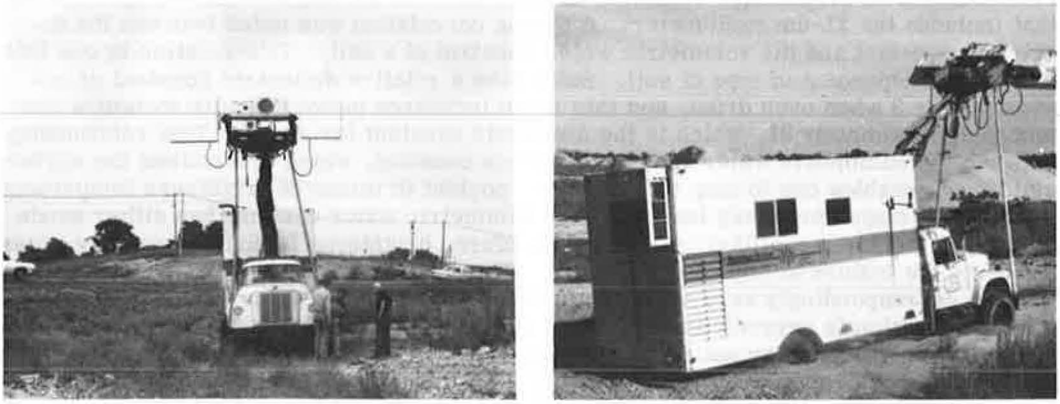
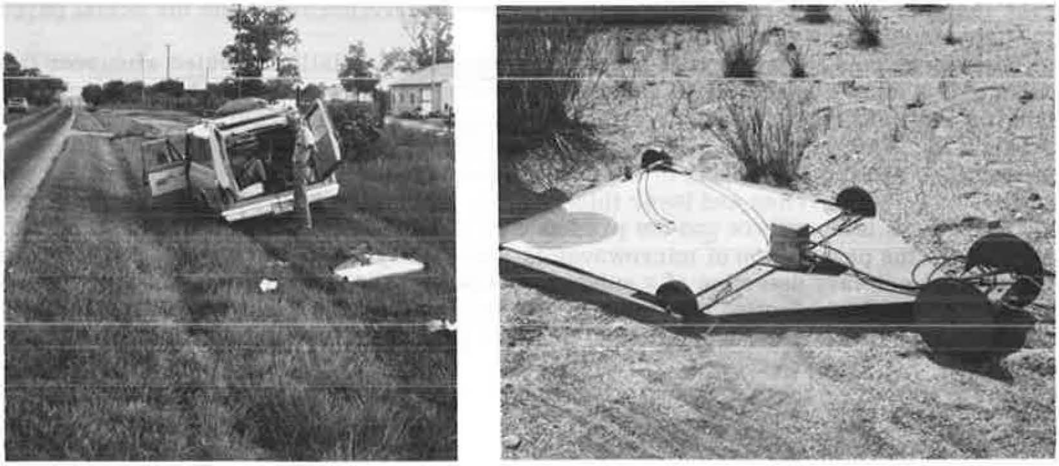


Figure 5. Vehicle and sled and impulse radar profiler.



configuration were conducted over suspected subsurface cavities at each test site. The direct-current instrument ran off dry cells and employed copper sulfate porous pots for potential electrodes. An initial field analysis of the data, based on an empirical method of interpretation (10), facilitated the collection of complete and relevant data. It was found, however, that empirical approaches were insufficient for the complex conditions encountered in Kansas where there were large resistivity contrasts between adjacent zones and subsurface layers. All the electrical soundings in this study were interpreted by using theoretical master curves (11). The interpretation of constant depth resistivity traverses was facilitated by comparison with theoretical curves (7) for traverses across vertical dikes and buried, tabular conductors or insulators.

## ANALYSIS OF GEOPHYSICAL DATA

Passive microwave traverses, a radar profiling survey, a constant depth resistivity traverse, and 9 geoelectrical soundings were conducted along survey line Galena A (Figure 6).

