Multi-geometry EM Sounding of a Freshwater Lagoon

Richard S. Taylor, Dualem Inc.
J. Scott Holladay, Geosensors Inc.
David Lalonde, Geosensors Inc.

SAGEEP EM Workshop, Charleston SC, April 2011

On behalf of my co-authors Scott Holladay and Dave Lalonde, let me express my thanks to the organizers of this SAGEEP workshop for the opportunity to present some of our recent work with new instrumentation.

Preview

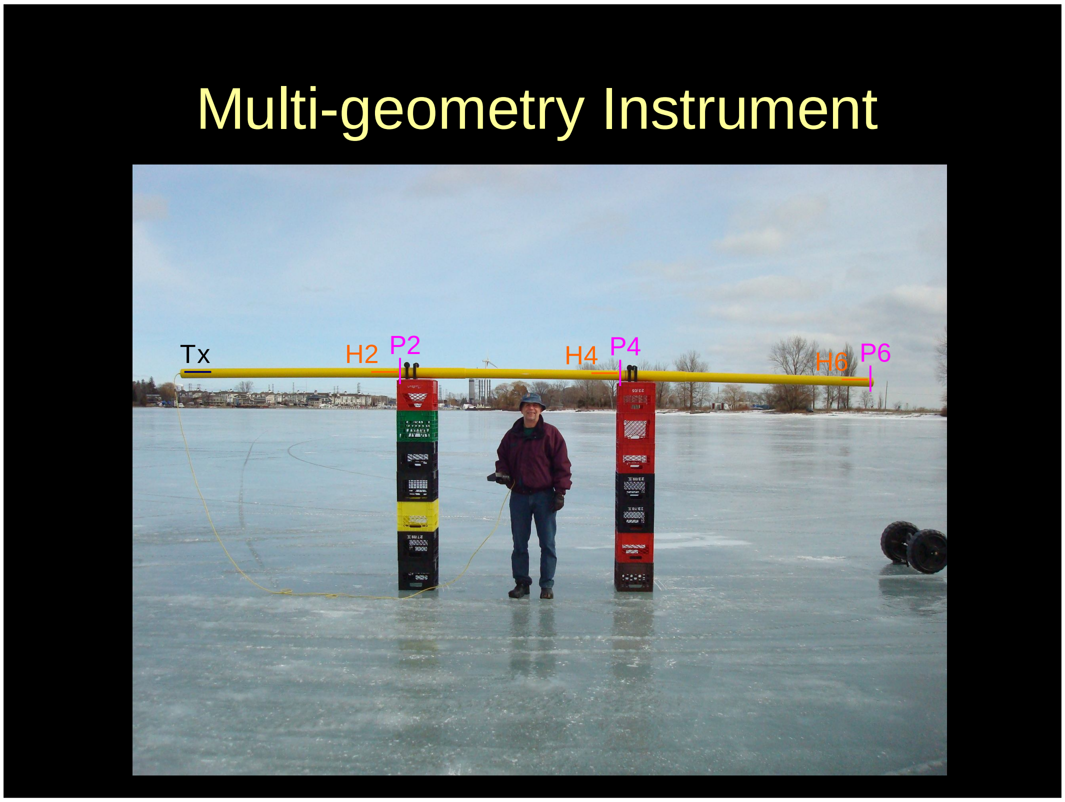
Instrumentation

Freshwater Lagoon Site

Characteristics from Traverses

Soundings and Interpretation

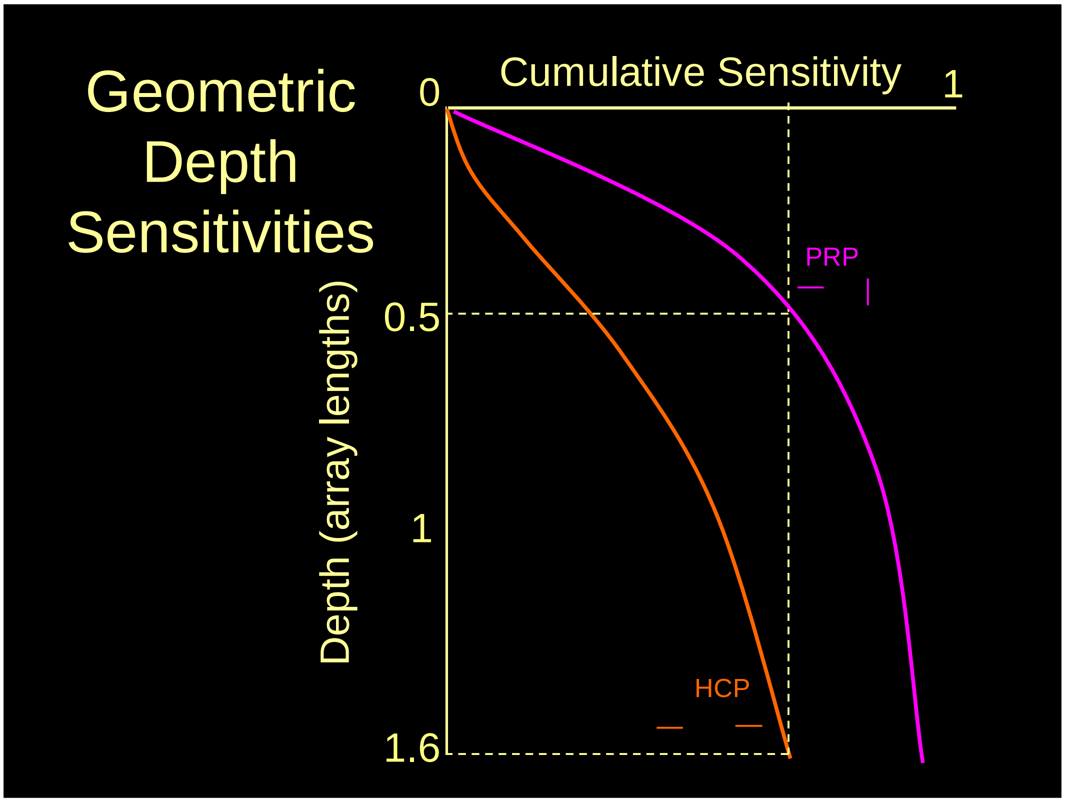
Our presentation will begin with a description of new EM instrumentation used to gather data at Frenchman’s Bay, a freshwater lagoon by Lake Ontario.
The bay is 30 km northeast of downtown Toronto, and receives conductive run-off from a temperate urban environment.
In early March of this year, the bay was covered with thick ice, on which we took profile- and sounding-measurements.
From these, we interpreted layered conductivity in the lagoon.



Here is the multi-geometry instrument we used, on sounding supports over the ice-covered lagoon.

The instrument is housed in a composite tube. One end of the tube has a horizontal-coil transmitter. There are 3 pairs of receivers at 2-, 4- and 6-m separation from the transmitter. For each pair, one receiver is a horizontal coil that is coplanar with the transmitter, and the other receiver is a vertical coil whose axis intersects the transmitter.

