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<p>This report documents an investigation of the utility of electromagnetic (EM) induction as a technique for measuring sea ice thickness. A computer code was used to calculate the theoretical response of an existing EM induction geophysical tool, the Geonics Ltd. EM-31D, to sea ice thickness. The code also was used to evaluate the expected effect on the thickness measurements of ice conductivity, seawater conductivity, instrument height, and water depth. The instrument was taken to the Arctic Ocean to test its actual response to ice thickness, including the effect of coils orientation and instrument height.</p> <p>The measurements made by the instrument generally corresponded well with theory. Correspondence for the vertical coplanar coils configuration was better than for horizontal coils configuration. For the ice thicknesses</p> <p align="right"><i>(Continued)</i></p>			
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tested, 0.10, 0.85 and 1.68 m, the instrument output for vertical coils deviated from physical measurements by an average of 0.06 meters. Even greater accuracy would be possible if on-ice calibration procedures were developed.

It is concluded that EM induction offers a practical and rapid method of measuring sea ice thickness. Modifications to the instrument to allow real-time ice thickness and water conductivity readouts are described. The application of this technology to air-droppable buoys is discussed.

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## 1. INTRODUCTION

This report documents an investigation of the utility of electromagnetic (EM) induction as a technique for measuring sea ice thickness. The work was conducted by Flow Research Company for the Defense Advanced Research Projects Agency (DARPA) as part of a Phase I Small Business Innovation Research (SBIR) project. The proposal for this work was submitted in response to Department of Defense (DOD) Solicitation 85.1, DARPA Topic 9, entitled: "Remote Sensing of Sea Ice Thickness". The solicitation states, "A reliable means is needed for estimating sea ice thickness from remote sensing platforms such as aircraft, satellites, and data buoys."

For almost all offshore Arctic military operations and scientific investigations, ice thickness is a major parameter of interest. The most commonly used technique of ice thickness measurement still remains the time-honored (and time-consuming) method of measuring the depth of a hole drilled through the ice.

A rapid and remote technique of ice thickness measurement would facilitate numerous military missions and activities in the Arctic. These include:

- Delivery of weapons through the ice cover, from above or from below
- Identification of safe, on-ice, aircraft landing sites for rescue operations or equipment deployment.
- Evaluation of the suitability of a region for on-ice encampments for scientific investigations.
- Identification of thin ice regions to permit surfacing by submarines.
- Characterization of the under-ice acoustic environment.
- Monitoring of ice growth over time.

The primary commercial application for a remote ice thickness sensor would be to assist oil companies in the exploration for and production of hydrocarbons in offshore Arctic regions. They need thickness measurements to accurately predict ice loads on offshore structures and to verify thickness for over-ice transport. It is estimated that American and Canadian oil companies have spent over 40 million dollars over the past ten years for the development of methodologies to measure ice thickness or to gather field data from which ice thickness can be inferred.

The original intent of this work was to evaluate EM induction as a technique for the remote sensing of sea ice thickness from an aircraft. In pursuit of this objective, a commercially-available, man-portable, geophysical instrument was to be used from the surface of Arctic ice to test the potential of the concept. In this way the technique could be tested in a practical way and at low-cost. Field test results, in conjunction with theoretical calculations, would then be used to develop a recommended configuration for airborne use.

After the project was authorized, it was found that an evaluation of an existing airborne EM induction system was being carried out by Mr. Austin Kovacs at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) under sponsorship of the U.S. Navy. Rather than duplicate that work, the emphasis of this effort was shifted from an airborne sensor to a surface-based sensor suitable for use by an individual on the ice surface or by air-droppable buoy. The use of the man-portable geophysical instrument to evaluate the technique of ice thickness measurement by EM induction was retained.

The approach taken in this project included both theoretical computer analyses and field testing. A computer code was used that calculates the theoretical response of an existing geophysical instrument to multi-layered materials. A simple two-layered model of the instrument response to sea ice thickness was found to be useful. The first layer was ice of specified thickness and conductivity. The second layer was seawater of specified conductivity and infinite depth. The computer code was also used to evaluate the expected effect of ice conductivity, seawater conductivity, instrument height, and water depth on the response of the instrument. The geophysical instrument was then taken to the Arctic and its actual response to ice thickness was tested. The theoretical response and the actual response of the instrument were then compared.

This report summarizes the Phase I effort. Section 2 provides a description of previous related work. Background information is provided in Section 3. The geophysical survey tool used in the program is described in Section 4. The experimental procedures and results, including theoretical calculations and arctic field measurements, are described in Section 5. The results of the program are discussed in Section 6. Conclusions and recommendations for future work are contained in Sections 7 and 8, respectively.

## 2. PREVIOUS WORK

Remote measurement of sea ice thickness has been the subject of numerous research efforts. Techniques that have been investigated include passive and active microwave imaging, infrared imaging, acoustic sounding, seismic techniques, and pulsed radar profiling. Microwave and infrared imaging systems currently provide only very coarse thickness estimates. The utility of acoustic sounding systems is limited by the soft and variable nature of the bottom (skeletal) ice layer, which provides a poor reflective surface. Additionally, internal layering above the ice-water interface may provide erroneous readings.

Pulsed radar profiling has been tested in a number of government and proprietary research and development programs. It has proved accurate in sounding the freshwater ice of glaciers and ice shelves (e.g., Morey, et al, 1984) and lakes and rivers (e.g., Chizhov, 1977). Because of the more complex nature of sea ice, the measurement of sea ice by this method has not been as successful. The system output must be interpreted and evaluated carefully by the operator. Even with this evaluation, it is not always possible to accurately assess ice thickness.

To facilitate the rescue of airmen downed on ice-covered seas, the Canadian government sponsored a program to develop a buoy system to measure ice thickness (Langleben, Pounder and Becker, 1971). The buoy was to be dropped by the rescue aircraft to verify that ice thickness was sufficient for landing. The investigation employed a seismic technique in which the ice sheet was excited by air-dropped explosives. The frequency of the air-coupled flexural ground wave was measured by the buoy. This frequency was a function of the ice thickness.

Some studies have been made of the use of ground electromagnetic (GEM) induction techniques for ice thickness measurements. Keller and Frischknecht (1966) made measurements of arctic ice approximately 5 meters thick using a coil separation on the order of 100 meters and a primary field excitation in the audio frequency range. Because the system was not absolutely calibrated, readings were taken at a number of frequencies and a curve matching procedure was used to interpret the results. On the average, their ice thickness measurements appeared to be accurate to about 10 percent.

A more recent GEM study conducted by Sinha (1976) involved a limited field test to determine the ice thickness measurement ability of a light-weight, portable, high-frequency electromagnetic prospecting system. Sinha used two



types of commercial equipment, each with a coil spacing of about one meter. One system had an operating frequency of 15 kHz and the other 8 kHz. Sinha encountered calibration problems with the equipment, and only the vertical gradient of the system response could be properly measured. The ice thickness was determined from this quantity. Under favorable conditions, accuracies of a few centimeters could be obtained for ice 25 to 75 cm thick.

An early version of the Geonics EM-31 ground conductivity meter was evaluated by Hoekstra, et al. (1979) as a tool for ice thickness measurement. This tool operated at a frequency of 39.2 kHz. They used only the in-phase response of the instrument to indicate ice thickness. From limited testing over ice in a brine tank, they concluded that the instrument had good potential for measuring the thickness of smooth pack ice. They obtained unreliable results over ridged ice at an offshore Arctic site. The poor field results were attributed to seawater-filled voids in the ice rubble.

A related use of an electromagnetic induction system was recently demonstrated by Zollinger, Becker and Morrison (1984). They used a commercially available, fixed-wing aircraft, induced pulse transient (INPUT) system to measure nearshore oceanic bathymetry. The system was used over a 17-mile flight path under which the water depth ranged from 0 to 40 meters. Flight altitude ranged from 550 to 750 feet and the flight velocity was 110 knots. When the depth estimates derived from the AEM system were compared with those provided on local bathymetric charts the average absolute error was about 2 meters.

Many investigators have used D.C. and audio frequencies to study the conductivity of sea ice. In situ measurements using the Wenner array technique were done by Fujino (1960) and Fujino and Suzuki (1963), and more recently by Buckley et al. (1986). A D.C. Schlumberger array was used by Thyssen et al. (1974). All these techniques are slow and labor-intensive. A VLF technique used by McNeill and Hoekstra (1973) enabled more rapid acquisition of data, but the accuracy of the data was not high.

### 3. BACKGROUND

This section contains background information relating to the measurement of ice thickness through electromagnetic (EM) induction means, including a summary of the use of EM geophysical survey systems, a brief description of the conductivity of seawater and the physical properties of sea ice, and details of the operation of electromagnetic induction systems for sea ice thickness measurement.

#### 3.1 A Summary of the Use of Electromagnetic Induction Geophysical Systems

Ground-based electromagnetic (GEM) and airborne electromagnetic (AEM) induction geophysical systems have been in commercial service for over thirty years. The primary early use of these systems was geophysical exploration to remotely detect anomalous conductors in the soil. As more quantitative interpretation techniques have been developed, some systems have been used for mapping ground conductivity. Some of the past applications for these systems included:

- General geological mapping
- Mapping conductive mineral deposits
- Delineating regions of permafrost
- Locating gravel deposits
- Mapping saline intrusions
- Mapping pollution plumes in groundwater

Recently it has been shown that airborne electromagnetic (AEM) induction can be used to measure coastal bathymetry. The feasibility of using existing AEM survey equipment for this purpose was shown by Morrison and Becker (1982) in a report submitted to The Office of Naval Research (ONR). The results of an experimental evaluation of the technique are reported by Zollinger, Becker and Morrison (1984).

These systems consist of a primary transmitter coil and a secondary receiver coil located a short distance away. The transmitter coil is energized with an alternating current. This creates a time-varying magnetic field which induces small currents in the earth. These currents generate a secondary magnetic field which is sensed by the receiver coil. The secondary magnetic field is a function of intercoil spacing, the operating frequency, and the conductivity of the ground. Additional information concerning the theory of operation can be found in Telford et al. (1976).

### 3.2 The Conductivity of Seawater and the Physical Properties of Sea Ice

Seawater conductivity is a function of its salinity and temperature. For most offshore areas, the under-ice temperature will be at the freezing point of the seawater which is defined by its salinity. For the expected range of under-ice salinities, 25 to 35 ppt, and water temperature, between -1 and -2 degrees Centigrade, the conductivity of the seawater will vary from about 2 to 3 siemens/meter (siemens/m (S/m) is equivalent to mho/m).

