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Helicopter Electromagnetic and Magnetic Geophysical Survey Data, Oakland, Ashland, and Firth Study Areas, Eastern Nebraska, March 2007

By Bruce D. Smith, Jared D. Abraham, James C. Cannia, Gregory V. Steele, and Patricia L. Hill

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Front Cover: Photograph showing helicopter electromagnetic system flying over part of the eastern Nebraska water resource project survey area. Photo by Jesse T. Korus, Lower Platte South Natural Resources District, Lincoln, NE.

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Conversion Factors, Datum, and Acronyms

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	247.1	acre
liter (L)	0.2642	gallon (gal)
nanotesla (nT)	1	gamma
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Electrical conductivity is given in milllisiemens per meter (mS/m) unless otherwise specified.
Electrical resistivity is given in ohm-meters (ohm-m) unless otherwise specified.
1 mS/m = 1000/ (1 ohm-m) thus 10 mS/m = 100 ohm-m.

Vertical coordinate information is referenced to the "North American Vertical Datum of 1988 (NAVD 88)" except as noted in text.
Horizontal coordinate information is referenced to the "North American Datum of 1983, Universal Transverse Mercator Zone 14 (NAD 83 UTM Zone 14N)" except as noted in text.
Airborne geophysical survey used World Geodetic System of 1984 (WGS84) for global positioning.

ACRONYMS USED IN THIS REPORT:

EM	Electromagnetic
DTM	Digital Terrain Model
GPS	Global Positioning System
HEM	Helicopter Electromagnetic
RTP	Reduced-to-Pole
TDEM	Time Domain Electromagnetic
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

ABBREVIATIONS USED IN THIS REPORT:

Hz	hertz
kHz	kilohertz

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Abstract

This report is a digital data release for a helicopter electromagnetic and magnetic survey that was conducted during March 2007 in three 93-square-kilometer (36-square-mile) areas of eastern Nebraska as part of a joint State of Nebraska and U.S. Geological Survey study. The objective of the survey is to improve the understanding of the relationship between surface-water and ground-water systems critical to developing water resource management programs. The electromagnetic equipment consisted of six different coil-pair orientations that measured electrical resistivity at separate frequencies from about 400 hertz to about 115,000 hertz. The electromagnetic data were converted to electrical resistivity geo-referenced grids and maps, each representing different approximate depths of investigation for each area. The range of subsurface investigation is comparable to the depth of shallow aquifers. The three areas selected for the study, Ashland, Firth, and Oakland, have glacial terrains and bedrock that typify different hydrogeologic settings for surface water and ground water in eastern Nebraska. The geophysical and hydrologic information from U.S. Geological Survey studies are being used by resource managers to develop ground-water resource plans for the area.

Introduction

The general objectives of the Eastern Nebraska Water Resources Assessment (ENRWA) have been recently described by Korus and Divine (2007) and are summarized here: The Eastern Nebraska Water Resources Assessment (ENWRA) is a cooperative effort involving ten local, state, and federal agencies to develop a three-dimensional geologic framework and water budget for the glaciated region, or eastern one-fifth of Nebraska. This region contains 70 percent of the state's population but is the most limited in terms of the state's ground-water supplies. Locally governed Natural Resources Districts (NRDs), charged with ground-water management in Nebraska, seek to improve their management plans in response to growing populations, hydrologic drought, and new conjunctive management laws. Detailed mapping and characterization are necessary to delineate aquifers, assess their degree of hydrologic connection with streams and other aquifers, and better predict water quality and quantity.

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Electrical geophysical methods can be used to image the subsurface of the earth using techniques very similar to medical computed axial tomography (CAT) scans of the human body (Won, 1990). Airborne electrical geophysical methods have been effectively used by the U.S. Geological Survey (USGS) in a variety of ground-water resource projects and programs (Smith and others, 2007). An example is the helicopter electromagnetic (HEM) survey successfully used in the upper Missouri River Basin (Poplar, Montana) to evaluate ground-water quality in a similar hydrologic setting to Nebraska (Smith and others, 2006). Based on the success of this and other ground-water studies using airborne geophysical methods, the USGS received support from Nebraska state agencies to evaluate the subsurface mapping application to eastern Nebraska. The project has been described by Abraham and others (2007) in a poster presentation at the 2007 annual Geological Society of America Meeting. The poster (PDF file) is included in Appendix I. The airborne geophysical data described in this report were collected by Fugro Airborne Surveys using a HEM system under contract to the USGS. The contractor's report is included as a PDF file (Appendix B). The digital airborne geophysical data collected along flight lines was processed by the contractor to produce digital maps. Additional data processing was done by the USGS, and supplemental maps were produced. These digital line data and maps are also included as part of the digital data release.