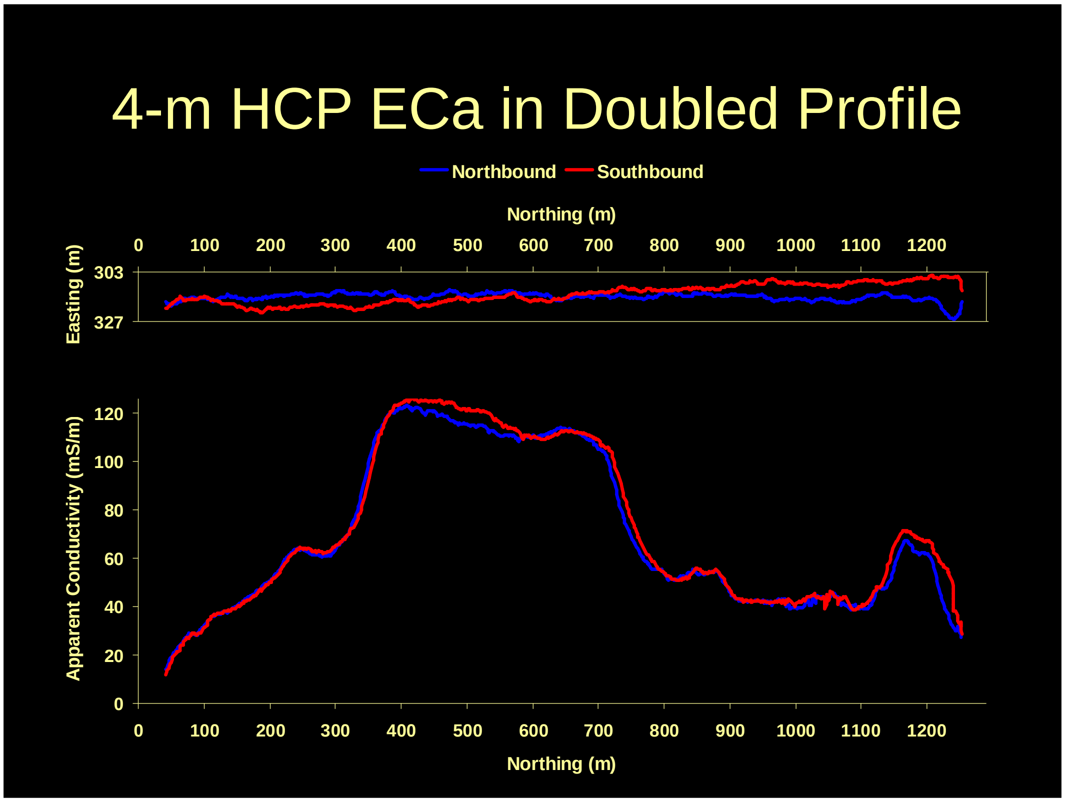
Thus, the instrument contains 6 arrays, (i) 2-m horizontal coplanar (HCP), (ii) 2-m perpendicular (PRP), (iii) 4-m HCP, (iv) 4-m PRP, (v) 6-m HCP and (vi) 6-m PRP.



The instrument incorporates multiple arrays to provide multiple depths of exploration.

A popular measure of depth of exploration (DOE) is the depth to which an array accumulates 70 % of its total sensitivity. By this measure at low induction number (LIN), the DOE of a PRP array is about half the array length, and the DOE of an HCP array is about 1.6 array lengths.

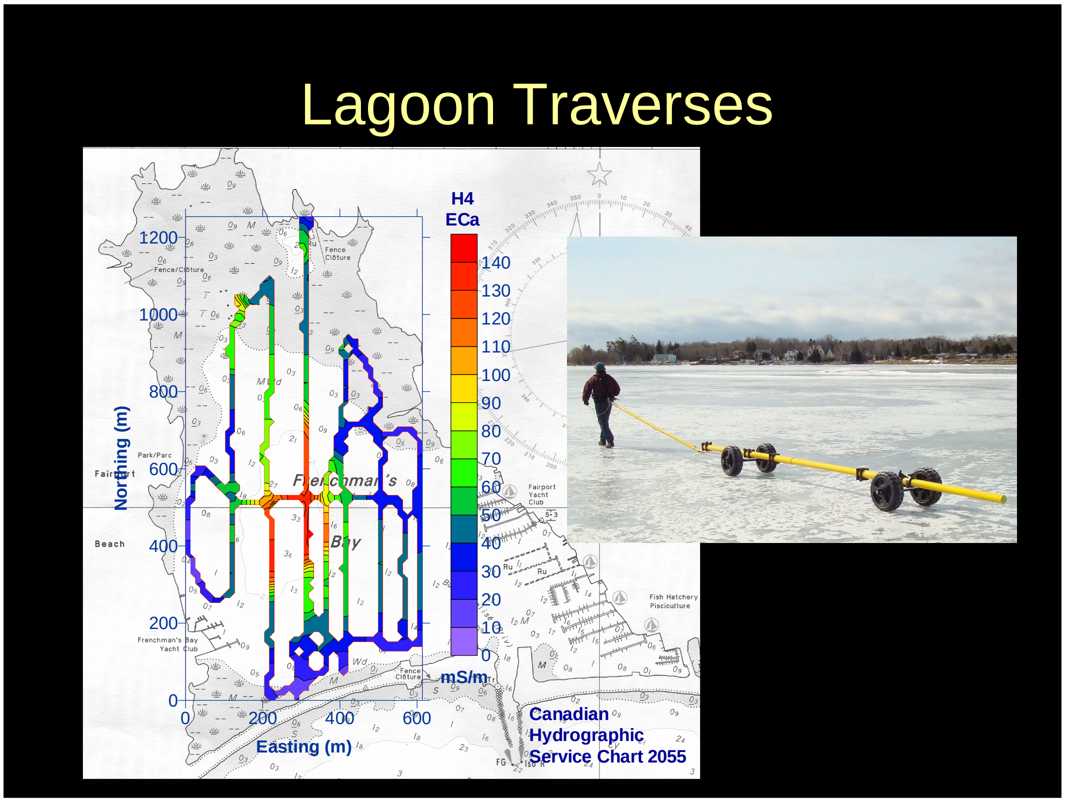
Accordingly, the instrument used here has 6 distinct LIN DOEs, ranging from 1 m to 10 m.



