United States
Environmental Protection
Agency

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Pre-issue
December 1988

Research and Development

EVALUATION OF AIRBORNE GEOPHYSICAL METHODS TO MAP BRINE CONTAMINATION

Brookhaven Oil Field, Lincoln County, Mississippi

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EVALUATION OF AIRBORNE GEOPHYSICAL METHODS TO MAP BRINE CONTAMINATION

BROOKHAVEN OIL FIELD, LINCOLN COUNTY, MISSISSIPPI

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Interagency Agreement
DW-14932583

Project Officer

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This study was conducted in cooperation
with the U. S. Geological Survey

ENVIRONMENTAL MONITORING SYSTEMS LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NEVADA 89193-3478

NOTICE

The information in this document has been funded by the United States Environmental Protection Agency under interagency agreement DW-14932583 with the U. S. Geological survey. It has been subjected to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Use of trade names and commercial product brand names does not constitute endorsement by the USGS or EPA or recommendation for use.

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FORWARD

The Branch of Geophysics of the U. S. Geological Survey (USGS) has conducted airborne geophysical studies near Brookhaven, Mississippi, as part of a general program to evaluate various geophysical methods to detect and delineate near-surface brine pollution associated with oil fields. This research project is specifically designed to evaluate suggestions from previous ground electromagnetic (EM) studies that airborne electromagnetic (AEM) methods might be effectively applied to mapping vertical and lateral distribution of brine (Fitterman, 1986; Fitterman, Raab, and Frischknecht, 1986). A particular problem in the use of either ground or airborne EM methods in mapping brine associated with oil fields is interference in electrical measurements caused by cultural sources. These sources of electrical noise include power lines, pipe lines, radio frequency transmissions, rail lines, and fences. The major objective of this study is to test whether AEM methods can be effectively used in an area such as Brookhaven with heavy cultural noise. Secondary objectives of the study are to evaluate different types of AEM methods which could be applied to the Brookhaven area and to suggest specific further processing and interpretation methods that are applicable to detection of shallow brine.

The study of brine pollution at the Brookhaven oil field was carried out in the following steps:

--> EPA contracts for ground electrical geophysical surveys and preliminary evaluation of various types of airborne electromagnetic systems.

--> EPA and USGS formulate a general project work plan funded through interagency agreement DW-14932583.

--> Existing borehole and surface electrical measurements for the area were evaluated to derive an interpreted generalized geoelectrical section.

--> On the basis of previous electrical studies, technical specifications were drawn up for a request for proposals (RFP) for an airborne electromagnetic survey of the Brookhaven area.

--> Proposals submitted to the USGS were evaluated according to contracting procedures with a resulting award to DIGHEM Surveys and Data Processing Inc. (referred to as DIGHEM) of Ontario, Canada.

--> Prior to the beginning of the airborne survey, a quality assurance document for the project was prepared and approved by USGS and EPA officials. The document follows the form of "Interim Guidelines and Specifications for Preparing Quality Assurance Plans (EPA-600/4-83-004)".

--> In May of 1988 the helicopter airborne geophysical survey was started by DIGHEM and completed within ten days. On site quality control as given in the final contract and the quality control document was carried out by USGS and EPA officials.

--> Preliminary data from the subcontractor was accepted by the USGS contract officer's representative in September 1988. By mid-November, final calibration corrections were completed for the active EM system. A multiplicative error in one of the data sets was discovered by the contractor and corrected in early December.

The following report describes details of the above steps in the investigation which are directly related to the airborne geophysical study. A USGS open-file report is currently being prepared to make the digital geophysical data available to the public.

While the major objective of the study has been accomplished, there is much more that can be done with the airborne data. An integrated interpretation of both hydrologic and geophysical data will be undertaken by the USGS, Branch of Geophysics, in cooperation with the EPA.

ABSTRACT

The Brookhaven oil field, one of the oldest in Mississippi, has produced a significant amount of brine associated with oil production. As a result of various brine disposal methods, there has been brine contamination of near-surface aquifers and some streams. Brine contamination is known to decrease the electrical resistivity (increase conductivity) of fresh water aquifers. In studies of other areas, various types of electrical geophysical ground surveys have been applied to mapping the distribution of shallow brine. However, a major problem in applying these methods in oil field environments is extensive cultural features such as cased wells, pipelines, electrical pumps, oil tanks, power lines, and fences. The major objective of this study is to evaluate whether airborne electromagnetic (EM) surveys could be used to map subsurface electrical features in the presence of high cultural noise present at the Brookhaven area.

A helicopter geophysical system was chosen for the survey based on better spacial resolution than faster flying fixed wing systems. The helicopter system, flown at a line spacing of 1/8 mile (200 meters) made total field magnetic and active and passive EM measurements of the area of brine contamination. The magnetic field data, corrected for regional variations, show numerous small semicircular anomalies that are due to steel oil tanks, pipe lines, and well casings. There are not any magnetic features that can be directly related to geologic features associated with subsurface brine distribution.

Passive EM systems are those which measure electromagnetic signals from sources other than those flown with the helicopter system. Data from the passive EM systems (60 Hz monitor and very low frequency EM) systems are dominated by noise from cultural features, mainly power lines. The data, as presented here, are not of very much potential use in mapping near-surface brine. However, these data are critical in determining possible cultural effects in the active EM data. The 60 Hz and VLF data may also be of use in interpreting cultural features such as abandoned wells that are indirectly associated with the subsurface brine distribution.

The active EM system has both transmitter and receiver instrumentation which are carried by the helicopter. In this survey, the transmitters and receivers are horizontal coils. The primary objective of this study is to evaluate the performance of active airborne EM systems in mapping subsurface resistivity variations. The DIGHEM system as used here measures EM signals at three frequencies, 56,000, 7,200, and 900 Hz which yield data reflecting an increasing depth of penetration into the earth. These measurements also show different responses to cultural noise. Measured EM signals were corrected for system calibrations and reduced to apparent resistivities by the contractor.

Cultural noise for the active EM systems varies between maps of apparent resistivity for each frequency. This type of noise

is characterized by narrow (short-wavelength) anomalous apparent resistivity responses that may or may not cross several flight lines. The amount of cultural noise is greatest for the highest frequency and least for the lowest frequency. The levels of apparent resistivity over power lines for the 7,200 Hz maps are almost the same as the background level. Consequently additional information, such as the passive EM data, needs to be used to determine areas of possible signal corruption by cultural features.

In spite of the high level of cultural noise, apparent resistivity data appears to map shallow vertical and horizontal resistivity variations. The highest frequency (56 kHz) has the largest apparent resistivities (median value of 150 ohm-meters) since it mostly maps the surface resistive loess deposits. The lowest median apparent resistivity (about 10 ohm-meters) is associated with the lowest frequency. Areas of very low resistivity could indicate areas of subsurface brine or low resistivity clay zones within the near-surface formations.

This study demonstrates that airborne electromagnetic methods can be used to map subsurface resistivity variations in areas of extreme cultural noise. Further interpretation is needed to more specifically relate low resistivity areas to possible brine contamination.

FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS	MEANING
AEM	--Airborne electromagnetic, refers to various geophysical methods
EM	--Electromagnetic
EPA	--Environmental Protection Agency
Hz	--Hertz, the fundamental frequency of a periodic signal measured in cycles per second
kHz	--1000's of Hz
nT	--nanotessla (unit of magnetic field intensity)
RFP	--request for proposal
UHF	--ultra high frequency
USGS	--U. S. Geological Survey
VLF	--very low frequency

ACKNOWLEDGMENT

Frank C. Frischknecht undertook the initial stages of this study including conception of the work and formulation of technical specifications for the geophysical contract. Unfortunately, due to his untimely accidental death, he did not see the fruits of his efforts. David V. Fitterman served as project chief during the remaining part of the study. Mr. Fred Hille, Mississippi Department of Natural Resources, visited the study area while the airborne geophysical survey was being done and helped to obtain current information for this study.

SECTION 1

INTRODUCTION

BACKGROUND

The Brookhaven oil field, located in northwestern Lincoln County, west of the city of Brookhaven, (Figure 1) is one of the oldest fields in Mississippi with completion of the first well in March of 1943 (Kalkhoff, 1986). Oil production from over 75 wells peaked in 1949. Since then production gradually decreased with production being limited to 20 wells by 1984. Water high in dissolved solids (brine) is produced along with the oil from the Cretaceous Tuscaloosa Formation. Kalkhoff (1986) gives the chemical composition of the brine as characterized by the average dissolved solids.

Very little brine in proportion to oil is produced in the early development stages of this type of oil field. As the oil resource is depleted, more brine is pumped to the surface. Since 1943, approximately 54.2 million barrels of brine have been pumped to the surface with a peak in the brine to oil production ratio of about 5.6. The three following brine disposal methods have been used at the oil field:

1) The earliest method of brine disposal was to pump the brine onto the ground or into a nearby stream.
2) A later method was to pump the brine into evaporation pits.
3) Since the above disposal practices were prohibited by 1978, brine has been reinjected by Class II wells into the deep (greater than 4000 feet below ground surface) oil producing formations.

All three of these disposal methods pose a threat to the quality of near surface water supplies. Impact of the first two disposal methods is obvious. The third method of disposal could contaminate near surface ground water by several possible mechanisms including defective or inadequate casing in the injection well. In addition it is possible that deep saline waters could seep to the surface through older improperly plugged abandoned wells or subsurface vertical fractures. The near-surface brine contamination probably is due to a combination of the above sources. Geophysical methods may help to delineate brine contamination and possibly identify the effects of these different sources.

PURPOSE AND SCOPE

The primary objective of this study is to evaluate the application of airborne electromagnetic (AEM) methods to mapping of near-surface brine bearing waters. The survey area is typical of many other oil fields which have possible brine contamination

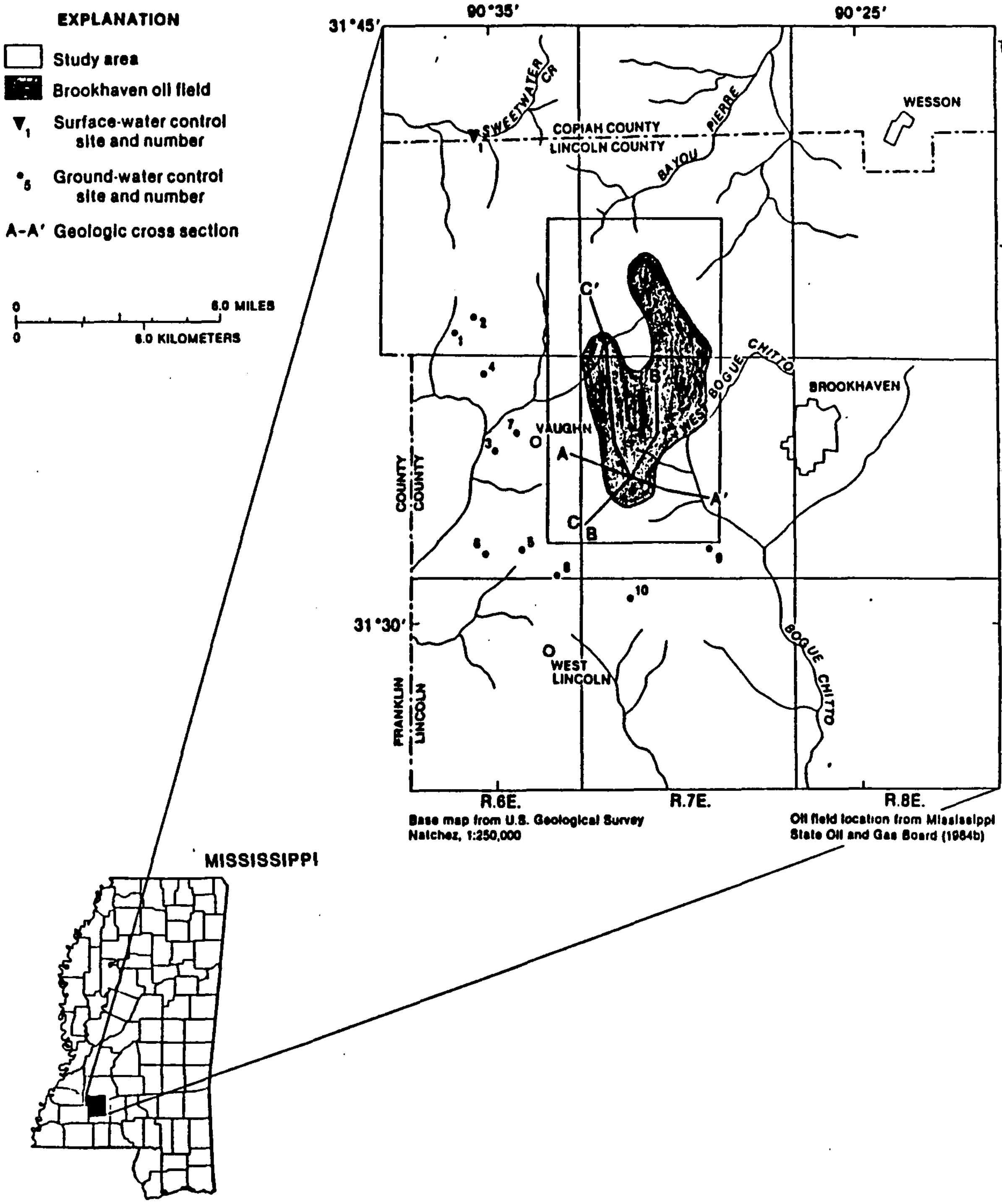


Figure 1 Location of the Brookhaven oil field (after Kalkhoff, 1986). Geologic cross section C-C' is given in Figure 2.

problems in that there are many sources of cultural electrical noise. These sources of electrical noise may make it impossible to carry out meaningful ground and airborne electromagnetic surveys. Consequently the most important consideration in the evaluation of AEM methods is whether any useful measurements can be made in areas such as Brookhaven that have many sources of cultural electrical noise. Two secondary objectives of this study are to continue evaluation of airborne magnetic methods to locate cased wells and to evaluate methods to further process the geophysical data to address specific environmental problems.

GEOLOGIC AND HYDROLOGIC SUMMARY (from Kalkhoff, 1986)

The shallow geologic units important to the geophysical study are unconsolidated sedimentary deposits of Tertiary and Quaternary age shown in Figure 2. Pleistocene loess and alluvium irregularly covers the area. In some areas, stream erosion has removed the loess and parts of the upper Pliocene Citronelle Formation. The upper Citronelle contains mostly sandy clays grading into thicker gravel in the basal part of the Formation. The Miocene Hattiesburg Formation has a clay and silt dominated lithology with three sand units (designated A, B, and C) which range in thickness from 10 feet to more than 90 feet (3 to 30 meters)

Gravels of the Citronelle Formation and sand layers in the Hattiesburg Formation are the main sources of waters for local use and serve as the main aquifers in the study area. All of the aquifers in the oil field have been contaminated by brine to a depth of at least 300 feet and contaminated outside of the oil field to an unknown degree. Brine can move from its sources in the Citronelle aquifer to discharge into nearby streams and can move vertically into underlying Hattiesburg aquifers.

GEOPHYSICAL SURVEYS

Two previous geophysical investigations have been contracted by the EPA for the Brookhaven area. The first investigation was an exploratory study of the near surface electrical conductivity variations (Nacht and Barrows, 1985). However, data gathered from these ground surveys was not interpreted in detail. In the second geophysical investigation, Becker and Morrison (1987) interpreted the shallow resistivity sounding data in order to input parameters for theoretical modelling of different airborne EM methods. They conclude from analysis of resistivity soundings that brine contaminated lithologies have a factor of 10 higher conductivity (or factor of 10 lower resistivity) than areas without brine. Both of these contracted studies were used to formulate the work plan for the present study.

The report by Becker and Morrison (1987) evaluates helicopter-borne EM (HEM) and fixed wing airborne EM (AEM) systems for mapping the distribution of near surface (within 300 feet) brine. Their conclusion is that HEM systems are best suited to mapping water contaminated by brine in the shallowest part of the Citronelle aquifer. The deeper penetrating fixed wing AEM system is most suitable to mapping deeper brine distribution within the Hattiesburg aquifer. However, conclusions from this analysis do not consider hypothetical effects of geological or cultural noise in measurements made with either system. Such sources of noise are difficult to estimate particularly in areas like Brookhaven because very few if any airborne EM measurements have been made in oil field environments.

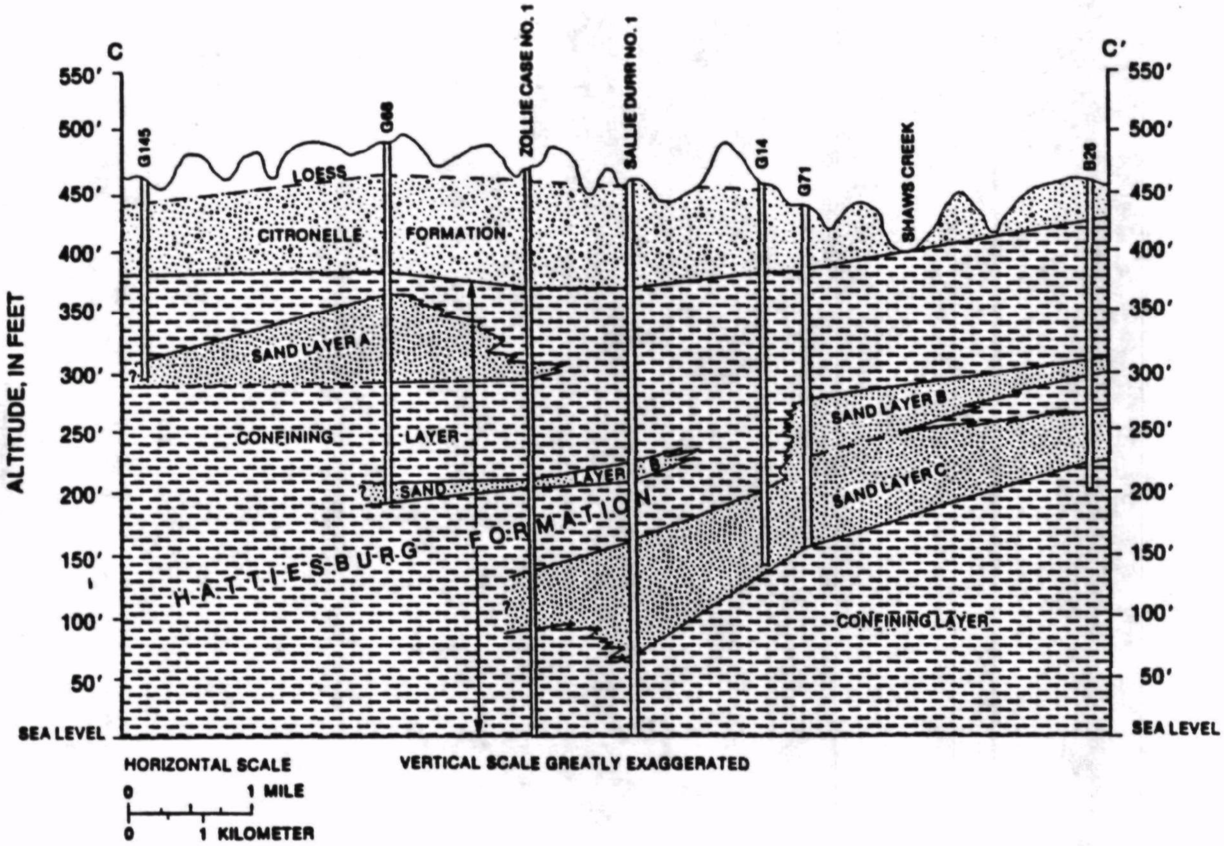


Figure 2 Geologic cross section of the Brookhaven oil field given by Kalkhoff (1986). Letters are keyed to *Figure* 1. *See text for description of* lithologies for various formations.

SECTION 2

CONCLUSIONS

GENERAL

The helicopter borne electromagnetic survey of the Brookhaven oil field, carried out by DIGHEM accomplished the main objective to test and evaluate airborne EM measurements as described in the work plan for this project. One unanticipated problem in doing this survey was that the flight plans had to be somewhat modified to avoid impacting populated areas and residences in the area. Flight lines which were planned to be flown straight east-west, deviated from a straight line to avoid houses and small communities. Using a helicopter versus a fixed wing system for the geophysical instrumentation greatly facilitated adjustment of flight line locations and also helped improve the spacial resolution of geophysical anomalies. Other conclusions are given in outline form below.

AEROMAGNETIC SURVEY

1. The most obvious features of the total field magnetic map (Figure 4) are circular and semicircular positive anomalies of 10 to several hundred nanotesslas (nT) which have a width less than 300 feet (96 meters). From previous USGS research on magnetic field measurements over oil fields (Frischknecht and others, 1985), these anomalies can be associated with well casings and other magnetic metallic features such as oil tanks, pipe lines, abandoned cars, and metal sheds. Identification of anomalies due to casings may be important in locating abandoned wells that could serve as flow paths allowing deep brine to seep into surface aquifers.

2. The 1/8 mile (660 feet, 200 meters) flight line spacing is not sufficient to define more subtle magnetic anomalies from well casings located between flight lines (Frischknecht and others, 1985).

3. The UHF radio positioning system which has a sensitivity of 3 feet (1 meter), produced an accuracy on the order of 30 feet (10 meters) for this survey. A radio positioning system is absolutely necessary for this type of survey to accurately locate well casing anomalies in ground follow-up studies.

4. The high resolution of the Cesium magnetometer (0.01 nT) was not really needed to resolve the magnetic anomalies from well casings. Motion of the magnetic field sensor towed beneath the helicopter caused a sinusoidal signal to be generated in the recorded data which was filtered out of final data.

5. A critical factor in defining the shape and location of magnetic anomalies from well casings is the data sampling rate

from the magnetic sensor. The measurement sampling rate of 10 per second was adequate to define magnetic anomalies along flight lines.

PASSIVE ELECTROMAGNETIC SYSTEM DATA

1) The VLF map of the survey area as given by the contractor, does not show any major features directly related to subsurface variations in the shallow electrical section. Cultural noise from power lines and other electrically conductive features dominates the map (Figure 5).

2) Standard commercial VLF instrumentation used in this survey does not measure a sufficient number of parameters of the EM field to be useful in this environment of high conductivities and cultural noise. However, ground VLF surveys which have higher resolution of EM signals and measure more parameters should be considered for ground follow-up surveys.

3) The 60 Hz monitoring system normally used to identify the location of power lines, appears to show anomalous responses away from the power lines. These responses could be due to other cultural features such as metallic fences or geologic features. Further data processing will be required to evaluate the usefulness of these data in mapping subsurface resistivity variations.

ACTIVE ELECTROMAGNETIC SYSTEM DATA

1) Apparent resistivity maps at different frequencies (900, 7,000, and 56,000 Hz; Figures 6, 7, and 8) computed from the survey data show a general increase in resistivity with increasing frequency. The highest frequency is most sensitive to the shallow resistive loess. Lower frequencies sense the deeper lower resistive formations.

2) The 56 kHz apparent resistivity map shows the most narrow or short wavelength features due to the variable thickness and character of the surficial material. In addition this part of the measurement system is most susceptible to corruption of signals by cultural noise which also causes some of the short wavelength features.