This is a large, multi-faceted study requiring successful coordination and planning between multiple levels of government. Public involvement and funding of water resources studies at the local, state, and federal levels have been and will continue to be vital to its long-term success.

Purpose and Scope

Three specific survey areas of about one township size were chosen for evaluation of the HEM method in mapping glaciated terrains of eastern Nebraska. Sites are located near Firth, Ashland, and Oakland, Nebraska, each representing a different hydrogeologic setting (fig. 1). Studies were initiated in 2006 and included test hole drilling, borehole geophysics, and time domain electromagnetic (TDEM) surveys in addition to the HEM survey for an integrated interpretation of hydrologic features. This report presents HEM and magnetic maps and data that were collected for the USGS by Fugro Airborne Surveys during March 22 to 26, 2007. The survey consisted of 1,170 line km (727 line mi). The ground data will be released in separate reports. In subsequent years, water quality studies, ground water age dating, hydrologic monitoring, and estimation of recharge to aquifers will be tested at the sites. The long-term vision for the program is to evaluate and apply the suite of tools developed in the pilot studies to provide data, interpretations, and models for improved water resources management in Eastern Nebraska.

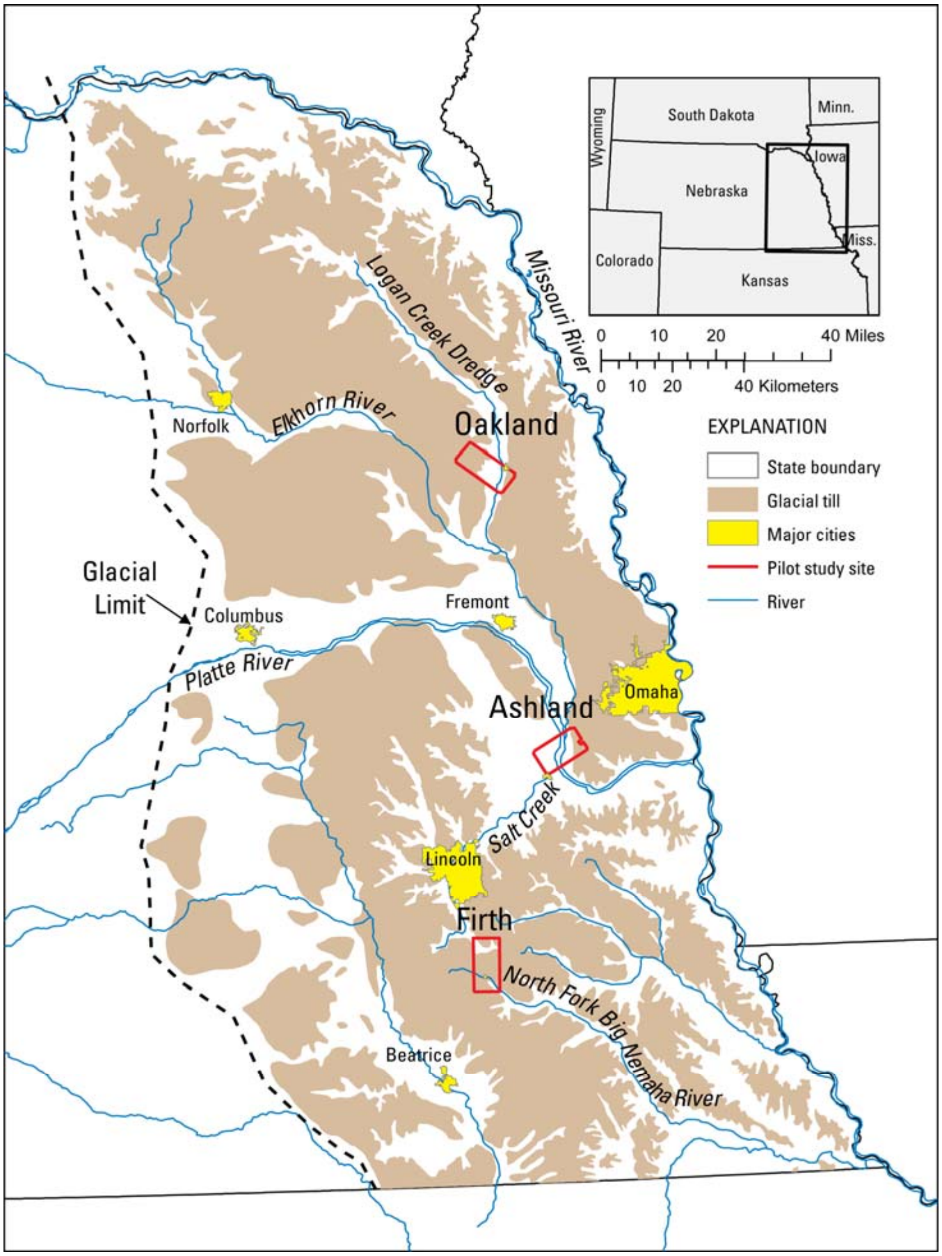
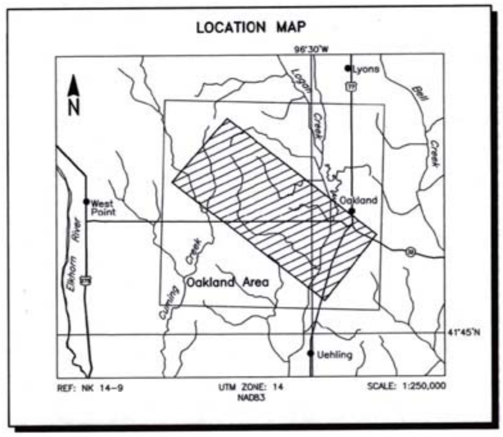
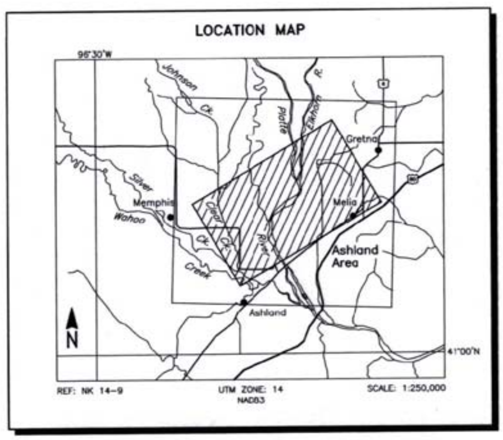


Figure 1. Location of study area and helicopter electromagnetic and magnetic survey.

a)



b)



c)

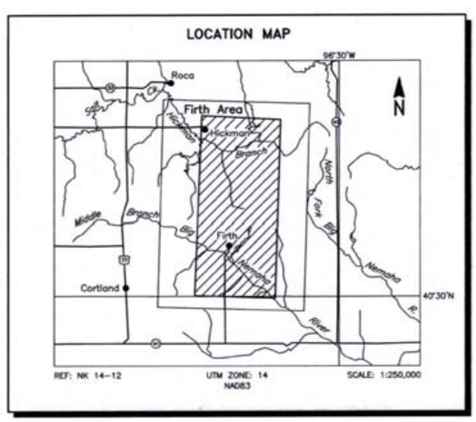


Figure 2. Detailed location maps for pilot study areas (shaded): a) location map for the Oakland area, b) location map for the Ashland area, and c) location map for the Firth area (adapted from Fugro Airborne report (Appendix II).

Geophysical Data Overview

The digital data from the airborne survey were acquired and processed by the contractor, Fugro Airborne LTD, as described in Appendix II. The USGS did quality control of the contractor's data acquisition, processing, and report. In addition, the USGS did some reprocessing of the data to meet specific requirements of this project. Both the contractor and USGS digital data are included in the present data release. Table 1 contains links to the digital data and a brief description of the files and directories. A more comprehensive discussion of the digital data is given in the "Digital Data" section.