A useful set of sea ice conductivity measurements were made by McNeill and Hoekstra (1973). Multiyear ice was found to have low conductivity, 0.1 mS/m, at the upper surface increasing to about 30 mS/m at the bottom. Even for the lower surface, the conductivity is two orders of magnitude less than seawater.

First-year ice is more highly conductive. Using the Wenner array technique in Antarctic first-year sea ice, Buckley et al. (1986) measured average conductivities ranging from 5 mS/m to 20 mS/m. They found a thin conductive layer at the surface of the ice and higher conductivities near the bottom surface of the ice.

### 3.3 Sea Ice Thickness Measurement by Electromagnetic Induction

An electromagnetic induction system measures sea ice thickness by sensing the distance from the instrument to the surface of the conductive seawater. In the case of a ground electromagnetic (GEM) induction system resting on the ice surface, the measured distance is the ice thickness. For a GEM system held above the ice surface, the distance from the ice surface to the sensor must be known. The sensor-to-ice distance is then subtracted from the sensor-to-seawater distance to obtain ice thickness. In addition, the EM system can also be used to measure the conductivity of seawater under the ice cover.

To easily and accurately measure ice thickness, the conductivity of the ice cover must be much lower than that of the underlying seawater. If the ice conductivity is sufficiently low relative to the seawater conductivity, it can be ignored, and accurate measurements can be made without knowing the actual ice conductivity. An ice conductivity that is high relative to the water conductivity can be a source of ice thickness measurement error unless the conductivity is known and is used to correct the thickness values.

Becker et al. (1983) investigated the theoretical sensitivity of airborne electromagnetic (AEM) ice thickness measurements to errors in estimates of ice conductivity and salinity. They considered seven possible conductivity models

of 2-meter thick sea ice. These models included ice of no conductivity, uniform conductivity of 0.03 S/m and 0.01 S/m, and four gradational models of low conductivity at the surface increasing with depth. They then calculated the effect of these differences on thickness measurements by a proposed AEM system. The greatest error, 23%, was given by ice having a uniform conductivity of 0.01 S/m. Other errors ranged from less than 1% to 7%.

The effect of seawater conductivity variations on the same proposed AEM system was also calculated by Becker and Morrison. They considered an ice thickness of 2 meters with a uniform conductivity of 0.03 S/m. Errors in ice thickness for seawater of 1, 2, 3 and 4 S/m ranged from 1% to 7%.

The above results show that electromagnetic induction measurements of ice thickness are sensitive to conductivity variations in the ice cover and the underlying seawater. However, reasonable estimates of both parameters can be made for a given region and good estimates of ice thickness can be made.

#### 4. DESCRIPTION OF THE EM-31D

An EM-31D ground conductivity meter (shown in Figure 1) was used to evaluate the feasibility of measuring ice thickness by EM induction means. The EM-31D is made by Geonics Ltd. of Mississauga, Ontario, Canada. It is a ground-based instrument designed to be carried by a single person to conduct surveys of apparent ground conductivity. The EM-31D measures the in-phase and quadrature-phase components of the magnetic field that it induces in the surrounding medium. Each of these is expressed as the magnitude of the induced field,  $Z$ , divided by the magnitude of the primary field,  $Z_0$ .

For operation over terrain of normal low conductivity, only the quad-phase component is required to measure the apparent conductivity. This is the typical operating mode of the instrument for ground surveys. Under these conditions, the secondary magnetic field is directly proportional to the ground conductivity and the phase of the secondary magnetic field leads the primary magnetic field by 90 degrees. Over more highly conductive materials, such as seawater, both the quad-phase and the in-phase components are necessary to obtain apparent conductivity.



Figure 1. Geonics EM-31D Conductivity Meter

Two output modes are possible with the EM-31. The unit has a single meter which reads in units of apparent conductivity. A switch permits the selection of either in-phase or quad-phase response. The unit also has an auxiliary connector which provides simultaneous voltage outputs for in-phase and quad-phase response. The apparent conductivity and the voltage outputs can be related to  $Z/Z_0$  through simple algorithms.

The normal configuration of the transmitter and receiver coils of the unit is horizontal coplanar. This produces vertical magnetic dipoles. By laying the unit on its side, one obtains vertical coplanar coils, producing horizontal dipoles. Measurements are rapid, taking 1 to 2 seconds each. Additional characteristics of this instrument are described in Table 1.

**TABLE 1. SPECIFICATIONS OF THE EM-31D GROUND CONDUCTIVITY METER**

Measured Quantity:	Apparent conductivity in mmhos per meter or in-phase and quad-phase components of received magnetic field in parts per million of primary field.
Primary Field Source:	Self-Contained Dipole Transmitter
Sensor:	Self-Contained Dipole Receiver
Intercoil Spacing:	3.66 meters
Operating Frequency:	9.8 kHz
Power Supply:	8 Alkaline "C" cell batteries
Measurement Precision:	+ 2% of full scale
Measurement Accuracy:	+ 5% at 20 mmhos/meter
Noise Level:	less than 0.1 mmhos/meter
Dimensions:	
Boom-	4.0 meters extended, 1.4 meters stored
Console-	24 x 20 x 18 cm
Weight:	9 kg

## 5. EXPERIMENTAL

This section describes the theoretical calculations made to characterize the expected response of the EM-31D to sea ice thickness. It also describes the methodology and results of the field program that was conducted to test the EM-31D response to Arctic sea ice.

### 5.1 Theoretical Response of EM-31D to Ice Thickness

The response of the EM-31D to sea ice thickness was calculated using an existing geophysical computer code, PCLOOP, provided by Geonics Ltd. This code calculates the electromagnetic inductive response of the tool to multi-layered materials. The output of the code was checked against the tabulated data of Frischknecht (1967) to ensure its accuracy.

The code first was used to determine the expected effect of ice conductivity on ice thickness measurements. A two layered model was assumed. The upper layer is ice of specified thickness and conductivity. The second layer is seawater of infinite depth and specified conductivity. Comparisons were made for ice thicknesses of 0.5 meters and 2.0 meters with a seawater conductivity of 3 siemens/m. The results are shown in Table 2.

Over a range of ice conductivities from 0.1 to 50 mS/m, the expected effect on ice thickness measurement is small. For horizontal coils, the maximum range of in-phase response is 0.0004  $Z/Z_0$  and quad-phase response is 0.00033  $Z/Z_0$  for 2.0-meter thick ice. This corresponds to an ice thickness error of 0.01 meters. For vertical coils, the maximum range of in-phase response is 0.0002  $Z/Z_0$  and quad phase response is 0.00132  $Z/Z_0$ . This corresponds to a thickness error of 0.007 meters. Greater error is introduced if the ice conductivity is higher than 50 mS/m. At 100 mS/m, for 2.0 meter thick ice, thickness errors are approximately 0.1 meters for both horizontal and vertical coils.

These results are qualitatively similar to that obtained by Becker et al. (1983) who found that expected variations in ice conductivity should have little effect on ice thickness measurements by an airborne EM system.

TABLE 2. THE EFFECT OF ICE CONDUCTIVITY ON THE THEORETICAL RESPONSE OF THE EM-31D.

HORIZONTAL COILS

Ice Thickness m	Ice Conductivity mS/m	In-Phase Z/Zo	Quad-Phase Z/Zo
0.5	100	1.2028	0.08018
0.5	50	1.2020	0.08141
0.5	10	1.2014	0.08220
0.5	5	1.2013	0.08276
0.5	1	1.2013	0.08420
0.5	0.1	1.2012	0.08260
2.0	100	1.1042	0.07991
2.0	50	1.1005	0.07928
2.0	10	1.1007	0.07890
2.0	5	1.1005	0.07928
2.0	1	1.1004	0.08057
2.0	0.1	1.1003	0.07895

VERTICAL COILS

Ice Thickness m	Ice Conductivity mS/m	In-Phase Z/Zo	Quad-Phase Z/Zo
0.5	100	1.1579	0.22784
0.5	50	1.1570	0.22585
0.5	10	1.1562	0.22429
0.5	5	1.1561	0.22416
0.5	1	1.1561	0.22366
0.5	0.1	1.1560	0.22386
2.0	100	1.0648	0.07840
2.0	50	1.0622	0.06748
2.0	10	1.0623	0.06799
2.0	5	1.0622	0.06748
2.0	1	1.0621	0.06667
2.0	0.1	1.0620	0.06681



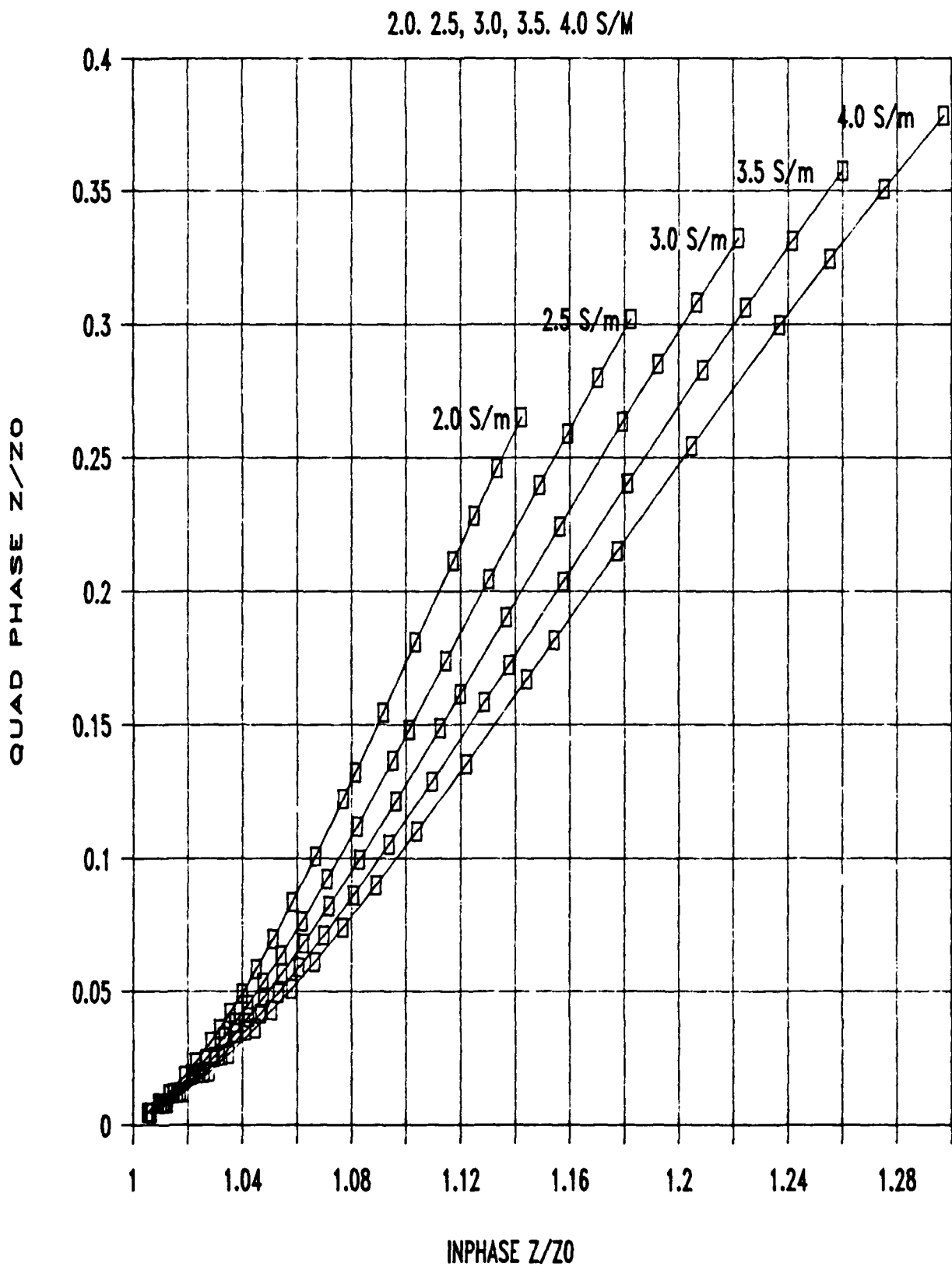
The second use of PCLOOP was to determine the minimum water depth that would appear as infinite to the EM-31D. It was determined that a seawater layer below the ice of 10 meters thickness or greater was sufficient to appear to the EM-31D as infinite. Measurements at sites deeper than this depth would be unaffected by the electromagnetic properties of the bottom sediments. Shallower than this, the conductivity of the bottom sediments determines the effect on the ice thickness measurements. More conductive materials such as wetted sand will have less effect than less conductive materials such as bedrock.

