

## **GEOS/MSL 695 – Field techniques in interdisciplinary sea-ice research**

### Module 3a: Ice sampling and fundamental physical property measurements

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#### *Aims and introductory comments*

This is the first part of a two-part module that will introduce you to the basic stages of sampling and analysis of ice cores in the field. Upon completion of this part of the module (3a) you will know how to:

- Obtain ice cores for studies of fundamental ice properties, including selection of suitable coring sites, basic aspects of safe drill operation, and ancillary measurements on the core site
- Complete basic measurements of temperature and density (along with photographs of core stratigraphy) at the core site needed to derive fundamental ice properties
- Subsample the core for laboratory measurements of salinity
- Complete measurements of electrolytical conductivity and salinity on melted core samples
- Calculate in situ air and brine volumes from measurements based on sea ice thermodynamic phase relations

#### *Reference materials*

- Eicken, H. (2003) From the microscopic to the macroscopic to the regional scale: Growth, microstructure and properties of sea ice. In: Thomas, D. N. and Dieckmann, G. S. (eds.) Sea ice - An introduction to its physics, biology, chemistry and geology. Blackwells Scientific Ltd., London, pp. 22-81
- Timco, G. W. and M. E. Johnston (2002) Sea ice strength during the melt season. In: Proc. 16<sup>th</sup> IAHR Int. Symposium on Ice, pp. 187-193.
- Example of core sampling sheet
- All documents can be downloaded at [ftp.gi.alaska.edu /pub/eicken/G695/Module3](ftp://ftp.gi.alaska.edu/pub/eicken/G695/Module3)

#### *Equipment needed*

- 10 cm diameter ice corer, couplings, safety disk, brush to clean off corer
- electric drill, power cord, ground-fault interrupt (GFI)
- 2kW Honda generator
- shovel
- meter stick
- core cutting and photographing bench
- digital camera (preferably to be provided by a team member)
- hand drill and half-tube with pre-drilled holes
- digital thermometer
- hand saw
- digital balance
- ruler and caliper
- ziplock bags, non-erasable pen for marking bags, and core containers
- salinometer

## ***Introduction and derivation of brine volume and air volume fraction from sea ice “state variables”***

Extraction of ice cores from an ice sheet is of fundamental importance in a wide range of studies of sea ice. In this course, several modules apart from this one will rely on ice coring and ice core analysis as an important step in the study of ice and the services it provides to a range of different users. The purpose of this module is to acquaint you with the basic aspects of ice coring and the subsequent analysis and processing of samples in the field. The actual process and protocol involved with this work are described in the subsequent section and will be discussed in more detail on site. You will also be making measurements of electrolytical conductivity (from which salinity is derived) on melted samples in the laboratory.

While a ice structural and stratigraphic analysis typically requires production of thick and thin sections in the laboratory (which is beyond the scope of this class), you will be introduced to a simple stratigraphic analysis of the core in order to help you decide whether the sample is in fact representative of the growth processes prevailing in a given area and to provide ancillary information for the other ice-core data collected as part of the course. Details of the stratigraphic analysis and the information that can be derived from examining the stratigraphy (i.e., the vertical layering and temporal sequence of growth processes shaping the crystal and brine/air inclusion morphology in sea ice) are provided in the reading material for this module.

The actual variables or ice properties that are to be measured as part of this module are the ice temperature, its density and its salinity. These three variables can be thought of as “state variables” for sea ice, such that knowledge of these three allows the physical state of the ice cover to be described to the extent that other key ice properties can be directly derived from these three variables through a model or estimated through empirical relationships. The thermodynamic phase relations (the “rules” that govern the co-existence of different phases such as liquid brine or solid ice) dictate that for an isothermal volume of sea ice in thermodynamic equilibrium at atmospheric pressure, the relative volume fraction of brine is fixed and depends solely on the ice temperature  $T$  and its bulk composition or rather, in the case of "standard" sea ice, its bulk salinity  $S_{si}$ . The salinity  $S_b$  of the brine contained within such an ice volume in turn also depends only on the temperature of the bulk ice volume. The coupling between these different variables is a key aspect of sea ice as a geophysical material as well as a biological habitat for microorganisms, since any temperature change directly affects the porosity and pore microstructure of the ice as well as the salinity of the brine. As direct measurement of these properties in the field is difficult, if not impossible, commonly the in-situ brine volume fraction and other properties are derived from the bulk salinity of an ice sample, its density and its temperature.