Table 1. Digital data organization and description for files and directories.

Directory	Description
METADATA	Metadata description of digital data.
GIS_SURVEY	Geographic information such as digital topographic map and survey areas.
GRIDS	Grids of the electromagnetic and magnetic field data for the horizontal coplanar coil pairs. The grids are in Geosoft OASIS MONTAJ (***http://www.geosoft.com/***) format, a standard of the geophysical industry used in many map display programs.
LINEDATA	Flight-line data are in ASCII standard format. The "readme" file in this directory contains a description of the channels of the digital line data. Data processing is described in detail in the contractor's report in Appendix II.
PLOTS	Geotiff (UTM14N. NAD83 projected ".tif" files) images of the grids. Each file has an associated world file (".tfw"). The digital version of plate 1 can be found in this directory. The original images of the airborne apparent resistivity maps generated by the contractor are included in the IMAGES/CONTRACTOR_PDF_MAPS.
REPORT	This report and appendixes I and II are in this directory as .pdf and Microsoft Word files.

Helicopter Electromagnetic and Magnetic Survey

Kirsh (2006) and Rubin and Hubbard (2005) give good overviews of geophysical principles and applications to ground-water studies. Airborne geophysical surveys are usually made along regularly spaced flight lines within specified survey areas (figs. 1 and 2). Flight lines can be as closely spaced as 50 m, although closer spacing is possible in special circumstances. The USGS has generally flown HEM surveys with 200-400 m spacing (1/8 to 1/4 mile: Smith and others, 2007), although flight lines with 800 m separation have been used to map regional structures in a carbonate aquifer setting (Smith and others, 2007). One objective of the present study is to evaluate the flight line spacing in terms of resolution of hydrogeologic features in the glaciated terrain of eastern Nebraska. Table 2 gives the flight line specifications for each survey area.

Table 2. Flight line direction and spacing for each survey area.

Survey Area	Traverse line azimuth	Tie line azimuth	Traverse line spacing (m)	Tie line spacing (m)	Traverse line distance (km)	Tie line distance (km)	Total
Oakland (A)	127°/307°	37°/217°	270	14,000	371.0	14.0	385.0
Ashland (B)	58°/238°	148°/328°	270	12,000	361.6	24.3	385.9
Firth (C)	90°/270°	0°/180°	280	6,000	367.8	30.1	397.9
				TOTAL	1100.4	68.4	1168.8

The RESOLVE HEM system was used for all of the surveys. The geophysical system, consisting of an electromagnetic transmitter and receiver, magnetometer, GPS, and a laser altimeter, is housed in a cylindrical tube or bird that is towed beneath the helicopter. Figure 3 shows the helicopter-borne instrumentation used for this survey. In the system flown by Fugro Airborne, all of the measurements from systems in the bird are digital and transmitted via cable to a processing and digital recording system in the helicopter. Measurements of the geophysical data (EM and total field magnetic readings) are made approximately every three meters along the flight line.