The PCLOOP program also was used to develop an expression of the response of the EM-31D as a function of: seawater conductivity; ice thickness, and coil orientation. For this series, ice conductivity was held constant at 10 mS/m. Figure 2 shows the theoretical response of the EM-31D in vertical coils configuration for seawater conductivities of 2.0, 2.5, 3.0, 3.5, and 4.0 S/m. The calculations were made for discrete ice thicknesses ranging from 0.0 to 8.0 m. The lines connect points of equal seawater conductivity. The points at the upper right of each line represent ice of zero thickness. Moving towards the lower right of each line, ice thickness increases to the maximum thickness of 8.0 meters. The same data are shown in Figure 3 for horizontal coils. In this case, the points representing thin ice to the right side of the plot and the points representing 8.0 meter thick ice are to the left. The same data, but showing lines of equal ice thickness, are shown in Figures 4 and 5 for vertical and horizontal coils, respectively.

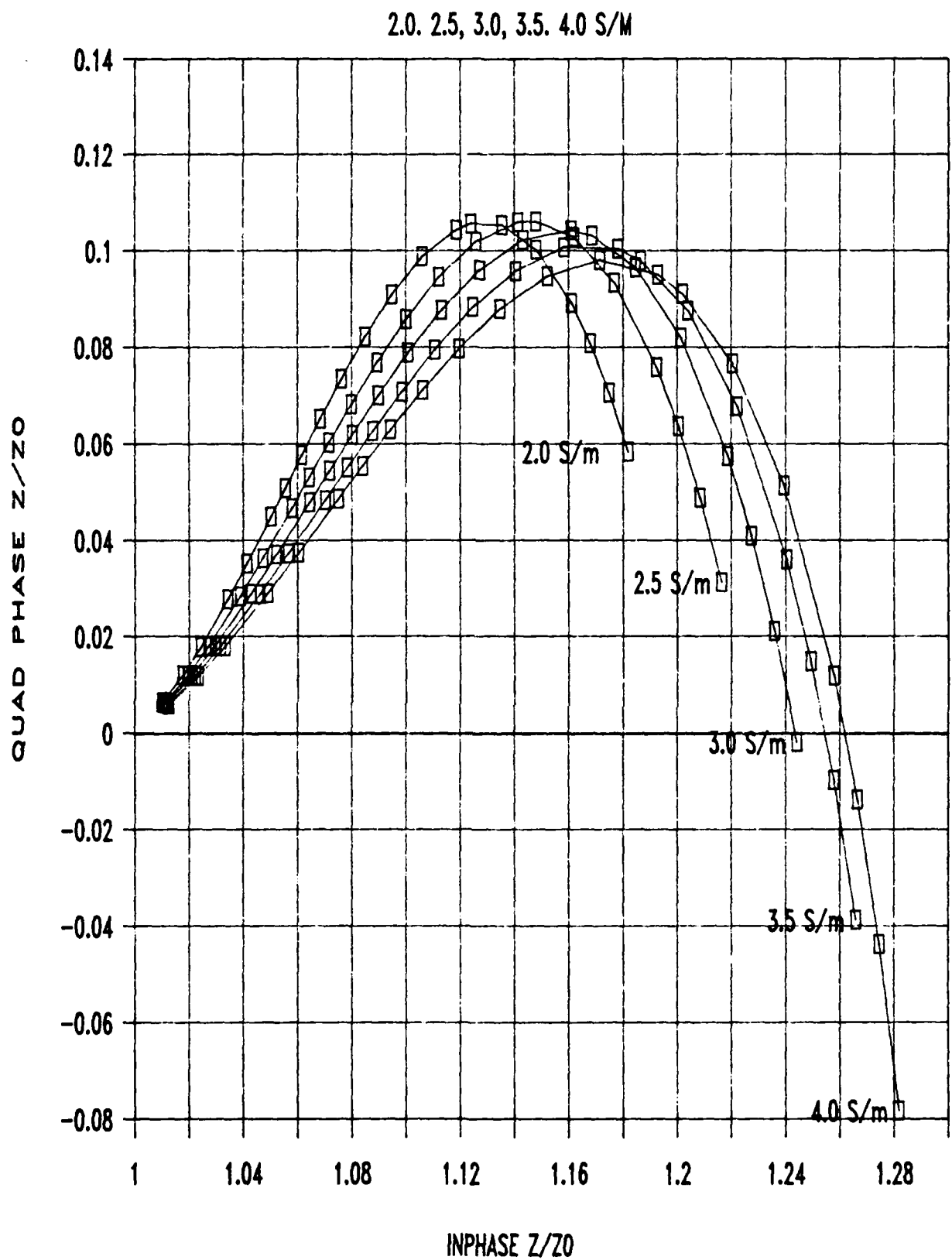
For each pair of in-phase and quad-phase values (a single measurement), one can obtain two parameters: ice thickness and the conductivity of the underlying seawater. For example, in Figure 4 a measurement corresponding to an in-phase value of 1.145 and a quad-phase value of 0.168 lies on the 1.00 m ice thickness line. As can be seen in Figure 2, this also lies on the 4.0 S/m seawater conductivity line.

Where the ice is very thick, the equal conductivity lines and the equal ice thickness lines converge (approaching values of 1 for in-phase and 0 for quad-phase). This means that there is a decreased sensitivity to ice thickness and seawater conductivity with increasing ice thickness.

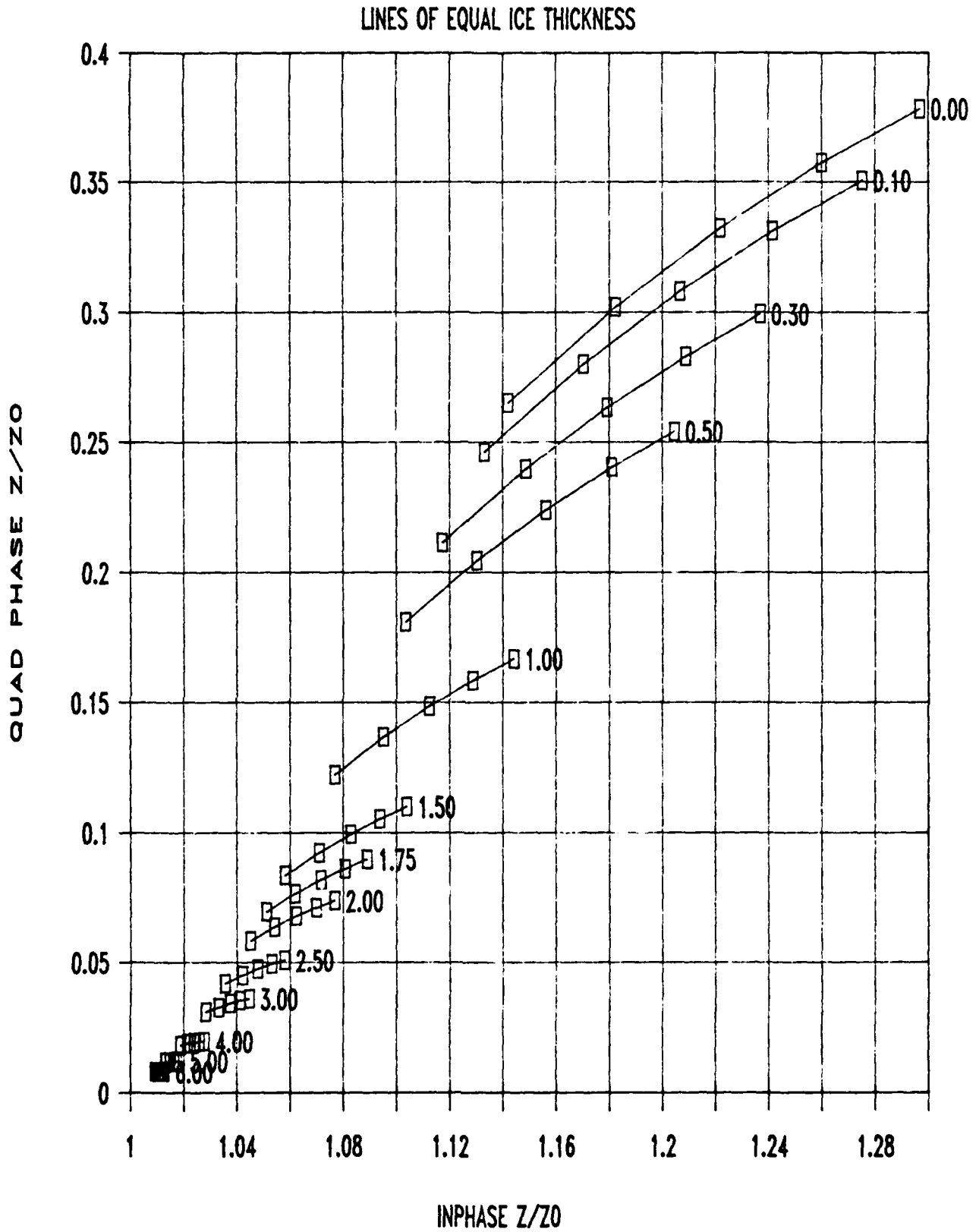
The horizontal coils configuration could provide ambiguous results when the seawater conductivity is not known. In the region of the peak of the



**Figure 2. Theoretical Response of EM-31D, for Seawater Conductivities of 2.0, 2.5, 3.0 3.5 and 4.0 s/m (Vertical Coils Configuration, for Ice Thicknesses from 0 to 8 Meters)**



**Figure 3. Theoretical Response of EM-31D, for Seawater Conductivities of 2.0, 2.5, 3.0, 3.5 and 4.0 s/m (Horizontal Coils Configuration, for Ice Thicknesses from 0 to 8 meters)**



**Figure 4. Theoretical Response of EM-31D in Vertical Coils Configuration (Showing Lines of Equal Ice Thickness from 0 to 6 meters)**

0, .1, .3, .5, 1, 1.5, 1.75, 2 & 3 M.