Here are the 4-m HCP apparent conductivities along 315 E in profile, for both the northbound and southbound traverses.

There is close correspondence between the data on the two traverses, especially if allowance is made for a minor lag of data relative to the traverse direction. The lag likely results from the GPS reporting to the internal logger slightly more promptly than the EM.

There is a little less correspondence over the local deepening near the north end of the line, but this likely results from lateral deviation from the line as the surveying platform was turned. The traverses cross at about 700 N, and at the southern end of the line; in both places, traverse measurements are nearly the same.



Frenchman’s Bay is a freshwater lagoon separated by a sand bar from Lake Ontario. The bar is cut by a channel for pleasure boats.

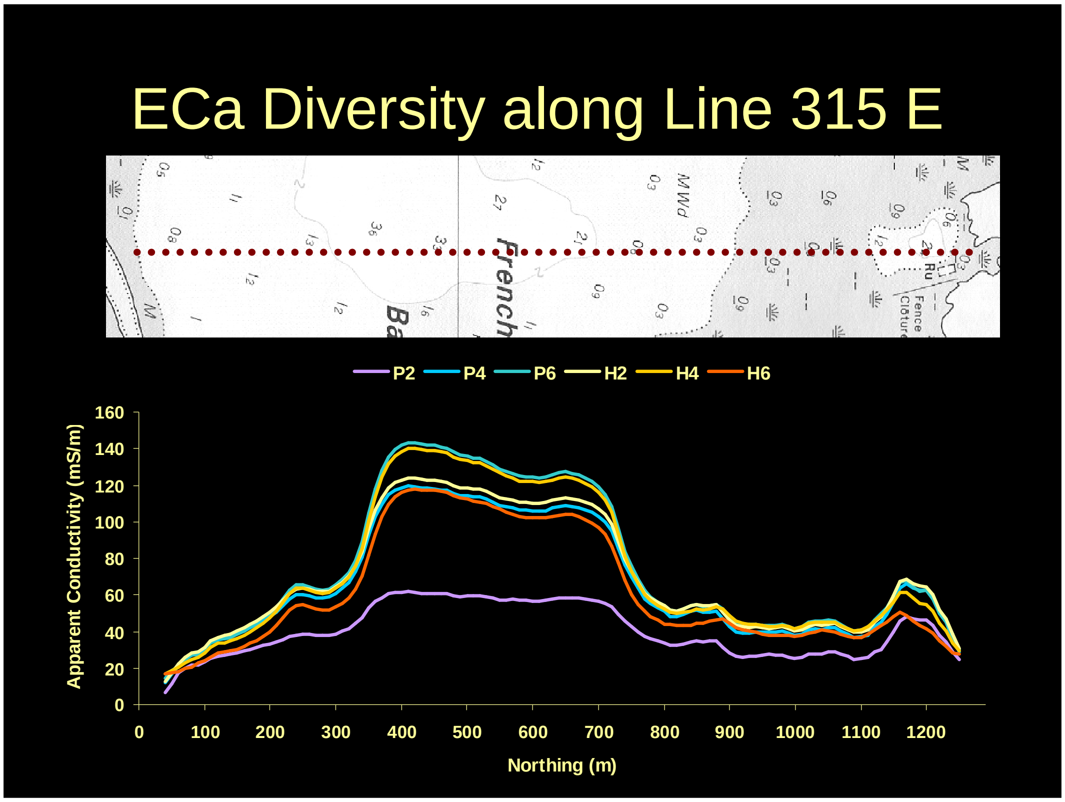
The northern end of the bay is marshy, and the maximum depth of water in the bay is less than 4 m. Part of the shore is parkland, but the lagoon is surrounded by city and receives urban runoff. For example, 17 lanes of highway lie within 200 m of the head of the bay, which receive frequent applications of road salt through the winter months.