3) The 900 and 7,200 Hz data generally show the same apparent resistivity variations. The general area of the oil field has a lower subsurface resistivity (higher conductivity). However spatial variations are not easily interpreted from the black and white contour maps of resistivity.

4) The contractor's choice to use an algorithm to compute apparent resistivity which relies on the phase of the EM signals appears to minimize the influence of noise from power lines.

5) The most important conclusion from this part of the study is that it is possible to collect airborne EM data which is not completely corrupted by cultural noise in an area like the Brookhaven oil field.

SECTION 3

RECOMMENDATIONS

Helicopter geophysical surveys using electromagnetic resistivity mapping and magnetic methods should be considered as one of the tools to efficiently map shallow oil field brine bearing water in geologic settings similar to Brookhaven. The technical specifications given in appendix A can provide general guidelines for such contracted surveys. The technical design of airborne surveys (such as selection of particular frequencies for EM measurements) is greatly aided by selected ground surveys and analysis of any available drill hole geophysical logs.

It is strongly recommended that an integrated interpretation be carried out of all available hydrologic and geophysical data. Application of geographic information systems (GIS) would probably greatly help to interpret the wide variety of digital data involved in the project. Recommendations for specific components of the project are given in outline form below.

MAGNETIC DATA

1) A current location map of operating and abandoned wells should be obtained for the area and compared with the location of semi-circular magnetic anomalies.

2) Particular anomalies could be modeled to estimate the magnetic characteristics of well casings.

3) If warranted, selected areas could be further evaluated with ground checks and ground magnetic profiling.

PASSIVE ELECTROMAGNETIC DATA

1) Limited further processing of VLF data may be warranted. However from preliminary analysis of the other airborne EM data, it is doubtful that the VLF measurements will be very useful to map brine distribution in this particular geologic and hydrologic setting. However, ground VLF surveys which measure more parameters and have greater resolution than airborne measurements should be considered for further ground geophysical surveys.

2) A theoretical evaluation should be made of the possible application of the more advanced USGS VLF system which measures more components of the EM fields than currently available commercial systems.

3) Data from the 60 Hz monitoring system should be processed to evaluate possible relationships between brine distribution and any anomalous EM responses away from power lines.

4) A theoretical evaluation should be made of the possible

application of the more advanced USGS airborne 60 Hz system. This evaluation should incorporate detailed analysis of signal to noise in the contractor's EM data.

ACTIVE AIRBORNE ELECTROMAGNETIC DATA

1) The contractor's resistivity maps should be enhanced to facilitate interpretation of spatial trends and variations. Several different enhancement methods should be tried including preparation of color maps and perhaps shaded relief maps.

2) Several different methods can be applied to the airborne data to estimate earth resistivity parameters. This interpretation can then be compared with the parameters interpreted from the ground electrical soundings.

3) A more comprehensive analysis of possible application of fixed wing airborne EM methods can be made based on the helicopter EM data.

INTEGRATED INTERPRETATION

1) The integrated interpretation of data pertaining to brine distribution at the Brookhaven oil field should be a cooperative effort of the USGS, EPA, and local offices of Water Resources Division and the Mississippi Department of Natural Resources.

2) A key factor in effectively carrying out an integrated interpretation is putting all appropriate data into a digital format. An example of data which is currently not in digital format includes known location of oil wells, power lines and other cultural features. Once a uniform formatted digital data base is assembled, a geographic information system (GIS) computer program can be used to analyze the data sets.

3) A complete integrated interpretation may require that additional supplemental data be acquired such as more current water quality measurements, ground checks of well locations, and additional ground geophysical surveys.

SECTION 4

AIRBORNE GEOPHYSICAL INSTRUMENTATION

GENERAL

Data from previous ground geophysical studies of mapping subsurface brine bearing water by the USGS (Fitterman, 1986; Fitterman, Raab, and Frischknecht, 1986) suggest that airborne geophysical methods can be applied to various environmental problems such as locating cased wells and mapping subsurface water bearing brine. On the basis of these and other studies, technical specifications were drawn up for a request for proposals (RFP) for an airborne magnetic and electromagnetic (EM) survey of the Brookhaven (MS) oil field. The technical portion of the RFP (USGS #7-4350), given in Appendix A, allowed proposals to be submitted from contractors using both fixed wing and helicopter based instrumentation.

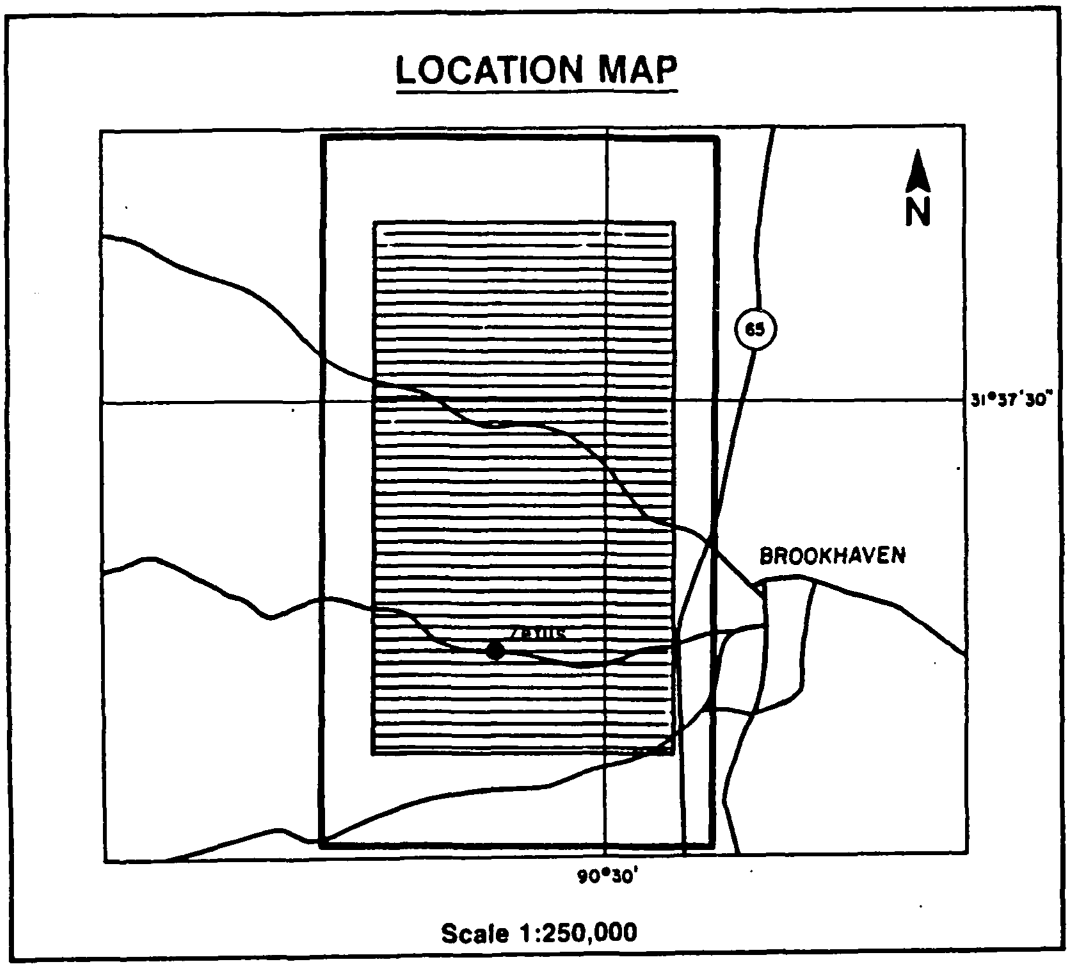
Proposals from contractors were evaluated on the basis of technical merits by a panel of four scientists with the following results. Proposals using fixed wing geophysical instrumentation were generally judged to have lower spatial resolution of EM anomalies and are more susceptible to noise from cultural features such as power lines. Of the proposals using helicopter geophysical instrumentation, the proposal by DIGHEM SURVEYS AND DATA PROCESSING (subsequently referred to as DIGHEM) of Canada was awarded the airborne contract. The technical part of the DIGHEM proposal given in Appendix B describes details of the geophysical hardware.

The AEM survey is limited to the immediate area of the Brookhaven oil field (Figure 3). The flight line spacing for the survey is 1/8 mile (200 meters). Flight lines are in an east-west direction since the oil field is slightly elliptical in a north-south direction (Figure 1). Two lines were flown north-south through the survey area in order to check and adjust base level changes in geophysical data between east-west flight lines. Though the planned flight line location is optimal for the geological setting, it was found that scattered dwellings and small population centers which had to be flown around produced less than straight flight lines.

The geophysical survey equipment used in the helicopter survey can be divided into the following four groups: 1) auxiliary equipment, 2) magnetic sensor, 3) passive EM sensors, and 4) active EM system. All of these systems are described in detail by the contractor's report given in Appendix C. The following subsections give a brief nontechnical description for each of the above systems.

AUXILIARY EQUIPMENT

This type of equipment consists of navigational and data recording instrumentation. In this survey, a UHF (ultra high



THE SURVEY AREA

Figure 3 Boundaries of the airborne geophysical survey (heavy lines) as specified in USGS contract number 7-4350 (Appendix A). Major cities are shown with major roads given by thinner lines.

frequency) radio system was used as the primary navigation system. The system uses two or three beacons or transponders that are located outside of the survey area. Real-time navigation information determined from the transponder signals is displayed for the helicopter pilot and digitally recorded with the other survey data. The UHF navigation system yields a much higher accuracy in retrieval of the flight path location than the standard method of using photographs as described below. The UHF navigation system is important in this particular survey because the flight lines had to be changed from straight east-west in order to avoid flying too close to houses and small populated areas.

Another component of the navigation system is the tracking camera on the helicopter which takes pictures of an area directly below the aircraft. A video camera was used in this survey which recorded on video tape images of the ground below the helicopter. The system also provides a real time display for the helicopter navigator.

Vertical position of the helicopter is digitally recorded from a radar altimeter. The altimeter senses the elevation above the nearest radar reflector. Ideally the measured elevation is from the ground surface. However in practice the nearest radar reflector below the helicopter can be the tops of trees (approximately 15-20 meters high) or buildings. The estimated altitude is used in reduction of the geophysical measurements.

Both analog and digital data records are made of the ancillary and geophysical measurement systems. The analog records provide real time display of data for the operator/navigator on board the helicopter. They are also used in evaluation of data quality during the course of the airborne geophysical survey.

TOTAL FIELD MAGNETOMETER SYSTEM

The magnetic field measurement system consists of a magnetometer towed beneath the helicopter and a base station recording magnetometer. The magnetometer used in this survey is a high sensitivity (0.01 nT) Cesium sensor towed about 50 ft. below the helicopter. The base station magnetometer is a standard proton precession system with a sensitivity of 0.50 nT. This magnetometer, located near the Brookhaven airport, provided an analog record of changes in the total magnetic field every five seconds during the geophysical survey. The timing for the base station magnetometer recording is recorded for correlation with the clock used in the airborne data acquisition system.

The records from the base station magnetometer serve two purposes. The first purpose is to provide an indication during the survey as to whether time changes in the magnetic field are too fast to provide reliable measurements from the helicopter surveying system. Large and rapid changes in the magnetic field occur during magnetic storms. Specifications for the rates of change that are permissible during the geophysical survey are given in Appendix A (subsection 2.7). The second use of the base station records is to correct the helicopter data for small amplitude time changes in the main magnetic field that take place during the survey.

PASSIVE ELECTROMAGNETIC SYSTEMS

These systems passively sense electromagnetic signals generated from sources external to the helicopter instrumentation. The two passive systems used in this survey sense EM signals from VLF (very low frequency) Navy transmitting stations and EM signals generated by power lines. The VLF measurements were made from three transmitting stations located at Cutler (Maine), Seattle (Washington), and Annapolis (Maryland). These stations transmit signals at frequencies ranging from 21 kHz to 25 kHz. Specifications for the VLF instrumentation is given in Appendix C.

The other passive EM system is termed a 60 Hz monitor and is used in most airborne EM surveys to sense the location of power lines which produce signals that usually corrupt the measurements of other EM systems. In this survey, the amplitude of the horizontal and vertical components for the 60 Hz magnetic field was measured and digitally recorded.

Recent research by the USGS (Frischknecht and others, 1986) on applying developing technology to new airborne EM mapping methods has resulted in a prototype system which uses signals from power lines. Data processing and interpretation methods are being developed to map variations in subsurface resistivity. Based on experience from this research, an informal arrangement was made with the contractor to modify their normal measurement procedure for the 60 Hz system. Normally the gain or amplification of the signals is minimal so that when the EM system is flown over a power line a characteristic signal is recorded. For this survey, gains for these channels were increased so that variations in the 60 Hz magnetic fields could be measured further away from power lines. Preliminary inspection of the data in the field and on the digital profiles shows that there are significant variations in amplitude of the magnetic fields which may be associated with either subsurface or surficial (cultural) conductive features. Further processing and interpretation needs to be done in order to determine how useful the 60 Hz monitor data might be for mapping subsurface brine. The contractors report (Appendix C) gives a good discussion of different anomalies in the 60 Hz data produced by various cultural features.

ACTIVE SOURCE ELECTROMAGNETIC SYSTEM

The term active source used in connection with airborne EM surveys indicates that both the EM transmitter and receiver are part of the geophysical system. The DIGHEM[I]V EM system employed in the geophysical survey, described in Appendix B, is the primary EM system that was tested for possible mapping of subsurface brine bearing water. In this system the transmitter and receiver are horizontal coil pairs operated at frequencies of 900, 7,200 and 56,000 Hz. The horizontal coil configuration is ideally suited to mapping variations in subsurface resistivities in the Brookhaven area since these variations are confined to horizontal layers. EM measurements were also made with a vertical coaxial transmitter-receiver coil system which was not specified in the final contract (Appendices A and B). This coil system is typically used in mineral exploration to define near narrow vertical areas of low resistivity. Further data processing of these data will be needed to determine possible applications to mapping lateral boundaries between fresh and brine bearing waters.

The broad range of frequencies in the EM system yield information about resistivity variations from near surface (10's of feet) to depths on the order of 200 to 300 feet. The depth of penetration or mapping generally is deepest for the lower frequencies (900 Hz) and shallowest for the higher frequencies 56,000 Hz. More quantitative estimates of the mapping depth require computer modeling of the EM data.

SECTION 5

TOTAL FIELD MAGNETIC SURVEY

The digital data and maps supplied by the contractor have been corrected for magnetic field drift recorded by the base station magnetometer as specified in the contract with DIGHEM (Appendix A). Further processing was carried out by the USGS to reduce the data supplied by the contractor. The first step in the processing was to remove the IGRF (international geomagnetic reference field) which caused a large south to north gradient in the contractor's magnetic contour map. This large gradient tended to obscure subtle magnetic anomalies.

After removal of the IGRF, a strong east to west magnetic gradient remained in the reduced data due to a large regional magnetic low to the west of the survey area. This gradient was removed by fitting a planar surface to the IGRF corrected magnetic field data. The map shown in Figure 4 is the residual magnetic field after removing this planer surface. Removal of the IGRF and a planer regional magnetic field allows small magnetic anomalies to be more easily seen in maps of airborne magnetic data.

The most obvious features of the reduced magnetic field data shown in Figure 4 are isolated circular and semicircular magnetic anomalies. These magnetic anomalies have positive amplitudes ranging from 10's to 100's of nanotesslas (nT). The short wave-length of these anomalies requires that the magnetic sources be at or near the ground surface. Detailed interpretation of these data is not a primary objective of this report. A description of interpretation of aeromagnetic data in oil field environments to locate well casings has been given by Frischknecht and others (1985). They conclude that semicircular magnetic anomalies such as those in Figure 4, can be caused by steel well casings in addition to a number of other sources. These sources include many different types of cultural features made of steel such as pipelines, buildings, storage tanks, and large machinery. In addition some oil fields are associated with detrital or authigenic magnetic minerals which can cause short wavelength magnetic anomalies (Frischknecht and others, 1985).

Short wavelength magnetic anomalies can be indirectly associated with the distribution of magnetic features related to oil production in the Brookhaven oil field. Several magnetic anomalies have been identified in Figure 4 which are typical of different magnetic features. The magnetic anomaly labeled A (Figure 4) is typical of large amplitude semicircular anomalies. This particular anomaly has an amplitude of 160 nT and is located over an oil storage tank shown on the topographic base map. The linear magnetic anomaly labeled B (Figure 4) which trends east-west is associated with a pipeline between oil tanks also shown on the topographic base map. In contrast to the high amplitude magnetic anomalies, there are many other lower amplitude semicircular magnetic anomalies such as C (Figure 4).

This positive 6 nT anomaly is not associated with any cultural feature shown on the topographic base maps. Consequently this particular positive magnetic anomaly could be caused by an steel casing in an abandoned oil well. Further interpretation should concentrate on obtaining information on locations of known locations of oil wells and other cultural features that could cause magnetic anomalies.

If the assumption is made that many of the short wavelength magnetic anomalies are at least indirectly associated with oil production, then the extent of drilling and other development activity is more extensive than the approximate boundaries shown in Figure 1. In particular, short wavelength magnetic anomalies that possibly indicate cased wells extend to the northeast and southeast of the oil field boundaries (Figure 1).

Additional data processing may help to enhance the magnetic signatures of steel well casings. In particular, computer modelling programs as described by Frischknecht and others (1985) may help to discriminate magnetic anomalies caused by shallow and deep well casings.

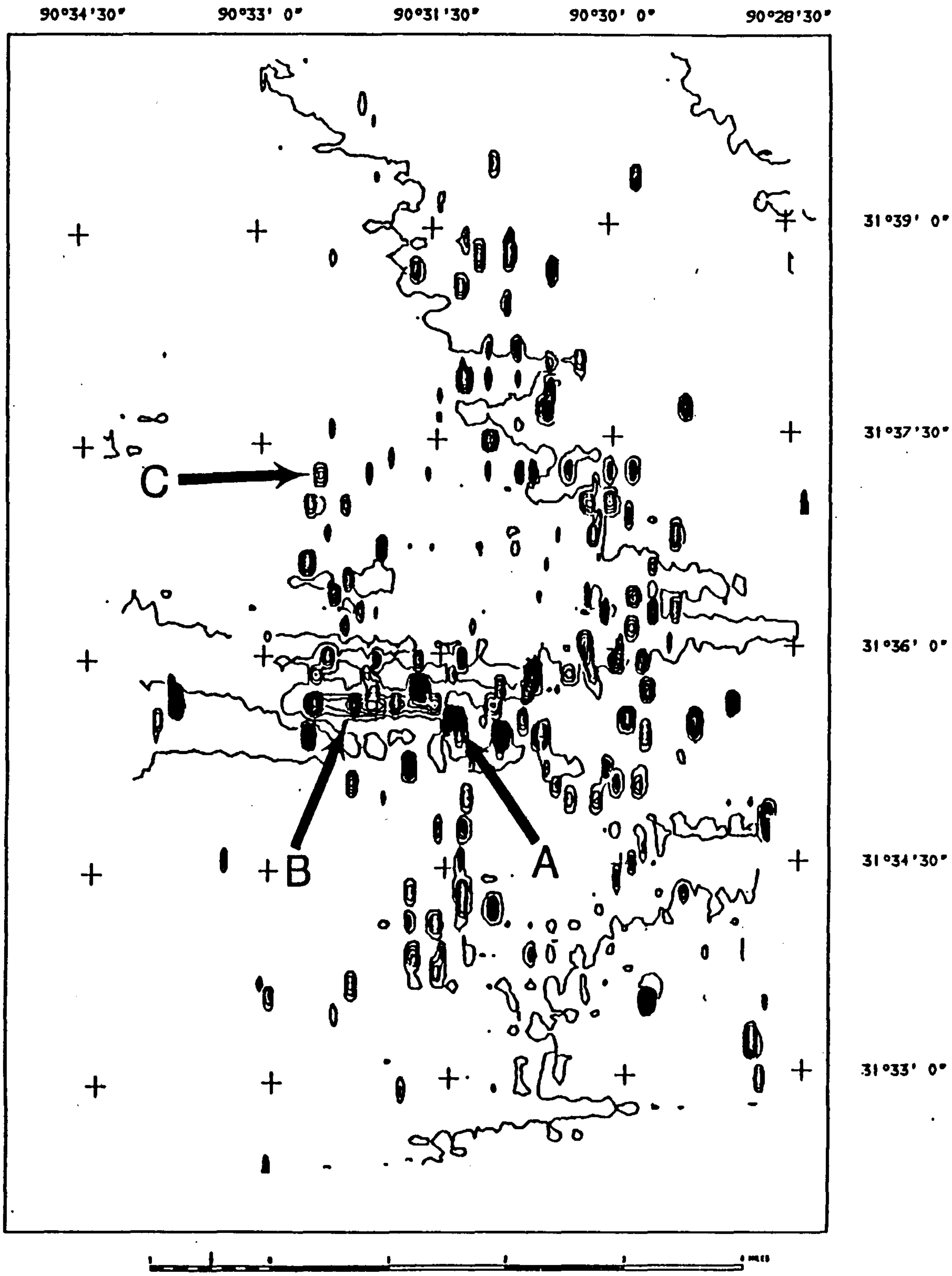


Figure 4 Contour map of the reduced total field magnetic data for the survey area shown in Figure 3. Areas identified by letters and data reduction methods are discussed in the text.

SECTION 6

ELECTROMAGNETIC SURVEYS

PASSIVE ELECTROMAGNETIC MEASUREMENTS

Neither of the two passive EM systems, described in Section 4 of this report, were considered to be the primary airborne systems for mapping the subsurface distribution of brine. The inexpensive VLF (very low frequency) method is usually used in electrically resistive geologic settings, such as crystalline rocks, to locate narrow low resistivity zones. The other passive EM system, the 60 Hz power line monitor, (also described in Section 5) is used in commercial airborne EM surveys to estimate the location of power lines and other sources of cultural noise.

A description of the VLF method and data reduction is given in the subcontractor's report (Appendix C). The total field digital data has been filtered to remove long wavelength anomalies and enhance short wavelength features. A contour map of the processed VLF total field data is shown in Figure 5.

The 60 Hz monitor data and topographic maps have been examined to estimate the location of power lines in relation to the linear features shown in the VLF contour map. Heavy dark lines in Figure 5 show possible locations of power lines. Feature A (Figure 5) follows a road and feature B is a large power line both of which are shown on the topographic map.

The VLF anomalies (Figure 5) are narrow linear features which cross several flight lines or are small circular features that seldom cross more than one flight line. The longer linear features are associated with north-south trending power lines such as anomaly A in Figure 5. The east-west power lines are not as prominent in the VLF data because they are nearly parallel to the direction of the flight lines. For example, the power line identified as B (Figure 5) only has a few associated small circular VLF anomalies because it trends almost parallel to the flight lines.

A vast majority of the VLF anomalies are probably due to cultural features such as power lines and metallic structures (for example, oil tanks and fences). However, old pits which were used to store brine (Kalkhoff, 1986) which produce small circular VLF responses that resemble cultural effects. Consequently a more comprehensive interpretation of the VLF data uis warranted. The association of VLF and positive magnetic anomalies should also be evaluated for possible additional information about location and characterization of geophysical anomalies from oil well casings.