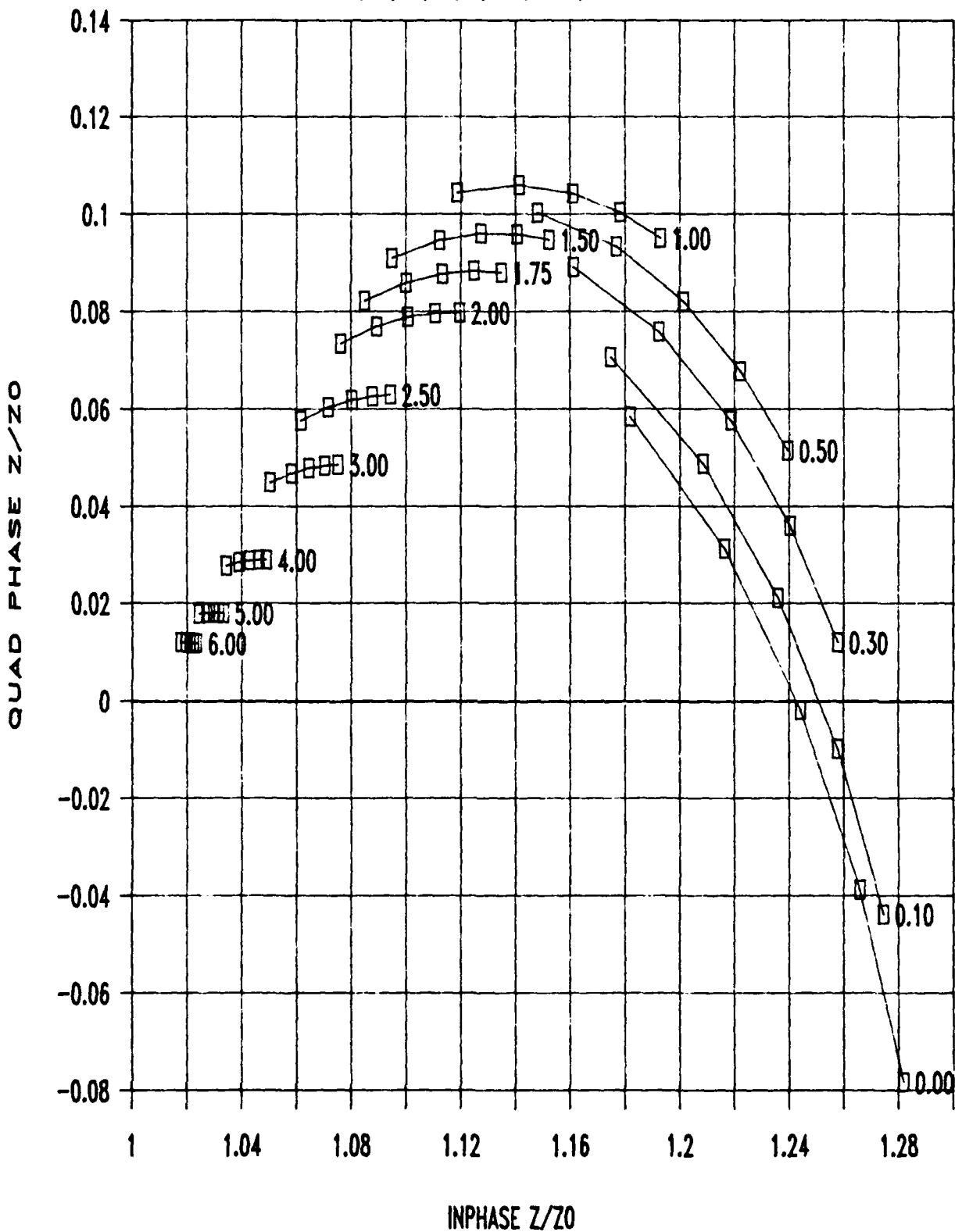


Figure 5. Theoretical Response of EM-31D in Horizontal Coils Configuration (Showing Lines of Equal Sea Thickness from 0 to 6 meters)

curve (Figure 5), lines for ice thicknesses below 1 meter and low seawater conductivities intersect with lines for ice thicknesses of 1 to 2 meters at high seawater conductivities. The curves for vertical coils are more nearly linear and do not have this ambiguity. For this reason, the vertical coils orientation is more appropriate for measuring ice thickness with the EM-31D if the expected range of thicknesses includes ice less than 1 meter.

## 5.2 Field Measurements

Before conducting the Arctic tests, the response of the EM-31 was tested over seawater without intervening ice. This was done near Seattle, Washington over the waters of Puget Sound. The objective was to take EM-31 measurements at various elevations above the water surface. This would simulate taking thickness measurements of ice having low conductivity.

It was necessary to take the measurements from a platform that was nonconductive over water of at least 10 meters depth. It was desirable to elevate the unit several meters above the water surface to simulate ice of that thickness. If a large wooden or fiberglass boat were used, it would be necessary to take the measurements away from the hull to avoid the water depression caused by the vessel displacement and to avoid the proximity of the engine. A boom arrangement would make it difficult to maintain the instrument height above water, even in smooth water conditions. A small rubber boat, displacing little water, could be used for near water tests but could not provide a sufficiently stable platform for the high elevations.

It was decided to take the measurements from the end of a wooden pier located along the Seattle waterfront. The water depth at the site was over 13 meters. The instrument was both lowered from the pier deck to the water level and also elevated above the deck on a non-conductive tripod. This provided a total elevation above the water surface of 6.5 meters.

The data taken at the pier corresponded moderately well with theoretical calculations. The vertical coils data corresponded much better than did the horizontal coils data. It is thought that some metal was present in the pier deck that adversely affected the readings. The results, however, were sufficiently encouraging to warrant an Arctic test.

A series of field trials were conducted over Arctic sea ice in order to evaluate the response of the EM-31 to actual sea ice. The tests were conducted in the nearshore Beaufort Sea using Deadhorse, Alaska as a

logistical base. The field team flew to the survey sites by helicopter. Three ice sites were investigated, all on 13 May 1986. The three sites, each of which provided first-year ice, were located north of Prudhoe Bay at water depths greater than 23 meters. It was planned also to investigate multiyear ice, but poor weather precluded additional work over the ice.

Before flying to the survey sites, the EM-31D was calibrated over permafrost ground in the vicinity of the Deadhorse airport. From previous electromagnetic surveys, this region is known to have very low conductivity, approximating zero conductivity. A single point calibration was made at this location by adjusting the instrument to read 0.0 mS/m.

#### 5.2.1 Ice Thickness and Supporting Measurements

At Site 1 the ice thickness was 0.805 meters. It was a large, nondeformed, refrozen lead. At Site 2 the thickness was 1.68 meters. The ice here also was smooth, extending hundreds of feet from the survey site. It appeared to be a refrozen area, perhaps formed slightly later than the lightly deformed ice surrounding it. The snow cover at both Sites 1 and 2 was approximately 6 inches. Site 3 was a recently refrozen lead containing ice 0.10 meters thick with no snow cover. The width of the lead was approximately 100 feet.

At all sites an EM-31 reading was taken at a central location and at five additional locations in a circular configuration at a radius of 2 meters from the central location. This was done to check the variability of the ice in the region of the measurement site. At each measurement location a hole was drilled into the ice to verify thickness. The deviation of physical measurements and the deviation of EM-31 output among the six measurement locations was negligible.

Cores were taken at Sites 1 and 2 to obtain ice temperature and salinity. Ice temperature was measured immediately upon removing the cores from the ice. A small hole was drilled into the side of the core and a thermister probe was inserted into the hole to obtain ice temperature. Air temperature at the time of sampling was  $-8^{\circ}\text{C}$ . Ice samples were returned to Seattle for later salinity analysis at the Oceanography Department at the University of Washington. The temperature and salinity data are shown in Table 3.

TABLE 3. ICE SALINITY AND TEMPERATURE MEASUREMENTS

<u>SITE 1</u>		
Depth m	Temperature Deg. C.	Salinity ppt
0.05	-3.5	
0.10	-3.0	6.92
0.20	-2.8	
0.30	-2.8	
0.40	-2.3	7.04
0.50	-2.2	
0.60	-2.1	
0.70	-1.8	7.24
0.80	-1.7	

<u>SITE 2</u>		
Depth m	Temperature Deg. C.	Salinity ppt
0.10	-3.7	4.05
0.20	-3.4	
0.30	-3.4	5.11
0.40	-3.1	
0.60	-3.7	
0.80	-3.3	4.22
1.00	-3.1	
1.20	-2.7	4.54
1.40	-1.8	
1.60	-2.1	7.31

Seawater samples were taken at depths of 1, 3 and 7 meters below the bottom surface of the ice, for temperature measurement and later salinity analysis. The water was well mixed over this depth range, with temperature of  $-1.7^{\circ}\text{C}$ . and salinity of 31.2 ppt. This results in a conductivity of 2.49 S/m.

The EM-31D data from the three sites are shown in Figures 6 and 7 for vertical and horizontal coils respectively. The distance values at each data point correspond to the ice thickness plus the vertical distance from the upper ice surface to the center of the coils. The vertical coils orientation data closely corresponds with the theoretical calculations. The horizontal coils data corresponds less well. The quad-phase values are too high at Sites 1 and 3 and too low for the thicker ice at Site 2.