From the data compiled by Assur [1960; references are given in reading material for this module] for the phase relations and based on the continuity equations for a multi-phase sea-ice mixture, Cox and Weeks [1983] derived a rather useful set of equations describing the brine volume fraction as a function of ice temperature and salinity.

$$\frac{V_b}{V} = \left(1 - \frac{V_a}{V}\right) \frac{\rho_i S_{si}}{F_1(T) - \rho_i S_{si} F_2(T)} \quad (1).$$

Here,  $V_b/V$  is the volume fraction of brine while  $V_a/V$  is the volume fraction of air in a sample. The density of pure ice is given as

$$\rho_i = 0.917 - 1.403 \times 10^{-4} T \quad (2)$$

with  $\rho_i$  in  $\text{g cm}^{-3}$  and  $T$  in  $^{\circ}\text{C}$ .  $F_1(T)$  and  $F_2(T)$  are empirical polynomial functions  $F_i(T) = a_i + b_i T + c_i T^2 + d_i T^3$ , based on the phase relations. The coefficients for different temperature intervals are listed in Table 1.

Table 1. Coefficients for functions  $F_1(T)$  and  $F_2(T)$  for different temperature intervals, from Leppäranta and Manninen [1988], Cox and Weeks [1983]

$T, ^{\circ}\text{C}$	$\mathbf{a}_1$	$\mathbf{b}_1$	$\mathbf{c}_1$	$\mathbf{d}_1$
$0 \geq T > -2$	-0.041221	-18.407	0.58402	0.21454
$-2 \geq T \geq -22.9$	-4.732	-22.45	-0.6397	-0.0174
$-22.9 > T \geq -30$	9899	1309	55.27	0.7160
	$\mathbf{a}_2$	$\mathbf{b}_2$	$\mathbf{c}_2$	$\mathbf{d}_2$
$0 \geq T > -2$	0.090312	-0.016111	$1.2291 \times 10^{-4}$	$1.3603 \times 10^{-4}$
$-2 \geq T \geq -22.9$	0.08903	-0.01763	$-5.330 \times 10^{-4}$	$-8.801 \times 10^{-6}$
$-22.9 > T \geq -30$	8.547	1.089	0.04518	$5.819 \times 10^{-4}$

The brine salinity and density can be approximated for temperatures above  $-23^{\circ}\text{C}$  as

$$S_b = \left(1 - \frac{54.11}{T}\right)^{-1} \times 1000\text{‰} \quad (3)$$

$$\rho_b = 1 + 8 \times 10^{-4} S_b \quad (4)$$

with  $T$  in  $^{\circ}\text{C}$ . The volume fraction of air  $V_a/V$  can be derived from a measurement of the density of a sea ice sample  $\rho$ :

$$\frac{V_a}{V} = 1 - \frac{\rho}{\rho_i} + \rho S_{si} \frac{F_2(T)}{F_1(T)} \quad (5).$$

Equations (1) through (5) thus provide us with a tool to derive key quantities of importance for a wide range of physical, biological and chemical studies of sea ice, given that properties such as ice strength or its electric conductivity depend to first order on the volume fraction of liquid and ice (and gas).