Preliminary analysis of VLF data as presented by the contractor has limited indirect application to the general problem of mapping subsurface brine. However, this observation should not be taken to indicate the usefulness of ground VLF measurements. Ground surveys are made with closer station

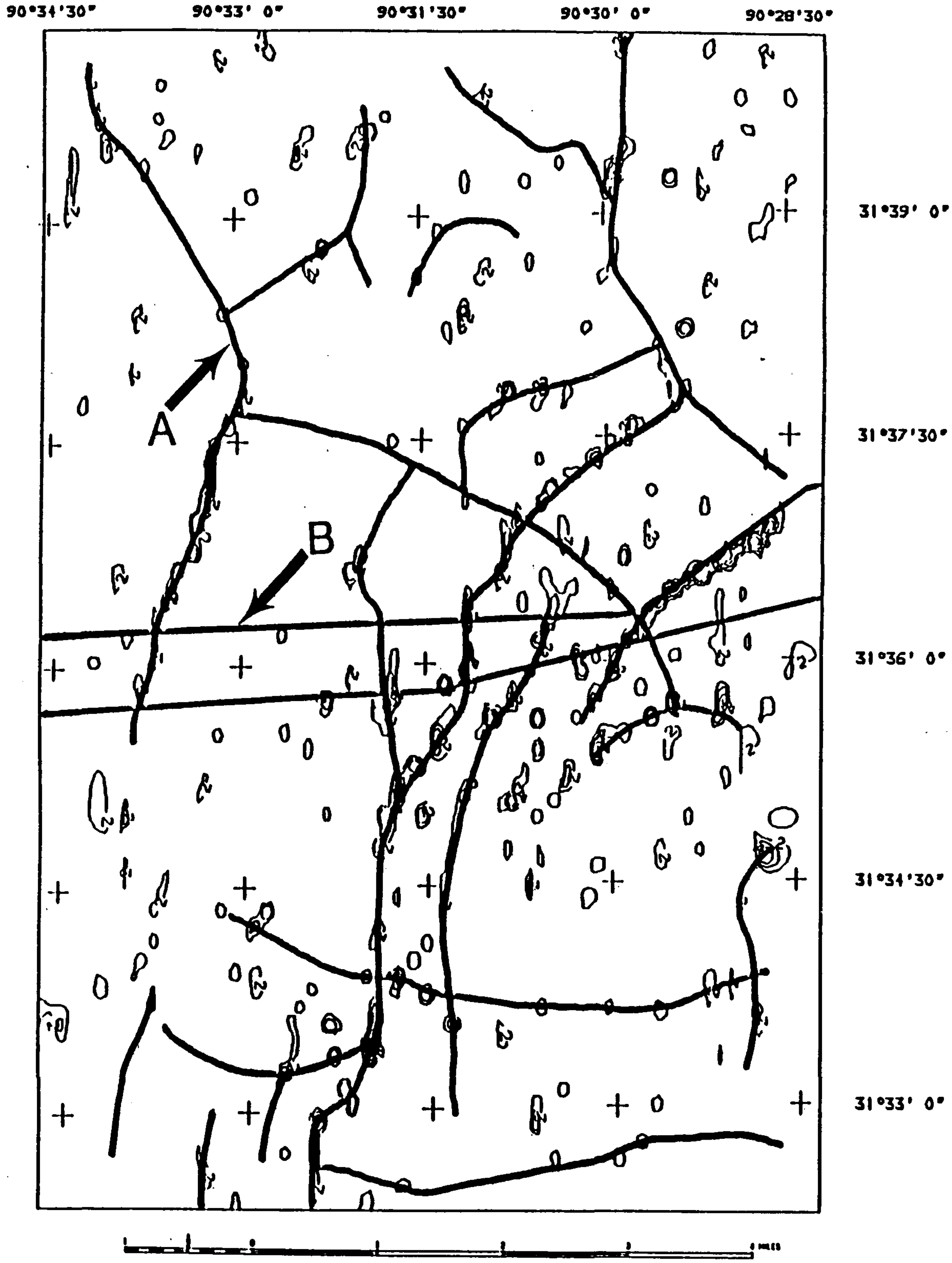


Figure 5 Contour map of the filtered airborne VLF total field (light lines). Heavy solid lines are some of the possible power lines identified by the 60 Hz monitor and cultural features on topographic maps.

spacing and measure more parameters than is possible in airborne systems. In particular, ground surveys can measure apparent resistivity by directly contacting the ground. Ground VLF surveys should be considered in a more comprehensive geophysical investigation of the Brookhaven area.

ACTIVE ELECTROMAGNETIC MEASUREMENTS

The primary objective of this study is evaluation of active EM systems to estimate the quality of data that can be acquired in an area with heavy cultural contamination. There are three major steps in data reduction , described below, that must be carried out to produce geophysical maps that can be used to interpret and map subsurface resistivity variations. The first important step in data reduction is removal of system calibrations done both on the ground and during the airborne survey. The low resistivity of subsurface units in this area requires that special care be taken with calibration procedures and system response removal in final contour maps. Preliminary maps delivered by the contractor showed some subtle variations in the reduced EM data that were due to problems in correction of system calibration which were subsequently corrected in the final delivered products. The second major step in processing is to convert the reduced EM data to apparent resistivity as discussed in Appendix C. Fraser (1978) also gives technical details of these computations. The third step in data processing, not required in the contract specification (Appendix A), was done by the contractor to remove small level changes in the apparent resistivity between a few flight lines. These level changes, mostly at the highest frequency, are caused by instrumentation drift that could not be corrected by the normal calibration procedures. The procedure used to remove level changes in geophysical data between flight lines is commonly termed decorrugation (Urquhart, 1988) and is a filtering process. All of the apparent resistivity maps given in this report have been filtered by DIGHEM using this method.

A grey scale presentation of the apparent resistivity map from the 56,000 Hz EM data is given in Figure 6. These and other apparent resistivity maps discussed below have been plotted at a scale suitable for page size presentation as required for this report. Original map plots of the data are at a scale of 1:24,000 which is much more suitable for evaluation and interpretation. One of the visual effects produced by decreasing the size of the maps is a loss in the resolution of small (short wavelength) features. Consequently many features of the map due to cultural noise are not prominent on maps given here.

There are two other considerations in the grey scale used for Figure 6 and other maps of apparent resistivity. The first is that the grey scale intervals are not linearly spaced. An approximate logarithmic interval was used because the apparent resistivity values span almost three decades in magnitude. A second consideration in the grey scale is the negative lower

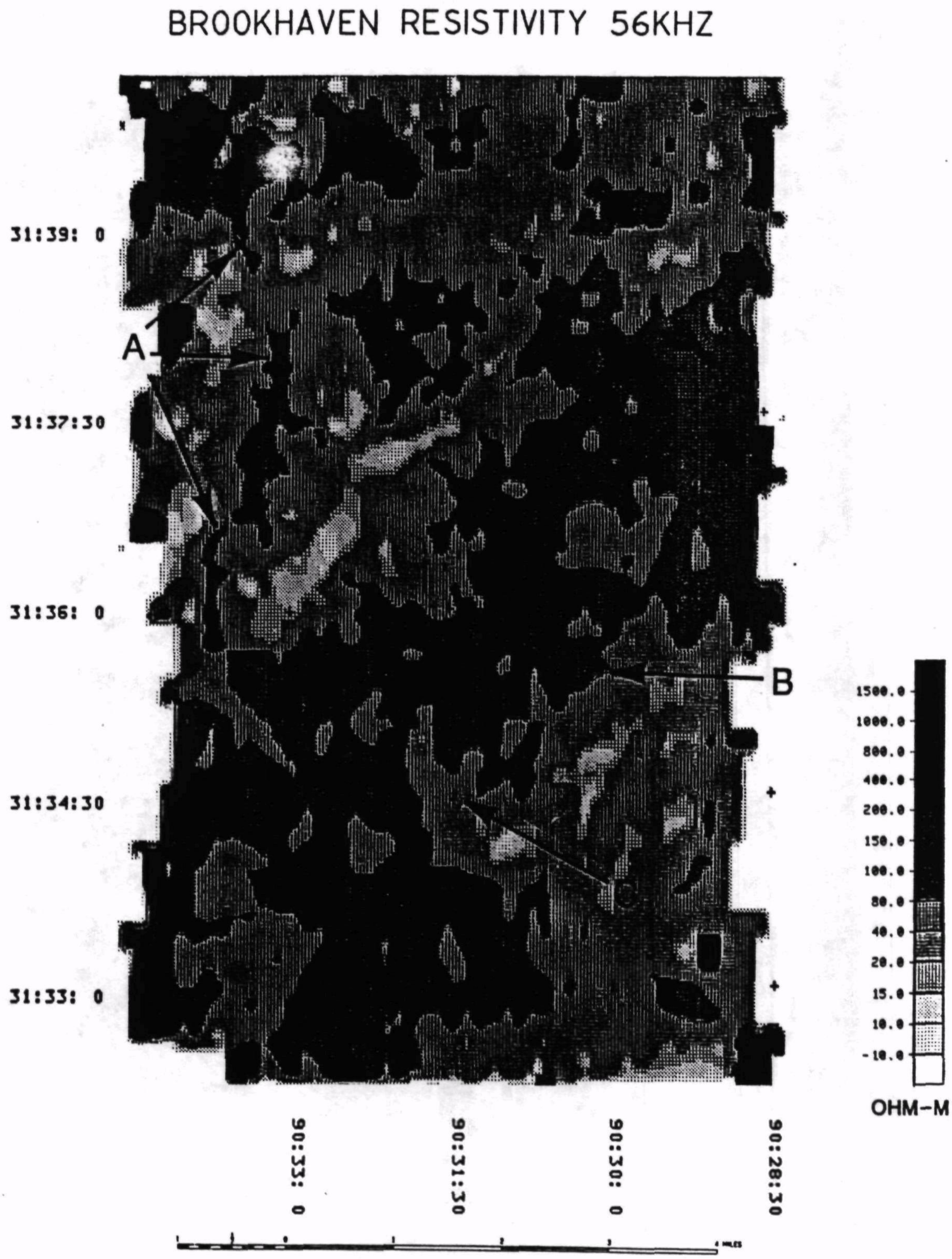


Figure 6 Grey scale apparent resistivity map computed from the 56,000 Hz EM data. Light areas are less resistive (more conductive) than the darker areas. Areas labeled A, B, and C are interpreted cultural responses discussed in the text.

BROOKHAVEN RESISTIVITY 7200HZ

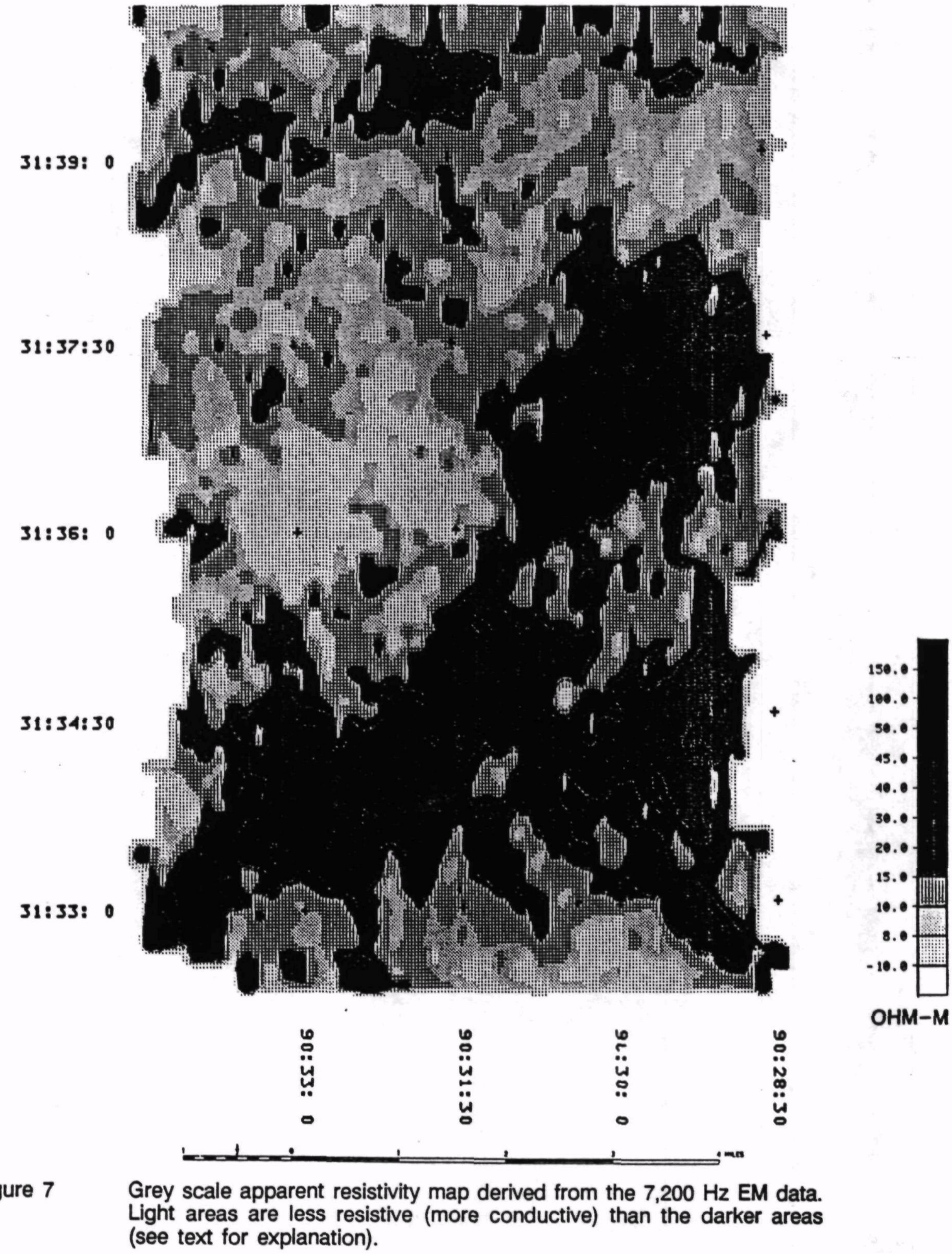


Figure 7 Grey scale apparent resistivity map derived from the 7,200 Hz EM data. Light areas are less resistive (more conductive) than the darker areas (see text for explanation).

bound of values (Figure 6). This was required by the USGS gridding and plotting programs and does not reflect the actual values computed from the measurements. Negative apparent resistivities are not possible for most electrical geophysical measurements.

The grey scale contour map (Figure 6) shows some features that can be directly related to the location and trend of power lines. The arcuate trend of resistivity highs in the northwest part of the survey area anomaly in (labeled A in Figure 6) follows the trend of a power line (Figure 5). A similar northeast trending the south central part of the survey (B in Figure 6) is associated with a power line. Though these two cultural features produce narrow high apparent resistivity trends, other power lines are associated with linear low resistivity trends. For example, the north-south power line located at area C (Figure 6) is associated with low and high resistivities. The difference in expression of power lines in apparent resistivity maps depends on a complicated interaction of the active EM system with the power line and also the background subsurface resistivity. In the Brookhaven survey, the variable signature of cultural noise is particularly hard to assess for the 56,000 Hz apparent resistivity maps because background shallow resistivity is highly variable.

Though there are many local areas where cultural noise have distorted the apparent resistivity signature of the subsurface, there are broad areas of both high and low resistivities shown in Figure 6. The areas of high resistivity, generally greater than 100 ohm-meters, probably reflect the distribution of loess and more resistive alluvium. The darkest areas in Figure 6 have resistivities greater than 200 ohm-meters with local areas approaching 1000 ohm-meters. These latter areas are most likely produced by corruption of the EM signals by cultural features since such high resistivities are not expected in this geological setting. Areas of low resistivity (Figure 6) are shallow (less than 10 meters) conductive features that could be cultural or geologic. Though the 56,000 Hz apparent resistivity map reflects the distribution of surficial features such as alluvium and loess, it provides a control for interpretation of the lower frequency data discussed below.

The grey scale used for the apparent resistivity map from the 7,200 Hz data (Figure 7) has a much more restricted range of values than the 56,000 Hz map (Figure 6). Computed values of apparent resistivity from the 7,200 Hz data are on the average a factor of seven lower than those computed from the higher frequency. Theoretically the lower frequency has approximately a factor of three greater depth of penetration than the higher frequency (21 versus 59 meters as described in Appendix B). Consequently the apparent resistivities shown in Figure 7 are not as sensitive to the thin surface layer of resistive loess. The signatures of cultural features are not as obvious in Figure 7 as they are in Figure 6. For example the arcuate narrow high resistivity anomalies labeled "A" in Figure 6 are more subtle in

Figure 7. Difficulty in recognition of responses caused by cultural sources is due to two factors. The first factor is the scale of the maps required for this report. On the larger maps at a scale of 1:24,000, subtle correlations can be seen in the trends of apparent resistivity and cultural features such as power lines.
The second factor is that in this particular geoelectric setting, the apparent resistivities from areas of cultural noise are nearly the same as produced from the subsurface lithology. Thus apparent resistivity maps must be examined very carefully in order to avoid interpreting surface cultural variations as subsurface features.

In general the Brookhaven oil field (Figure 1) is associated with a broad resistivity low of less than 15 ohm-meters which is most likely due to a decrease in the subsurface resistivity. This decrease is expected from near surface brine contamination (Becker and Morrison, 1987). Areas of low resistivity are probably not all due to near surface brine unless contamination is much more extensive than described by Kalkhoff (1986). One possible geologic source of the low resistivity zones are clay rich sand units within the Citronelle or the upper part of the Hattiesburg Formation.

Another major trend in the 7,200 Hz apparent resistivity map (Figure 7) is the general increase in apparent resistivity in the southeastern part of the survey area. There is approximately a factor of ten increase in the apparent resistivity between light (northwest) and dark (southeast) parts of Figure 7. The northeast trending irregular contact between these two areas is probably due to a number of different geologic and hydrologic sources. However without further geologic information, it is not possible to specifically interpret this feature. Grey scale intervals used for the apparent resistivity map derived from the 900 Hz EM measurements (Figure 8) are the same as used for the 7,200 Hz map (Figure 7). Generally the 900 Hz map has less dark areas indicating resistivities greater than 15 ohm-meters than the apparent resistivity maps for higher frequencies (Figures 6 and 7). Since the 900 Hz EM measurements have the greatest depth of penetration the general conclusion is that the subsurface lithologies sensed by these signals have lower resistivities than the shallower features mapped by the higher frequencies.

There are some obvious correlation of trends in low apparent resistivities and power lines indicated by the letters shown in Figure 8. However these and other cultural effects do not obscure the broader apparent resistivity variations probably related to changes electrical characteristics of the subsurface. The Brookhaven oil field (Figure 1) is associated with a broad resistivity low of less than 10 ohm-meters. Low resistivities occur throughout the northern 2/3 of the survey area (Figure 8). Consequently further interpretation will be needed to evaluate the possible signature of shallow subsurface brine.

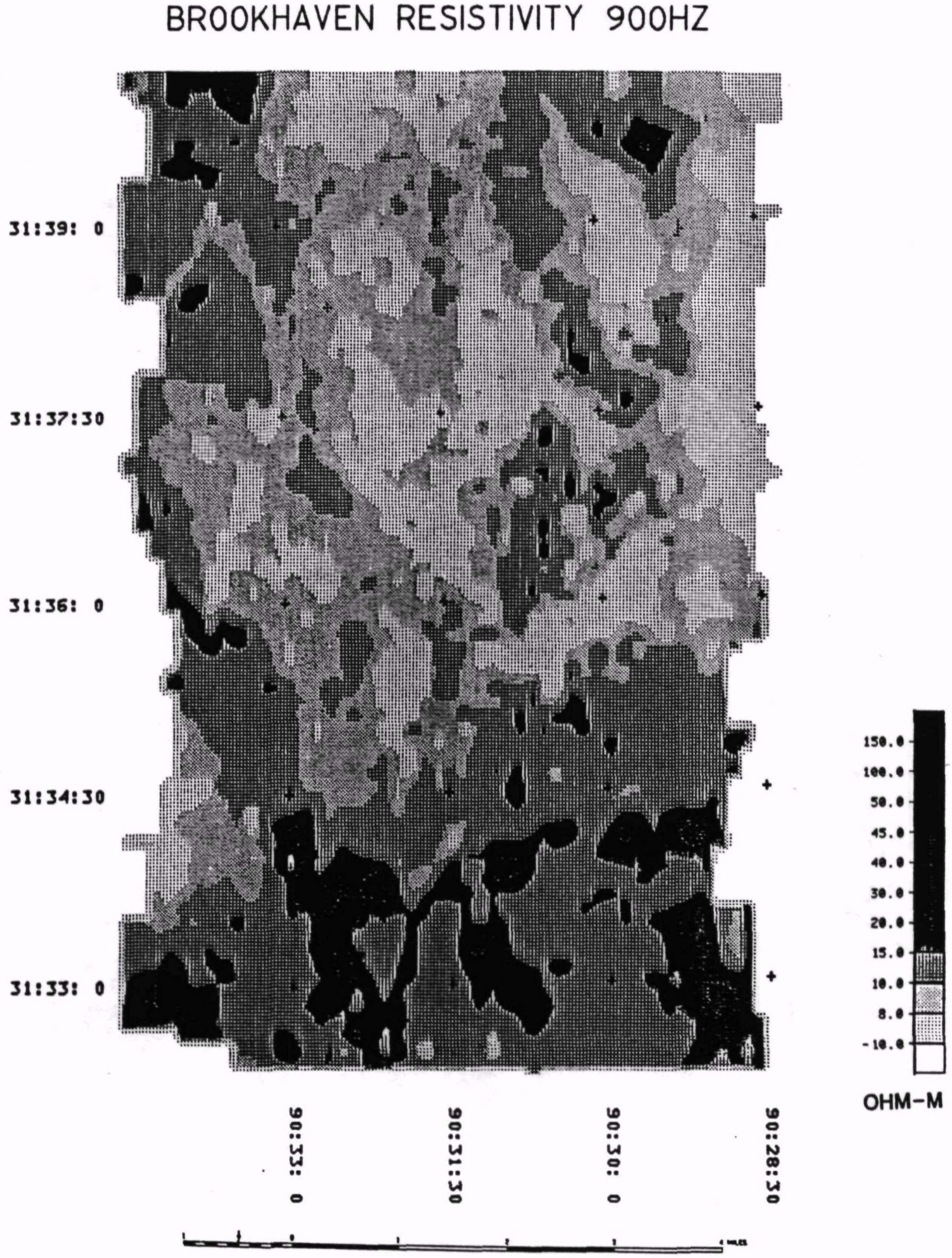


Figure 8 Grey scale apparent resistivity map derived from the 900 Hz EM data. Light areas are less resistive (more conductive) than the darker areas (see text for explanation).