SITES 1, 2, AND 3, VERTICAL COILS

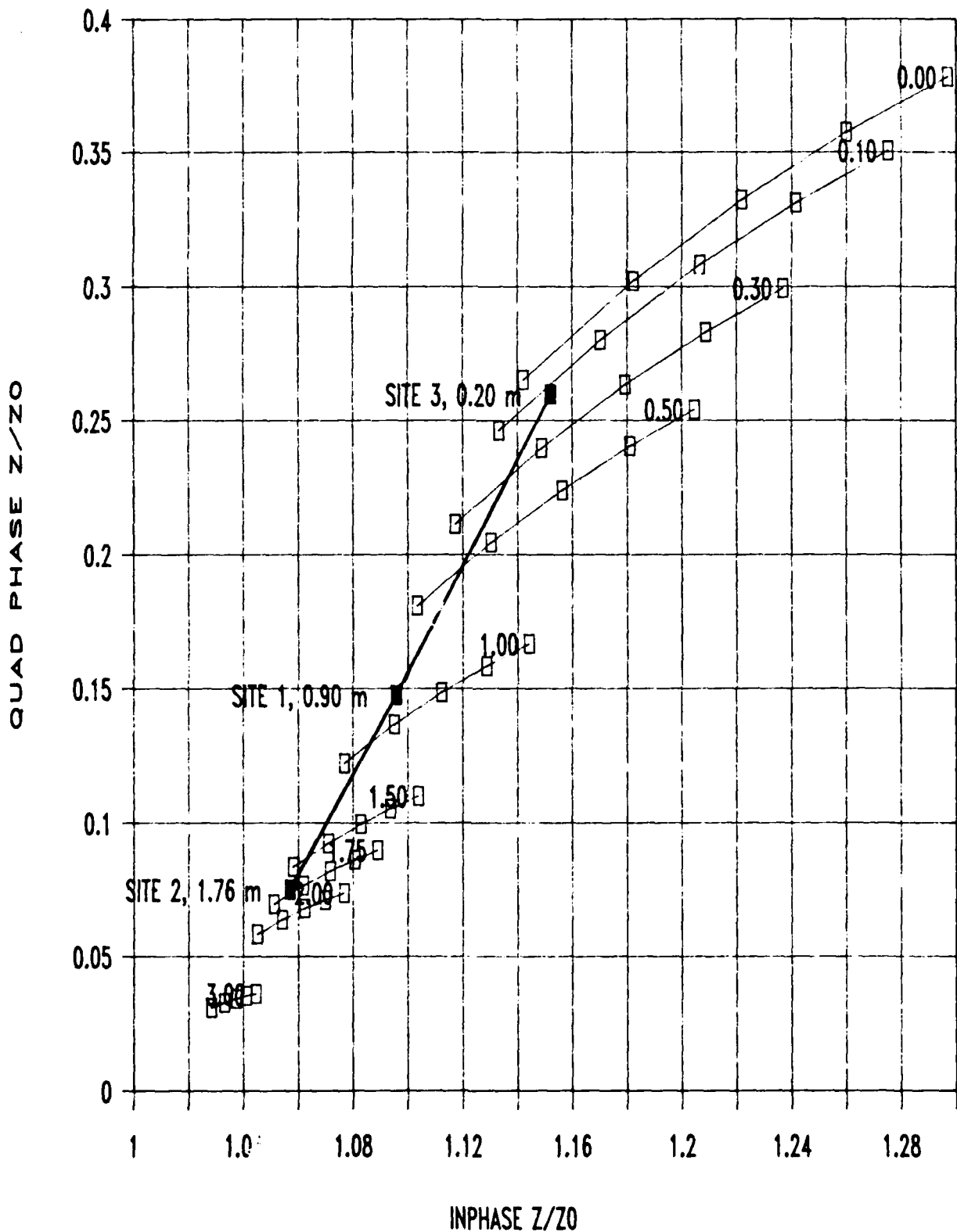


Figure 6. Theoretical Response and Ice Thickness Measurements at Arctic Sites 1, 2, and 3 (Vertical Coils Configuration)

SITES 1, 2, AND 3, HORIZONTAL COILS

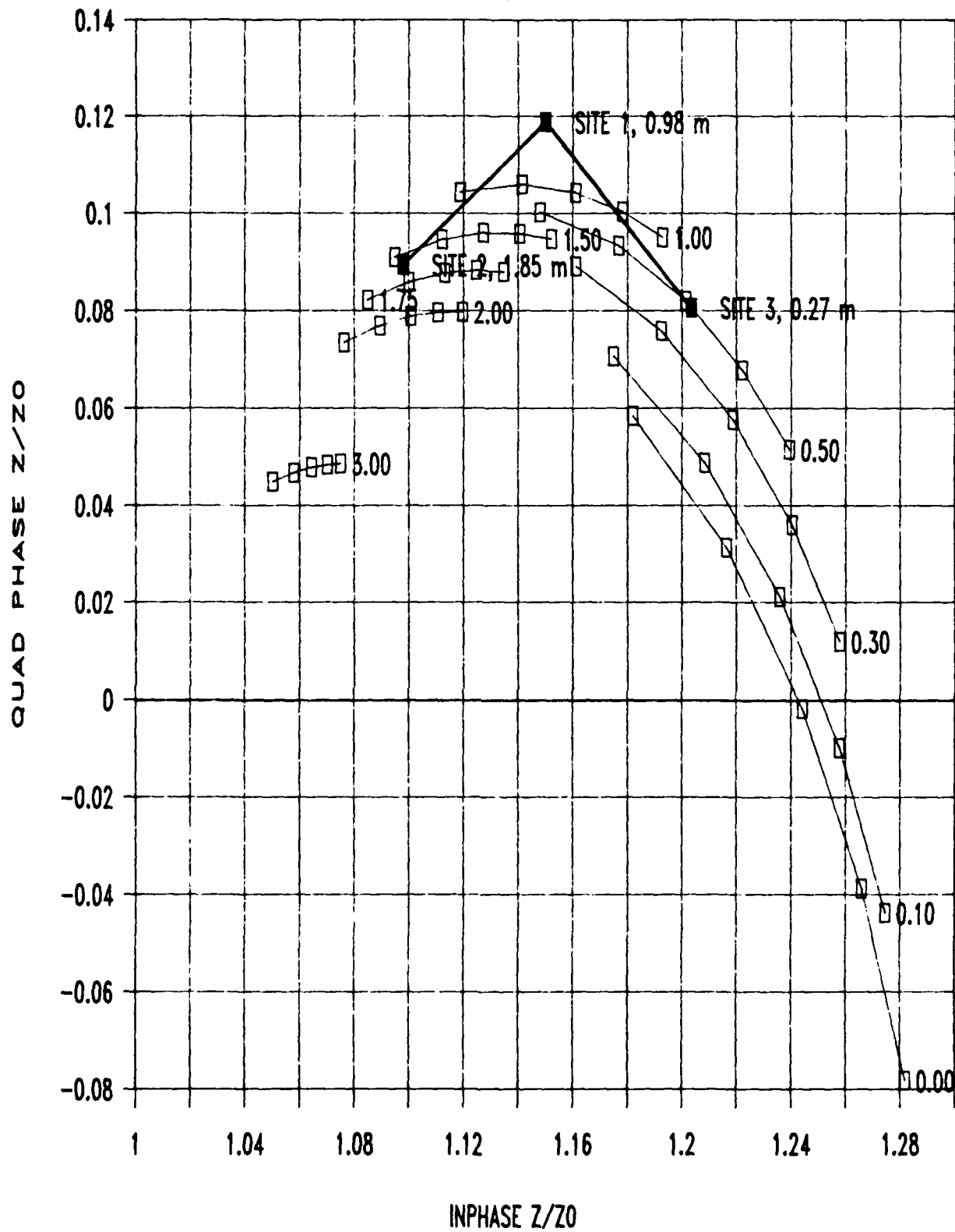


Figure 7. Theoretical Response and Ice Thickness Measurements at Arctic Sites 1, 2, and 3 (Horizontal Coils Configuration)

The thickness results are summarized in Table 4. For vertical coils, the errors in thickness are small, averaging 0.06 meters. Horizontal coils data correlate with the theoretical data less well. The horizontal coils EM data at Site 1 are beyond the expected range of measurements, making thickness difficult to interpret. The deviations for the remaining sites are 0.28 and 0.23 meters.

TABLE 4. ARCTIC ICE THICKNESS MEASUREMENTS AND EM-31 DATA

VERTICAL COILS

	Vertical* Distance m	Distance by EM-31/PCLOOP m	Deviation m
Site 1	0.90	0.85	0.05
Site 2	1.76	1.70	0.06
Site 3	0.20	0.12	0.08

HORIZONTAL COILS

	Vertical* Distance m	Distance by EM-31/PCLOOP m	Deviation m
Site 1	0.97	-	-
Site 2	1.85	1.57	0.28
Site 3	0.27	0.50	0.23

\*Vertical distance is ice thickness plus the distance from the upper ice surface to the center of the EM-31D coils.

The EM-31D, in vertical coils orientation, provided an output corresponding to a seawater conductivity of approximately 2.3 S/m (as can be seen from Figure 6). This compares reasonably well with the actual measured seawater

conductivity of 2.49 S/m. In horizontal coils orientation the seawater conductivity is less uniform among the three sites. At Site 2 the conductivity would be interpreted as 2.5 S/m, while at Site 3 conductivity appears to be 3.1 S/m. The data at Site 1 are beyond the expected range of measurements, making conductivity difficult to interpret.

#### 5.2.2 Measurements above the Ice Surface

At Sites 1 and 2 the EM-31 was raised above the ice surface to simulate the measurement of thicker ice. A nonconductive tripod was used to lift the instrument to a maximum elevation of 3.6 meters above the ice surface. Data were taken at 0.5-meter increments.

The elevation measurements at Site 1 are shown in Figures 8 and 9 for vertical and horizontal coils, respectively. The same information is displayed for Site 2 in Figures 10 and 11. The dark line and solid squares represent the EM-31D output for the elevations given. The other lines are PCLOOP lines of equal elevation for seawater conductivities of 2.0 S/m at the left end and 2.5 S/m at the right end of each line. PCLOOP was used in a two-layer configuration with the first layer as sea ice of appropriate thickness. Layer two was seawater of desired conductivity. The elevation above the ice was then varied to produce the same values as the field elevation measurements. This, in effect, created a third layer which was air.

At both Sites and for both coil orientations, the data points lie to the left of the expected values. The data generally are near the 2.0 S/m range of the plot, whereas the measured conductivity of the seawater was 2.5 S/m, which is at the right end of the equal thickness lines.

The elevation data are listed in Tables 5 and 6 for Sites 1 and 2, respectively. For vertical coils orientation, the deviations from theory generally increase with elevation. For vertical coils, the deviations average 0.20 meters at Site 1 and 0.13 meters at Site 2.