## Passive Microwave Radiometers

The microwave brightness temperature curves shown in Figure 6 are for the 21-cm wavelength and 30-deg viewing angle traverse. No significant differences were noted between the horizontally and vertically polarized microwave plots. The traverses found low brightness temperatures, which is a pattern that might be expected for cavities between stations 12+70 and 13+30, 16+70 and 18+30, and 18+70 and 19+40. The anomaly between stations 12+70 and 13+30 was traced to a black, mucky clay that lies near the surface and rutted easily during vehicle traverses. The subcontractor (4) attributed the large, broad microwave cool area between stations 16+70 and 18+30 to a sharp increase in material density. Instead, there appears to be groundwater seepage in this area. The evidence is a strip of heavy grass and small trees adjacent to the survey line and extending between the same survey stations. The microwave anomaly between stations 18+70 and 19+40 is centered about station 19+15, which lies within an area of mapped mine workings (8). We can examine the anomaly between stations 18+70 and 19+40 as a possible extension of the mine workings.

## Impulse Radar Profiler

After analyzing the enhanced radar profile for Galena A, the contractor suggested 8 locations where borings would presumably find subsurface voids less than 8 ft (2.4 m) below the surface (3). These recommended boring sites are indicated by arrows above the interpreted soil-rock profile at the bottom of Figure 6. The radar patterns for 2 of the potential sites (at stations 18+65 and 19+10) are shown in Figure 7. These anomalous patterns were similar to those obtained over known cavities.

The impulse radar profiler records reflections from dielectric interfaces that could be voids or the related fractures that can propagate into the ceiling rock. They also could simply be contacts between earth materials, such as slumpage materials or filled areas, that have different complex dielectric constants. Thus, full interpretation of the radar profiles was delayed until the geophysical data were analyzed. In the final analysis, several dielectric interfaces did correlate with features such as shale-filled slumps, filled areas, or near-surface bedrock.

## Constant Depth Resistivity Traverse

Certain geological information can be extracted directly from the constant depth traverse (Figure 6). For other stations, the traverse provides information useful in the interpretation of electrical soundings. The most notable feature of the traverse is the symmetrical rise in apparent resistivity centered around station 15+70. Inspection of theoretical curves for a Wenner configuration traverse across a vertical contact indicates that there must be a more resistive material that can be modeled as a vertical dike in the subsurface between stations 14+50 and 16+70. The W-shaped traverse between stations 11+80 and 13+50 probably indicates a resistive material that is closer to the surface under station 12+70. The unusual peak in apparent resistivity at station 19+25 occurred because the current electrode was directly opposite the large collapsed area shown in Figure 3. The peak in apparent resistivity does not represent a resistive, subsurface material under station 19+25.

## Geological Soundings

Nine geoelectrical soundings, or depth tests, were performed along line Galena A. Large resistivity contrasts occurred between adjacent subsurface layers. The dry, crushed chert overburden had resistivities of approximately 1000 Ω•m; the underlying chert bedrock had values of approximately 500 Ω•m; and the conductive slump or fill materials at intermediate depths had values near 75 Ω•m. The weathered rock layers