### Field work

In brief, the activities for this module including the selection of a proper sampling site, identified after removal of the snow cover (first measuring snow depth at the prospective coring site) and consideration of other key factors such as presence of deformation features, water depth etc. With brine loss from samples and sample warming key concerns, coring of ice samples requires a well-organized sampling approach and laying out all necessary equipment prior to drilling. Once the generator is set up, all cords and the GFI are in place and the electric drill and corer are held in a safe manner (with the core barrel exactly vertical), drilling of the core can begin. Please be sure to remove core cuttings that build up around and in the hole by regular lifting of the corer. Other considerations and potential problems encountered during drilling will be discussed at the site.

Once a core of sufficient length is in the barrel and the core has broken free from the bottom of the hole, the corer is extracted, opened at the top end and the core transferred onto the core cutting bench for photographs. After that, ice core temperature is measured in holes drilled

with the handdrill (shading the core with the plastic half tube provided) at 5 to 10 cm intervals. Then the core surface is marked at 10 cm intervals and the core sectioned into 10 cm subsamples. Please be sure to work swiftly and cleanly. 10 cm subsamples are transferred into pre-labeled ziplock bags. These bags are weighed on the digital balance (subtracting bag weight) and the core section dimensions are measured with the caliper/ruler. The sample is then transferred into the core container for transport back to the lab. After a full hole is drilled, the freeboard and draft are measured. Some coordination with the ice engineering module is required in order to derive measures of ice strength for the hole drilled for deployment of the borehole jack (detailed discussion at field site).

### ***Laboratory measurements***

The core samples that were transported back to the lab are then allowed to melt. That same day or the next morning the ice salinity is measured on the sample based on its electrolytical conductivity. Samples can be discarded and containers cleaned (if leakage occurred) after the measurements.

In reporting ice salinities, typically the practical salinity scale (pss) is adopted for relating measurements of conductivity to that of standard seawater, with measurements reported in practical salinity units (psu). It should be noted, however, that the pss is only defined for standard seawater of a given composition for the interval between 1 and 42. Hence, many measurements reported for sea ice fall outside of this validity interval either because of lower salinities or because of significant deviations from the chemical composition of standard seawater. This circumstance can be acknowledged by reporting the result of salinity measurements in permille (‰) rather than psu.

### ***Report and analysis***

The report for this module should consist of a brief description of sampling activities along with a complete tabulation and presentation (including plots) of all data collected in the field and laboratory, as well as the derived variables discussed in more detail below. The ftp site provides a simple template for such a tabulation of results but you do not need to follow that format. Please also include a composite core stratigraphy photograph alongside the salinity and density profile so that these variables can be discussed in context with the core stratigraphy.

In addition to the measured variables the report should present and discuss the air and brine volume fraction profiles derived from the salinity, temperature and density measurements following the approach outlined in the section “Introduction and derivation of brine volume ...” above. Please discuss the sources of error that enter into this analysis.

As discussed above and in more detail on site, ice core measurements are fundamental to many other studies of the sea ice. At the same time, in comparing measurements on ice cores with measurements made in-situ, such as the geoelectric surface array measurements that are part of Module 3b or the ice-engineering measurements that are part of Module 5, questions of scale need to be taken into consideration. In order to link measurements made at different scale, you are asked to derive profiles of electric resistivity (or conductivity) and ice strength from the data that you have collected, using the air and brine volume fraction profiles as input parameters. A broader discussion of this approach can be found in the references that are provided with this module, but a brief explanation of the calculations required follows below.

### *Electric resistivity/conductivity from measurements of brine volume fraction*

As discussed in Eicken [2003] and Ingham et al. [2008] provided with the course materials, the resistivity of sea ice is largely governed by the volume fraction and connectivity of the brine, owing to the negligible contribution of the ice matrix itself which has a high resistivity or low conductivity  $\sigma$  that can be considered constant for the purposes of this study. A common approximation in describing the resistivity of porous composite media is based on Archie [1942], assuming that pore space is fully saturated with brine, such that the bulk resistivity ( $\rho$ ) of sea ice can be approximated by relating the resistivity of the pure brine  $\rho_b$  and the volume fraction of brine:

$$\rho = \phi^{-m} \rho_b \quad (6)$$

where  $\phi$  is the porosity (assumed here to equal  $V_b/V$ ) and  $m$  is an empirically determined exponent. The term  $\phi^{-m}$  is often referred to as the formation factor. The conductivity of the brine  $\sigma_b (=1/\rho_b)$  as a function of temperature  $T$  [ $^{\circ}\text{C}$ ] is given by

$$\sigma_b = -T \exp(0.5193 + 0.08755T) \quad (7).$$

The parameter  $m$  is dependent on the microstructure and in particular connectivity of the pores (see discussion in Ingham et al., 2008) and can be assumed to equal 1.89 in the context of this study.