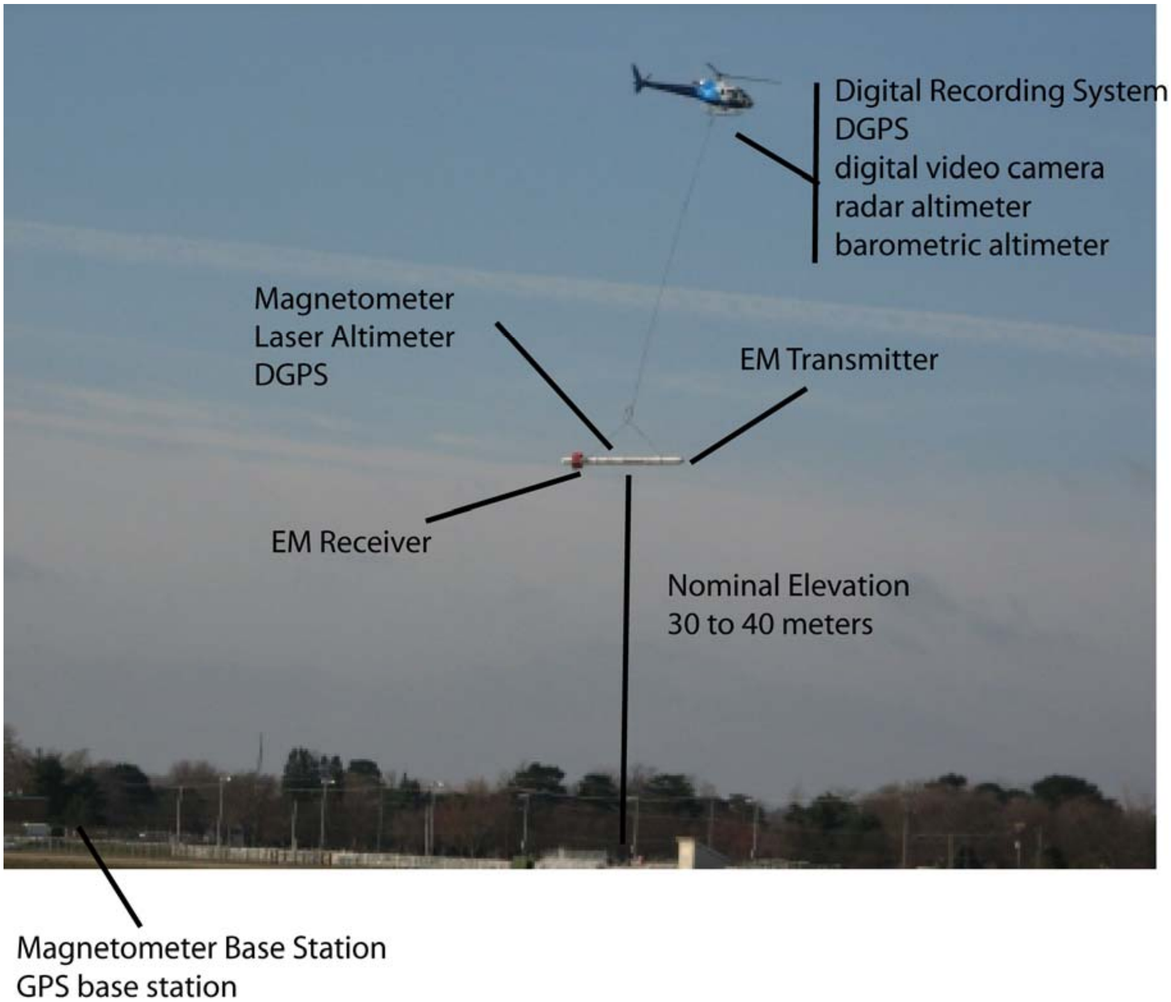


Figure 3. Helicopter-borne Resolve geophysical system used in the Nebraska survey flying near Fremont, NE: Electromagnetic, magnetic, DGPS, and laser altimeter sensors are housed in a “bird”, a cigar-shaped 9-m-long tube, which is kept at about 30–40 m above ground level. The digital data recording system, additional altimeters, and navigation systems are installed in the helicopter. The base station records the time-varying, diurnal, total magnetic field variations.

Electromagnetic Measurements

The principles of HEM methods are well summarized by Siemon (2006) and Paine and Minty (2005). The RESOLVE© HEM system flown by Fugro Airborne Surveys is described in detail in Appendix II. The EM measurements are made using six coil pairs that measure EM signals at separate frequencies from about 400 hertz (Hz) to about 115,000 Hz (115 kHz). Five of the coil pairs were oriented in a horizontal, coplanar position, and one of the coil pairs was oriented in a vertical, coaxial position. The specific frequencies, separation, and orientation of the coil pairs are given in table 3. The nominal frequency is the one originally designed for the particular EM system used in this survey. The actual frequency was the specific frequency used in this survey as measured during system calibrations at the survey site.

Table 3. Frequencies and sensitivities for the HEM survey. The coil separation is 7.9 meters for all configurations except for the coaxial, which is 9.0 meters.