On March 5, we mounted the multi-geometry instrument on wheels and traversed the ice-covered lagoon on several lines. The surveyor was guided by positional information displayed from a differential GPS receiver in the instrument.

The lines are rendered in color, according to the apparent conductivity measured by the 4-m HCP array. There appear to be several factors that influence apparent conductivity. Conductivities tend to be lower around the margins of the lagoon and near the channel. At 10- to 20-mS/m, they are similar to apparent conductivities measured the previous summer through and just outside the channel.

A zone of elevated apparent-conductivity extends from the northwestern corner of the surveyed area into the central portion of the bay, and values tend to be highest where the water depth exceeds 3 m. Also noteworthy is a small zone of elevated conductivity near the northern end of the survey area, which coincides with a local deepening of the lagoon to more than 2 m.

To assess the repeatability of measurements, the line around 315 E was traversed twice, northbound then southbound. From north to south, this line crosses the local deep, some shallow marsh, the deepest area with highest conductivity, and ends just north of the bar.

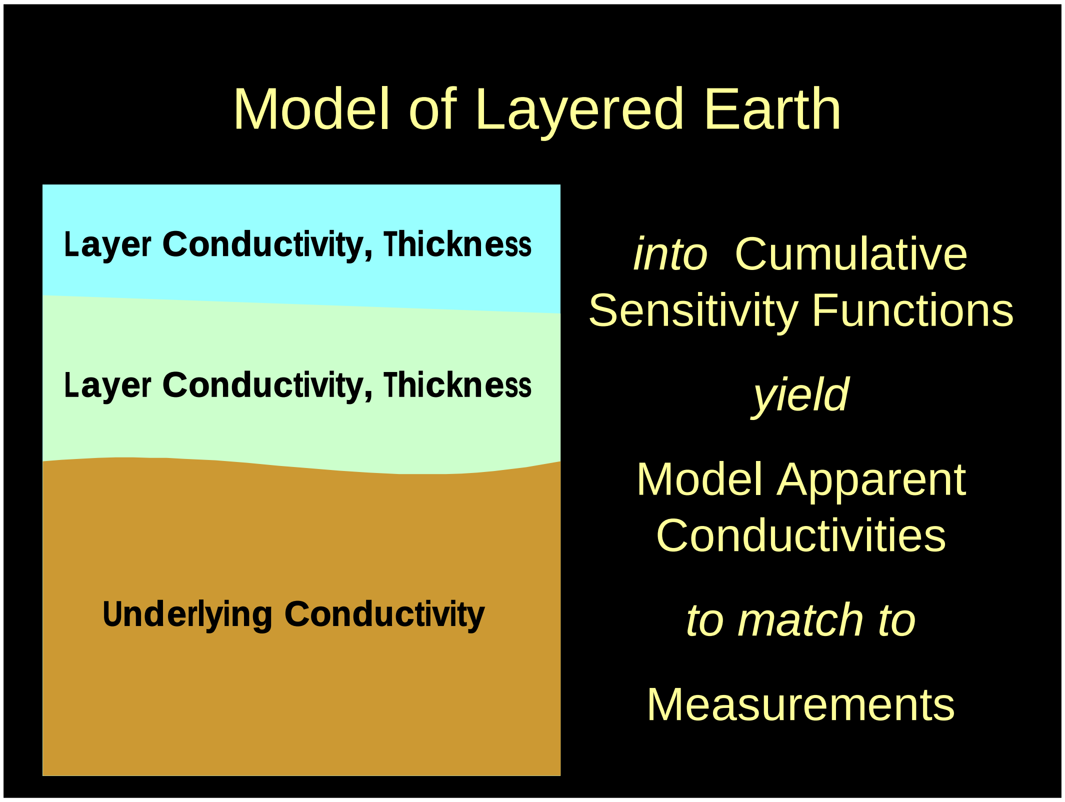


Here are the 6 apparent conductivities measured along line 315 E, after averaging northbound and southbound values. The 4-m HCP values are shown in orange; they are similar to the apparent conductivities from the 6-m PRP array, shown in turquoise, and both tend to be higher than the values measured with the other arrays.

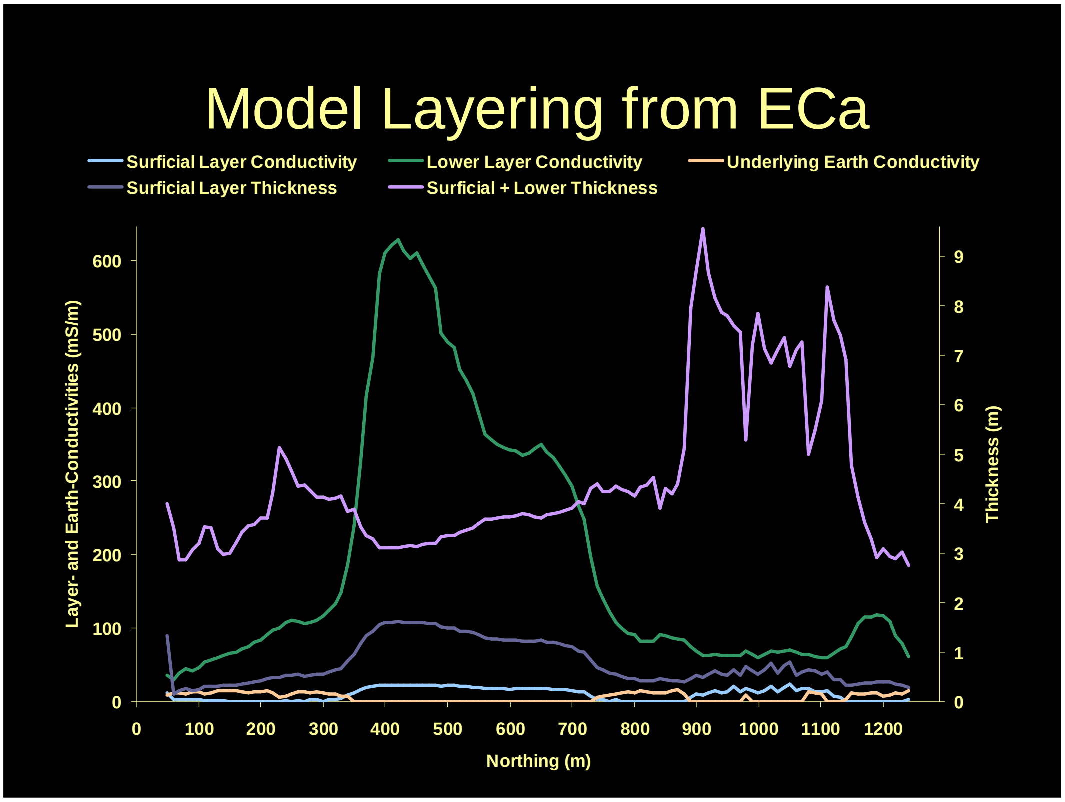
Arrays with less DOE than the 4-m HCP are the 2-m PRP, 4-m PRP and 2-m HCP. Lower values measured with these arrays are attributable to their increased sensitivity to shallower ice and lagoon water.

