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THE ELECTROMAGNETIC INTEGRATED DEMONSTRATION AT THE IDAHO NATIONAL ENGINEERING LABORATORY COLD TEST PIT

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ABSTRACT

The electromagnetic integrated demonstration (EMID) is a baseline study in electromagnetic (EM) exploration of the shallow subsurface (< 10 m). Eleven distinct EM systems, covering the geophysical spectrum, acquired data on a grid over the Idaho National Engineering Laboratory (INEL) Cold Test Pit (CTP). The systems are investigated and evaluated for the purpose of identifying and reviewing existing geophysical characterization instrumentation (commercial and experimental), integrating those technologies with multi-dimensional interpretational algorithms, and identifying gaps in shallow subsurface EM imaging technology. The EMID data, are valuable for testing and evaluating new interpretational software, and developing techniques for integrating multiple datasets. The experimental field techniques shows how the acquisition of data in a variety of array configurations can considerably enhance interpretation. All data are available on the world wide web (http://vetem.lbl.gov). Educators and students are encouraged to use the data for both classroom and graduate studies. The purpose of this paper is to explain why, where, how and what kind of data were collected. It is left to the reader to assess the value of a given system for their particular application. Information about the EMID is organized into two general categories: survey description and system evaluation.

INTRODUCTION

Electromagnetic (EM) techniques have been successfully used in exploration of the shallow subsurface for many years (Ward, 1990). Many problems in environmental characterization can be successfully solved with simple anomaly mapping techniques, however more complex problems require high resolution sounding methods and corresponding interpretational techniques. To solve the latter category of problems, advances are needed in both data acquisition techniques and interpretational approaches. In order for progress to proceed in an efficient manner gaps in existing technology must be identified. A baseline study identifies holes in the measurement spectrum, and supplies an extensive dataset for the development and testing of interpretational techniques and methods of integrating related datasets acquired on the same grid.

There are many disconnects between the optimal way to collect and the optimal way to interpret EM data. For example, it is relativity easy to collect dense, broadband data in the time domain, but interpretational approaches are limited due to mathematical difficulties. Frequency domain data tend to be temporally sparse and data acquisition time consuming, but interpretational techniques are more highly developed, because of the mathematical elegance of the frequency domain. In forward numerical modeling, either finite-difference, finite-element, or integral equation techniques, the most expensive step is creating the earth (discretization), then exciting the earth (transmitters) and the lastly computing the response (receivers). In contrast, it is often the receiver is the most demanding component of a data acquisition system. General access of a comprehensive and

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comparable dataset acquired by both theoreticians and field practitioners is a step in closing these gaps.

Eleven systems, filling the geophysical sounding range from ground penetrating radar (GPR) to low-frequency electrical geometrical techniques are represented in this study as depicted in Figure 1. The terms high frequency and early time imply that both conduction and displacement currents are appreciable in the measurement range, while low frequency implies that displacement currents are negligible (the quasi-static approximation). Standard methods were included in the study along with new prototype systems. A list of contacts for each system participating in the EMID is available in the Table 1. At least one of the authors of this paper was present in the field for all eleven surveys.

Two goals of the study are (1) identifying methods for acquiring data that can support multi-dimensional inversion, and (2) that the data will be interpreted many times by different individuals and groups. Interpretation of the data is not the intention of this paper, but inversion results are an important part of the overall study: Alumbaugh and Newman (1997) are performing multi-dimensional inversion of data acquired with the loop-loop Slingram frequency domain method; Frangos, (1997) has been working with colleagues on the induced polarization data; and Tezkan and Zacher (1997) are performing 2-D inversion on data collected with the plane wave (magnetotelluric) method utilizing radio sources . Tests with the application of 1D inversion on the loop-loop data resulted in a model showing conductive bedrock at depth instead of a shallow conductor — a classic response for the case of 1D inversion over a highly 3D target. In contrast a 2D approximation is quite an effective interpretation approach in a 3D environment.