Coil Configuration	Nominal Frequency (Hz)	Actual Frequency (Hz)	Sensitivity parts per million
Coplanar	385	380	0.12
Coplanar	1,500	1,760	0.12
Coaxial	3,300	3,270	0.12
Coplanar	6,200	6,520	0.24
Coplanar	25,000	26,640	0.60
Coplanar	115,000	116,400	0.60

The EM measurements along flight lines are reduced to apparent resistivity values as described in the contractor's report (Appendix II). One important consideration of Earth subsurface imaging from the HEM measurements is that the depth of imaging is dependent on the frequency and resistivity of the Earth. One estimate of the depth of exploration (depth of mapping) for the frequencies used in the RESOLVE© system is shown in figure 4. In this figure, the depth of exploration is defined as half of the skin depth (the point at which a plane electromagnetic wave has attenuated to 37 percent of the initial amplitude). The depths of exploration estimates shown in figure 4 are conservative, since one skin depth generally is considered to be the depth limit of HEM measurements (Fraser, 1978). Generally, at the highest frequency, depths of exploration are just a few meters. At the lowest frequency, 400 Hz, the depth of exploration may be on the order of 80 m. This aspect of HEM resistivity measurements is the basic principle that allows depth images to be constructed.

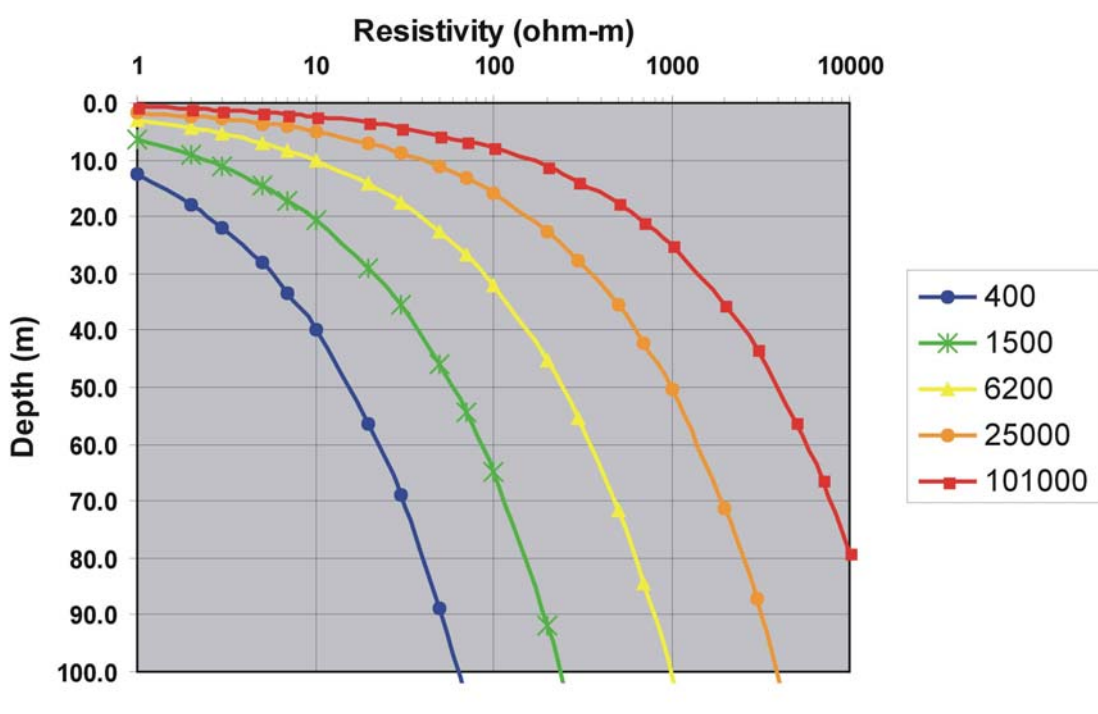


Figure 4. Estimated depth of penetration or imaging as a function of frequency and earth resistivity for the RESOLVE© system (Hodges, Fugro Airborne, 2004, written commun.).