**Figure 6. Geophysical data and interpreted soil-rock profile for survey line Galena A.**

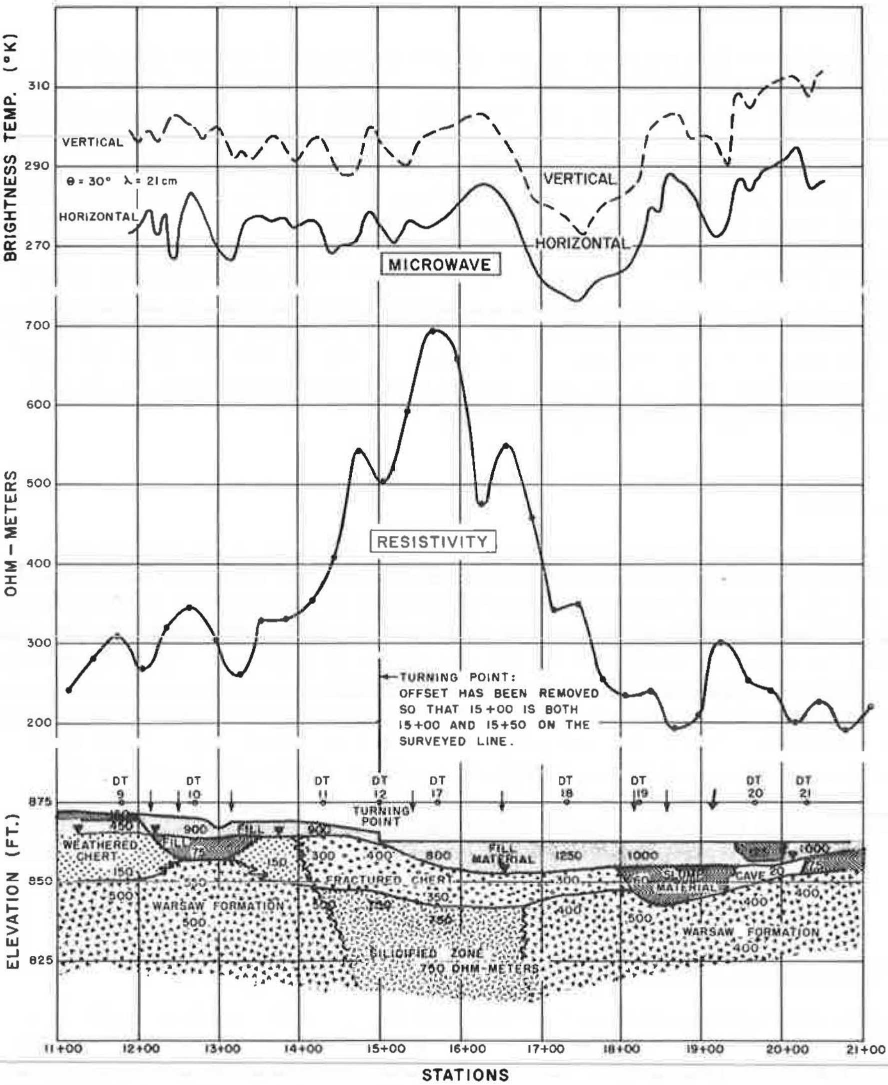
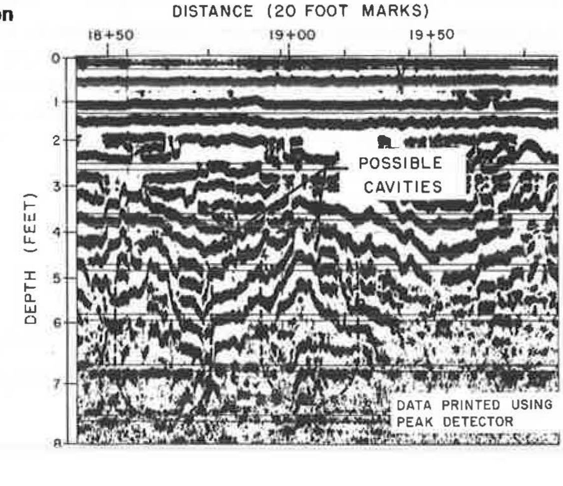



**Figure 7. Enhanced radar profile indicating location of possible cavities along a portion of survey line Galena A.**



had lower resistivities than the parent rock. Detailed curves are included in the FHWA report (2). Distinguishing the conductive earth materials from possible water-filled openings is difficult. To do so requires a detailed consideration of the principle of equivalence in geoelectrical prospecting (12), and distinguishing the materials may finally be impossible even though their resistances are different. This uncertainty occurs because, for certain relations of the parameters of a 3-layer geological section, changes in the resistivity and thickness of the middle layer do not produce noticeable changes in the electrical sounding curve. In the case of a conductive middle layer, increasing or decreasing the thickness and resistance of the intermediate layer by a multiplicative factor is possible, within certain critical limits given by Pylaev's nomograms (12), without changing the measured field curve. A thin, water-filled cavity thus can be electrically equivalent to a thicker, more resistive layer of fill, and only geological reasoning can help to resolve the uncertainty. For example, the interpreted electrical sounding at station 12+70 indicated the possibility of a fill material with a thickness of 9 ft (2.74 m) and resistivity of 75 Ω·m or the possibility of an extensive, excellent conductor (water-filled opening) at a depth of 5 ft (1.5 m). This latter condition was geologically improbable at this location; therefore, a layer of fill was interpreted to overlie an old erosional surface on the chert bedrock. This interpretation also explains the W-shaped constant depth traverse across this area.

The presence of a subsurface void was suggested near station 15+40. However, analysis of electrical depth tests 12 and 17 indicated the presence of a resistive material at a shallow depth. The constant depth traverse similarly indicated the presence of a high resistivity material in the form of a vertical dike through this section. This harder material was interpreted to be chert, which is evident as outcrops at an offset to stations 16+00 and 16+20.