The deviations for horizontal coils are greater than for vertical coils, averaging 0.30 at Site 1 and 0.20 meters at Site 2. At the lowest level at Site 1 (instrument resting on the ice surface) the data point is beyond the expected range of measurements (see Figure 9), making a thickness estimate impossible to determine. This point represents a total combined distance to seawater of 1 meter, which is the ambiguous region of the horizontal coils response described earlier.

ELEVATIONS in METERS, VERTICAL COILS

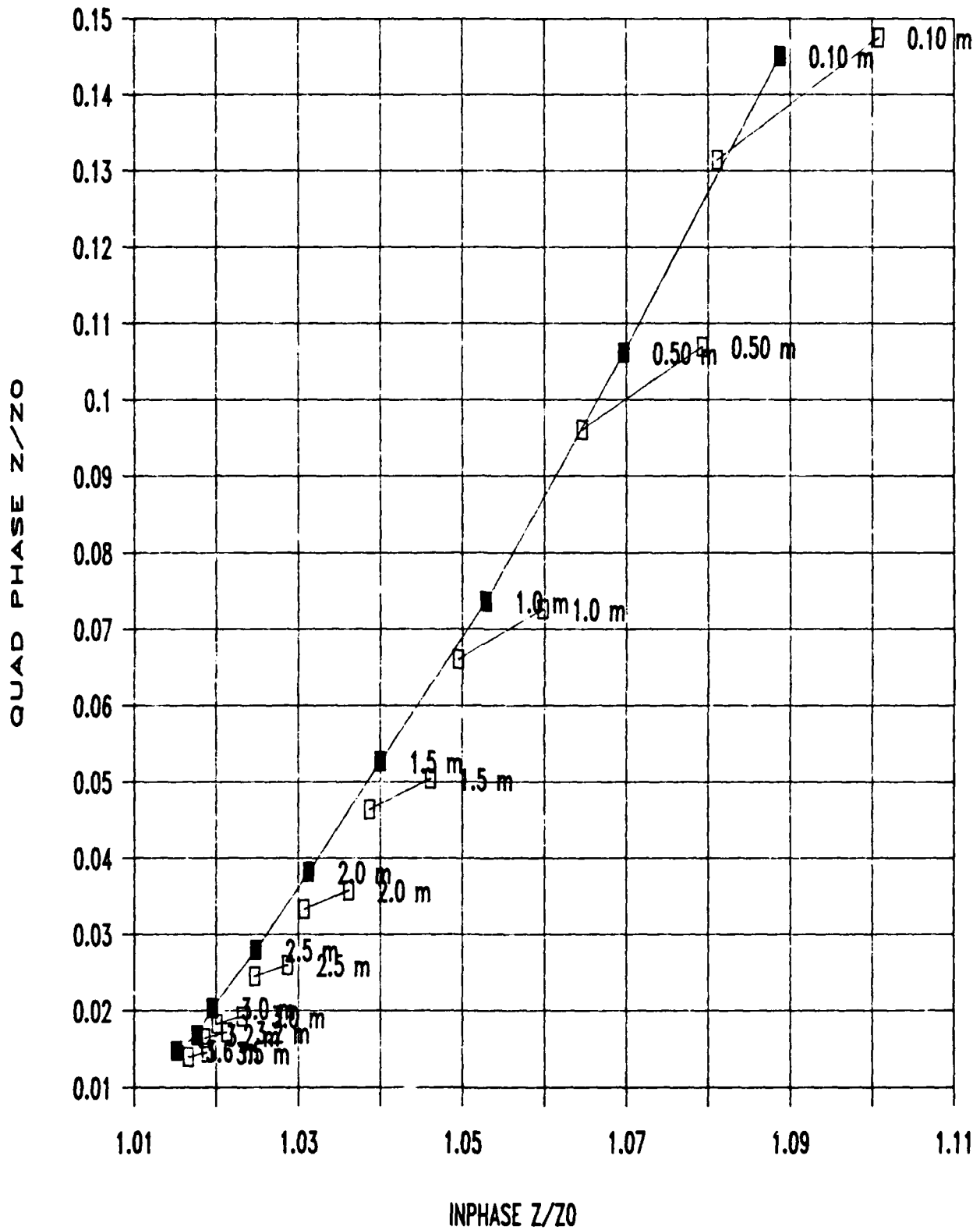


Figure 8. Theoretical Response and Elevation Measurements at Arctic Site 1 (Vertical Coils Configuration)

ELEVATIONS in METERS, HORIZONTAL COILS

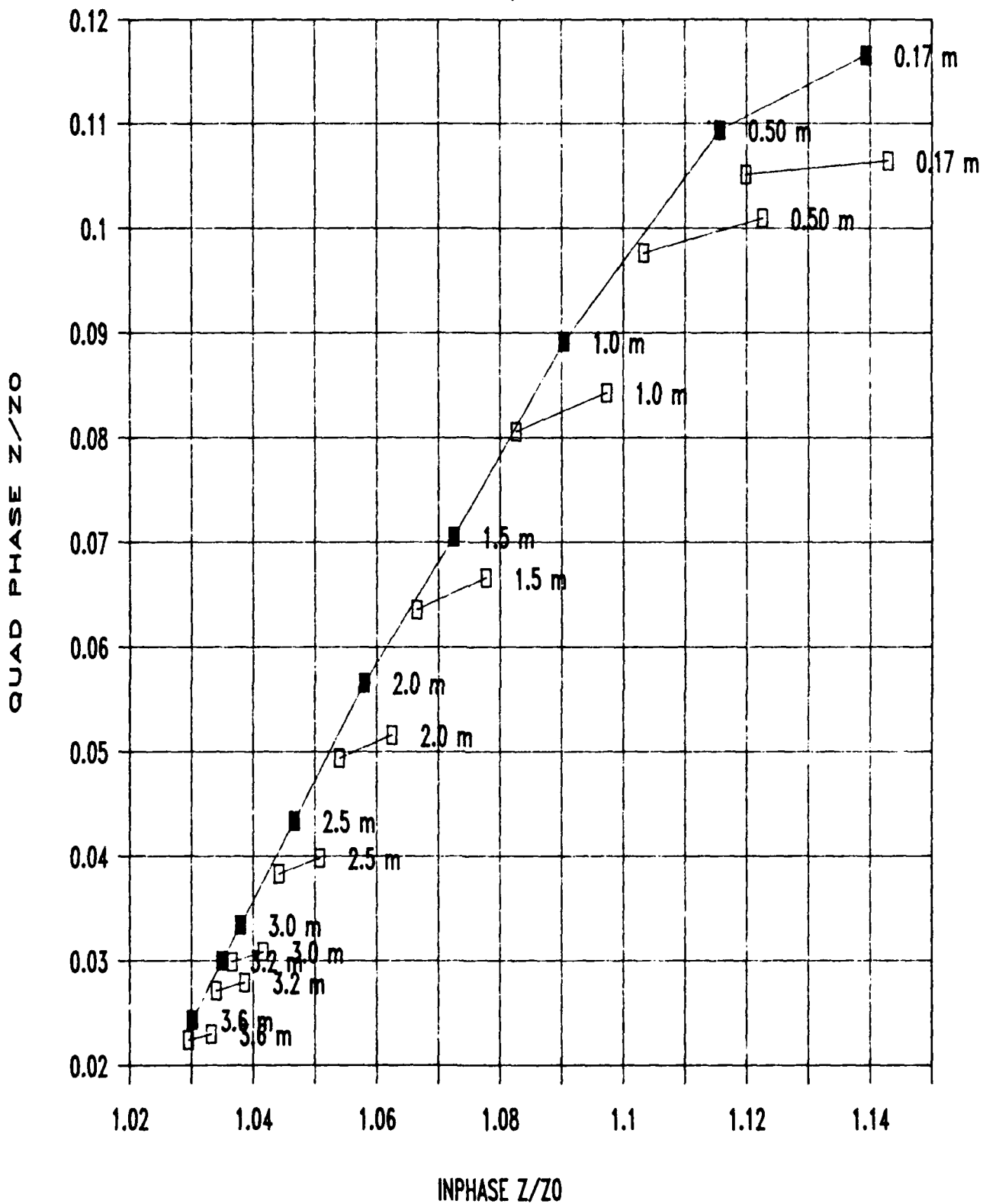


Figure 9. Theoretical Response and Elevation Measurements at Arctic Site 1 (Horizontal Coils Configuration)

ELEVATIONS in METERS, VERTICAL COILS

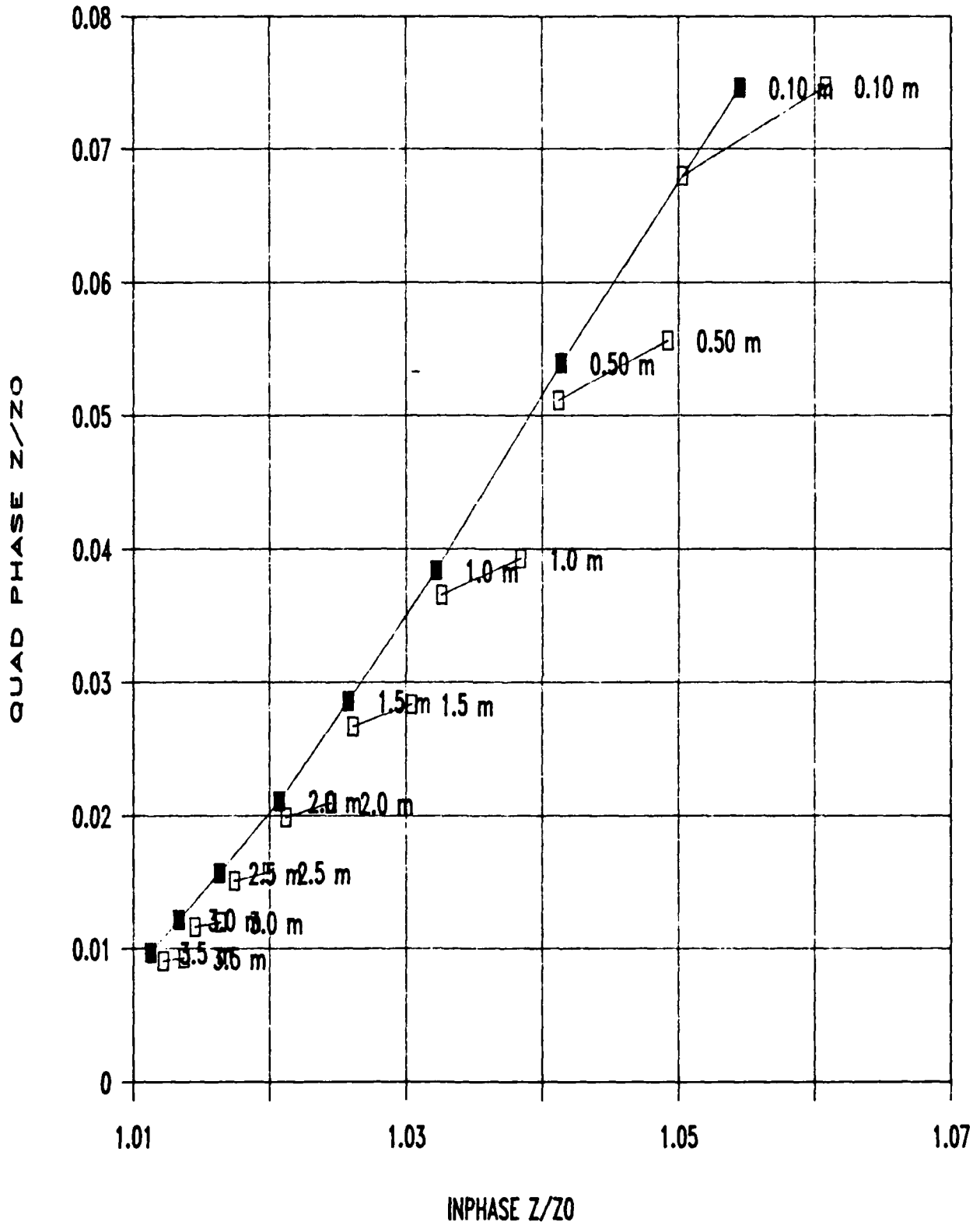


Figure 10. Theoretical Response and Elevation Measurements at Arctic Site 2 (Vertical Coils Configuration)