The EM signals are recorded for each frequency as in-phase and quadrature (out-of-phase), as referenced to the transmitted signal. These signals are post-processed to apparent resistivity for each frequency and a corresponding apparent depth as described in Appendix II and by Fraser (1978). The apparent resistivity is, as the name implies, not the intrinsic electrical resistivity of the Earth but an estimated value based on assumptions of the measurement and of a homogeneous Earth (Fraser, 1978). Estimates of the intrinsic resistivity can be obtained through a variety of methods of imaging the subsurface resistivity (Seimon 2006, and Hodges, 2004). The differential resistivity and depth transformation (Haung and Fraser, 1996) is one simple depth-imaging method that has proven effective for HEM survey data (Smith and others, 2003). Both the apparent resistivity and differential data are given in the digital line data files (see Table 1).

An important part of the data processing is leveling the EM signals for system drift and calibrations. The specific steps used in the data processing are described in Appendix II. The digital line data (.xyz files in *LINEDATA* directory) gives the raw in-phase and quadrature data and the processed data from which the apparent resisitivties are computed. The final leveled data are also given. These data are included in the database, in case the original data are needed for reprocessing.

Total Magnetic Field Measurements

The magnetic field consists of the Earth's main magnetic field and the local magnetic field due to magnetized lithologies within the crust and ferromagnetic metallic sources at the surface. The system measures the Earth's total magnetic field to an accuracy of 0.01 nanoTesla (nT). The total field measurements are affected by short-term variations in the main magnetic field, which are independent of local sources and are caused mainly by solar activity. A magnetic field base station, set up by the contractor near the base of operations, is used to record these short-term variations in the Earth's total magnetic field, which are subtracted from the measurements made during the survey.

The contractor also processed the total magnetic field to remove the spatial variation from the Earth's main magnetic field. This spatial variation is defined by the International Geomagnetic Reference Field or IGRF. Sharma (2002) describes the basic principles of the main magnetic field removal from magnetometer measurements.

An additional processing step has been applied by the USGS to the magnetic field data to reduce the data to the magnetic north pole. This reduction to the pole (RTP) shifts magnetic highs directly over the causative body instead of being located slightly to the south. The RTP magnetic data processing was done using Oasis Montaj software (Geosoft, Inc., 2006).

Ancillary Measurements

The HEM system monitors 60-Hz signals in coaxial and coplanar coil configurations given as CXPL and CPPL channels in the line database (*LINEDATA*). The data are given as arbitrary voltage levels, which generally increase over power lines. The expression of power lines is quite variable due to a number of factors such as the size of the line, how well it is grounded, and the electrical resistivity of the Earth. In general, the infrastructure around urban development, transmission towers, and along major roads has a higher cultural noise level, resulting in high 60-

Hz signals. The HEM system also monitors electrical noise from lightning (spheric or atmospheric noise; Sharma, 2002) and is the CPSP channel in the line database (*LINEDATA*).

Positioning measurements of the bird and the helicopter are critical in processing and making accurate maps. Location data from the GPS system in both the bird and helicopter are given in the files in the *LINEDATA* directory. Elevation data from the laser altimeter on the bird, as well as the radar and barometric altimeters on the helicopter, are given in the *LINEDATA* files. An important aspect of the contractor's data processing is that the elevation data are given in the WGS84 Spheroid and have NOT been reduced to an ellipsoid. The contractor's report explains that additional processing needed to do this data reduction was not part of the USGS contract.

Digital Data

Digital data are given in the directories described in table 1. The following describes the digital data in each subdirectory.

Metadata

The ***METADATA*** directory contains files that describe the Ashland, Oakland, and Firth geophysical survey blocks (fig. 1). These survey blocks are the boundaries for line data, digital grids, and plots. The metadata also describes the projection used for all of the digital plots, which is NAD83 UTM14N (meters).

GIS Data

The ***GIS_SURVEY*** directory contains various files that may be useful in map preparation. The flight line location files are in dxf format (AUTOCAD). Outlines for each survey area are given as ESRI shape files (.shp and ancillary files).

Grids

Flight line data are interpolated into a regular grid in order to produce digital map plots. One of the challenges of gridding airborne geophysical data is that the spacing between flight lines is much greater than the sampling along the line (a few meters). Specialized gridding methods have been developed to deal with this aspect of processing airborne geophysical data. The contractor has used a modified Akima spline method (Appendix II, and also in a Fugro technical note: *http://www.fugroairborne.com/resources/technical_notes/time_domain_em/pdfs/Akima_tension_III.pdf*).
The contractor grids are given in the ***GRIDS*** directory in the ***FUGRO*** subdirectory. These grids have not been modified. The nomenclature for the grid names is given in the a_readme.txt file.