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APPENDIX A

TECHNICAL SPECIFICATIONS USED IN RFP

Material given in this appendix gives the technical specifications section of the request for proposals (RFP #7-4350) as issued by the USGS Branch of Procurement and Contracts. The following text is presented in the format required by the USGS and presented as it originally appeared in the RFP. The contents of these specifications are presented as part of this report for the following reasons:

1) These specifications and the response of the contractor (Appendix B) serve as the basis for quality control documentation.

2) The technical section of the RFP may serve as a guideline for future geophysical contracts for airborne surveys in similar geological settings. and

3) Distribution of the specifications can result in improvements for subsequent applications.

The complete RFP is not included since many details of contracts vary between government agencies.

PART I STATEMENT OF WORK

1.0 Objectives: In many oil fields large quantities of brine are produced along with oil. Generally, the brine is separated from the oil and reinjected into the producing horizon or another horizon that already contains poor quality water. However, leaks in the injection wells or conduits between aquifers, such as leaky abandoned wells, sometimes allow brine to enter aquifers containing fresh water. As part of a research program on identification and mitigation of brine contamination of fresh water the U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency plans to test the use of airborne electromagnetic methods as a means of mapping brine pollution in near-surface aquifers.

The Brookhaven Oil Field and parts of the surrounding area in Mississippi have been selected as the test area (see attached map). In parts of the Brookhaven field the Citronelle formation, which is a near surface unconfined aquifer, is contaminated. Locally, sand layers which serve as aquifers in the underlying Hattiesburg formation also are contaminated. The objectives of the airborne survey(s) are to map significant variations in resistivity that occur within 100-120 m of the surface. A possible secondary objective is to make high resolution magnetic measurement to locate abandoned wells.

2.0 Scope of work: The area to be flown encompasses 45 square miles (see attached map) the area is generally flat or gently rolling although locally the elevation changes as much as 70 feet in 1/4 mile or less. It may be difficult to adequately map resistivity variations throughout the depth range of interest using a single system. Therefore, the possibility of using both a helicopter system that can operate at several high frequencies and a fixed wing transient system will be considered. Proposals for either or both types of systems are solicited.

3.0 General requirements for survey

3.1 The preferred flight direction is east-west but the proposal should include costs for both east-west and north-south flight lines.

3.2 The desired line spacing is 150 to 400 meters. The proposal should include costs per line mile for EM surveying only and for combined EM and magnetic surveying for spacings of 150, 200, 250, 300 and 400 meters.

3.3 Tie lines shall be flown at intervals of approximately 4 miles.

3.4 The flight height shall be specified in the proposal along with a brief discussion of the instrumental and operational factors that were considered in selecting the height.

3.5 Before beginning routine surveying approximately 20 line miles will be flown and evaluated by the Contractor and the Contracting Officers Technical Representative (COR). The COR's evaluation will be done overnight in the field. To the extent possible system parameters will then be optimized before routine surveying is started.

PART II TECHNICAL SPECIFICATIONS

1.0 Electromagnetic System

To sense changes in the resistivity of both aquifers, measurements must be made at several frequencies or times. In particular, the response from the lower layer will exhibit a maximum at a frequency that depends on the parameters of all the layers.

Part of the area is covered by loess and alluvium which may be as much as 20-30 feet thick. Immediately beneath the loess, or outcropping where loess and alluvium are absent is the Citronelle Formation which is composed of discontinuous sand and gravel units separated by sandy clay lenses. Beneath the Citronelle Formation is the Hattiesburg Formation which consists mainly of silty clays; however, a number of thick discontinuous sand layers occur within the Hattiesburg Formation. Shallow resistivity soundings indicate that the resistivity of the Citronelle Formation is relatively high except where it contains brines. Generally the resistivity of the upper unsaturated part of the Citronelle Formation is highest. The most extreme gradients in the water table are only 20 to 40 feet per mile so by following the surface topography the height of an aircraft above the water table will vary. Electric logs indicate that the resistivity of the confining layers in the Hattiesburg is relatively low and that the resistivity of the sand layer is much higher. Typical estimated parameters for the various layers are:

	Thickness	Resistivity
Loess	0-30 ft	50-200
Citronelle (without brine)	20-120	400-2000
Hattiesburg (confining layer)	--	--
Hattiesburg (sands)	--	--

To the extent possible the system should be sensitive to variations in resistivity of the sand layers in the Hattiesburg Formation as well as to variations in the Citronelle Formation.

The proposal shall contain a general description of the electromagnetic system plus specific information as follows:

1.1 Coil configuration-- The orientations and spacings of all coil configurations that will be used should be specified.

1.2 The frequencies and/or gate times that will be available for use shall be specified.

1.3 Static and in-flight system noise levels shall be specified assuming that sferic levels are typical for morning hours excluding the summer period May 1 - Sept. 15. The specified noise levels will become a requirement. Measurements of the static noise level and in-flight noise level at altitude shall be made before the survey.

1.4 Maximum rates of system drift due to both mechanical and electronic changes shall be specified. The specified drifts will become a requirement: The procedures that will be used for monitoring and correction of drift shall be specified.

1.5 The techniques that will be used to calibrate the system shall be described briefly. The system must be calibrated as often as necessary to ensure that it operates within stated specifications.

1.6 The level of 60 Hz power line noise shall be monitored; a brief description of the monitor shall be provided.

2.0 Magnetometer System

Acquisition of magnetic data is an option which may be exercised by the Government). A general description of the magnetometer shall be given in addition to the following specific information:

2.1 The static resolution of the system shall be given. It must be 0.1 nanoteslas (nT) or better.

2.2 The maximum sample rate shall be specified for each sensitivity. Readings shall be taken and recorded at a rate of no less than two per second.

2.3 The inflight noise envelope shall be specified. "Quiet" air conditions may be assumed but the specified noise envelope will be a requirement.

2.4 The figure of merit or other measure of performance for pitch, roll and yaw maneuvers shall be specified and shall become a requirement. It shall be verified before the survey begins.

2.5 The errors due to changes in heading shall be specified and shall become a requirement. Heading error shall be verified before the survey begins by flying over the same point on magnetic north, east, south, and west directions at least twice. Verification shall be repeated if mechanical parts of the aircraft are changed or if the magnetometer is repaired or modified.

2.6 An analog record of variations in the Earth's magnetic field shall be made during periods when airborne data is being collected. The monitor station may be placed near the contractors base in a magnetically quiet location. The ground monitor station shall have a noise envelope less than 0.4 nT. The chart speed shall be no less than 1 inch/per 5 minutes and the vertical scale shall be no less than 25 nT per inch. The analog records shall contain time marks that permit recovery of actual time to within 15 secs and the record shall be annotated to indicate date, absolute value of the magnetic field, time and vertical and horizontal scales.

2.7 Airborne surveys shall not be conducted when variations of the earth's magnetic field exceeds 2 nT from a chord two minutes long, as determined from the analog record on the ground monitor.

2.8 A digital record of the earths magnetic field shall be made during the periods when airborne data is being collected. The station shall be placed in a magnetically quiet area within 10 miles of the survey area. The resolution of the magnetometer shall be 0.1 nT or better and the noise envelope shall be 0.2 NT or better. The field shall be measured and recorded at least once per 2.0 seconds. The airborne and digital base station magnetometer shall be synchronized with an accuracy of 1.0 second or better. Synchronization shall be checked at the end of each days flights.

3.0 Altimeter Specifications

Continuously recording radar and barometric altimeters shall be employed.

3.1 The resolution of both altimeters shall be specified, and shall become a requirement.

3.2 The absolute accuracy of the radar altimeter over flat terrain shall be specified and shall become a requirement.

3.3 The procedures that will be used to correct the barometric altimeter for changes in air pressure shall be described.

3.4 The methods used to calibrate the altimeters shall be specified. The altimeters shall be calibrated at the beginning of the survey and as often is required to ensure that the altimeters are operating within specifications.

4.0 Navigation and Flight Path Recovery Systems

4.1 The system used for aircraft navigation shall be specified (visual, electronic indicator). If the spacing between survey lines exceeds 1.5 of the stated flight line spacing for more than 0.5 mi, a fill-in line shall be flown at the contractors expense unless the deviation is caused by safety requirements or FAA regulations.

4.2 The flight path shall be recovered within ± 50 feet of the true position in the along track and cross track directions. This accuracy shall be verified by use of a tracking camera or other specified means.

5.0 Analog Records

The system used for analog recording shall be specified.

5.1 The analog records shall be of sufficient resolution to enable visual checks to be made of the system performance (e.g. noise levels).

5.2 At least four channels of EM data shall be recorded by the contractor. The information on these channels will be mutually agreed upon by the COR and the contractor.

5.3 The remaining analog data shall consist of: 60 Hz noise level, magnetometer readings, radio altimeter data and fiducial data.

5.4 Analog records shall be adequately labeled with at least: date, line number, flight direction, and project name.

5.5 Records shall be made available to the COR upon request during the survey.

6.0 Digital data recording

6.1 Digital data shall represent the analog traces including (EM), and altimeters, within (0.3%) or better of full scale value of analog trace.

6.2 Final data tapes shall include x, y position of the flight lines and fiducial points along with the other digital data. These position points shall be in a coordinate system (e.g. lat., long., etc.) agreed upon by the COR and the contractor.

6.3 The contractor shall provide the government with sufficient information to establish the integrity of the digital data.

6.4 Tape specifications: (a) 9 tract, NRZI compatible, odd parity with 800 bpi recording density. Recording mode to be EBCOIC (formatted). Character set limited to IBM 028 Keypunch code set. (b) All floating point data to be in F format. Fortran E format is not acceptable. (c) Blocksize shall not exceed 8,000 characters in length. (d) Data may be blocked (more than one logical record per physical record or block). If blocking is performed the logical record size shall remain fixed in any one field and, except for the last block shall be equal in size. If blocking is not performed, physical records may be of varying length. Computer system recording methods employing "link words", key or other system dependent recording modes are not acceptable. (e) Computer system labels shall not be recorded (i.e., "unlabeled" tapes). Optionally, user readable identification records may be supplied. (f) More than one data file may be present on one data tape (multifile reels). (g) Each tape supplied shall have a unique visual label attached to each reel, and correlating with supplied descriptive material or its contents.

7.0 General Specifications for Data Processing

7.1 The analog records and logs must be examined daily in the field to make certain that the equipment is operating properly and that altitude deviations are not excessive. Proper functioning of the flight path recovery system shall be verified in the field.

7.2 The flight path shall be recovered and plotted at a scale of 1:12,000 over a topographic base derived by enlargement of USGS 1:24,000 topographic maps.

7.3 Contour maps at a scale of 1:12,000 shall be prepared for the area flown showing the reduced total field magnetic data overlain on a topographic base. Diurnal variations are to be removed by use of the base station magnetometer data and levelling shall be verified by use of tieline data. The contour interval shall be decided by mutual agreement between the contractor and COR.

7.4 The electromagnetic data shall be levelled and contour maps at a scale of 1:12,000 overlain on a topographic base shall be prepared for each component at each frequency or each time gate. The contour interval shall be decided by mutual agreement between the contractor and COR.

7.5 The corrected magnetic, four channels of corrected electromagnetic, 60 Hz monitor and the altimeter data shall be plotted as stacked profiles at a scale of 1:12,000. The contractor and COR shall agree on which four electromagnetic channels shall be plotted.

8.0 Interpretation of Electromagnetic Data

Interpretation of the reduced EM data is an option which may be exercised by the government.

8.1 All EM anomalies that are thought to be caused by cultural features shall be identified and indicated on a map. The region around the cultural feature within which the EM response is substantially affected shall be estimated and outlined on a map at a scale of 1:12,000.

8.2 Ideally, the data would be inverted for the entire area, excluding regions of cultural anomalies, using four or five layer one-dimensional models. However, proposals to produce other products based on simpler models, including a homogeneous earth model, will be considered.

PART III QUALITY CONTROL

1.0 Data acquisition, processing, and interpretation must be carried out under the requirements of a Quality Assurance Plan written by the U.S. Geological Survey and approved by the Environmental Protection Agency. The contractor will be responsible for adjustment and calibration of equipment, operation of equipment to meet specifications, and processing and interpretation of data to meet specifications.

1.1 All geophysical and navigation equipment shall be checked, adjusted and calibrated according to manufacturers recommendations immediately before commencing data acquisition or within the time specified by the manufacturer. The contractor shall provide copies of manufacturers adjustment and calibration procedures for each piece of equipment and a log giving the dates and procedures that were followed.

1.2 Before commencing surveys the readings of the airborne and ground magnetometers shall be compared by making successive measurements with the sensors in the same location. To carry out this procedure the aircraft must be moved after readings with the airborne magnetometer are taken on the ground.

1.3 The analog portion of the data acquisition system shall be calibrated by injecting known signals from a dc standard and recording and recovering the output.

1.4 All steps in data processing in which data is corrected, transformed or changed in any way shall be described and included as part of the final report.

1.5 The models used and all steps in which data are altered or transformed in interpretation shall be described and included in the final report.

1.6 The contractor shall allow the COR to inspect equipment and data in the field and data and results in the Contractors Office to verify adherence to specifications.

PART IV DELIVERABLE ITEMS

1.0 Original data and Quality Control items.

1.1 All Quality Control items specified under Part III.

1.2 Flight logs indicating production times, lines flown, operational problems and other relevant data.

1.3 All analog records for airborne systems and ground monitor systems.

1.4 Records documenting magnetic heading effect as described in Part II.

1.5 Records documenting magnetometer manuever noise as specified in Part II.

1.6 Records documenting accuracy and of navigation system as specified in Part II.

1.7 Records of static and in-flight noise level for the EM system as specified in Part II.

1.8 Records of altimeter calibrations and control for pressure variations for barometric altimeter.

1.9 Original digital data tapes with a complete description of the format.

2.0 Processed Data — Single copies.

2.1 Flight line maps on stable base as specified in Part II.

2.2 Magnetic contour maps on stable base as specified in Part II.

2.3 EM contour maps on stable base as specified in Part II.

2.4 Stacked profiles as specified in Part II.

2.5 Magnetic tape containing digital information written according to specifications in Part II, containing the information given in the stacked profiles as specified in Part II.

2.6 Magnetic tape containing the flight path, written according to specifications in Part II.

2.7 Magnetic tapes, written according to specifications in Part II containing gridded data used in preparation of magnetic and electromagnetic contour maps.

2.8 Map or maps showing interpretation of electromagnetic data.

2.9 Magnetic tape, written according to specifications in Part II, containing gridded data used in preparation of interpretative map of electromagnetic data.

3.0 Multiple copies.

3.1 Four copies of the final report including all required information on data acquisition and processing.

3.2 Four copies of the final report on interpretation of the data.

PART V INSPECTION AND ACCEPTANCE

1.0 The Government reserves the right to visit the contractor in the field or at the contractor's place of business to ascertain that proper procedures are being employed in the acquisition and compilation of the data. Any data processing or field techniques that are deemed proprietary by the Contractor will be maintained proprietary by the USGS inspector(s).

1.1 The Government will conduct a review of preliminary paper copies of contour maps and profiles as described in Part IV 2.1, 2.1, 2.3, and 2.4 entitled "Deliverable Items", within twelve (12) calendar days after receipt of the above-described rough data and return the rough drafts of the completed data to the contractor by the fourteenth day.

1.2 The Government will conduct a review of preliminary paper copies of interpreted data as described in Part IV, 2.8 within twenty (20) calendar days after receipt and return the rough drafts by the twenty-second day.

1.3 If the Government review exceeds the periods referenced above, the contract delivery data shall be automatically extended one (1) day for each day of delay caused by the Government review.

1.4 With the submittal of all final deliverables as listed the contractor shall have met all criteria as specified herein and shall have made all corrections required resulting from the Government. The Government reserves the right to review again the deliverables for compliance prior to acceptance by the Contracting Officer. Until final acceptance, deliverables may be returned to the contractor for compliance with corrections listed during the Government review.

APPENDIX B

SUBCONTRACTOR'S RESPONSE TO RFP

Responses to the RFP (#7-4350) were evaluated on the basis of technical merits and cost. This evaluation resulted in award of a contract for helicopter airborne geophysical survey of the Brookhaven area to DIGHEM Signal Processing and Surveying Inc. (Toronto, Ontario, Canada). Material in this appendix is the contractor's proposal. This material is presented in the form submitted by the contractor with page numbers added to conform to EPA specifications for this report. The vitae of the personnel have been deleted since this information is not particularly relevant to the technical performance of the geophysical equipment.

The contractor's proposal is presented without any editorial changes. Acceptance of the proposal by means of award of the contract means that exceptions to the technical specifications given in the proposal replace those given in appendix A. The conclusions presented in the proposal are the sole responsibility of the contractor and are not directly or uindirectly endorsed by the EPA or the USGS.

U. S. G. S.

SOLICITATION NO.

7-4350

DIGHEM SURVEYS

& PROCESSING INC.

VOLUME II

Respectfully Submitted,

Richard S. Taylor

TABLE OF CONTENTS

1. INTRODUCTION

Dighem proposes to map areas of brine saturation in the Citronelle and Hattiesburg formations using its DIGHEM^{IV} electromagnetic system. The system is also capable of mapping abandoned well casings using a Cesium magnetometer flown in conjunction with the DIGHEM^{IV} sensor.

We anticipate that the apparent resistivity of the ground within the survey area is complex, with significant vertical and lateral variations of resistivity within each horizon. A small-scale helicopter-borne EM (HEM) system will be best able to define these variations of resistivity. A HEM system with maximum coil separation will give maximum penetration. Dighem's 7.98 m coil separation is not surpassed by any commercially available system. The depth penetration of the DIGHEM^{IV} system should be adequate for the anticipated depths to brine saturated earth.

The discontinuous zones to be mapped may be assumed to be roughly horizontal. Because of EM response characteristics, horizontal transmitter-receiver coil-pairs are more suitable for data acquisition than vertical coil-pairs. The DIGHEM^{IV} system has 3 horizontal coil-pairs, more than any other HEM system. A HEM system with a broad frequency range will have the best chance at separately identifying various layers. Dighem's 62-fold frequency spread (900 Hz to 56000 Hz) is the largest of any commercially available system.

Since 1967, Dighem has flown numerous surveys requiring high signal-to-noise electromagnetic and magnetic data for mapping applications. Dighem has been furnishing its clients with airborne resistivity maps since 1975. The DIGHEM^{IV} system, first flown in 1984, meets the above mentioned criteria for optimum data acquisition on this project. Dighem's 12 years of experience with identifying cultural effects and delivering accurate resistivity maps from a wide variety of surveys should contribute to the usefulness of the resistivity maps from this survey.

2. TECHNICAL DISCUSSION OF APPROACHES

2.1 Modeling

To quantify system selection parameters, the mapping problem has been simplified into three workable models. The first model (depicted in Figures 1 through 3) shows a 3, 6 and 9 meter thick loess layer (100 ohm-m) on top of a half space of dry Citronelle formation (1000 ohm-m). These figures illustrate the response of this model to the DIGHEM^{IV} frequencies (900, 7200 and 56000 Hz). In all the figures, CPI is the horizontal coil inphase response, CPQ is the horizontal coil quadrature response, DP is the apparent depth to conductive earth and RES is the apparent resistivity of the earth.

The 900 Hz resistivity (Figure 1) is relatively indifferent to loess thicknesses up to 9 m. At 7200 Hz (Figure 2), a little more resistivity variation is seen. The 56000 Hz resistivity (Figure 3) gives the most accurate measure of loess resistivity, although it significantly overestimates the resistivity where the loess is thin. For the most likely thickness and resistivity of loess, the lower frequencies yield resistivity estimates of about 600 ohm-m for a combined loess and dry Citronelle sequence.

Model 2 (Figures 4-6) and model 3 (Figures 7-9) illustrate the response of the DIGHEM^{IV} system to the Citronelle formation saturated with fresh water and with brine. The most probable combined sequence of loess and dry Citronelle formation is represented by a 25 m thick layer of 600 ohm-m material. The Hattiesburg formation is represented by a 20 ohm-m half space. Fresh water saturated Citronelle formation is represented in model 2 (Figures 4-6) as a 120 ohm-m layer of variable thickness. The 900 Hz frequency (Figure 4) maps the Hattiesburg formation. The 7200 Hz frequency (Figure 5) is increasingly influenced by the Citronelle formation as it thickens. Where the loess and Citronelle formation are thin, the 56000 Hz frequency (Figure 6) yields a half space resistivity matching the Hattiesburg formation. However, the resistivity climbs rapidly with increasing thickness of dry or fresh water saturated Citronelle formation.

Model 3 (Figures 7-9) represents the same layered situation as model 2 (Figures 4-6), but brine replaces fresh water as the pore fluid of the Citronelle formation. The 900 Hz frequency (Figure 7) maps the Hattiesburg formation well in the absence of brine. The 7200 Hz frequency (Figure 8) maps the brine layer very well. The 56000 Hz frequency (Figure 9) also responds to the brine layer but much of its energy is absorbed by the 25 m of 600 ohm-m cover.

2.1.1 Depth of Penetration Considerations

The maximum depth of exploration is 250 m for a lower half space of 1 ohm-m. This yields a coplanar signal of 4 ppm (vs noise of 1 to 2 ppm). These signal levels assume a sensor flying height of 30 m. A 1 ohm-m resistivity would equate to sea water salinity in rock having a porosity of 25%. These figures also assume that the overlying material is infinitely resistive. Since the overlying material is not infinitely resistive, skin depths at our three frequencies will provide limitations. For example, if the resistivity of the cover is 100 ohm-m, the skin depths at our frequencies are as follows:

Frequency Hz	Skin Depth m
900	168
7200	59
56000	21

These figures illustrate that the low frequency of 900 Hz is more than adequate for the program. They also indicate that our broad range of frequencies are necessary to provide various sounding depths. For example, the 56000 Hz frequency samples the near surface, while the 900 Hz frequency yields deep sounding.

2.2 DATA ACQUISITION

2.2.1 EM System

A DIGHEM^{IV} system would be utilized for EM data acquisition. A concise description of the system follows:

1. Coil Configuration: 1 vertical coaxial coil-pair
   3 horizontal coplanar coil-pairs
2. Coil Spacing: 7.98 m for the vertical coaxial and two of the three horizontal coplanar coil-pairs. 6.32 m for the third horizontal coplanar coil-pair.
3. Frequencies: 900 Hz for the vertical coaxial and the first horizontal coplanar coil-pairs.
   7200 Hz for the second horizontal coplanar coil-pair.
   56000 Hz for the third horizontal coplanar coil-pair.
4. Noise Levels: Less than 1 ppm static and less than 3 ppm in straight and level flight for the horizontal coplanar coil-pairs.
5. System Drift: System drift is less than 1 ppm per minute and is linear over a time period of ten minutes. Drift compensation is accomplished by taking the sensor out of ground effect in order to establish zero levels. This procedure is performed at the end of every survey line.

6.	Calibration:	System calibration consists of phasing and gain adjustment. Phasing control is accomplished by introducing a ferite rod into the primary field. This produces a negative inphase response and no quadrature response. System gain is adjusted by introducing calibrated coils into the primary field. These coils are calibrated to provide a 100 ppm response.
7.	Sferics and 60 Hz Monitoring:	Sferics and 60 Hz noise are monitored utilizing the coaxial coil-pair. A separate sferics channel indicates the presence of sferics and 60 Hz interference.