Electrical depth test 20 (station 19+65) was completed adjacent to the area of the collapsed ceiling rock (Figure 3) and indicated a conductive intermediate layer which, from ground observation, was identified as the water-filled opening. A conductive surface layer, with a surface expression of tall grass and moss ground cover, was located over the water-filled opening. A conductive intermediate layer also was indicated by depth test 19 at station 18+20. This raised the question of whether the cavity extended to this station or whether slump material was present. The radar and microwave anomalies in this region indicated the possibility of the extension of the water-filled cavity from station 19+10 to station 18+20, but the lateral contact between slump material and the water-filled opening could not be defined.

## COMBINED ANALYSIS AND BORING RESULTS

A combined analysis of the constant depth traverse and electrical sounding 10 suggested that an area of fill is between stations 12+00 and 13+50. It was reasonable for the radar profiling anomalies at stations 12+15, 12+50, and 13+15 to be dielectric interfaces within the fill or at the contact of the fill with the old ground surface. A shallow hole was augered at station 13+15 to test this interpretation. Chert gravel with a clay matrix was found to a depth of 5.3 ft (1.6 m) where there was a transition to practically clay-free chert gravel. An electromagnetic pulse experiences the same phase shift when it passes from clay-rich to clay-free material as it would passing from soil to an air-filled void. The transition in clay content was probably the interface that had been interpreted as a void. The fill material continued to a depth of 8.8 ft (2.7 m) where chert bedrock was encountered.

An analysis of electrical soundings 12 and 17 suggested that fractured and then probably massive chert should be near the surface at station 15+40, a location where the radar profiling unit found a subsurface dielectric interface. The constant depth traverse indicated that the massive chert should extend between stations 14+50 and 16+70. A shallow test hole was drilled at station 15+30, and this hole verified the presence of first fractured and then massive chert below a depth of 3.2 ft (0.97 m).

The large microwave cool area between stations 16+40 and 18+30 is believed to be due to groundwater seepage, and the dielectric interface at station 16+50 could be either groundwater or the near-surface chert. The smaller microwave cool area between stations 18+70 and 19+40 could reflect an extension of the mine workings that were mapped between stations 19+10 and 20+30, and, because of the principle of equivalence, the electrical sounding at station 18+20 could not verify or disprove this hypothesis. The warm microwave temperatures between stations 19+40 and 20+15 could have resulted from the tall grass between these stations and cannot be interpreted as either the presence or absence of a subsurface water-filled opening. A drill hole was completed at station 18+80 to test whether the microwave radiometer had delineated an extension of the mapped cavity. The boring found clay-free chert cobbles to a depth of 6.6 ft (2 m) and then clay-bound chert with minor amounts of limestone to 19.3 ft (5.9 m) where chert bedrock was encountered. The drill had found slump material and not an extension of the mining activity.

## CONCLUSIONS

This report describes the analyses of 3 geophysical systems for detecting subsurface cavities for test line Galena A. Additional surveys were performed in the Galena area as well as in 3 other test areas. The conclusions are based on the analysis of data from all the test sites as reported in the FHWA staff report (2).

The penetration of microwaves is sufficiently limited in all natural earth materials so that primary detection of a subsurface opening is probably impossible with a passive microwave radiometer. Near-surface soil moisture content may occasionally reflect the presence of an air- or water-filled subsurface opening. However, this physical basis of operation is tenuous and is easily disrupted by the effects of surface drainage, groundwater seepage, and subtle changes in topography. The operational requirement of a ground surface that is smooth at the observational wavelength is an additional restriction in areas with natural, vegetative cover. Passive microwave radiometers are not well suited for detecting subsurface openings.

The impulse radar profiling system produced a graphical output that displayed a close approximation to the subsurface soil, rock, water, and void interfaces. The depth of penetration was limited to a maximum of 8 ft (2.4 m) because of the presence of the moist, clay-rich soils that greatly dissipated the energy propagated by the system. An advantage of this system is that an initial version of the profile can be obtained while the survey vehicle is still in the field, which permits field personnel to auger isolated holes in order to identify the important material interfaces.

Electrical resistivity proved to be the most useful technique for delineating subsurface materials. Geoelectrical soundings are well suited to locating conductive and insulative subsurface materials. However, because of the principle of equivalence, distinguishing a water-filled cavity from another conductive subsurface layer or distinguishing an air-filled opening from another highly resistive layer may be impossible.

A combined analysis of the geophysical data provided more information than would have been available from any single system. Radar profiling and resistivity are complementary geophysical systems, and the radar system would be even more valuable if the depth of penetration under conditions encountered in the test areas could be increased. The passive microwave radiometer did not provide sufficient information to warrant its additional cost.

## ACKNOWLEDGMENT

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