The 6-m HCP array has substantially greater DOE than the 4-m HCP array. Lower values measured by the 6-m array, shown in red, suggest that less conductive material underlies relatively conductive material at mid-depth.

The diversity of the apparent conductivities measured with the various arrays suggests that reasonable estimates might be made for parameters of conductive layering in the lagoon.



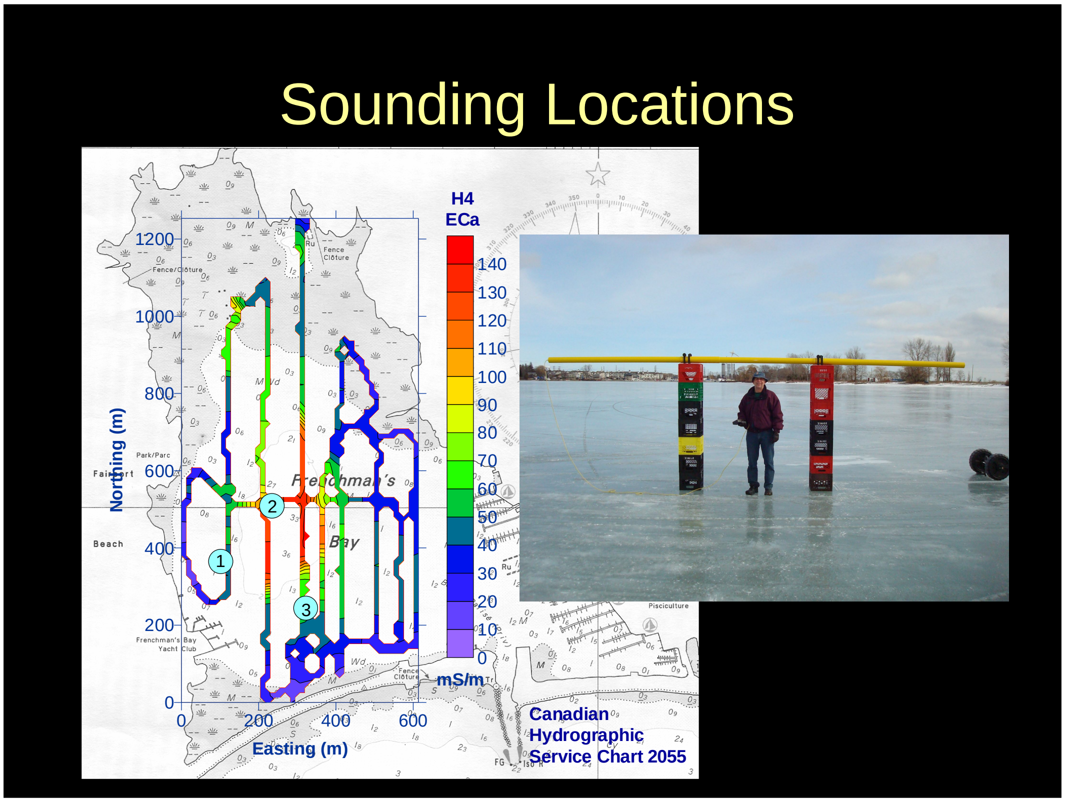
If we represent the earth by a model that has relatively few parameters, we can use our measurements to estimate realistic values for the parameters.
Here, we represent the earth by a model that has 5 parameters, i.e. conductivity of a surficial layer, thickness of the layer, the conductivity of a lower layer, the thickness of the lower layer, and conductivity of the earth underlying the layers.
To estimate realistic values for these parameters, we search for parameter values that, when plugged into our cumulative sensitivity functions, yield apparent conductivities that most closely match the apparent conductivities we measured.



Here are the parameter values that provide close matches to our measurements. The conductivities of the surficial layer and underlying earth range from zero to 25 mS/m. The conductivity of the layer in-between ranges from 30 to 600 mS/m.

Over most of the profile, estimates of surficial-layer thickness are less than 1 m, roughly in agreement with ice thickness measured at several points with an auger. Estimates exceed 1 m, as well as auger measurements, where conductivities are highest.