The horizontal coil-pair response is twice the vertical coil-pair response from a layered earth. The horizontal coil-pair is null coupled to sferic fields, and this coil-pair is less susceptible to aerodynamic noise. For these signal and noise reasons, horizontal coils are most suitable for this survey.

Static Resolution:	0.01 nT
Sample Rate:	10 Hz
Inflight Noise Envelope:	0.2 nT
Figure of Merit:	not applicable - towed bird
Heading Error:	not applicable - towed bird
Diurnal Recording:	
Standard:	Digitally recording Geometrics proton magnetometer Resolution 0.5 nT Sample Rate - 0.2 Hz
Optional:	Digitally recording Scintrex Cesium magnetometer Resolution 0.01 nT Sample Rate - 2 Hz
Diurnal Specifications:	2 nT from a chord two minutes long

2.2.3 Ancillary Equipment

1. Radar Altimeter: Sperry AA220

   Sensitivity: ± 1 foot

   Accuracy: ± 5 feet

Altitude will be recorded in both analog and digital formats.

Calibration is by voltage input.

2. Flight Camera: Geocam 35 mm camera.

Primary field variation due to aerodynamic vibration is the principal source of noise in a HEM system. The primary field strength at the receiver coil decreases with the cube of coil separation. While a 7 m coil separation is common in the industry, the separation on Dighem's low and medium frequency coils is 7.98 m. This wider spacing yields a 50% increase in signal-to-noise ratio. The shorter coil spacing of 6.32 m at 56000 Hz is not a problem due to the high signal levels generated by this frequency.

The modeling of Figures 1 to 9 shows that distinctively different responses are received at the three frequencies of 900, 7200 and 56000 Hz. Our survey experience shows the breadth of this frequency range is entirely satisfactory for the variation of resistivities expected in the survey area.

2.2.2 Magnetometer System

Should the government require magnetic data acquisition, a Scintrex/Varian Cesium magnetometer will be used. It is flown in a bird approximately 45 metres above the ground. The following magnetometer specifications apply:

2.2.4 Recording of Data

1. Analog — RMS GR33 32 channel graphics recorder
2. Digital — Scintrex CDI 6 digital acquisition system with a Digidata 9-track magnetic tape transport.

RECORDING SENSITIVITIES

Channel Number	Parameter	Analog Sensitivity per mm	Sensitivity on digital tape
01	coaxial inphase (900 Hz)	2.5 ppm	0.20 ppm
02	coaxial quad (900 Hz)	2.5 ppm	0.20 ppm
03	coplanar inphase (900 Hz)	2.5 ppm	0.20 ppm
04	coplanar quad (900 Hz)	2.5 ppm	0.20 ppm
05	coplanar inphase (7200 Hz)	5.0 ppm	0.40 ppm
06	coplanar quad (7200 Hz)	5.0 ppm	0.40 ppm
07	coplanar inphase (56000 Hz)	7.5 ppm	0.80 ppm
08	coplanar quad (56000 Hz)	7.5 ppm	0.80 ppm
09	altimeter	10 ft	1 ft
10	magnetics, coarse	10 nT	0.01 nT
11	magnetics, fine	2 nT	----
12	coaxial sferics/60 Hz	2.5 ppm	0.20 ppm
	range 1 Navigation		1 ft
	range 2 Navigation		1 ft

Real time verification of the header block information is an integral part of the data system. All digital data will be verified post flight, in the field.

2.2.5 Technical Approach to Data Processing

Dighem proposes to produce the following deliverables at a scale of 1:12000:

1. Apparent resistivity contour maps for each of the three coplanar frequencies of 900, 7200 and 56000 Hz.

2. Apparent depth contour map for the 900 Hz frequency if signal levels are strong, otherwise for the 7200 Hz frequency.

3. Inphase and Quadrature contour maps for each coplanar frequency.

4. Stacked magnetic, eight channels of electromagnetics, 60 Hz monitor, altimeter, three resistivity and three depth profiles.

If the material overlying the fresh water or brine-saturated layer is reasonably resistive, Dighem's apparent depth map will accurately show depth to the layer. Refer to the depth profiles of Figures 4 and 7.

If the overlying material is fairly conductive, the apparent depth will underestimate the true depth. In this case, Dighem will supply the following optional contour maps if requested:

1. Resistivity of the upper layer (above the water table. This assumes that the major conductivity contrast occurs at the top of the water table).
2. Depth to the water table.
3. Resistivity of the lower layer (below the water table).

These optional maps will be produced using Dighem's pseudo-layer two-layer inversion program.

Figure 10 (in map pocket) supports the above comments. It illustrates $DIGHEM^{IV}$ data over the Night Hawk test range in Ontario. The conductor is a wide graphite body buried beneath 90 m of sand. True resistivities of graphite and cover are respectively 1 and 250 ohm-m. The apparent resistivities illustrate that, (a) the 56,000 Hz frequency does not penetrate to the graphite, while (b) the 900 Hz frequency senses the target well. This separation of response helps ensure a reliable two-layer inversion.

2.2.5.1 Resistivity Analysis

Apparent resistivity maps are normally prepared from DIGHEM survey data. We use the "pseudo-layer half space model" described in the attached publication entitled "Resistivity Mapping with an Airborne Multicoil Electromagnetic System" (map pocket). This half space model avoids errors in the apparent resistivity calculations resulting from altimeter errors. Altimeter errors can result from trees or topographic variations. If such errors do not exist, the pseudo-layer half space algorithm will also give a reliable thickness of the upper layer providing it is transparent to the frequency.

As an option, we can employ our two-layer analytic technique, termed the "pseudo-layer two-layer model". This method yields separate resistivity maps of the upper and lower layers, and a thickness map of the upper layer.

2.2.5.2 Electromagnetic Map

The desired geological responses are best displayed as resistivity and depth contour maps. An EM map would comprise two classes of anomalies:

1. Anomalies due to culture, eg., power lines and fences.
2. Anomalies due to broad conductivity increases and to

local decreases in flying height.

The second (geological) class of anomalies is of limited use assuming resistivity maps are generated. The first (cultural) class may be of interest. We can produce a map of either or both classes as an optional product. Regardless of whether such a map is requested, we shall indicate areas thought to be affected by cultural features.

2.3 Project Management Plan

Project Schedule:

As per F901 (page 15 of 44) of the U.S.G.S. solicitation.

Base of Operations: Brookhaven, Mississippi

Helicopter Contractor: Midstate Helicopter
(1st. choice)

Pilot: Mike Ward, Chief Pilot

Experience: 13500 hours

Alternate Pilot: Richard Santmyer, Director of Operations
7500 hours

The DIGHEM^{IV} survey equipment will be mobilized to Brookhaven. It is anticipated that installation will take two days. Testing requirements (See sections 1.2.5, 2.1.3, 2.2.3, 2.2.4 and 3.1.2 of the RFP) will take place immediately following installation. At this point, any optimization of system parameters as requested by the U.S.G.S. will be undertaken where practical. Actual survey flying will commence immediately upon acceptance of test data by the U.S.G.S. It is anticipated that 7 days will be required to complete the survey.

3. STATEMENT OF COMPLIANCE

Dighem agrees to comply with the requests set forth in the Statement of Work, with the following exceptions:

1. Barometric altimeter is quoted as an optional item under this proposal. This is because lack of knowledge of barometric pressure, as height above sea level, does not affect the integrity of EM or magnetic data.

2. A 2 Hz, 0.01 nT, digitally recording ground magnetometer is quoted as an optional item. This is because our experience has indicated that the standard 0.2 Hz, 0.5 nT, digitally recording magnetometer provides sufficient control for the removal of diurnal variations to the 1 nT level. Further, the removal of long wave length diurnal variations does not contribute to the detection of well hole casings as their signature is primarily in the high frequency components.

3. A price reduction is provided if inphase and quadrature ppm contour maps are deleted from the requirements. Such maps will primarily highlight flying height variations rather than conductivity variations. Conductivity variations are shown, without distortion caused by flying height variations, on the resistivity contour maps.

4. CAPABILITIES OF ORGANIZATION, PERSONNEL & EQUIPMENT

4.1 Organizational Experience

Dighem has continously flown HEM surveys since 1969. Almost all of these have been combined EM/magnetometer surveys. Clients have included most of the major exploration companies in the world, as well as the governments and agencies of the U.S.A., Canada, Japan, Germany, Italy, France and Austria. Dighem has flown 2 surveys for the U.S.G.S.

In recent years, electronic navigation has been employed on the majority of our surveys.

The following is a summary of Dighem's work for the U.S. Government:

AGENCY	$/KM	COST (US$)	LINE-KM	CONTRACT NO.	CONTRACT OFFICER
FHA	82	193,000	2366	DOT-FH-11-9144	Mr. J.F. Koca
USGS	70	144,700	2080	14-08-0001-18881	Dr. D.B. Hoover
NOO	139	44,500	320	N62306-84-C-0013	Mr. D.G. Burkell
USGS	75	18,714	251	5-4400-1310075	Ms. L.M. Davidson

Note: Dighem acted as principal subcontractor in the Federal Highways Administration (FHA) and Naval Oceanographic Office (NOO) contracts. The dollars shown indicate Dighem's billings. Other surveys have been flown for U.S. State governments.

4.1.1 Subcontractors

See section 2.3 of this proposal.

4.2 Personnel Qualifications

Curricula Vitae follow, after figures 1 to 9, for the Dighem personnel to be involved in the execution of this project.

4.3 Equipment and Procedures

4.3.1 Survey Equipment

The equipment to be used will be the DIGHEM^{IV} helicopter EM system which was developed in 1984. This system was developed under a grant from the Canadian Federal Government. The first commercial surveys were undertaken in 1985. In addition to numerous mineral exploration surveys, projects flown with this system have included salinity mapping for the U.S.G.S., structural mapping in various environments, mapping of shear zones and identification of poorly conductive mineralization.

This unique system operating at frequencies up to 56000 Hz allows the mapping of resistivities from 0.1 to 30,000 ohm meters.

4.3.2 Data Processing - Facilities & Procedures

4.3.2.1 Facilities

Dighem computer facilities for processing geophysical survey data include:

(i) Computers

* VAX 11/780 virtual memory computer with 650 Mbytes of on-line data storage, a high performance magnetic tape drive, multiple CRT terminals and printers.

* MicroVAX-II virtual memory computer with 1.2 Gbytes of on-line data storage, magnetic tape drive and multiple CRT terminals.

* Multiple IBM PC/AT compatible imaging workstations with image processors and high resolution monitors.

All of the above computers are linked via a high performance Local Area Network using Ethernet links and DECnet software.

(ii) **Plotters**

* Versatec Model 8224, 200 dot per inch, 24 inch width electrostatic plotter for preliminary display and working copy plots.

* Calcomp Model 970, 52 x 80 inch wet-ink plotter for final cartographic quality plots.

Both plotters are interfaced to the VAX computers. Many of our products are displayed in color using Applicon and Iris ink-jet plotters.

(iii) Digitizer

* Hi-State Model 4260, high precision 42 x 60 inch table digitizer with VAX computer on-line interface.

4.3.2.2 Procedures

(i) Data Compilation

The object of the data compilation is to ensure an error-free database before actual data processing commences. This is achieved by:

* Input, checking and editing of the flight log.
* Input and editing of the raw field tape data including checking for invalid characters, misaligned data records, noise, sensor equipment errors and fiducial problems. Errors are corrected by reporting or displaying the affected lines and correcting the problems.
* Input and editing of positional data. Digital positional data from the electronic positioning system is plotted and fitted to the 1:12,000 topographic maps.

(ii) Electromagnetic Processing

Dighem's electromagnetic data processing procedures are well known to a number of U.S.G.S. personnel from surveys flown earlier. The EM signals are used to compute the ground resistivity, to yield resistivity profiles and contour maps. For this survey, the resistivity will be computed for 900, 7200 and 56000 Hz, and contour resistivity maps will be prepared for all frequencies.

(iii) Magnetic Processing

The Cesium magnetometer will typically yield a ±0.1 nT noise envelope. In the presence of the horizontal coplanar EM fields, this may at times rise to ±0.2 nT. Our data processing yields maps contoured at 1, 2, 5 or 10 nT, depending on the client's instructions. The IGRF field will be removed.

Tie lines and ground base station data are used in the magnetic data processing to eliminate diurnal responses. Optional processing is available to extract magnetic signatures caused by culture, e.g., drill hole casings.

(iv) Gridding

The line gridding algorithm yields uniform grids from survey data collected along nominally parallel survey traverses. Control of the gridding operation is given by Akima's function which is a modified local slopes method. Line gridding features and benefits include:

* Setting a minimum separation for adjacent survey traverses to prevent the creation of sharp steps in the final grid;
* Setting a limit to the excursion of the Akima function to prevent the creation of spurious "high" and "low" enclosures between adjacent survey traverses;

* Accepting bi-directional survey traverse data. Initially, each of the two sets of survey data are gridded separately. A final grid is calculated as the average of the two initial grid values, each of which is weighted by its inverse square of distance to the survey traverse from which it was derived;

* Gridding of irregular shaped survey areas and areas with "holes"; and

* Optional, automatic detrending of narrow linear features at acute angles to the nominal survey line direction. The benefits of detrending are a reduction of oval contour enclosures, more aesthetically pleasing contour maps, and grids more suitable for derivative work such as vertical gradient, reduction-to-pole, depth-to-basement, etc.

(v) <u>Contouring</u>

The contouring algorithm utilizes an advanced contour threading routine that is based on logic rather than mathematics. This greatly improves the contour mapping speed and quality. The contouring package is especially suited to geophysical survey data because of its capability to depict fine detail over large amplitude variations.

The principal features of the contouring program include:

* Gradient dependent supression of annotation and contour lines;
* Multiple contour levels given in incremental or discrete mode;
* LEROY template characters for contour annotation;
* Control of the frequency of contour annotation, orientation, content, etc. Annotation is always up-gradient;
* Different line widths and styles, e.g., solid, dashed, dotted, for different contour levels. Enclosed lows are marked by triangular teeth;
* Grid windowing for map sheet presentation.

(vi) Additional Processing Information

Magnetic archive tape will be provided as per paragraph 2.6.4 of the U.S.G.S. solicitation (page 8 of 44).

5. QUALITY CONTROL PROCEDURES

Heading Compensation:	Not applicable to a towed bird system.
Inflight Data Acquisition:	Data quality is monitored utilizing a analog display (RMS GR33) which is visible to the operator at all times. Selective portions of the digital data are dumped after the completion of the survey flight.
Flight Path Location:	Flight path will be guided by an electronic positioning system.
Ground Magnetometer:	Monitored at all times utilizing an analog recorder. Data is also recorded in memory and then transferred to a floppy disk.

Data acquisition, processing, and interpretation will be carried out under the requirements of a Quality Assurance Plan written by the U.S.G.S. and approved by the E.P.A. These specifications are defined in sections 3.1.1 to 3.1.6 of the U.S.G.S. solicitation.

6. CONTINGENCY PLAN

Three major areas cover the resources that will be required for this project. They are aircraft, geophysical equipment and personnel.

6.1 Aircraft

Should the helicopter subcontractor default on any critical commitment to the project, the following nearby companies have suitable survey helicopters and external cargo licenses:

Air Logistics, Lafayette, LA

Commercial Helicopters Inc., Lafayette, LA

Industrial Helicopters, Lafayette, LA

Each will be contacted after contract award to determine rates and availability in case of need.

6.2 Geophysical Equipment

The complete Dighem^{IV} system, including magnetometer and all ancillary equipment, has been used in Dighem's ongoing survey operations since July, 1985. During this time, it has had an average production rate of 90 line km per day on-site. Dighem stocks sufficient spares to maintain four systems in the field.

6.3 Personnel

Curricula vitae follow, after Figures 1 to 9, for Dighem personnel who will substitute for other personnel if required.

7. SUMMARY

The U.S.G.S. requires rapid, cost-effective and detailed mapping of brine saturated portions of near surface aquifers. Since this survey is experimental in nature, a state-of-the-art system designed for the mapping of discontinuous horizontal layers should be selected to maximize the likelihood of success.

To satisfy these requirements, Dighem proposes to acquire and process data from a DIGHEM^{IV} system, outfitted with an optional Cesium magnetometer. We believe this is the most appropriate system for the survey because:

1.	Helicopter-borne:	Better mapping detail than can be provided by fixed-wing systems.
2.	7.98 m coil spacing:	Greater depth penetration than for the common 7 m HEM birds, due to 50% larger signals.
3.	3 horizontal coil-pairs:	Greater signal from horizontal layers; strike independent.
4.	900, 7200, 56000 Hz frequencies:	Broad spectrum of response for maximum differentiation of resistivity modeling.

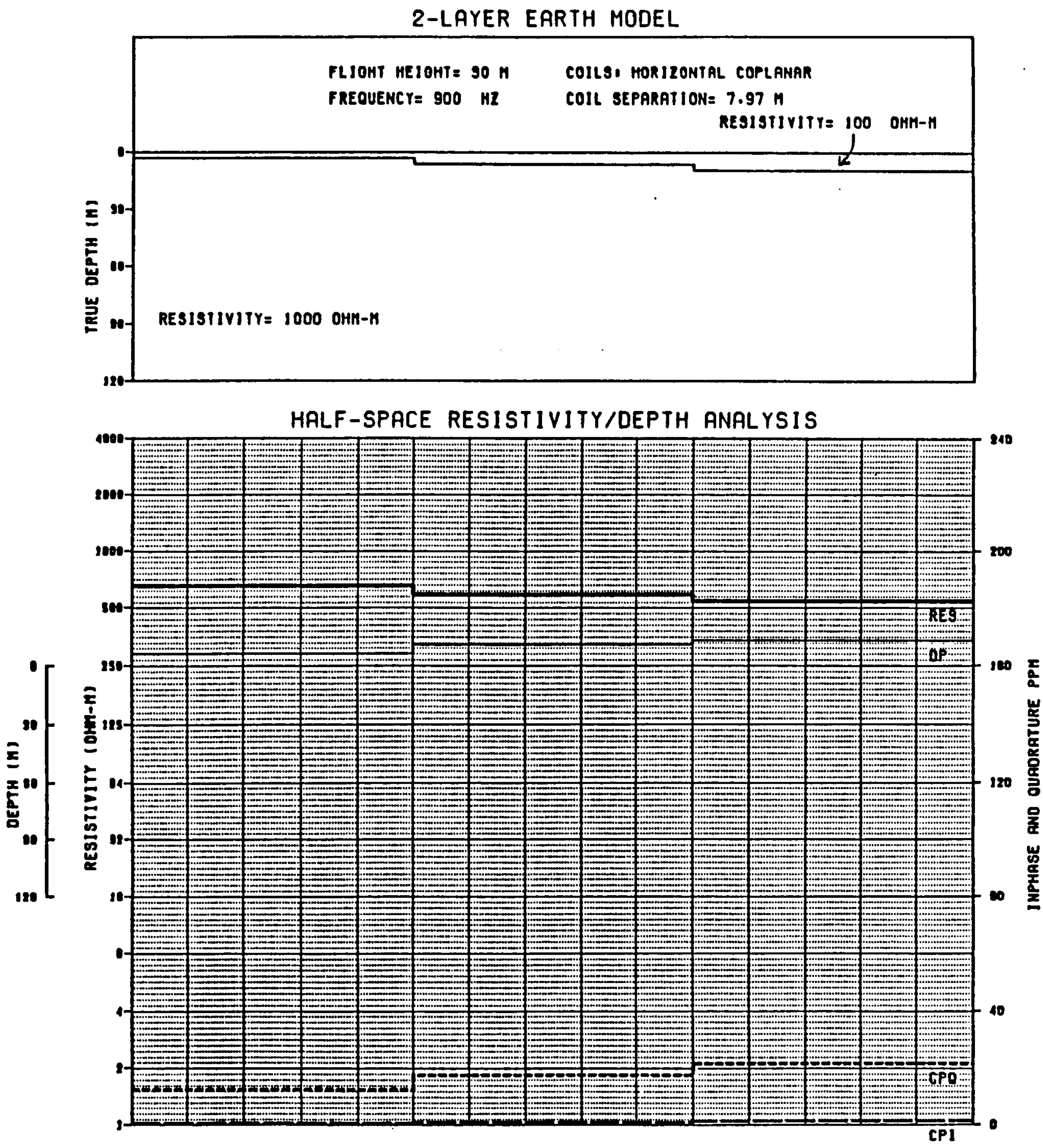
5. Cesium magnetometer: Maximum sensitivity and sample rate for detecting small, weak magnetic anomalies.

With three years of commercial experience with the DIGHEM^{IV} system and 12 years of experience with resistivity mapping, Dighem has refined its systems to minimize inherent noise and has developed procedures to keep noise and drift insignificant relative to geological variability.

Dighem's processing techniques for producing reliable resistivity and magnetic maps, and recognizing cultural effects, have been developed over numerous surveys in populated areas of North America and Europe.

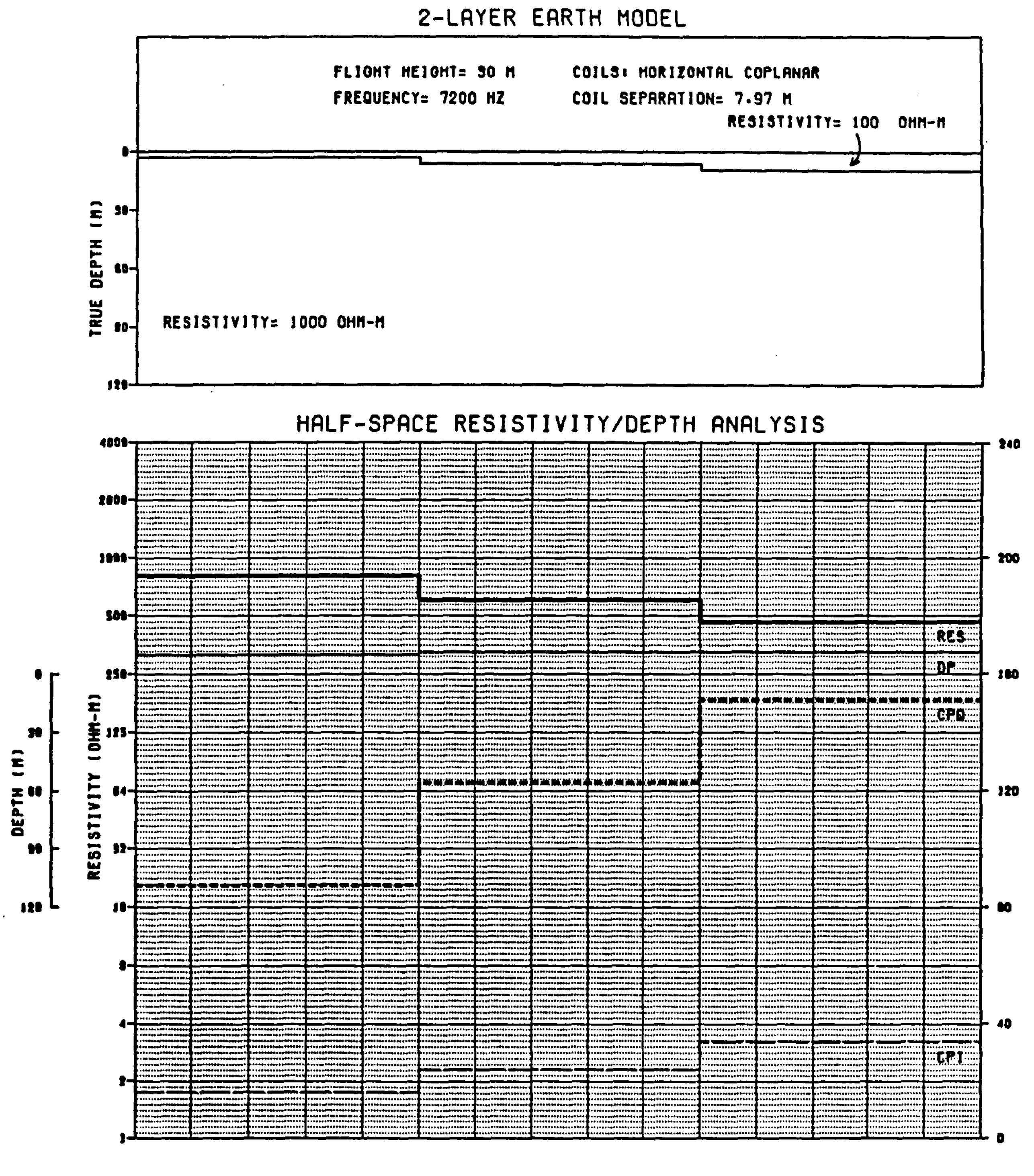
In summary, the U.S.G.S. can be confident that its objectives are most likely to be met if it selects Dighem's system, people and experience for this project.