ELEVATIONS in METERS, HORIZONTAL COILS

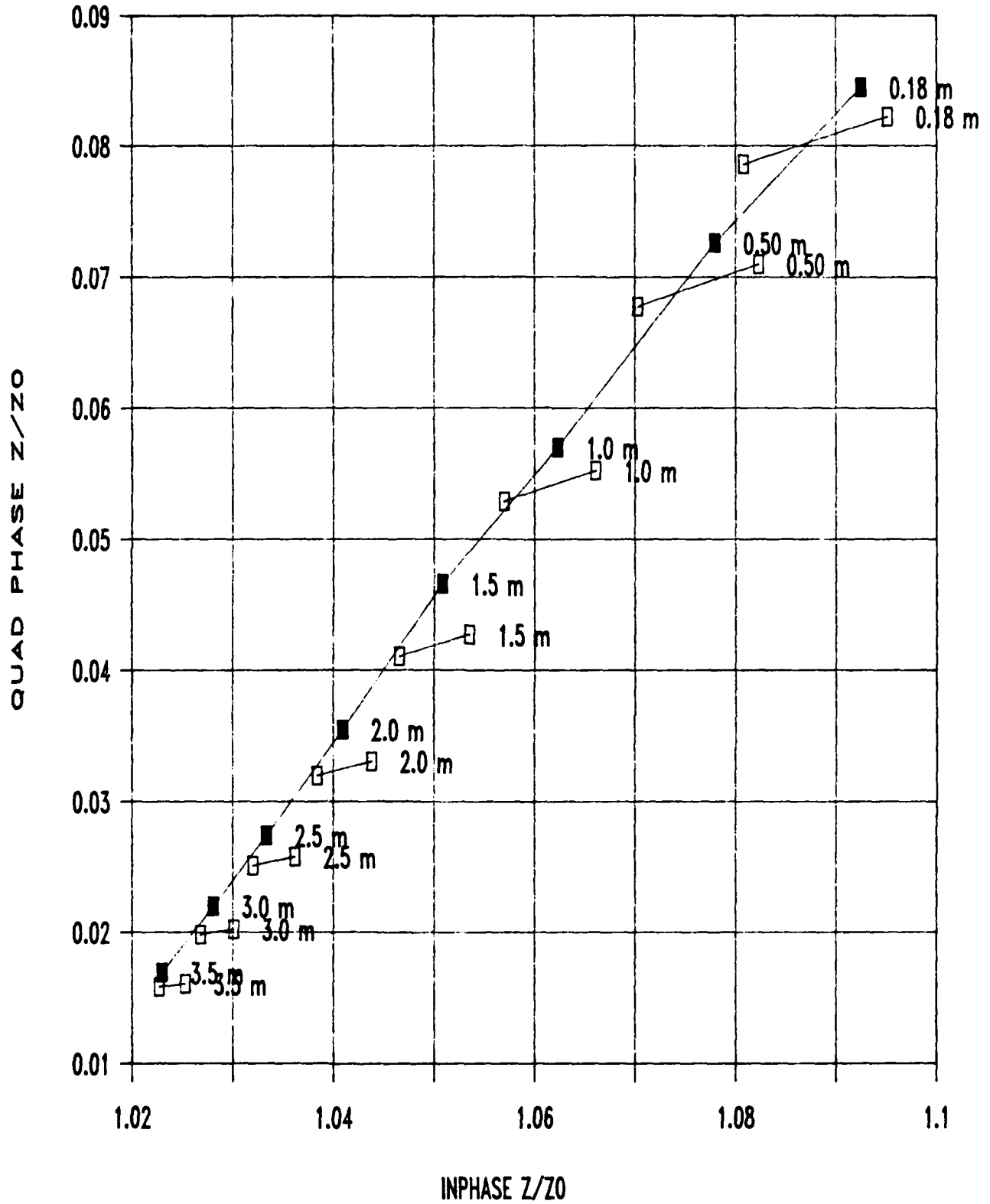


Figure 11. Theoretical Response and Elevation Measurements at Arctic Site 2 (Horizontal Coils Configuration)



TABLE 5. ARCTIC ELEVATION MEASUREMENTS AT SITE 1

The Site 1 EM-31 data, at the elevations above the ice surface shown in column one, were interpreted using PCLOOP. The interpreted elevations are given in column two. The deviation between the actual measurements and those provided by the EM-31 are given in column three.

VERTICAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m
0.10	0.03	0.07
0.50	0.38	0.12
1.00	0.90	0.10
1.50	1.30	0.20
2.00	1.75	0.25
2.50	2.20	0.30
3.00	2.70	0.30
3.20	3.05	0.15
3.60	3.25	0.35

AVERAGE OF DEVIATIONS 0.20 +0.10 m

HORIZONTAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m
0.17	-	-
0.50	0.0	0.5
1.00	0.72	0.28
1.50	1.24	0.26
2.00	1.71	0.29
2.50	2.20	0.30
3.00	2.71	0.29
3.20	2.94	0.26
3.60	3.40	0.20

AVERAGE OF DEVIATIONS 0.30 +0.09 m

TABLE 6. ARCTIC ELEVATION MEASUREMENTS AT SITE 2.

The Site 2 EM-31 data, at the elevations above the ice surface shown in column one, were interpreted using PCLOOP. The interpreted elevations are given in column two. The deviation between the actual measurements and those provided by the EM-31 are given in column three.

VERTICAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m
0.10	0.00	0.10
0.50	0.42	0.08
1.00	0.88	0.12
1.50	1.37	0.13
2.00	1.87	0.13
2.50	2.34	0.16
3.00	2.84	0.16
3.50	3.35	0.15
AVERAGE OF DEVIATIONS		0.13 $\pm$ 0.03 m

HORIZONTAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m
0.18	0.08	0.10
0.50	0.38	0.12
1.00	0.86	0.14
1.50	1.24	0.26
2.00	1.71	0.29
2.50	2.30	0.20
3.00	2.76	0.26
3.50	3.34	0.26
AVERAGE OF DEVIATIONS		0.20 $\pm$ 0.07 m

## 6. DISCUSSION

### 6.1 Coils Orientation

The best correlation with theory was obtained in the vertical coils orientation; the horizontal coils data corresponded significantly less well. One possible cause of this variation could be instrumental, perhaps simply an inaccurate internal calibration of the EM-31.

This deviation also could result from the basic difference in magnetic field properties between the coil configurations. A characteristic of the vertical coils configuration is that material closest to the instrument contributes most the the signal. In the case of sea ice, the is the region of least conductivity. The region that provides the greatest influence on the signal for horizontal coils is not at the surface but at a depth of approximately 0.4 times the intercoil spacing (McNeill, 1980). For the EM-31D this is a depth of 1.5 meters. For the Arctic measurements made, this is either within the seawater layer or is in the more conductive lower layers of the ice. This feature of the horizontal coils configuration, in concert with the anisotropic nature of sea ice, makes its use less desirable for ice thickness measurements.

### 6.2 Instrument Calibration

The arctic ice thickness measurements obtained in this program were made with the instrument calibrated at a single end point; it was zeroed over ground assumed to have negligible conductivity. This calibration point is beyond the normal range of instrument readings for ice thicknesses.

In practice, the EM-31 showed good correlation with theory in quad-phase component but the in-phase values were consistently low. This resulted in a seawater conductivity value lower than actually present and ice thickness measurements generally less than actually present.

If the instrument were calibrated on the ice to read the proper seawater conductivity, or were calibrated to read the proper ice thickness at a measured calibration point, significantly greater accuracies would result. To demonstrate the potential effect on the measurement accuracies, the Arctic data were modified by increasing the in-phase values to a point corresponding to the 2.5 S/m line. The quad-phase values were held constant. The original data and the results of the corrections for the three sites are shown in

Table 7. For vertical coils, the accuracies (deviations) improved from 0.06 meters to 0.02 meters.

The elevation measurements were corrected in a similar fashion. The original data and the corrected results are shown in Figures 8 and 9 for Sites 1 and 2, respectively. For vertical coils, the deviations were reduced from 0.20 to 0.06 m at Site 1 and from 0.13 to 0.03 m at Site 2. For horizontal coils, the deviations were reduced from 0.30 to 0.20 m at Site 1 and from 0.20 to 0.13 m at Site 2.

Overall, the corrected data were more accurate by factors of between 3.0 and 4.3 for vertical coils. These results suggest that an improved calibration procedure will significantly increase the accuracy of the ice measurements.

TABLE 7. CORRECTED EM-31 ARCTIC ICE THICKNESS MEASUREMENTS

Column one is the vertical distance from the bottom surface of the ice to the center of the EM-31 coils. The EM-31 ice thickness measurements, as interpreted by PCLOOP are shown in column two. The difference between the physically measured distance and the EM-31 measurements are in column three. Corrected EM-31D measurements and the deviations for those data are shown in columns four and five respectively.

VERTICAL COILS

Site	Vertical Distance m	Distance by EM-31/PCLOOP m	Deviation m	Corrected Vertical Distance m	Deviation After Correction m
1	0.90	0.85	0.05	0.88	0.02
2	1.76	1.70	0.06	1.77	-0.01
3	0.20	0.12	0.08	0.18	0.02
AVERAGE OF DEVIATIONS			0.06 m		0.02 m

TABLE 8. CORRECTED ARCTIC ELEVATION MEASUREMENTS AT SITE 1.