An alternate gridding method is the minimum curvature method implemented by Webring (1981) for geophysical airborne data. This gridding method is used in the Oasis Montaj program (*http://www.geosoft.com/resources/papers/pdfs/topicsingriddingworkshop.pdf*). We have used this algorithm to produce grids from selected channels of the flight line data. These data are found in the ***GRIDS*** directory in the ***USGS_GRIDS*** subdirectory. File naming convention is given in the a_readme.txt file.

The resistivity data have been gridded with a variable cell size to reflect both the increasing size of the footprint of the HEM measurements (Rubin and Hubbard, 2005) and the higher noise levels of the lower frequencies (400 and 1500 Hz) due to cultural sources. The lower frequencies have been gridded with a cell size of 100 meters and the higher frequencies with a cell size of 50 meters.

The USGS grids also include the magnetic RTP data, digital elevation, and powerline monitor data. These grids have a 50 m cell size. The grids are in the Oasis Montaj format (.grd file extension) commonly used in many geophysical software packages. The grids can be viewed in free software distributed by GEOSOFT (*http://www.geosoft.com/pinfo/oasismontaj/free/montajviewer.asp*). The grids can also be imported into ESRI ARCMAP applications with a plug-in provided by GEOSOFT (*http://www.geosoft.com/resources/releasenotes/plugins/arcGISplugin.asp*). Plug-ins for other software packages can be found on the GEOSOFT web site (*http://www.geosoft.com/downloads/*). Plots produced from the grid files are described below.

Plots

The contractor provided plots for each survey area of the apparent resistivity data at each frequency and plots of the IGRF-corrected total magnetic field (described above). These plots are given as PDF files in ***PLOTS*** directory (table 1). Note that for the apparent resistivity, the color scales have been stretched for each frequency to emphasize the maximum (red) and minimum (blue) range. Consequently, the color scales are not directly comparable between maps with different frequencies. The plots were made from the data as gridded by the contractor using methods described in the project report (Appendix II).

The USGS has created plots of the gridded data described above as geo-referenced tiff format (geotiff) plots. The projection used for the geotiff plots is the same as the grids, NAD83 UTM14N. The geotiff images have been made as both flat color (clr files) and as color shaded relief images(csr). The color scale for all of the resistivity maps is the same and given as the *RES.jpg file. The color scale shows high resistivity as warm colors (reds) and low resistivity as cool colors (blues). Color scales for the magnetic and digital elevation maps are also given as bitmap .jpg files.

Digital Flight Line Data

The flight line data for each area is given in the directory ***LINEDATA***. The files are given in ASCII format with column headings as described in the 'readme file'. The contractor's report in Appendix II also describes the digital flight line data.

Acknowledgments

The authors would like to thank Jesse Korus and Dana Divine of the Lower Platte South Natural Resources District for their guidance and effort as the ENWRA Project Coordinators. The authors would also like to thank Igor Sram of Fugro Airborne Surveys for his insight and technical support with organizing, collecting, processing, and interpreting the HEM data. We also wish to recognize Susan Olafsen Lackey, Paul Hanson, Matt Joeckel and Matt Marxsen, of Conservation and Survey Division, University of Nebraska-Lincoln for the test hole and geologic interpretation. Special recognition goes to the ENWRA project partners; Lower Platte North, Lower Platte South, Lower Elkhorn, Nemaha, Lewis and Clark and Papio-Missouri Natural Resources Districts, and the Department of Natural Resources for supporting this project.

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APPENDIX I: 2008 Geological Society of America Annual Meeting Poster

Preliminary Results of Hydrogeological Framework Studies of Surface Water - Ground Water Systems in Eastern Nebraska Using Airborne and Ground Geophysics

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The poster is given in ***REPORT*** directory as pdf file ENWRA_GSA_20071015.pdf.

APPENDIX II: Fugro Geophysical Report

The contractor's report (07026rep.pdf) is given in the ***REPORT*** directory.