THE INEL COLD TEST PIT

The INEL CTP was built to demonstrate characterization, stabilization and retrieval technologies for the remediation of buried waste sites (Watson, 1994). The CTP is located just outside the Radioactive Waste Management Complex on the Snake River plain in south central Idaho. Flood basalts compose bedrock at a depth of 20-30 feet from the surface; depth to groundwater is in excess of 500 feet. The CTP was excavated and then backfilled with soil from another area., and there is a detectable contrast in electromagnetic properties of the native soil and the imported soil (Pellerin, et al, 1993). Variable cap material is 1-2 meters thick. The majority of the CTP was built in 1988 and a calibration cell of small targets was added to the north of the main CTP in 1992. The site has been graded relatively flat, but topography across the survey area on the order of 0.5 meters does exists. The site was chosen by the Department of Energy office responsible for the funding of this project. The excavation and backfill of the cells between the primary grid and the calibration cell, typical activities at a waste site, was underway during the EMID. Full, detailed excavation of the site is planned for groundtruth and closure of the project.

The EMID survey area is shown in Figure 2. The EMID grid covers the calibration cell to the north and the three southern cells containing: stacked cardboard and metal drums, boxes full of metal and asphalt, and the large object pit with a variety of objects. The mix of cardboard and metal drum was used to simulate a 30 to 40 year old waste pit. The stack of drums varies from 1 to 5 drums deep from west to east respectively. Four profile lines over the box and drum cells, called the primary lines, were used by all participants. A 2-D grid over the large object pit and the calibration cell were used when appropriate. Line spacing is five feet and station spacing along the lines varies with each system, but is staked every 5 feet. Data over the large object pit and calibration cell were acquired with north-south and east-west lines to include both polarization modes of excitation.

EMID DESCRIPTION AND EVALUATION

The physical and qualitative parameters that describe the survey are summarized in Table 2, while Table 3 is an attempt to summarize the more subjective qualities of the systems. Properties such as depth of investigation involve many parameters, (host conductivity, target size and conductivity) and cannot be reduced to a number as can be station spacing. However we can assess the performance relative to expectations.

Ground Penetrating Radar

Due to unfavorable surface conductivities and high magnetic losses of the soils, the GPR method is ineffective at the INEL. Different antennas and array configurations were used with little success. The method was well represented by Sensors and Software, and the results do not reflect the method or the system, as GPR is often problematic where conductive soils are present, such as clay caps over waste pits.

Early Time — High Frequency

Two systems should enjoy special attention for attempting to fill the critical gap between GPR and traditional diffusive EM: the high frequency ellipticity (HFE) system (Sternberg and Poulton, 1994, 1996) and the very early time EM (VETEM) system (Pellerin et al., 1994, 1995; Wright et al., 1996). A fundamental problem in working in this range is the earth loads the transmitter changing the calibration of the system and hence the ability of quantified interpretation of the data. The HFE group took an empirical approach by training neural networks with data acquired at a test field facility for data interpretation. The ellipticity parameterization reduces calibration problems and the neural network incorporates the system response into the solution, but problems can occur when the network encounters a dataset for which it is not trained. The VETEM team took a theoretical approach to interpreting data. Data were collected at the CTP with the VETEM instrument, but the system is still under development and the outcome of this approach is not yet known. The theoretical approach adopted by the VETEM team demands well calibrated data, so the VETEM system may only by useful as an anomaly hunter.

Time Domain

Time domain methods are represented by a metal detector (Geonics EM-61), one of the most popular and widely-used geophysical tools, and a broad-band, three-component (3C) receiver system (Zonge NanoTEM). The metal detector worked quite well for locating metallic objects, as designed, and contouring of the data is a rapid and appropriate approach. Although 3C data are not routinely collected, much information is in the horizontal components and interpretation of the broad-band 3C data is a goal of future work. Inspection of the raw data show that outside of the waste there is about a decade and a half of signal before the transient decays to noise, whereas there is over four decades of signal over the waste areas, indicating that the majority of the signal is coming from currents confined to the conductive waste. It is not clear whether the depth to host beneath the waste can be recovered from the data. Both in- and out-of-loop data were collected.

Loop-loop Frequency Domain

Slingram techniques encompassed systems with both fixed (Geophex GEM2) and variable (Apex Parametrics MaxMin I) coil separation. A constant separation between the transmitting and receiving loops is critical for accurate measurement of the in-phase component, because of the large contribution of the free-space component. The use of a rigid, fixed-separation system alleviates the problem of exactly locating the coils, but it also eliminates the powerful geometric sounding parameter. We found we could not locate the coils with a variable separation accurately enough for in-phase measurement with small separations.