Based on this simple Archie's model approach, please calculate the resistivity profile from the ice core data and plot it in conjunction with the other core profile data. You will examine this data further in the context of Module 3b; as part of this report for module 3a, please briefly discuss the shape of the profile in relation to other ice properties and key sources of error. Also, keep in mind that this data may help inform interpretation of the measurements of apparent conductivity made with the EM-31 as part of Module 2.

### *Ice strength from brine and gas volume fractions*

As discussed elsewhere in this course, the ability of an ice cover to bear a load is a key aspect of the services it provides to different users and key components of Arctic ecosystems. Module 5 discusses in more depth how the ability to bear loads is commonly expressed in terms of ice flexural strength, i.e., the maximum stress level  $\sigma_f$  that can be sustained without (catastrophic) failure of the ice cover. It is intuitively obvious that the air and brine contained in a volume of ice are not likely to contribute in any significant fashion to its strength and hence one finds that ice strength scales inversely with ice porosity. While a number of different models of varying degrees of complexity have been derived (see discussion in Eicken [2003]), a simple model that is effective in describing key aspects of sea ice behavior and is microstructurally justified describes  $\sigma_f$  as a function of  $(\phi)^{1/2}$  (see details in Timco and Johnston [2002] provided with the course materials):

$$\sigma_f = 1.76 \exp(-5.88\sqrt{\phi}) \quad (8).$$

Please compute the flexural strength profile based on your ice core measurements and derived variables and plot this in conjunction with the other core profile data. As outlined in the paper by Timco and Johnston [2002] comparing such derived strength values with in-situ measurements (e.g., with borehole jacks) is possible but not straightforward and will be discussed further in the course.

## GEOS/MSL695 – Field techniques in interdisciplinary sea-ice research

### Module 3b: Electrical resistivity of sea-ice

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#### *Aims and introductory comments*

The aim of this module is to provide you with a brief introduction into measurements of the electrical resistivity of sea-ice, give you an appreciation of the complexity of the resistivity structure, and illustrate how this is related to the microstructure of the ice.

#### *Reference material*

The following can be downloaded at [ftp.gi.alaska.edu /pub/eicken/G695/Module3](http://ftp.gi.alaska.edu/pub/eicken/G695/Module3)

- Buckley, R.G., Staines, M.P., Robinson, W.H., 1986. In situ measurements of the resistivity of Antarctic sea ice. *Cold Reg. Sci. Technol.*, **12**, 285–290.
- Ingham, M., Pringle, D. & Eicken, H., 2008. Cross-borehole resistivity tomography of sea ice. *Cold Reg. Sci. Technol.*, **52**, 263-277.;
- rhohmodels.doc

The following can be downloaded from [www.interpex.com/ix1d/ix1d.htm](http://www.interpex.com/ix1d/ix1d.htm)

- Interpex data analysis software.

#### *Introduction*

Most people have, at some stage, met Ohm's Law which relates the current,  $I$ , in a wire to the voltage (or potential difference),  $V$ , applied across its ends.  $I$  and  $V$  are related by the resistance of the wire,  $R$

$$V = IR \quad (1)$$

The resistance of a wire depends upon both the length and the cross-sectional area of the wire. A thicker wire can be thought of as allowing more space for the current to pass through and has a lower resistance. On the other hand, the longer the wire the more resistance it has to current passing through it. The resistance therefore, can be seen to depend upon the dimensions of the wire.