FIGURE 1



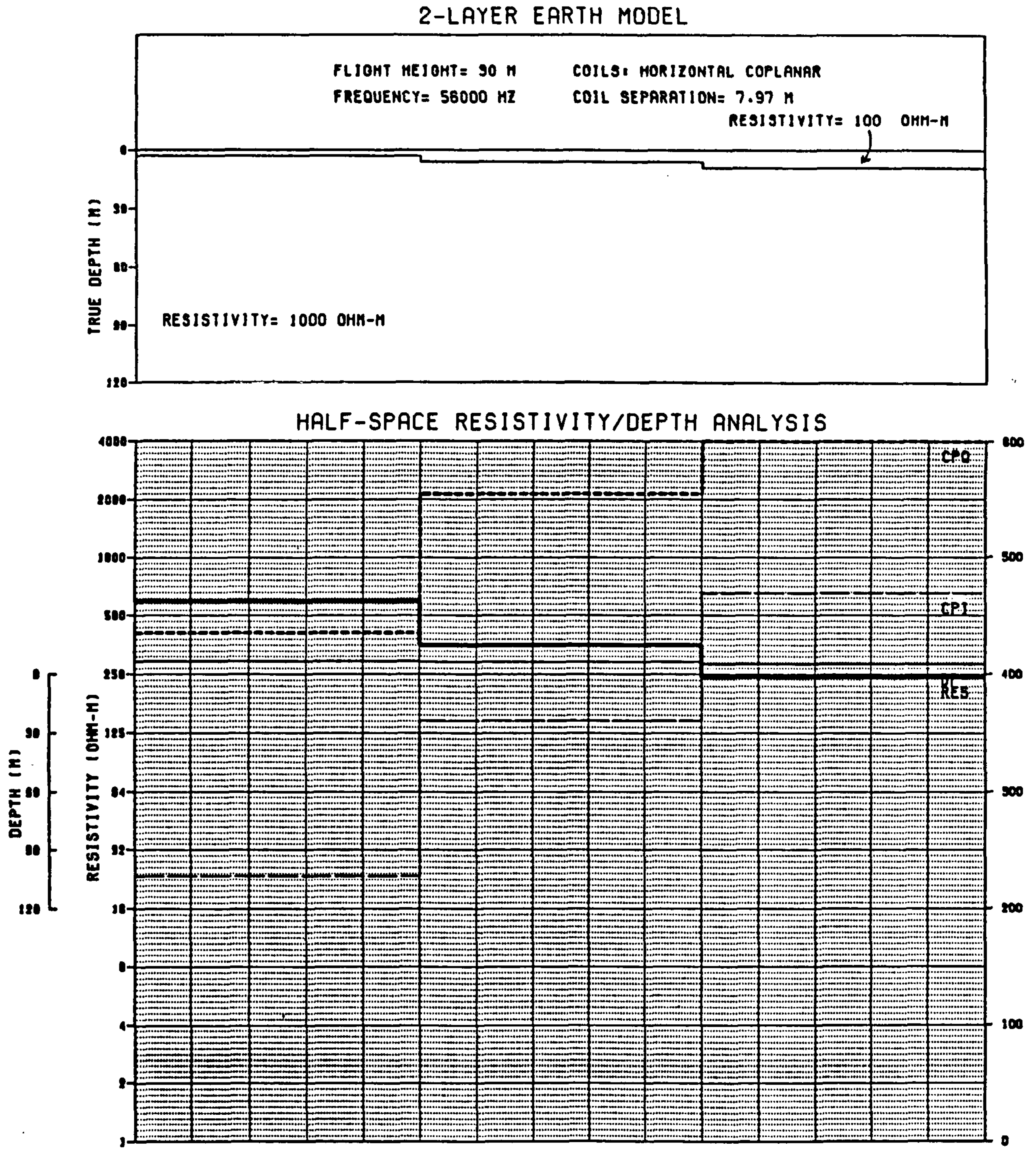
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 2



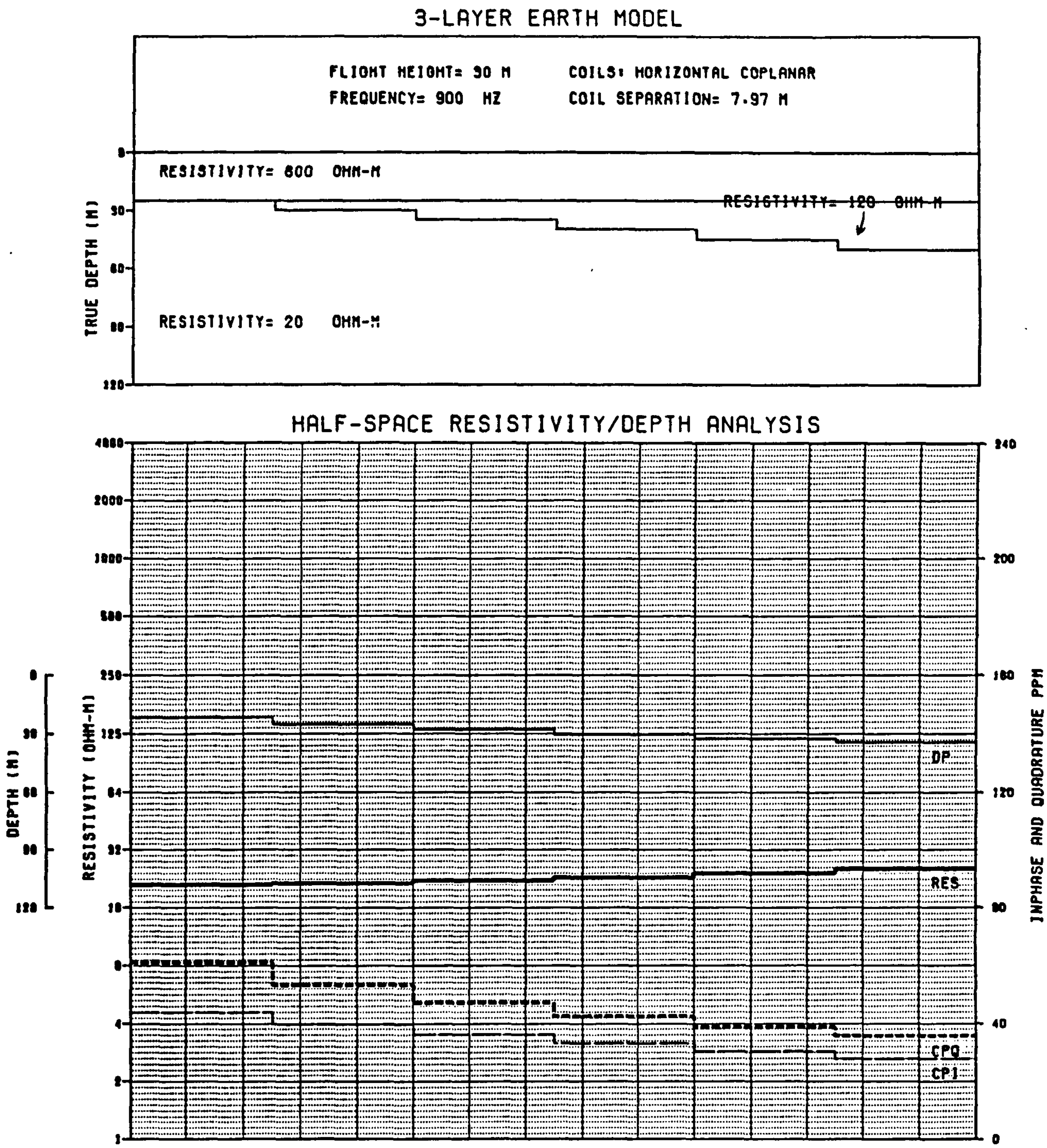
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 3



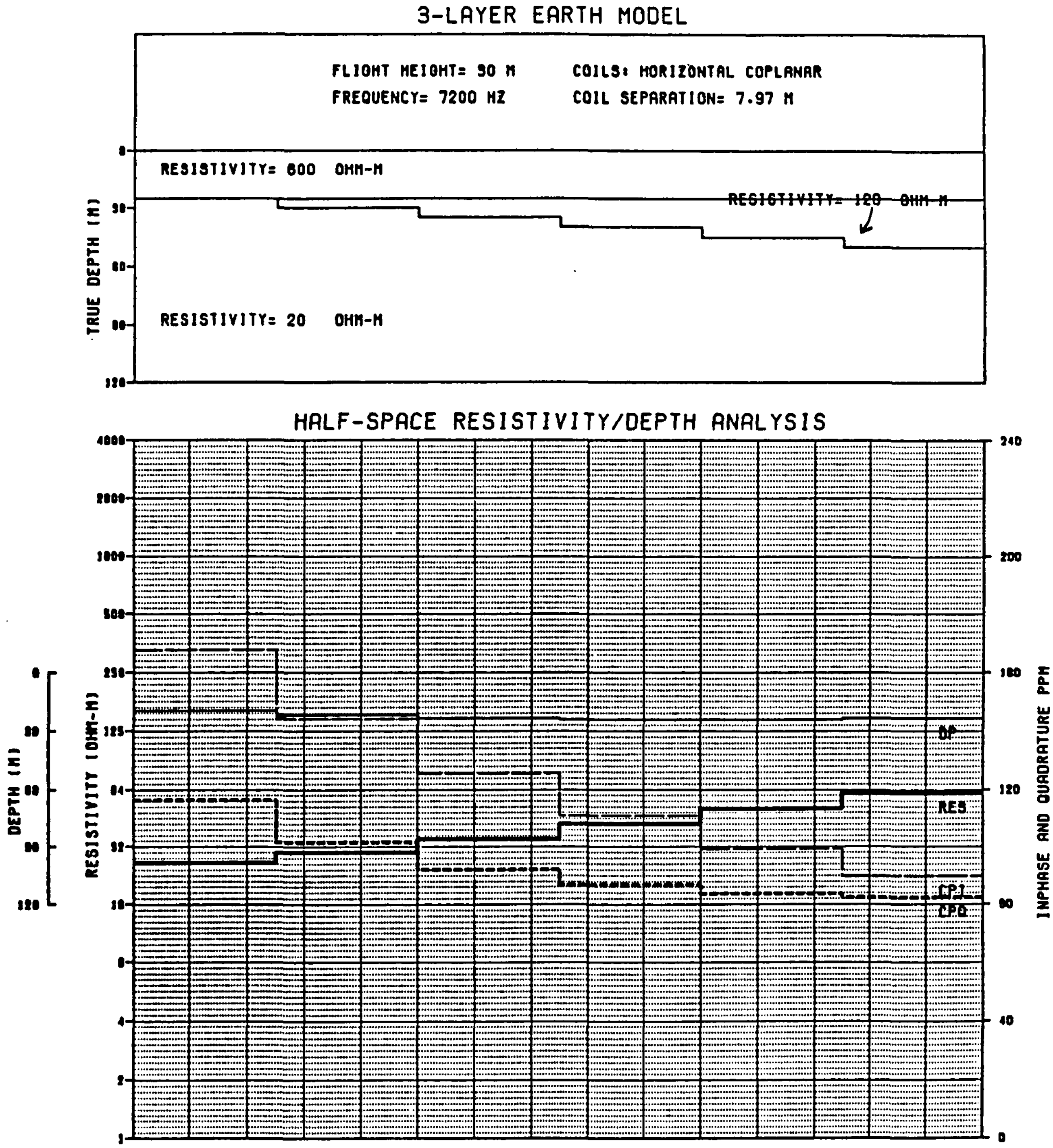
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 4



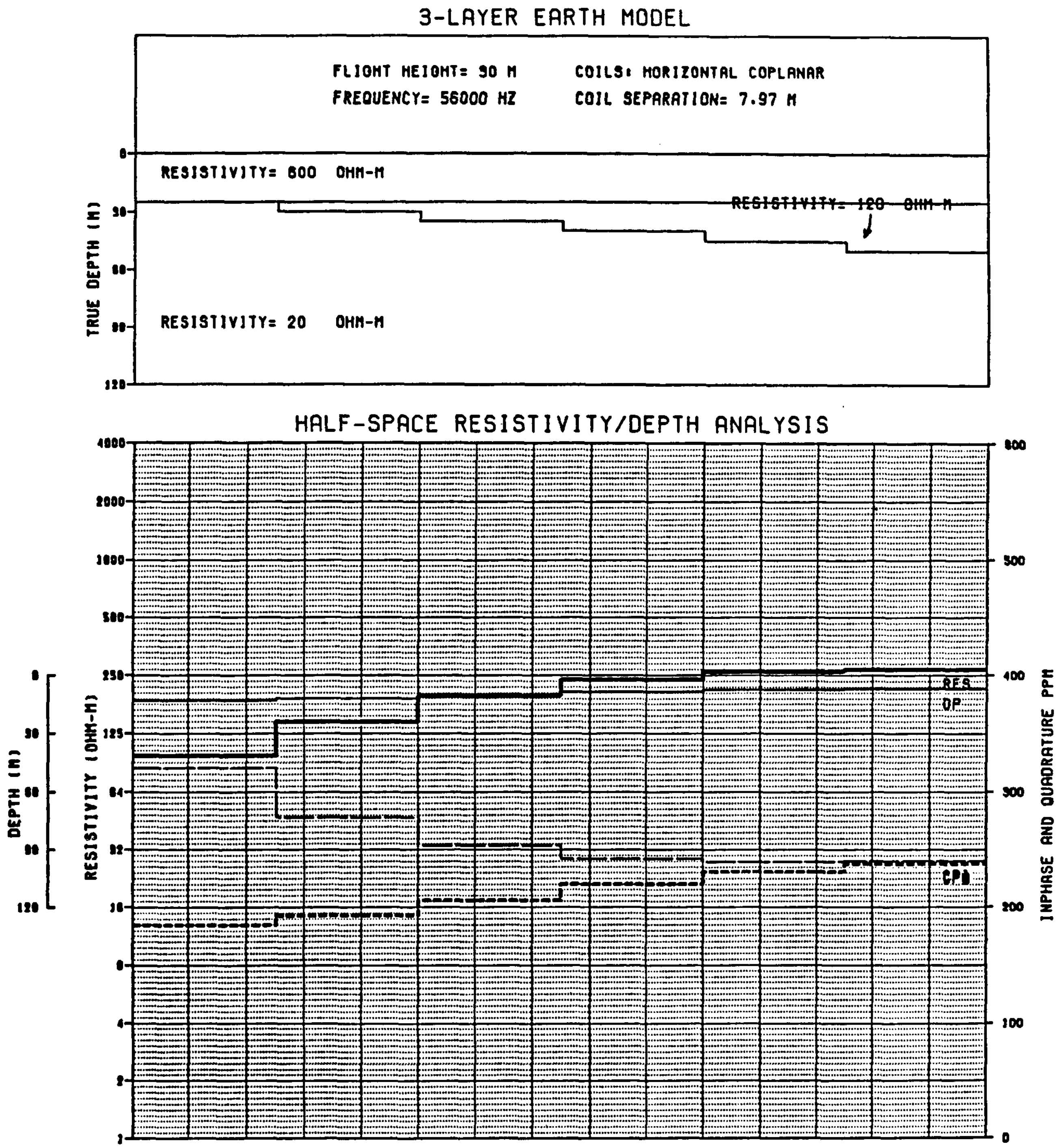
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 5



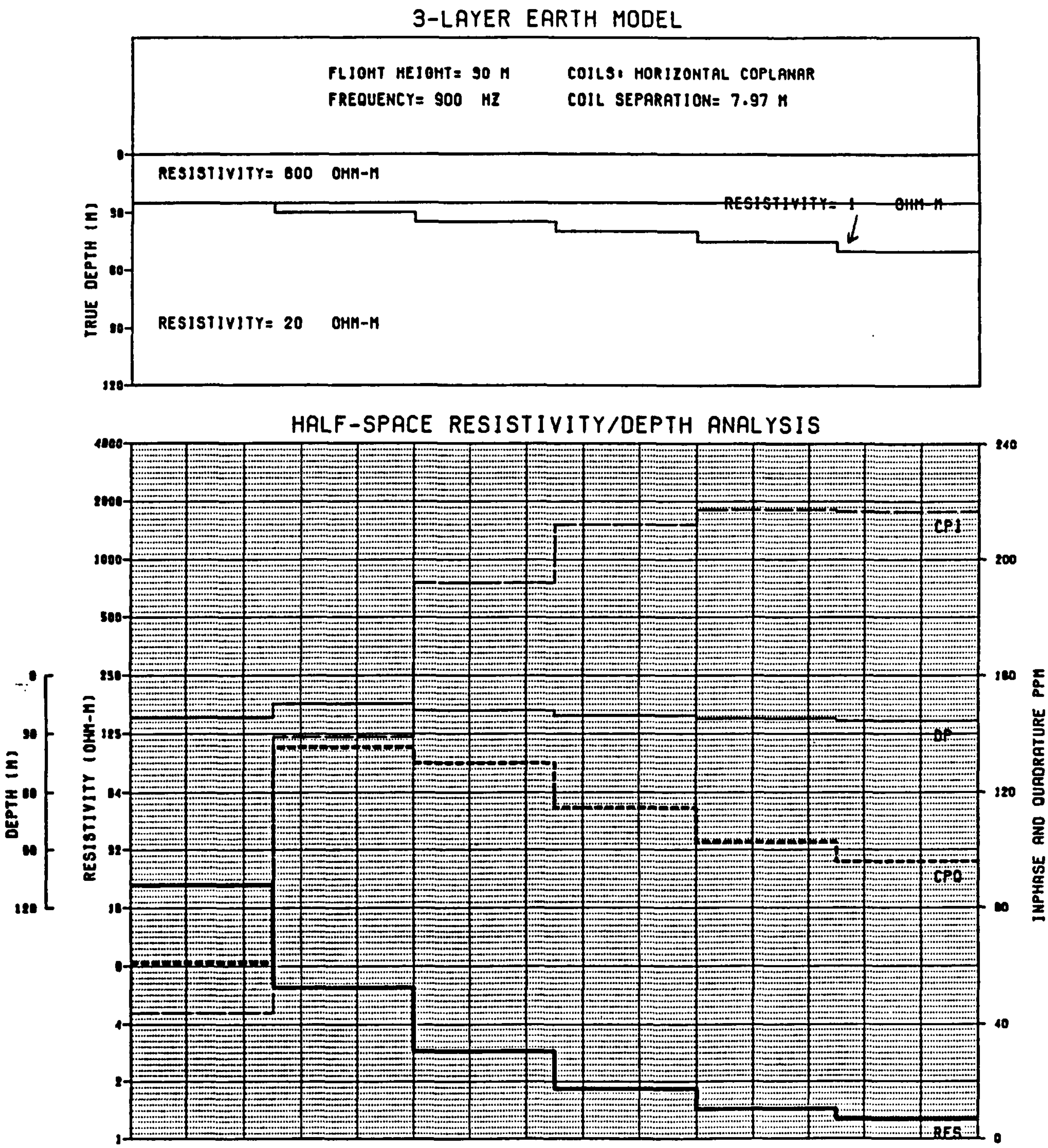
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 6



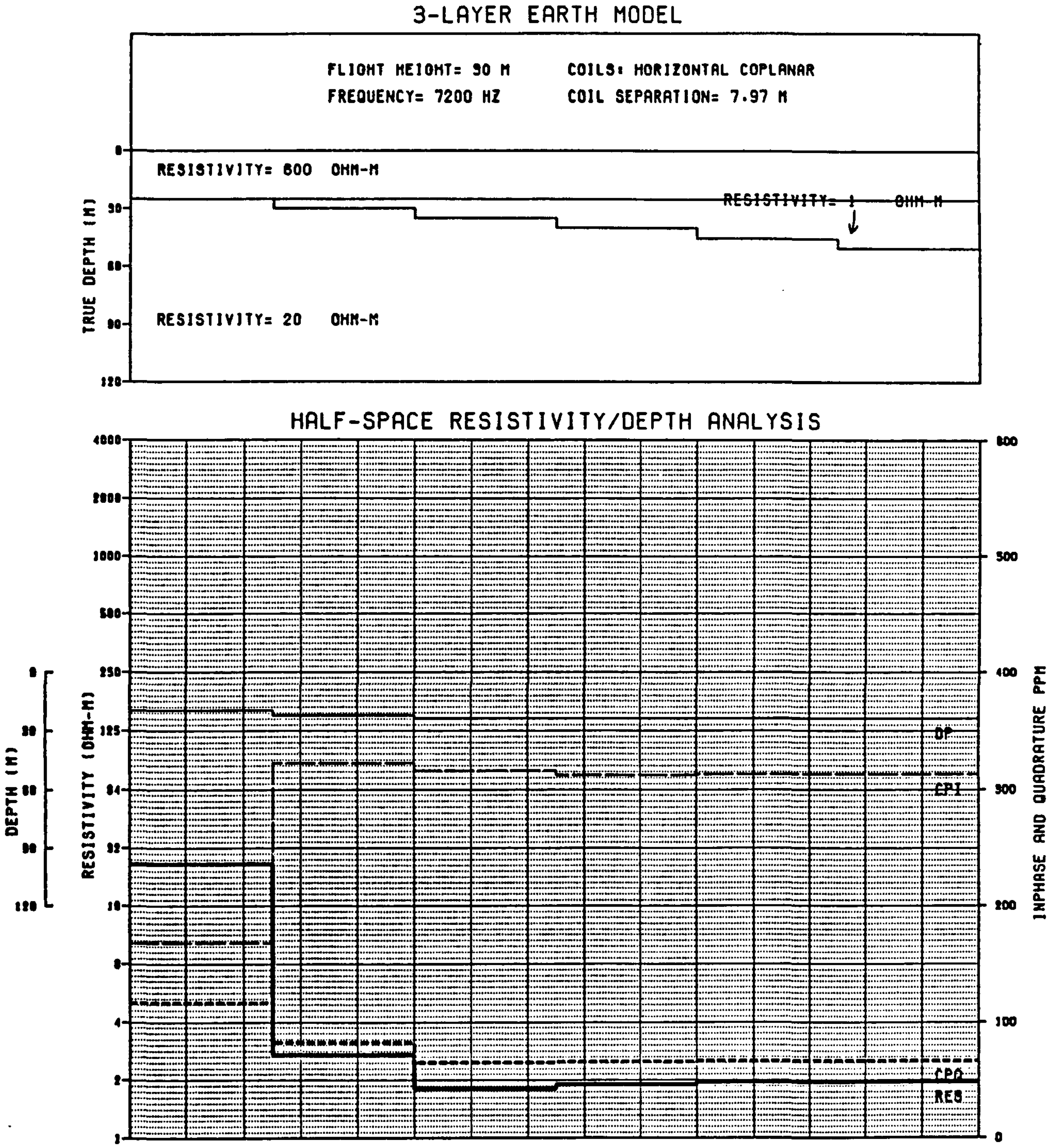
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 7