Surveys over the calibration cell clearly illustrate the difference between detecting a metallic object and a good conductor. The small metallic objects on the north side of the calibration cell were easily detected, while the more subtle conductive features at the south end of the calibration cell were essentially invisible.

Plane Wave

Two plane wave and techniques are included in the EMID: radio magnetotellurics (Univ. of Koln, RMT) and controlled source audio magnetotellurics (EMI/Geometrics CSAMT). Plane wave techniques are the most highly developed EM methods in terms of interpretation, hence 2D inversion algorithms are not only available, but comparison of various codes is possible. The RMT method can be limited by the lack of available transmitting signal in remote areas such as the INEL. Only four frequencies were being broadcast from a transmitter on a butte due east of the CTP. Fortunately the frequencies were well spaced and the excitation mode was optimal. The CSAMT data contains the lowest frequengy, or equivalent late time, data and the existence of bedrock beneath the waste is discernible in the phase data.

Electrical

Geoelectric methods have always been a basic tool in geophysical exploration and this is also the case in the EMID. A new capacitive electric field system (Geometrics OhmMapper) was tested and data were compared to that collected with a traditional galvanic system (Auriga) with excellent results. The OhmMapper results had a consistent upward bias when compared to the Auriga measurements and the system is very sensitive to coupling when small dipole antenna (2.5 m) are used, but data acquisition rates are very rapid. IP inversion results are spectacular, while the resistivity results were not as satisfying. A rapid IP system would be an important contribution to the toolbox of geophysics techniques for exploration of the shallow subsurface.

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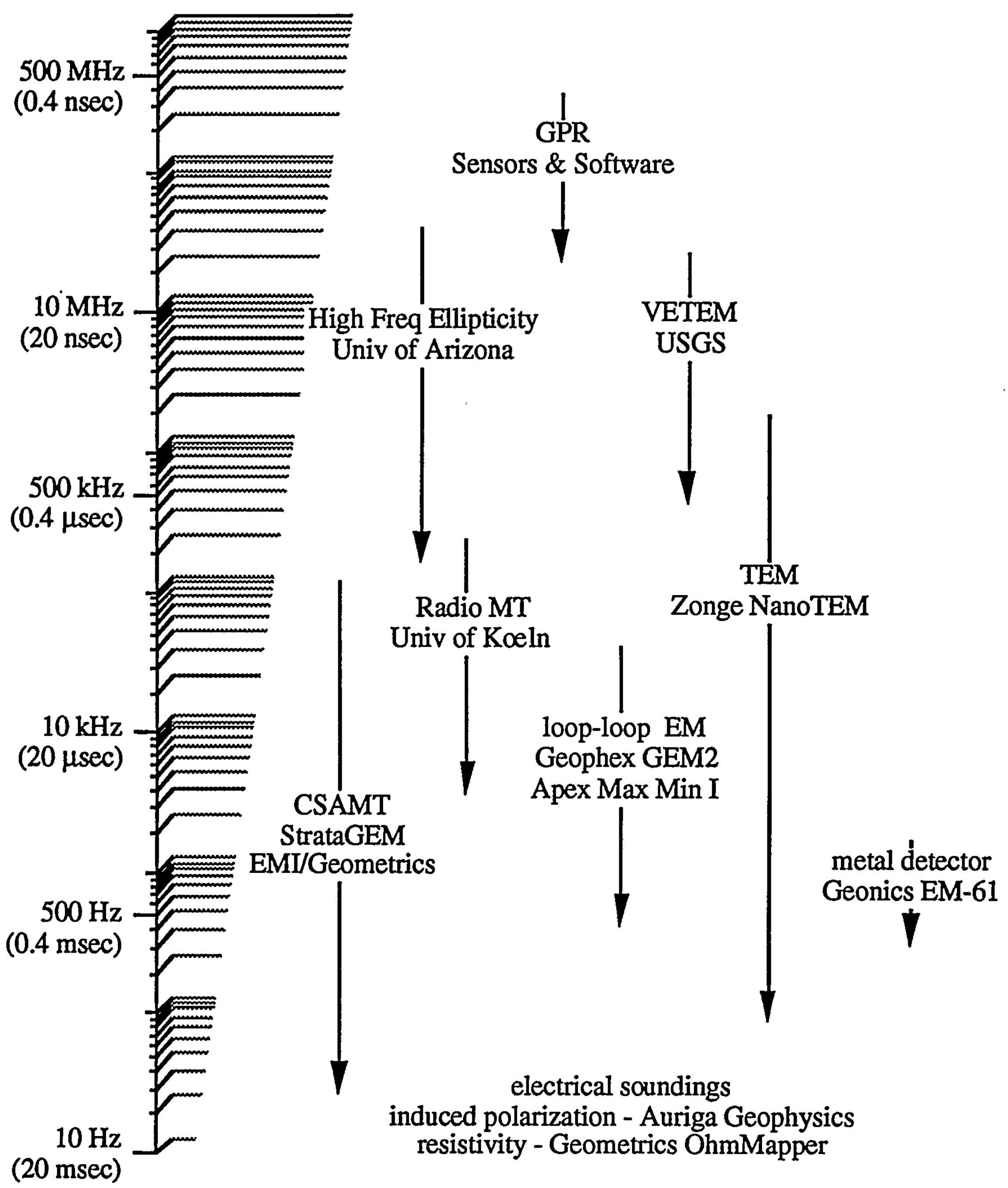