The Site 1 EM-31 data, at the elevations above the ice surface shown in column one, were interpreted using PCLOOP. The interpreted elevations are given in column two. The deviation between the actual measurements and those provided by the EM-31 are given in column three. Corrected EM-31 data and the deviations from those data shown in columns four and five respectively.

VERTICAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m	Corrected Elevation by EM-31/PCLOOP m	Deviation After Correction m
0.10	0.03	0.07	0.12	0.02
0.50	0.38	0.12	0.51	0.01
1.00	0.90	0.10	0.97	0.03
1.50	1.30	0.20	1.45	0.05
2.00	1.75	0.25	1.90	0.10
2.50	2.20	0.30	2.40	0.10
3.00	2.70	0.30	2.90	0.10
3.20	3.05	0.15	3.20	0.00
3.60	3.25	0.35	3.50	0.10
AVERAGE OF DEVIATIONS		0.20 $\pm$ 0.10 m		0.06 $\pm$ 0.05 m

HORIZONTAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m	Corrected Elevation by EM-31/PCLOOP m	Deviation After Correction m
0.17	-	-	-	-
0.50	0.0	0.5	0.1	0.4
1.00	0.72	0.28	0.83	0.17
1.50	1.24	0.26	1.35	0.15
2.00	1.71	0.29	1.81	0.19
2.50	2.20	0.30	2.32	0.18
3.00	2.71	0.29	2.82	0.18
3.20	2.94	0.26	3.01	0.19
3.60	3.40	0.20	3.44	0.16
AVERAGE OF DEVIATIONS		0.30 $\pm$ 0.09 m		0.20 $\pm$ 0.08 m

TABLE 9. CORRECTED ARCTIC ELEVATION MEASUREMENTS AT SITE 2.

The Site 2 EM-31 data, at the elevations above the ice surface shown in column one, were interpreted using PCLOOP. The interpreted elevations are given in column two. The deviation between the actual measurements and those provided by the EM-31 are given in column three. Corrected EM-31 data and the deviations from those data shown in columns four and five respectively.

VERTICAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m	Corrected Elevation by EM-31/PCLOOP m	Deviation After Correction m
0.10	0.00	0.10	0.10	0.00
0.50	0.42	0.08	0.54	-0.04
1.00	0.88	0.12	1.03	-0.03
1.50	1.37	0.13	1.48	0.02
2.00	1.87	0.13	1.98	0.02
2.50	2.34	0.16	2.50	0.00
3.00	2.84	0.16	2.95	0.05
3.50	3.35	0.15	3.43	0.07
AVERAGE OF DEVIATIONS		0.13 $\pm$ 0.03 m		0.03 $\pm$ 0.04 m

HORIZONTAL COILS

Elevation Above Ice m	Elevation by EM-31/PCLOOP m	Deviation m	Corrected Elevation by EM-31/PCLOOP m	Deviation After Correction m
0.18	0.08	0.10	0.10	0.08
0.50	0.38	0.12	0.44	0.06
1.00	0.86	0.14	0.94	0.06
1.50	1.24	0.26	1.32	0.18
2.00	1.71	0.29	1.86	0.14
2.50	2.30	0.20	2.35	0.15
3.00	2.76	0.26	2.83	0.17
3.50	3.34	0.26	3.37	0.17
AVERAGE OF DEVIATIONS		0.20 $\pm$ 0.07 m		0.13 $\pm$ 0.05 m

### 6.3 Maximum Ice Thickness Measurement Capability

The following is a brief discussion of the potential of the EM-31 for measuring thick sea ice (beyond the nominal maximum thickness of 2 m for first-year ice). The accuracy of a thick ice measurement will, in part, depend on the uniformity of conductivity of the ice and the magnitude of that conductivity relative to the conductivity of the seawater below. These factors will vary from region to region and will vary by ice type. The accuracy will also depend on the accuracy and resolution of the instrument.

The accuracy of the unit, as stated by the manufacturer, is  $\pm 5\%$  at 20 mS/m. For 5-meter thick ice this corresponds to a theoretical thickness accuracy of  $\pm 0.07$  meters. This assumes a seawater conductivity of 2.5 S/m and a uniform ice conductivity of 10 mS/m. For 10-meter thick ice this corresponds to a potential accuracy of approximately  $\pm 0.5$  meters, for 15-meter thick ice the expected accuracy will be on the order of 1.3 meters.

At Arctic Site 2, the combined distance from the upper elevation measurement to the bottom surface of the ice was 5.2 meters. The deviations from theory, after correction, for the higher two elevations are 0.05 and 0.07 meters (from Table 9). These values compare well with the theoretical accuracy of  $\pm 0.07$  m for 5 meter thick ice described above. These two data points are not statistical expressions of accuracy. However, they do provide some confirmation that the instrument, under Arctic conditions, is capable of providing thickness accuracy similar to that expected from the performance specifications of the instrument.

### 6.4 Limitations of Ice Thickness Measurement by EM Induction

While EM induction has great potential for sea ice thickness measurement, there are some limitations of the technique. Limitations identified by this project, or by previous investigators, are summarized below.

1. Strongly stratified seawater (increasing conductivity with depth) beneath the ice will produce errors in the thickness estimates. However, if the stratification is known, the thickness measurements can be corrected for this effect.

2. The conductivity of the underlying seawater must be large relative to that of the sea ice. Thickness measurements over brackish water, such as at the mouth of a river, will not be accurate.
3. The technique is best applied over water that appears infinitely deep to the instrument. For the EM-31D this is a layer of water approximately 10 meters beneath the ice. If the water depth and the conductivity of the ocean bottom are known, the measurements can be corrected for the bottom effect.
4. The technique measures an average thickness over a region rather than at a single point. The size of the region is generally a function of the intercoil spacing and the height of the coils above the seawater layer. As either of these two parameters is increased, the region sampled also increases.
5. Because EM induction is an area measurement rather than a point measurement, ice thickness profiles of rough multiyear ice will tend to be smoothed. The extent of smoothing will depend on the physical scale of the ice roughness as well as the instrument parameters of coil spacing and coil elevation. For an airborne system, this problem increases as aircraft altitude increases.
6. Measurements over ice rubble, such as at first-year ridges, will not provide accurate thicknesses (as noted by Hoekstra et al. 1979). Unfrozen seawater in the voids between the submerged ice blocks will adversely affect the readings. However, an EM induction sensor may provide an indication of the consolidation of a first-year ridge or rubble area. A newly formed ridge will be porous, having numerous pockets of seawater and producing a high apparent conductivity. As the ridge ages during the winter, the pockets near the cold atmosphere will tend to refreeze, and the trapped brine will drain, thereby lowering the overall conductivity of the ice as seen by the instrument.



### 6.5 Application to Air-Droppable Arctic Buoy

A useful application of EM induction is the measurement of ice thickness by an air-droppable buoy. The buoy could be configured as a cylinder to fit existing buoy launch tubes in military aircraft. The intercoil spacing could be provided by placing the coils at each end of the package. Upon launch, a parachute could deploy to lower the instrument to the ice surface. Orientation of the coils could be maintained through gimbaling. An alternative configuration would be to shock-harden the electronics and allow the package to free-fall to the ice surface, thereby eliminating the need for a parachute.

From initial calculations, it appears that an instrument with an intercoil spacing of 0.5 to 1 m would provide a thickness accuracy of 0.02 to 0.1 m for ice up to 2 m thick. Thicker ice could be measured but at reduced accuracy. The ice thickness measurement could be relayed to the deploying aircraft by radio link.

Such a buoy system would be inexpensive and would not require a permanent installation within the aircraft. The thickness measuring capability could be transferred easily from one aircraft to another, depending on the mission.

## 7. CONCLUSIONS

In general, the Phase I effort showed that electromagnetic induction is a practical and useful methodology for the measurement of sea ice thickness. It also demonstrated that the EM-31D ground conductivity meter has the potential to rapidly and accurately measure sea ice thickness.

Specific conclusions are as follows:

1. The EM-31D is capable of accurately measuring the thickness of first-year sea ice. Without on-ice calibration, the thickness can be measured with an accuracy of better than 0.1 meters. It is expected that with on-ice calibration, the accuracy can be improved to on the order of 0.03 meters.
2. The EM-31D has the potential of accurately measuring thick multiyear ice. It is expected that 5-meter thick ice can be measured with an accuracy of between 0.07 and 0.2 meters.
3. From theory, the accuracy of the thickness measurements made by the EM-31 is relatively unaffected by sea ice conductivity over a range of ice conductivities of 0.1 to 50 mS/m.
4. The horizontal coils configuration (vertical dipoles) for the EM-31 has the potential for ambiguous ice thickness interpretation for ice approximately 1 meter thick. For this reason, the vertical coils configuration (horizontal dipoles) is generally more appropriate for ice thickness measurement.
5. The standard readout provided by the EM-31 is inappropriate for ice thickness measurement. Significant processing is necessary to convert the data to ice thickness. With the addition of signal conditioning electronics, real-time readout of ice thickness is possible. With this modification, each ice thickness measurement would take only a few seconds.

6. Currently there is no procedure for on-ice calibration of the unit. For use on long-term manned camps it will be necessary to calibrate the instrument to ensure its continued accuracy. Additionally, on-ice calibration will increase the accuracy of the unit in general by a factor estimated at between two and five. Electronics modifications can be made to the unit and procedures developed that will enable on-ice calibration.
  
7. An EM induction ice thickness measurement system can be configured as a small, low-cost, air-droppable buoy.

## 8. RECOMMENDATIONS FOR FUTURE WORK

The following work is recommended to develop the EM-31 as a practical, man-portable tool for routine sea ice thickness measurements.

- o Add signal conditioning and display electronics to the EM-31 to permit real-time display of ice thickness and seawater conductivity.
- o Develop electronics and procedures to permit the on-ice calibration of the EM-31.

This same EM induction technology can be used to measure the conductivity of sea ice. Presently no rapid method exists to obtain these measurements. The most recent technique used (Buckley, et al., 1986) is the Wenner array technique, which requires electrodes to be emplaced in the ice. A tool, similiar to the EM-31, could be developed to rapidly and remotely measure ice conductivity. This tool could be used to for scientific investigations of sea ice properties for remote sensing and electromagnetic propagation studies. It would be especially useful to investigations of airborne EM induction systems for ice thickness measurements.

The sea ice conductivity tool would be configured with shorter intercoil spacing and higher frequency than the EM-31. This would to limit the penetration distance of the tool and would reduce the effect of the conductive seawater on the signal.

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