The resistivity,  $\rho$ , of a material, on the other hand, is an intrinsic property of the material. A copper wire has a different resistivity to an aluminium wire. If we had wires copper and aluminium which both had the same length and the same cross-section, their resistances would be different due to the fact that they are made of different materials. For the simple case of a wire the resistance and resistivity are related by

$$R = \rho \frac{L}{A} \quad (2)$$

where  $L$  is the length of the wire and  $A$  the cross-sectional area.

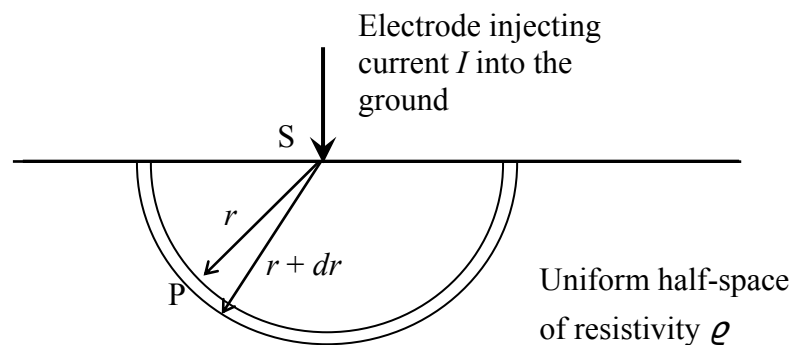
In geophysics measurement of the resistivity of a sub-surface structure is therefore one means of remotely identifying what the material is. In most cases, near the surface, the bulk

resistivity is in fact controlled by how much fluid is present in the ground. Simple resistivity surveys of the kind that you will do are therefore much used in hydrology for identifying and studying the distribution of groundwater.

In general, sea ice has a much higher resistivity than sea water. In fact sea water has one of the lowest resistivities of any substance that occurs naturally in bulk. The first resistivity measurements on sea ice were therefore aimed at using the contrast between the resistivity of the ice and the underlying sea water to determine the thickness of the ice. As you will see, such measurements were unsuccessful (e.g. Buckley et al., 1986) and measurements of sea ice resistivity are now being used as a means of trying to understand the microstructure of the ice - in other words, how the solid ice and brine components that make up sea ice interact and interconnect.

### *Theory of resistivity measurements*

We will consider first the case of an electric current  $I$  which is injected into a half-space of uniform resistivity  $\rho$  at a single surface point S. As the resistivity is the same in all directions symmetry dictates the current that will spread out uniformly in all directions so that at a distance  $r$  from S it passes through a hemisphere of surface area  $2\pi r^2$ . Because the current is perpendicular to this surface, the surface is one over which the electric potential (voltage) is a constant - it is an equipotential surface. Suppose that the electric potential on a surface a distance  $r$  away from S is  $V$ . As it is a difference in potential that causes a current the potential on a second surface at a distance  $r + dr$  must be slightly different - say  $V + dV$ .



As we saw above, when a current passes through a wire of resistivity  $\rho$ , cross-sectional area  $A$ , and length  $L$ , the electrical resistance is related to the resistivity and the dimensions of the wire by

$$R = \rho \frac{L}{A} \quad (3).$$

By analogy with this, for the material between the two hemispheres above,  $L = dr$  and  $A = 2\pi r^2$  and the resistance may be written as

$$R = \rho \frac{dr}{2\pi r^2} \quad (4).$$

The difference in potential between the hemispheres can be expressed in terms of Ohm's Law.