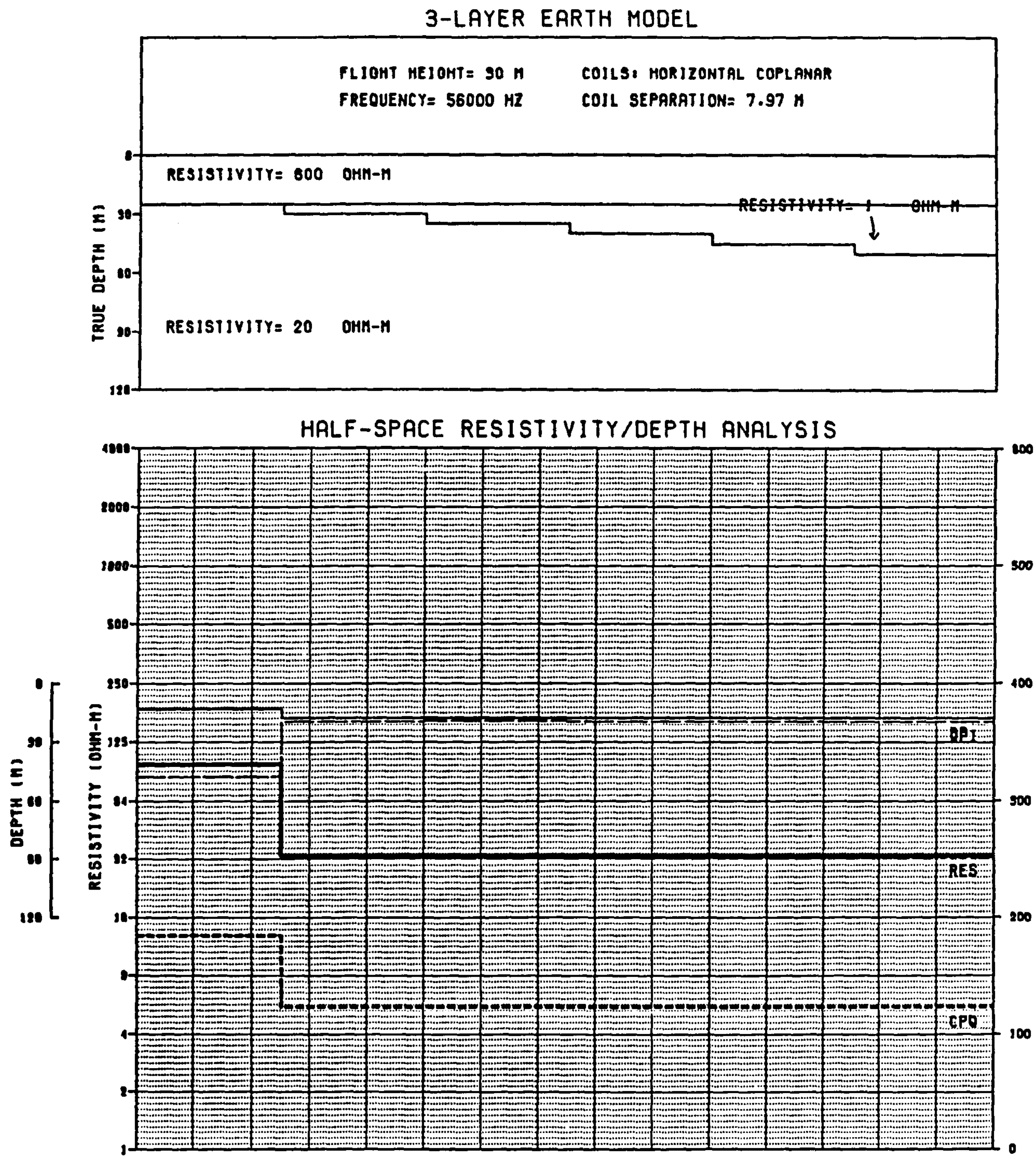
THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 8



THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

FIGURE 9



THE EARTH MODEL YIELDS THE OUTPUT PPM AND RESISTIVITY ANALYSIS

APPENDIX C

SUBCONTRACTOR'S FINAL REPORT

DIGHEM was required as part of the contracted work (see appendix A) to write a final project report. This report is not meant to be an in-depth scientific analysis of the geophysical data. It describes the instrumentation, data processing methods, and makes general recommendations about further data processing. The report included in this appendix has not been edited to conform to any USGS or EPA report standards. Conclusions and recommendations are the sole responsibility of the contractor.

Also part of the deliverable items for the contract are digital data on 9-track computer compatible tape. These data will be made public through USGS open-file procedures.

Report #537

DIGHEM IV SURVEY
FOR
U.S. GEOLOGICAL SURVEY
PROJECT 8-9380-4038
MISSISSIPPI

DIGHEM SURVEYS & PROCESSING INC.
MISSISSAUGA, ONTARIO
September 6 1988

Douglas L. McConnell
Geophysicist

A0537SEP.89R

SUMMARY

A DIGHEM^{IV} survey was flown for the United States Geological Survey, over a survey block near Brookhaven, Mississippi.

The purpose of the survey was to detect resistivity contrasts in order to map the contamination of fresh water acquifers with brine. A secondary objective was to make high resolution magnetic measurements to locate abandoned oil wells.

The 900, 7,200 and 56,000 Hz data were used to produce resistivity maps. The different levels of penetration of the three frequencies through conductive earth, results in resistivity maps that show the conductive properties at different depths. The total field magnetic contours show numerous bull's-eye anomalies due to cultural sources. The VLF contours have also been influenced by cultural sources.

A comparison of the three resistivity parameters, and additionally the calculated depth channels, should be useful in determining the depths and extent of conductive sources below surface.

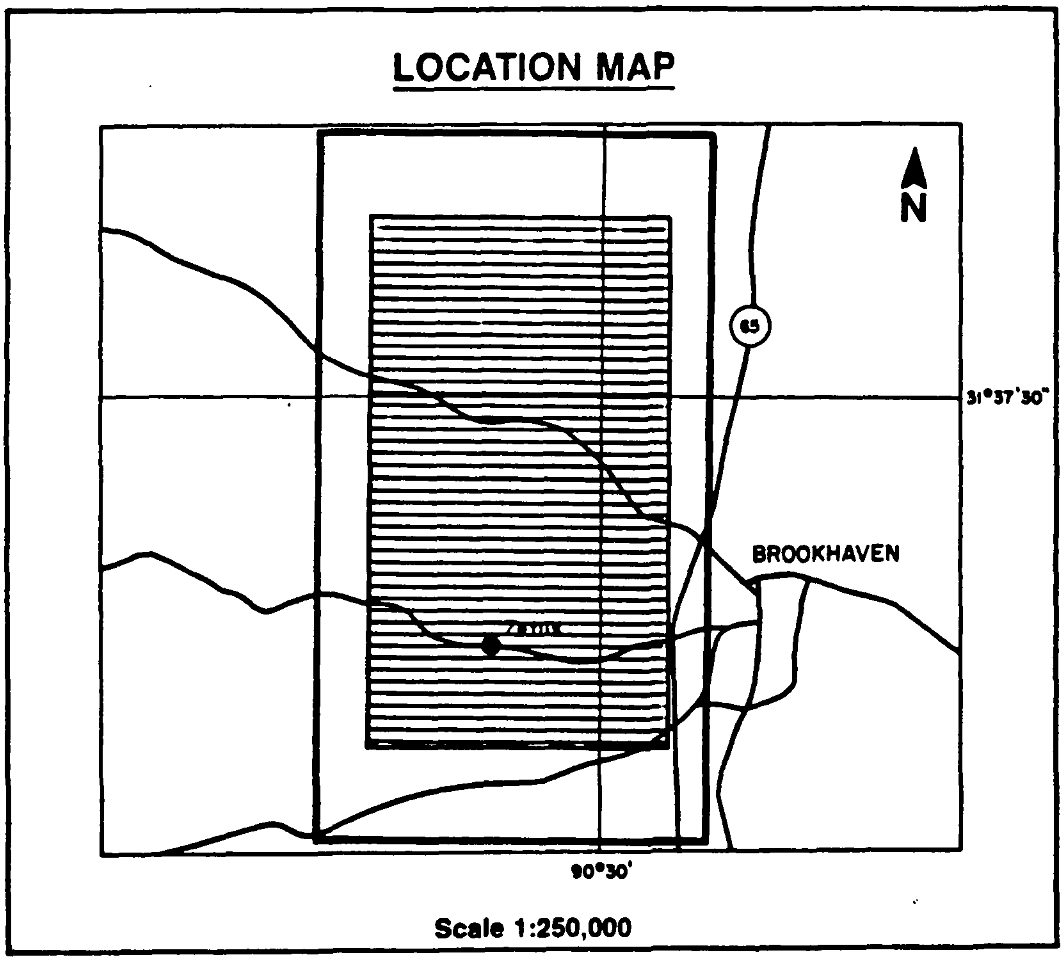


FIGURE 1

THE SURVEY AREA

CONTENTS

INTRODUCTION

A DIGHEM^{IV} electromagnetic/resistivity/magnetic/VLF survey was flown for the U.S. Geological Survey, from May 12 to May 16, 1988, over a survey block near Brookhaven, Mississippi. This block is located on the Zetus and Brookhaven, Mississippi, U.S.G.S. map sheets (Figure 1).

Survey coverage consisted of approximately 422 line-miles. Flight lines were flown with a line separation of approximately 1/8 of a mile (200 metres) in an azimuthal direction of 090°/270°. Tie lines were flown perpendicular to the flight line direction.

The survey employed the DIGHEM^{IV} electromagnetic system. Ancillary equipment consisted of a magnetometer, radio altimeter, video camera, analog and digital recorders, a VLF receiver and an electronic navigation system.

This report is divided into six sections. Section 2 provides details on the equipment used in the survey and lists the recorded data and computed parameters. Section 3 reviews the data processing procedures, with further information on the various parameters provided in Section 5. Section 4 describes the geophysical results.

The survey results are shown on 1 separate map sheet for each parameter. Table 1-1 lists the products which can be obtained from the survey. Those which are part of the contract are indicated in this table by showing the presentation scale. These total 6 maps.

Recommendations for additional products are included in Table 1-1. These recommendations are based on the information content of products that would contribute to meeting the objectives of the survey.

Table 1-1 Plots Available from the Survey

MAP	NO. OF SHEETS	ANOMALY MAP	PROFILES ON MAP	CONTOURS		SHADOW MAP
				INK	COLOR	
Flight Lines	1	N/A	-	24,000	-	-
Electromagnetic Anomalies	-	-	-	N/A	N/A	N/A
Probable Bedrock Conductors	-	-	N/A	N/A	N/A	N/A
Resistivity (900 Hz)	1	N/A	-	24,000	**	-
Resistivity (7,200 Hz)	1	N/A	-	24,000	**	-
Resistivity (56,000 Hz)	1	N/A	-	24,000	**	-
EM Magnetite	-	N/A	-	-	-	-
Total Field Magnetics	1	N/A	-	24,000	-	-
Enhanced Magnetics	-	N/A	-	-	-	-
Vertical Gradient Magnetics	-	N/A	-	-	-	-
2nd Vertical Derivative Magnetics	-	N/A	-	-	-	-
Magnetic Susceptibility	-	N/A	-	-	-	-
VLF	1	N/A	-	24,000	-	-
Electromagnetic Profiles(900 Hz)	-	N/A	-	-	-	-
Electromagnetic Profiles(7200 Hz)	-	N/A	-	-	-	-
Overburden Thickness	-	N/A	-	-	-	-
Digital Profiles		Worksheet profiles				-
		Interpreted profiles				12,000

N/A Not available
*** Highly recommended due to its overall information content
** Recommended
* Qualified recommendation, as it may be useful in local areas
- Not recommended
24,000 Scale of delivered map, i.e, 1:24,000

SURVEY EQUIPMENT

This section provides a brief description of the geophysical instruments used to acquire the survey data:

Electromagnetic System

Model:	DIGHEM^{IV}
Type:	Towed bird, symmetric dipole configuration, operated at a nominal survey altitude of 100 feet. Coil separation is 26.2 feet.
Coil orientations/frequencies:	coaxial / 900 Hz coplanar/ 900 Hz coplanar/ 7,200 Hz coplanar/56,000 Hz
Sensitivity:	0.2 ppm at 900 Hz 0.4 ppm at 7,200 Hz 1.0 ppm at 56,000 Hz
Sample rate:	10 per second

The electromagnetic system utilizes a multi-coil coaxial/coplanar technique to energize conductors in different directions. The coaxial transmitter coil is vertical with its axis in the flight direction. The coplanar coils are horizontal. The secondary fields are sensed simultaneously by means of receiver coils which are maximum coupled to their respective transmitter coils. The system yields an inphase and a quadrature channel from each transmitter-receiver coil-pair. The system is also equipped to provide two environment noise monitor channels.

Magnetometer

Model: Picodas Cesium

Sensitivity: 0.01 nT

Sample rate: 10 per second

The magnetometer sensor is towed in a bird 50 ft. below the helicopter.

Magnetic Base Station

Model: Geometrics G-826A

Sensitivity: 0.50 nT

Sample rate: once per 5 seconds

An Epson recorder is operated in conjunction with the base station magnetometer to record the diurnal variations of the earth's magnetic field. The clock of the base station is synchronized with that of the airborne system to permit subsequent removal of diurnal drift.

VLF System

Manufacturer: Herz Industries Ltd.

Type: Totem-2A

Sensitivity: 0.1%

The VLF receiver measures the total field and vertical quadrature components of the secondary VLF field. Signals from two separate transmitters can be measured simultaneously. The VLF sensor is towed in a bird 33 feet below the helicopter.

Radar Altimeter

Manufacturer: Honeywell/Sperry

Type: AA 220

Sensitivity: 1 ft

The radar altimeter measures the vertical distance between the helicopter and the ground. This information is used in the processing algorithm which determines conductor depth.

Analog Recorder

Manufacturer: RMS Instruments

Type: GR33 dot-matrix graphics recorder

Resolution: 4x4 dots/mm

Speed: 1.5 mm/sec

The analog profiles were recorded on chart paper in the aircraft during the survey. Table 2-1 lists the geophysical data channels and the vertical scale of each profile.

Digital Data Acquisition System

Manufacturer: Scintrex
Type: CDI-6
Tape Deck: RMS TCR-12, 6400 bpi, tape cartridge recorder

The digital data were used to generate several computed parameters.

Tracking Camera

Type: Panasonic Video
Model: AG 2400/WVCD132

Fiducial numbers are recorded continuously and are displayed on the margin of each image. This procedure ensures accurate correlation of analog and digital data with respect to visible features on the ground.

Navigation System

Model: Del Norte 547
Type: UHF electronic positioning system
Sensitivity: 3 feet
Sample rate: 0.5 per second

The navigation system uses ground based transponder stations which transmit distance information back to the helicopter. The ground stations are set up well away from the survey area and are positioned such that the signals cross the survey block at an angle between 30° and 150°. After site selection, a baseline is flown at right angles to a line drawn through the transmitter sites to establish an arbitrary coordinate system for the survey area. The onboard Central Processing Unit takes any two transponder distances and determines the helicopter position relative to these two ground stations in cartesian coordinates.

Aircraft

The instrumentation was installed in an Aerospatiale Lama 315B turbine helicopter. The helicopter flew at an average airspeed of 70 mph with an EM bird height of approximately 100 feet.

Table 2-1. The Analog Profiles

Channel Name	Parameter	Sensitivity per mm	Designation on digital profile
CX1I	coaxial inphase (900 Hz)	2.5 ppm	CXI (900 Hz)
CX1Q	coaxial quad (900 Hz)	2.5 ppm	CXQ (900 Hz)
CP2I	coplanar inphase (900 Hz)	2.5 ppm	CPI (900 Hz)
CP2Q	coplanar quad (900 Hz)	2.5 ppm	CPQ (900 Hz)
CP3I	coplanar inphase (7200 Hz)	5.0 ppm	CPI (7200 Hz)
CP3Q	coplanar quad (7200 Hz)	5.0 ppm	CPQ (7200 Hz)
CP4I	coplanar inphase (56 kHz)	10.0 ppm	CPI (56 kHz)
CP4Q	coplanar quad (56 kHz)	10.0 ppm	CPQ (56 kHz)
CXSP	coaxial sferics	2.5 ppm	
CPSP	coplanar sferics	2.5 ppm	
ALT	altimeter	3 m	ALT
VL1T	VLF-total: primary station	5%	
VL1Q	VLF-quad: primary station	5%	
VL2T	VLF-total: secondary stn.	5%	
VL2Q	VLF-quad: secondary stn.	5%	
MAGC	magnetics, coarse	20 nT	MAG
MAGF	magnetics, fine	2.0 nT	MAG

Table 2-2. The Digital Profiles

Channel Name (Freq)	Observed parameters	Scale units/mm
MAG	magnetics	2 nT
ALT	bird height	6 m
CXI (900 Hz)	vertical coaxial coil-pair inphase	2 ppm
CXQ (900 Hz)	vertical coaxial coil-pair quadrature	2 ppm
CPI (900 Hz)	horizontal coplanar coil-pair inphase	2 ppm
CPQ (900 Hz)	horizontal coplanar coil-pair quadrature	2 ppm
CPI (7200 Hz)	horizontal coplanar coil-pair inphase	4 ppm
CPQ (7200 Hz)	horizontal coplanar coil-pair quadrature	4 ppm
CPI (56 kHz)	horizontal coplanar coil-pair inphase	10 ppm
CPQ (56 kHz)	horizontal coplanar coil-pair quadrature	10 ppm
CXPL	vertical coaxial power line monitor	4 ppm
	Computed Parameters	
CDT	conductance	1 grade
RES (900 Hz)	log resistivity	.06 decade
RES (7200 Hz)	log resistivity	.06 decade
RES (56 kHz)	log resistivity	.06 decade
DP (900 Hz)	apparent depth	6 m
DP (7200 Hz)	apparent depth	6 m
DP (56 kHz)	apparent depth	6 m

PRODUCTS AND PROCESSING TECHNIQUES

The following products are available from the survey data. Those which are not part of the survey contract may be acquired later. Refer to Table 1-1 for a summary of the maps which accompany this report and those which are recommended as additional products. Most parameters can be displayed as contours, profiles, or in colour.

Base Maps

Base maps of the survey area were prepared from 1:24,000 topographic maps.

Flight Path

The cartesian coordinates produced by the electronic navigation system were transformed into UTM grid locations during data processing. These were tied to the UTM grid on the base map. In the case of a photomosaic base map, the UTM grid must be transferred from a topographic map to the photomosaic.

Prominent topographical features were correlated with the navigational data points, to ensure that the data is accurately registered on the base map.

Electromagnetic Anomalies

Anomalous electromagnetic responses are selected and analysed by computer to provide a preliminary electromagnetic anomaly map. This preliminary EM map is used, by the geophysicist, in conjunction with the computer generated digital profiles, to produce the final interpreted EM anomaly map. This map includes bedrock, surficial and cultural conductors. A map containing only bedrock conductors can be generated, if desired.

Resistivity

The apparent resistivity in ohm-m may be generated from the inphase and quadrature EM components for any of the frequencies, using a pseudo-layer halfspace model. A resistivity map portrays all the EM information for that frequency over the entire survey area. This contrasts with the electromagnetic anomaly map which provides information only over interpreted conductors. The large dynamic range makes the resistivity parameter an excellent mapping tool.

EM Magnetite

The apparent percent magnetite by weight is computed wherever magnetite produces a negative inphase EM response.

The results are usually displayed on a contour map.

Total Field Magnetics

The aeromagnetic data are corrected for diurnal variation using the magnetic base station data. The regional IGRF gradient is removed from the data, if required under the terms of the contract.

Enhanced Magnetics

The total field magnetic data are subjected to a processing algorithm. This algorithm enhances the response of magnetic bodies in the upper 1,500 feet and attenuates the response of deeper bodies. The resulting enhanced magnetic map provides better definition and resolution of near-surface magnetic units. It also identifies weak magnetic features which may not be evident on the total field magnetic map. However, regional magnetic variations, and magnetic lows caused by remanence, are better defined on the total field magnetic map. The technique is described in more detail in Section 5.

Magnetic Derivatives

The total field magnetic data may be subjected to a variety of filtering techniques to yield maps of the following:

vertical gradient

second vertical derivative

magnetic susceptibility with reduction to the pole

upward/downward continuations

All of these filtering techniques improve the recognition of near-surface magnetic bodies, with the exception of upward continuation. Any of these parameters can be produced on request. Dighem's proprietary enhanced magnetic technique is designed to provide a general "all-purpose" map, combining the more useful features of the above parameters.

VLF

The VLF data can be digitally filtered to remove long wavelengths such as those caused by variations in the transmitted field strength. The results are usually presented as contours of the filtered total field.

Digital Profiles

Distance-based profiles of the digitally recorded geophysical data are generated and plotted by computer.

These profiles also contain the calculated parameters which are used in the interpretation process. These are produced as worksheets prior to interpretation, and can also be presented in the final corrected form after interpretation. The profiles display electromagnetic anomalies with their respective interpretive symbols. The differences between the worksheets and the final corrected form occur only with respect to the EM anomaly identifier.

Contour, Colour and Shadow Map Displays

The geophysical data are interpolated onto a regular grid using a cubic spline technique. The resulting grid is suitable for generating contour maps of excellent quality.

Colour maps are produced by interpolating the grid down to the pixel size. The distribution of the colour ranges is normalized for the magnetic parameter colour maps, and matched to specific contour intervals for the resistivity and VLF colour maps.

Monochromatic shadow maps are generated by employing an artificial sun to cast shadows on a surface defined by the geophysical grid. There are many variations in the shadowing technique, as shown in Figure 3-1. The various shadow techniques may be applied to total field or enhanced magnetic data, magnetic derivatives, VLF, resistivity, etc. Of the various magnetic products, the shadow of the enhanced magnetic parameter is particularly suited for defining geological structures with crisper images and improved resolution.