THE EMID SPECTRUM

Figure 1. The spectrum of the geophysical measurements acquired at the EMID at the INEL.

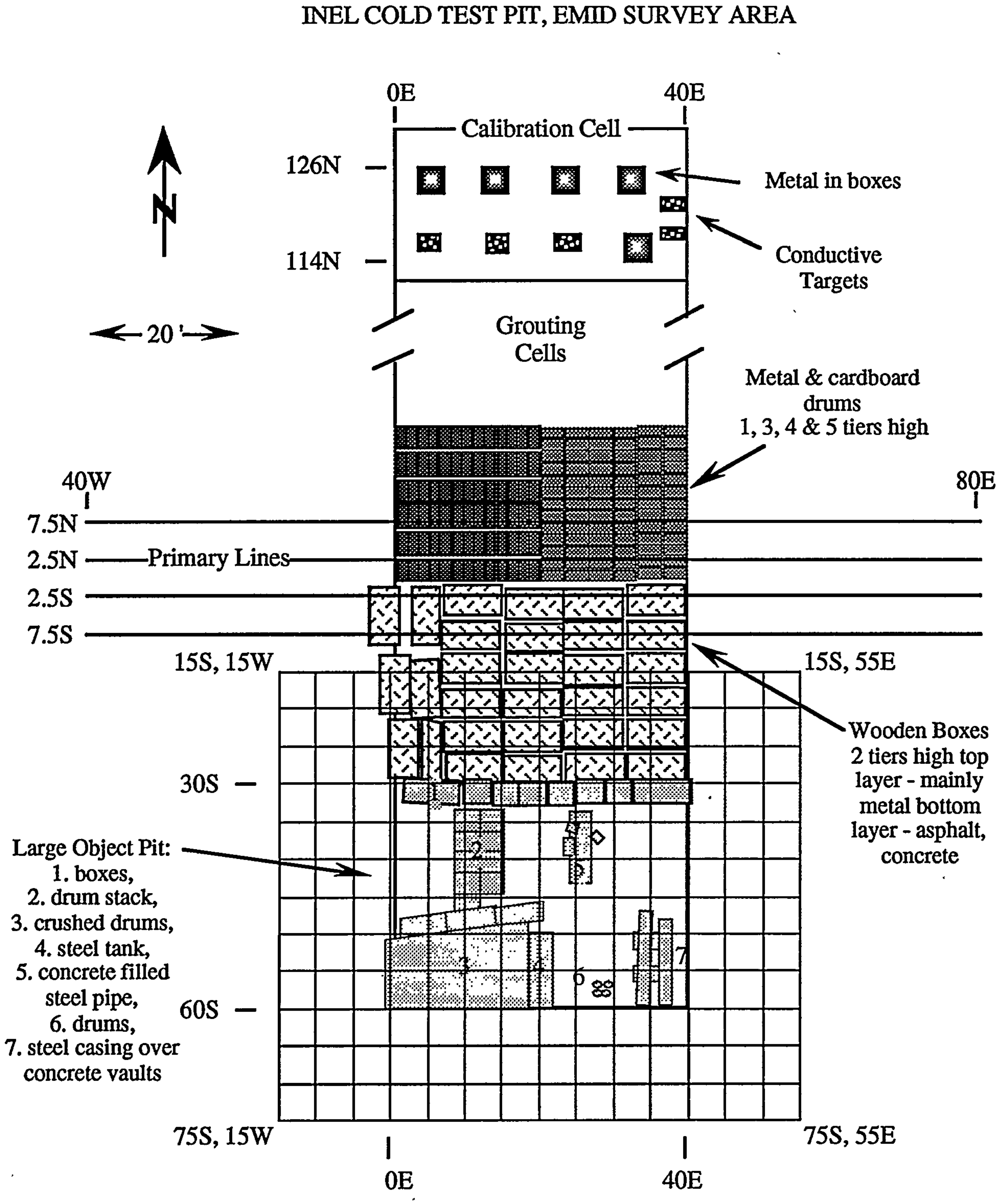

Figure 2. A schematic of the INEL CTP. The 8' waste seam is covered with about 4-5' of a soil cap. Bedrock (basalt) is at 20-30'. Excavation of the CTP is planned for groundtruth.

EMID PARTICIPANT LIST

Method	Instrument	Contact
ground penetrating radar	Pulse Echo Sensors and Software	Peter Annan/Steve Cosway Tel: (905) 624-8909 Fax (905) 624-6395 apa@sensoft.on.ca
very early time EM	VETEM U.S. Geological Survey	David Wright / Victor Labson Tel: (303) 236-1381/1312 Fax (303) 236-1409 dwright@usgs.gov
time-domain EM metal detector	Super EM-61 Geonics Ltd.	Duncan McNeill / Mike Capalano Tel: (905) 670-9585/9580 Fax (905) 670-9204
time-domain EM (TEM)	NanoTEM Zonge Engineering	Ken Zonge / Norm Carlson Tel: (520) 327-5501 Fax (520) 325-1588 ken@zonge.com
high-frequency EM	High Frequency Ellipticity System University of Arizona	Ben Sternberg Tel: (602) 621-2439 Fax (602) 621-8330 bks@ccit.arizona.edu