$$\Delta V = RI \quad (5).$$

Noting that current goes from high potential to low potential, the variation of potential with distance  $r$  from S can be derived:

$$V - (V + dV) = -dV = \rho I \frac{dr}{2\pi.r^2} \quad (6)$$

showing that the potential varies with distance from S so that

$$\frac{dV}{dr} = - \rho \frac{I}{2\pi.r^2} \quad (7).$$

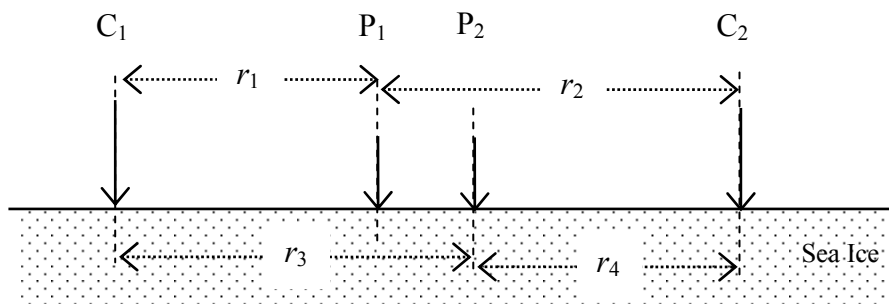
An analytic expression for  $V$ , the potential at point P due to the current injected at S, can be found by integrating this equation. This gives

$$V = \rho \frac{I}{2\pi.r} + \text{constant} \quad (8).$$

Assuming that if P is infinitely far from S the potential will be zero, shows that the constant in the above expression is zero. Therefore the variation of V with distance from S is given by

$$V = \rho \frac{I}{2\pi.r} \quad (10).$$

Now consider a situation where a current  $I$  is injected into the ground (ice) at an electrode  $C_1$ , taken out of the ground at an electrode  $C_2$  and the potential difference  $\Delta V$  is measured between two further electrodes  $P_1$  and  $P_2$ .



Following the theory above, the potential at  $P_1$  will be the sum of the potential due to current being put into the ground at  $C_1$  plus the potential due to the current being taken out of the ground at  $C_2$

$$V_1 = \rho \frac{I}{2\pi.r_1} - \rho \frac{I}{2\pi.r_2} \quad (11).$$

The second term has a minus sign because the current is being taken from the ground.

Similarly, the potential at  $P_2$  will be

$$V_2 = \rho \frac{I}{2\pi.r_3} - \rho \frac{I}{2\pi.r_4} \quad (12)$$

and the measured potential difference between  $P_1$  and  $P_2$  will be

$$\Delta V = V_1 - V_2 = \rho \frac{1}{2\pi} \left( \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right) \quad (13).$$

It follows that measuring  $\Delta V$  for known values of the current  $I$ , and electrode separations  $r_1$ ,  $r_2$ ,  $r_3$  and  $r_4$  allows the uniform resistivity of the ground  $\rho$  to be calculated.

A half-space of uniform resistivity does not of course occur in nature. However, it is still standard practice to measure  $\Delta V$ ,  $I$ ,  $r_1$ ,  $r_2$ ,  $r_3$  and  $r_4$  and to express the result in terms of an *apparent resistivity*

$$\rho_a = \frac{2\pi R}{G} \quad (14)$$

where  $R$  has been used for the ratio of the measured potential difference and the current

$(\Delta V / I)$  and  $G$  is the geometric factor  $\left( \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right)$  depending on the positions of the

electrodes.

A dc resistivity sounding involves making a series of measurements of  $\rho_a$  for different electrode positions. Typically this involves gradually moving the current electrodes  $C_1$  and  $C_2$  further apart so that the current penetrates deeper and deeper into the subsurface. Because it is possible, for any actual resistivity structure - for example a series of layers of different resistivity - to calculate theoretically how  $\rho_a$  will depend on electrode positions, such a series of measurements can then be modelled and interpreted in terms of the actual resistivity structure of the ground.

### ***Instrumentation and measurements***

You will make a resistivity sounding on the sea-ice. For ice that is of the order of 1.5 m thick it is necessary to make measurements which will cover the whole thickness of the ice. Hence you will start with current electrodes which are only 0.3 m apart and make a series of measurements out to a current electrode separation of 12 m.