Dighem software provides several shadowing techniques. Both monochromatic (commonly green) or polychromatic (full color) maps may be produced. Monochromatic shadow maps are often preferred over polychromatic maps for reasons of clarity.

<u>Spot Sun</u>

The spot sun technique tends to mimic nature. The sun occupies a spot in the sky at a defined azimuth and inclination. The surface of the data grid casts shadows. This is the standard technique used by industry to produce monochromatic shadow maps.

A characteristic of the spot sun technique is that shadows are cast in proportion to how well the sunlight intersects the feature. Features which are almost parallel to the sun's azimuth may cast no shadow at all. To avoid this problem, Dighem's hemispheric sun technique may be employed.

<u>Hemispheric Sun</u>

The hemispheric sun technique was developed by Dighem. The method involves lighting up a hemisphere. If, for example, a north hemispheric sun is selected, features of all strikes will have their north side in sun and their south side in shadow. The hemispheric sun lights up all features, without a bias caused by strike. The method yields sharply defined monochromatic shadows.

The hemispheric sun technique always improves shadow casting, particularly where folding and cross-cutting structures occur. Nevertheless, it is important to center the hemisphere perpendicular to the regional strike. Features which strike parallel to the center of the hemisphere result in ambiguity. This is because the two sides of the feature may yield alternating patterns of sun and shadow. If this proves to be a problem in your survey area, Dighem's omni sun technique may be employed.

<u>Omni Sun</u>

The omni sun technique was also developed by Dighem. The survey area is centered within a ring of sunlight. This lights up all features without any strike bias. The result is brightly defined monochromatic features with diffuse shadows.

<u>Multi Sun</u>

Two or three spot suns, with different azimuths, may be combined in a single presentation. The shadows are displayed on one map by the use of different colors, e.g., by using a green sun and a red sun. Some users find the interplay of colors reduces the clarity of the shadowed product.

<u>Polychromatic Maps</u>

Any of the above monochromatic shadow maps can be combined with the standard contour-type solid color map. The result is a polychromatic shadow map. Such maps are esthetically pleasing, and are preferred by some users. A disadvantage is that ambiguity exists between changes in amplitude and changes in shadow.

Fig. 3-1 Shadow Mapping

SURVEY RESULTS

Resistivity

Apparent resistivity maps were prepared from the 900, 7,200 and 56,000 Hz coplanar EM data. These maps show the conductive properties of the survey area.

The 56,000 Hz data has the greatest dynamic range but is biased towards surficial conductivity. In general, the 56,000 Hz map shows higher resistivities than either the 900 or 7,200 Hz maps. This is indicative of a relatively resistive upper layer overlying a conductive layer or layers. This resistive cover may be thinner where the 56,000 Hz resistivity agrees closely with the lower frequencies. For example, a low resistivity trend of 10 to 15 ohm-m extends from fiducial 2200 on line 10270, to fiducial 3640 on line 10410 on the 56,000 Hz map.

The 7,200 Hz data is likely penetrating through the surficial layer to a greater extent than the 56,000 Hz resistivity. It generally agrees with the 900 Hz resistivity, except in a few isolated areas. In areas where it yields higher resistivities the relatively resistive surficial layer may be thicker.

The resistivity contours do not appear to have been affected to a high degree by cultural sources. EM anomalies due to cultural sources, such as power lines, are primarily the result of current channelling. This yields a high amplitude response but little phase shift and therefore no appreciable change in the inphase to quadrature ratio. As the resistivity calculation is based on the phase, which is changed as a result of inductive coupling, the cultural sources do not usually distort the resistivity map to a high degree. In some areas excessive noise in the form of spiking or hash on the EM channels resulted from culture. In such areas the data was left out of the resistivity calculation to ensure that the resistivity contours were not distorted.

Magnetics

The total field magnetic data have been presented as contours on the base map using a contour interval of 1 nT where gradients permit. The IGRF gradient across the survey block has not been removed. The maps show the magnetic properties of the rock units underlying the survey area. The isolated bull's-eye anomalies are likely due to cultural sources. Some of these may be attributed to oil wells. The narrow response yielded by such a source may easily be missed at a 1/8 mile line spacing, therefore many of these sources may not have been detected.

VLF

VLF results were obtained from three transmitting stations, Cutler, Maine (NAA - 24.0 kHz), Seattle, Washington (NLK - 24.8 kHz) and Annapolis, Maryland (NSS - 21.4 kHz). The use of three different stations was necessitated by signal interruptions at the source of transmission. Results from the transmitter at Annapolis, Maryland were presented as contours of the filtered total field. The contour patterns are greatly influenced by cultural sources.

The VLF method is quite sensitive to the angle of coupling between the conductor and the proposed EM field. Consequently, conductors which strike towards the VLF station will usually yield a stronger response than conductors which are nearly orthogonal to it.

Closely-spaced conductors, conductors of short strike length or conductors which are poorly coupled to the VLF field, may escape detection with this method. Erratic signals from the VLF transmitters can also give rise to strong, isolated anomalies which should be viewed with caution.

Electromagnetic Anomalies

The electromagnetic anomalies are displayed on the digital profiles. Corresponding to each anomaly identifier is either an "L" or "H" interpretive symbol. The "L" symbol reflects an anomaly that is due to a line source or culture. The "H" interpretive symbol is used to denote a response from a conductor which fits a half space model, such as a buried, flat lying layer. The coplanar EM channels will be maximum coupled to these flat lying conductors, and therefore these sources are best represented on the resistivity parameters. Refer to the sections on "Recognition of Culture" and "Resistivity Mapping" in section 5 for more information.

BACKGROUND INFORMATION

This section provides background information on parameters which are available from the survey data. Those which have not been supplied as survey products may be generated later from raw data on the digital archive tape.

ELECTROMAGNETICS

Resistivity mapping

Areas of widespread conductivity are commonly encountered during surveys. In such areas, anomalies can be generated by decreases of only 5 m in survey altitude as well as by increases in conductivity. The typical flight record in conductive areas is characterized by inphase and quadrature channels which are continuously active. Local EM peaks reflect either increases in conductivity of the earth or decreases in survey altitude. For such conductive areas, apparent resistivity profiles and contour maps are necessary for the correct interpretation of the airborne data. The advantage of the resistivity parameter is that anomalies caused by altitude changes are virtually eliminated, so the resistivity data reflect only those anomalies caused by conductivity changes. The resistivity analysis also helps the interpreter to differentiate between conductive trends in the bedrock and those patterns typical of conductive overburden. For example, discrete conductors will generally appear as narrow lows on the contour map and broad conductors (e.g., overburden) will appear as wide lows.

The resistivity profiles and the resistivity contour maps present the apparent resistivity using the so-called pseudo-layer (or buried) half space model defined by Fraser (1978)[1]. This model consists of a resistive layer overlying a conductive half space. The depth channels give the apparent depth below surface of the conductive material. The apparent depth is simply the apparent thickness of the overlying resistive layer. The apparent depth (or thickness) parameter will be positive when the upper layer is more resistive than the underlying material, in which case the apparent depth may be quite close to the true depth.

The apparent depth will be negative when the upper layer is more conductive than the underlying material, and will be zero when a homogeneous half space exists. The apparent depth parameter must be interpreted cautiously because it will contain any errors which may exist in the measured altitude of the EM bird (e.g., as caused by a dense tree

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[1] Resistivity mapping with an airborne multicoil electromagnetic system: Geophysics, v. 43, p.144-172

cover). The inputs to the resistivity algorithm are the inphase and qaudrature components of the coplanar coil-pair. The outputs are the apparent resistivity of the conductive half space (the source) and the sensor-source distance are independent of the flying height. The apparent depth, discussed above, is simply the sensor-source distance minus the measured altitude or flying height. Consequently, errors in the measured altitude will affect the apparent depth parameter but not the apparent resistivity parameter.

The apparent depth parameter is a useful indicator of simple layering in areas lacking a heavy tree cover. The DIGHEM system has been flown for purposes of permafrost mapping, where positive apparent depths were used as a measure of permafrost thickness. However, little quantitative use has been made of negative apparent depths because the absolute value of the negative depth is not a measure of the thickness of the conductive upper layer and, therefore, is not meaningful physically. Qualitatively, a negative apparent depth estimate usually shows that the EM anomaly is caused by conductive overburden. Consequently, the apparent depth channel can be of significant help in distinguishing between overburden and bedrock conductors.

The resistivity map often yields more useful information on conductivity distributions than the EM map. In comparing the EM and resistivity maps, keep in mind the following:

(a) The resistivity map portrays the absolute value of the earth's resistivity, where resistivity = 1/conductivity.

(b) The EM map portrays anomalies in the earth's resistivity. An anomaly by definition is a change from the norm and so the EM map displays anomalies, (i) over narrow, conductive bodies and (ii) over the boundary zone between two wide formations of differing conductivity.

The resistivity map might be likened to a total field map and the EM map to a horizontal gradient in the direction of flight[2]. Because gradient maps are usually more sensitive than total field maps, the EM map therefore is to be preferred in resistive areas. However, in conductive areas, the absolute character of the resistivity map usually causes it to be more useful than the EM map.

2 The gradient analogy is only valid with regard to the identification of anomalous locations.

Recognition of culture

Cultural responses include all EM anomalies caused by man-made metallic objects. Such anomalies may be caused by inductive coupling or current gathering. The concern of the interpreter is to recognize when an EM response is due to culture. Points of consideration used by the interpreter, when coaxial and coplanar coil-pairs are operated at a common frequency, are as follows:

1. Channel CXPL monitors 60 Hz radiation. An anomaly on this channel shows that the conductor is radiating power. Such an indication is normally a guarantee that the conductor is cultural. However, care must be taken to ensure that the conductor is not a geologic body which strikes across a power line, carrying leakage currents.

2. A flight which crosses a "line" (e.g., fence, telephone line, etc.) yields a center-peaked coaxial anomaly and an m-shaped coplanar anomaly. When the flight crosses the cultural line at a high angle of intersection, the amplitude ratio of coaxial/coplanar response is 4. Such an EM anomaly can only be caused by a line. The geologic body which yields anomalies most closely resembling a line is the vertically dipping thin dike.

Such a body, however, yields an amplitude ratio of 2 rather than 4. Consequently, an m-shaped coplanar anomaly with a CXI/CPI amplitude ratio of 4 is virtually a guarantee that the source is a cultural line.

3. A flight which crosses a sphere or horizontal disk yields center-peaked coaxial and coplanar anomalies with a CXI/CPI amplitude ratio (i.e., coaxial/coplanar) of 1/4. In the absence of geologic bodies of this geometry, the most likely conductor is a metal roof or small fenced yard.[3] Anomalies of this type are virtually certain to be cultural if they occur in an area of culture.

4. A flight which crosses a horizontal rectangular body or wide ribbon yields an m-shaped coaxial anomaly and a center-peaked coplanar anomaly. In the absence of geologic bodies of this geometry, the most likely conductor is a large fenced area.[5] Anomalies of this type are virtually certain to be cultural if they occur in an area of culture.

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[3] It is a characteristic of EM that geometrically similar anomalies are obtained from: (1) a planar conductor, and (2) a wire which forms a loop having dimensions identical to the perimeter of the equivalent planar conductor.

5. EM anomalies which coincide with culture, as seen on the camera film or video display, are usually caused by culture. However, care is taken with such coincidences because a geologic conductor could occur beneath a fence, for example. In this example, the fence would be expected to yield an m-shaped coplanar anomaly as in case #2 above. If, instead, a center-peaked coplanar anomaly occurred, there would be concern that a thick geologic conductor coincided with the cultural line.

6. The above description of anomaly shapes is valid when the culture is not conductively coupled to the environment. In this case, the anomalies arise from inductive coupling to the EM transmitter. However, when the environment is quite conductive (e.g., less than 100 ohm-m at 900 Hz), the cultural conductor may be conductively coupled to the environment. In this latter case, the anomaly shapes tend to be governed by current gathering. Current gathering can completely distort the anomaly shapes, thereby complicating the identification of cultural anomalies. In such circumstances, the interpreter can only rely on the radiation channel CPS and on the camera film or video records.

MAGNETICS

The magnetometer data are digitally recorded in the aircraft to an accuracy of 0.01 nT for cesium magnetometers. The digital tape is processed by computer to yield a total field magnetic contour map. When warranted, the magnetic data may also be treated mathematically to enhance the magnetic response of the near-surface geology, and an enhanced magnetic contour map is then produced. The response of the enhancement operator in the frequency domain is illustrated in Figure 5-1. This figure shows that the passband components of the airborne data are amplified 20 times by the enhancement operator. This means, for example, that a 100 nT anomaly on the enhanced map reflects a 5 nT anomaly for the passband components of the airborne data.

The enhanced map, which bears a resemblance to a downward continuation map, is produced by the digital bandpass filtering of the total field data. The enhancement is equivalent to continuing the field downward to a level (above the source) which is 1/20th of the actual sensor-source distance.

Because the enhanced magnetic map bears a resemblance to a ground magnetic map, it simplifies the recognition of trends in the rock strata and the interpretation of

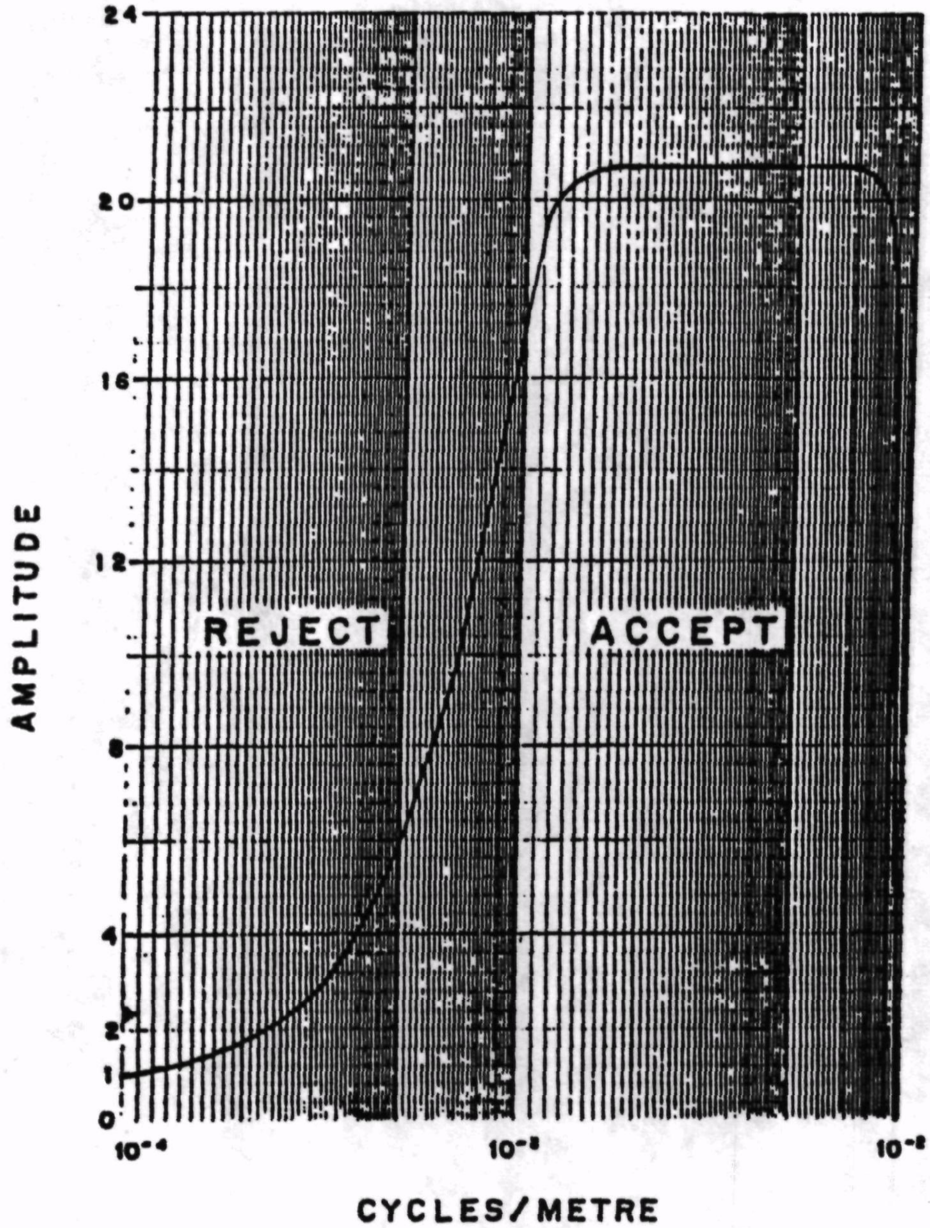

Fig. 5-2 Frequency response of magnetic enhancement operator for a sample interval of 50 m.

geological structure. It defines the near-surface local geology while de-emphasizing deep-seated regional features. It primarily has application when the magnetic rock units are steeply dipping and the earth's field dips in excess of 60 degrees.

Any of a number of filter operators may be applied to the magnetic data, to yield vertical derivatives, continuations, magnetic susceptibility, etc. These may be displayed in contour, colour or shadow.

VLF

VLF transmitters produce high frequency uniform electromagnetic fields. However, VLF anomalies are not EM anomalies in the conventional sense. EM anomalies primarily reflect eddy currents flowing in conductors which have been energized inductively by the primary field. In contrast, VLF anomalies primarily reflect current gathering, which is a non-inductive phenomenon. The primary field sets up currents which flow weakly in rock and overburden, and these tend to collect in low resistivity zones. Such zones may be due to massive sulfides, shears, river valleys and even unconformities.

The VLF field is horizontal. Because of this, the

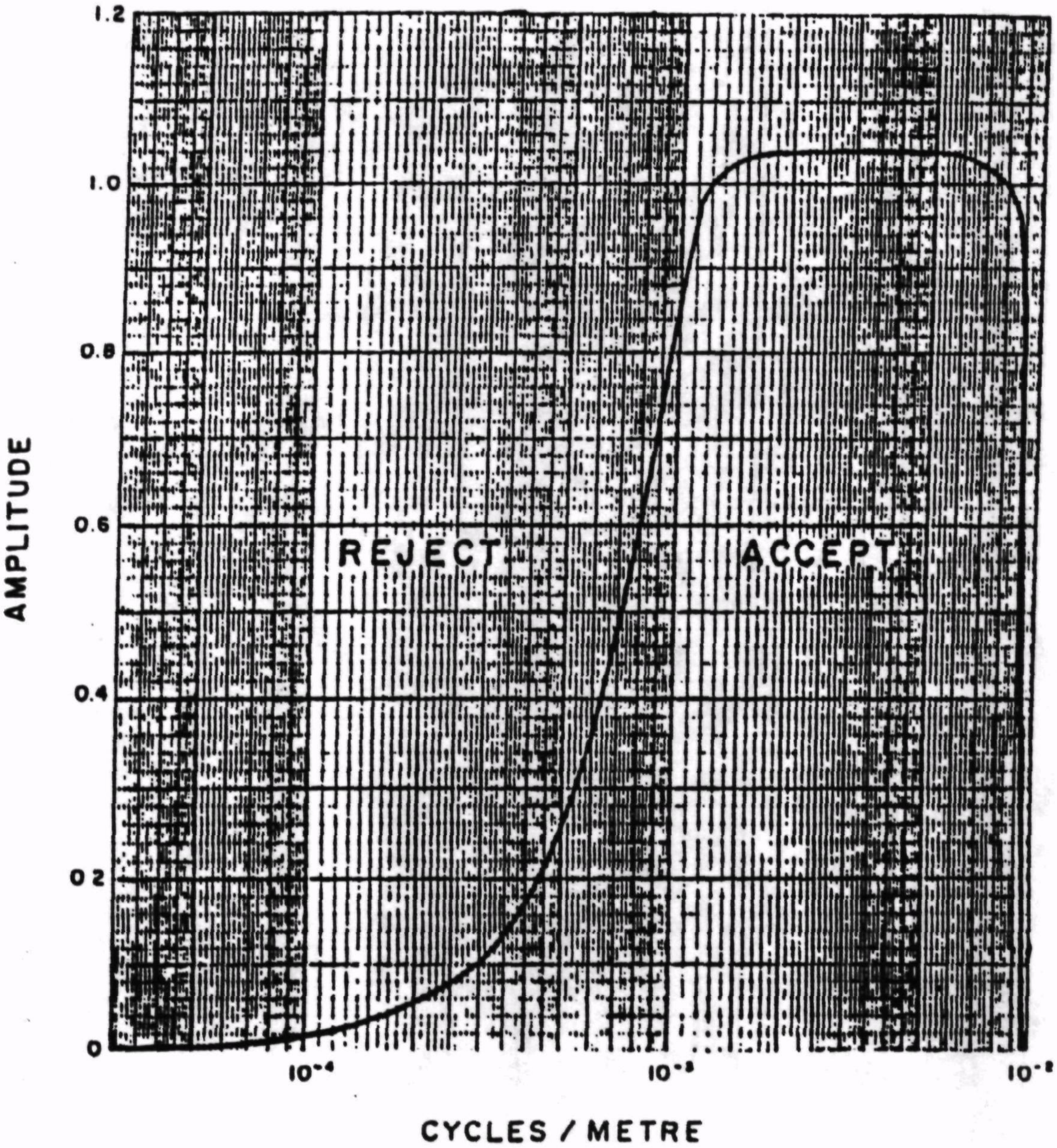

Fig. 5-3 Frequency response of VLF operator.

method is quite sensitive to the angle of coupling between the conductor and the transmitted VLF field. Conductors which strike towards the VLF station will usually yield a stronger response than conductors which are nearly orthogonal to it.

The Herz Industries Ltd. Totem VLF-electromagnetometer measures the total field and vertical quadrature components. Both of these components are digitally recorded in the aircraft with a sensitivity of 0.1 percent. The total field yields peaks over VLF current concentrations whereas the quadrature component tends to yield crossovers. Both appear as traces on the profile records. The total field data are filtered digitally and displayed as contours to facilitate the recognition of trends in the rock strata and the interpretation of geologic structure.

The response of the VLF total field filter operator in the frequency domain (Figure 5-2) is basically similar to that used to produce the enhanced magnetic map (Figure 5-1). The two filters are identical along the abscissa but different along the ordinant. The VLF filter removes long wavelengths such as those which reflect regional and wave transmission variations. The filter sharpens short wavelength responses such as those which reflect local geological variations.

CONCLUSIONS AND RECOMMENDATIONS

This report provides a brief description of the survey results and describes the equipment, procedures and logistics of the survey.

The various maps included with this report display the magnetic and conductive properties of the survey area. The survey results should be reviewed in detail, in conjunction with all available geological, geophysical and geochemical information.

It is also recommended that additional processing of existing geophysical data be considered, in order to extract the maximum amount of information from the survey results. Resistivity colour plots may aid in identification of resistivity contrasts.

Respectfully submitted,

DIGHEM SURVEYS & PROCESSING INC.

Doug McConnell

Douglas L. McConnell
Geophysicist

DLM/mg

A0537SEP.89R