low-frequency loop-loop with fixed separation	GEM2 Geophex Ltd.	I.J. Won Tel: (919) 839-8515 Fax (919) 839-8528 ijwon@nando.net
low-frequency loop-loop with variable separation	MaxMin I Apex Parametrics	Tapio Varre Tel: (905) 852-5875 Fax (905) 852-9688
mid-frequency plane wave 1	Radiomagnetotelluric (RMT) Universität zu Köln	Bülent Tezkan Tel: +49-221-470-3386 Fax: +49-221-470-5198 tezkan@geo.uni-koeln.de
low-frequency plane wave 2	Stratagem CSAMT Electromagnetic Instruments Inc./ Geometrics	Jeff Johnston ABnormal Geophysics Tel/Fax: (510) 704-9659 abnormal@netcom.com
electrical resistivity	OhmMapper Geometrics	Dick Wold Tel: (408) 734-4616 Fax: (408) 745-6131 rwold@geom.geometrics.com
induced polarization	IP Auriga Geophysics	Will Frangos Tel: (510) 527-5643 Fax (510) 642-3805 willy@csem.lbl.gov

Table 1. A summary of methods, instruments and contacts. The frequency modifiers, 'low', 'mid' and 'high', refer to whether displacement currents are neglected (low & mid) or included (high/early time).