For electrodes you will use stainless steel screws inserted into the ice to a depth of about 2 cm. You will connect the resistivity meter to these using crocodile clips on the ends of cables. You will use an electrode geometry known as the *Wenner array*. In this the electrodes are all co-linear and are equally spaced with a basic spacing which is denoted  $a$ . You will need to draw up in your field book a table for recording measurements for electrode separations of  $a = 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1, 1.5, 2, 3$  and 4 m. It may be useful to make a table with current and potential electrode positions for each spacing.

The instrument that you will use is an ABEM resistivity meter. The instrument has 4 terminals, labelled  $C_1$  and  $C_2$  for the current and  $P_1$  and  $P_2$  for the potential, to which the electrodes are connected. The magnitude of the current you wish to use is selectable (10 mA is sufficient) as is the number of separate readings for any measurement that you wish to average (4 is suitable). Once the electrodes have been connected for a given value of  $a$ , make sure that the measurement selected is  $R$  (for the ratio of potential difference to current), turn on the instrument by flicking the switch to the right, and press the red button. The instrument will now cycle through 4 readings which appear on the LCD screen in turn accompanied by an audible beep. The final reading, which is the one you should note down in your table, has slightly longer beep. When you have copied this reading down, make sure that you **TURN OFF THE INSTRUMENT** before moving the electrode connections.

Although the technique is often referred to as dc (direct current) resistivity sounding, in practice the current is a somewhat randomized square wave which reverses in direction at a low frequency. This is standard for such measurements and is done because of the so-called "self potential" of the subsurface - some materials show a voltage between the electrodes  $P_1$  and  $P_2$  even if there is no current induced through  $C_1$  and  $C_2$ .

## ***Report and analysis***

- (1) Calculate the appropriate geometrical factor  $G$  for a Wenner array and convert your table of readings of  $R$  into a series of values of  $\rho_a$  for different values of  $a$ .
- (2) Use the Interpretex 1-D Sounding software to input the data and produce 1-D models of the resistivity structure. Produce models which fit the data both with a minimum number of layers, and with about 12 layers. Make a note of these models.
- (3) Compare the apparent ice thickness derived from the resistivity data with that obtained from direct measurements on the ice core. Explain the difference between these values (you may need to refer to both Buckley et al. (1986) and Ingham et al. (2008)).
- (4) Download the file rhohmodels.doc. This shows images of the horizontal component of the resistivity as measured between two boreholes in the sea-ice on three separate occasions in April, May and June 2006. From the image for May (for which the state of the sea-ice should most closely correspond to now) construct an (approximate) plot of how  $\rho_H$ , the horizontal component of the resistivity, varies with depth in the ice (the dashed line shows the measured ice thickness at the time of measurement).
- (5) Using your model of the Wenner sounding which has  $\sim 12$  layers match features in the two resistivity profiles so that they occur at the same depth (i.e. stretch your Wenner model so that the depths of particular features match those in the plot of  $\rho_H$  with depth).
- (6) From your match of the two plots calculate how the vertical component of the resistivity  $\rho_V$ , the vertical resistivity component, varies with depth. How can you explain the differences between  $\rho_H$  and  $\rho_V$  in terms of the microstructure of the ice? You may also wish to consider the variation with depth of the brine resistivity  $\rho_b$  and your values of ice resistivity calculated theoretically in Module 3a using Archie's Law.

The report should contain the following parts:

- A) Description of the Wenner measurements.
- B) Results of the Wenner measurements (i) presented both in tabular form and graphically as a plot of  $\log_{10}(\rho_a)$  v.  $\log_{10}(a)$ ; (ii) the derived layered models.
- C) The method and results of your comparison of the Wenner model with the variation of  $\rho_H$  with depth derived from the borehole measurements, including your derived variation of  $\rho_V$  with depth.
- D) Discussion - this should demonstrate that you have an understanding of the complexity of the resistivity structure of sea-ice and how it relates to the microstructure. Include also, from a comparison of the three borehole images, a discussion on how you infer that the microstructure of the ice changes as it warms during the spring.