SURVEY DESCRIPTION

System	frequency time range	array	measured quantities	data density along line	production rate for a primary line	field note
Sensors & Software Pulse Echo GPR	25, 100 & 450 MHz, 32-2048 ns	common offset = 1m common midpoint	voltage	co = 0.2 m cm = 0.4m	5 min	hot and windy
USGS VETEM	25 - 70 MHz 0-1900 ns sample rate = 2 ns	HCP & null 1 & 2 meter antenna separation	magnetic fld implemented - voltage also available	10 cm	15 min	cold and windy
Geonics Super EM-61 metal detector	0.134 to 0.750 ms (10 samples)	VMD -70cm vertical antenna offset	transient decay in volts	10 cm	5 min	cold and windy
Zonge NanoTEM	1.2 microsec to 2.5 millisec	10m vmd tx, 6 x 6 grid of 1 m 3 comp rx / tx	transient decay in volts	1 m	1 hour	hot & windy
Univ. of Arizona HF ellipticity	30 kHz to 32 MHz	VMD tx 3 comp rx 2 - 8 m separation	3 component voltage reduced to ellipticity	1/4 to 1/2 coil separation	1 hour	cold and windy active construction
Geophex GEM2	0.5 to 56 kHz	VMD/HMD coplanar, 1.67 m separation	real & quad ppm of free space response	2.5 feet	5 min	cold and windy
Parametrics Apex MaxMin	0.44 to 56 kHz	VMD coplanar, 15, 30 & 60' separations	real & quad % of free space response	5' @ 15 & 30' sep 10' @ 60'	1 hour	hot and windy
Univ. of Köln RMT	24, 60, 120 & 200 kHz	1 m E-W elec dipole, N-S mag field	apparent resistivity & phase from E_{ew} and H_{ns}	2.5' on primary lines, 5' on LOP	1.5 hour	rain, snow and high winds
EMI and Geometrics Stratagem CSAMT	10 Hz to 72 kHz	orthogonal 15' dipoles and mag coils	Ex, Ey, Hx and Hy	15 feet	1 hour	rain, snow and high winds
Geometrics OhmMapper	16 kHz (capacitive)	5 & 10 m di-dipole profile	voltage	5 feet	10 min	hot and windy
Auriga IP	1 Hz, .01 to 10 Hz on L7.5N	2 & 5 m di-dipole soundings	volts/amp and milliradians	dipole spacing to 6th separation	3 hours	trip 1 - stormed out trip 2 - hot and windy

Table 2. A summary of the survey parameters used by the various systems participating in the EMID. Production rates are for one of the primary grid lines 120 feet in length, not including set-up time.

SYSTEM EVALUATION

system	depth of investigation	noise level	easy of use	level of interpret	level of development	comments
Sensors & Software Pulse Echo GPR	< 1 m	dr = 168 db, repeatability good	2 person trained crew, variable terrain	visual inspection of sections	commercial surveys & instrument available	GPR problematic at INEL
USGS VETEM	0-2 m	dr = 80db, 0.5% tx variation	2-3 person - 1 highly trained, truck/winch	not developed	research proto-type	system under development
Geonics Super EM-61 metal detector	5 cm to 5 m		1 trained operator, 0.5 m clearance	profile or contour data	commercial surveys & instrument available	excellent metal detector
Zonge NanoTEM	< 20m	dr=190 db, repeatability < 2% for early time	2-3 person trained crew, all terrain	profile/time contour/time 1D inversion	commercial surveys & instrument available	extremely dense dataset - three component
Univ. of Arizona HF ellipticity	< 3 m	dynamic rg volt = 120db ellip = 60db, repeat < 1%	2-3 person trained crew, 2 ATVs	neural network, inversion	engineering proto-type	available for selected sites
Geophex GEM2	< 5 m	instr = 1ppm noise, repeatability 50-200 ppm	1 trained operator, all terrain	contour field data	commercial surveys & instrument available	rapid anomaly mapper
Apex Parametrics MaxMin	1/4 to 1/2 coil separation	repeatability quad 0.05 to .4%	2 person trained crew, all terrain	profile inspection, 3-D inversion	commercial instrument available	problematic to acquire in-phase data
Univ. of Köln RMT	skin depth estimates	repeatability rho < 2% pha < 0.5°	2 person - 1 trained oper, all terrain	MT pseudo-sections, 2D inversions	undergoing commercialization	limited tx available
EMI and Geometrics Stratagem CSAMT	skin depth estimates	dr=18bit a/d, data variance rho +/- 10% pha +/- 2.5°	2 persons- 1 trained oper, all terrain	MT pseudo-sections, 2D inversions	commercial surveys & instrument available	work stoppage limited field time
Geometrics OhmMapper	1/4 to 3 dipole lengths	repeatability < 3%	2 person crew, all terrain	pseudo-section, inversion	proto-type system	coupling problems with 2.5 m dipole
Auriga IP	1/4 to 3 dipole lengths	instr<0.1 mV repeatability rho < 5% pha < 2 mR	2-4 person 1 trained oper, all terrain	pseudo-section, inversion	commercial surveys & instrument available	labor intensive

Table 3. A summary of the subjective factors used for evaluation of the various systems participating in the EMID. Depth of investigation estimates are a combination of theory and experiences at the CTP. Noise is reported in terms of data repeatability and/or dynamic range (dr), drift or instrument noise.