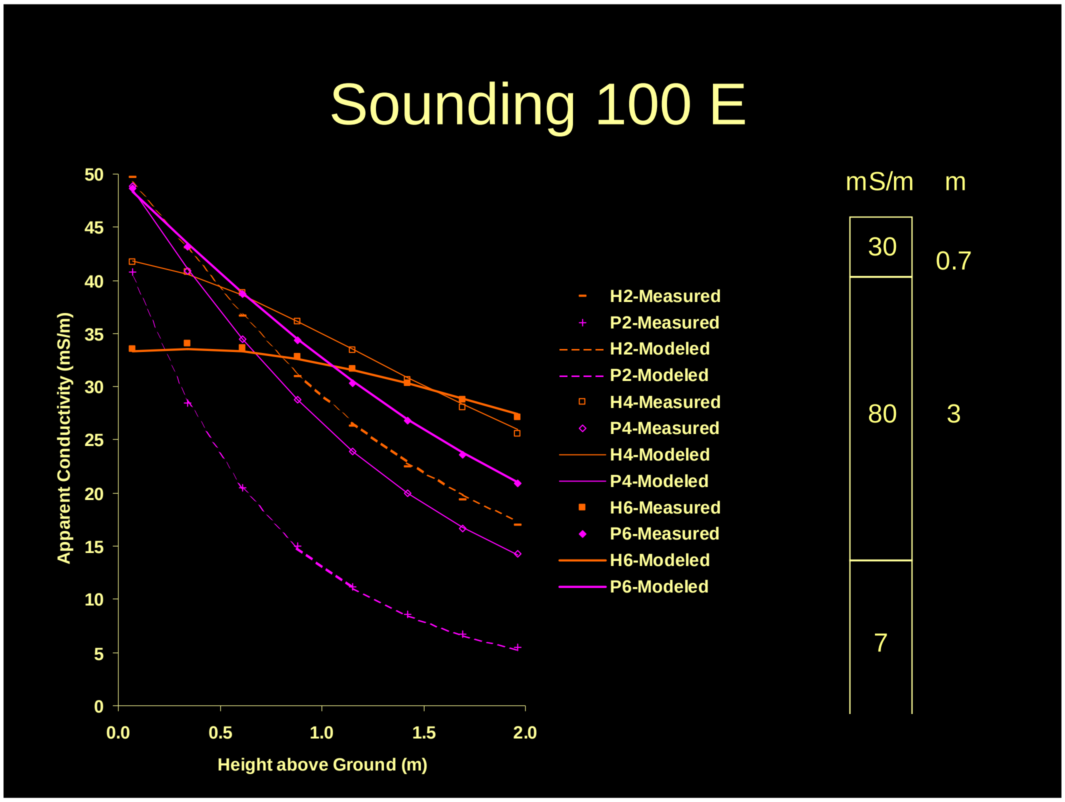
Estimates of surficial layer thickness are added to estimates of lower-layer thickness to yield combined thickness, which ranges from 3 m to 9 m. Larger estimates show greater variability.



In addition to the traverses, we also performed vertical soundings at 3 sites. Site 1 was on the western edge of the zone of elevated conductivity, site 2 was in the area of high conductivity, and site 3 was on the profile we are examining in detail, but to the south of the highest conductivities.

The vertical-sounding at each site consisted of making measurements at 8 heights. The lowest measurement was made with the sensor on the ice. Height was increased by placing the instrument on two stacks of rented (not liberated) crates. The highest measurement was at 2 m.

Changing the height of measurement changes the sensitivity of the arrays to the given depth-intervals occupied by air, ice, water and earth.



Apparent conductivities measured in the soundings are shown by the individual symbols. For the sounding at 100 E, on the western edge of the zone of elevated conductivity, on-ground measurements ranged from 34- to 50-mS/m. The lowest value was measured by the deepest-sounding 6-m HCP array. The highest values were measured with the 2-m HCP and 6-m PRP arrays, which have intermediate depths of sounding.

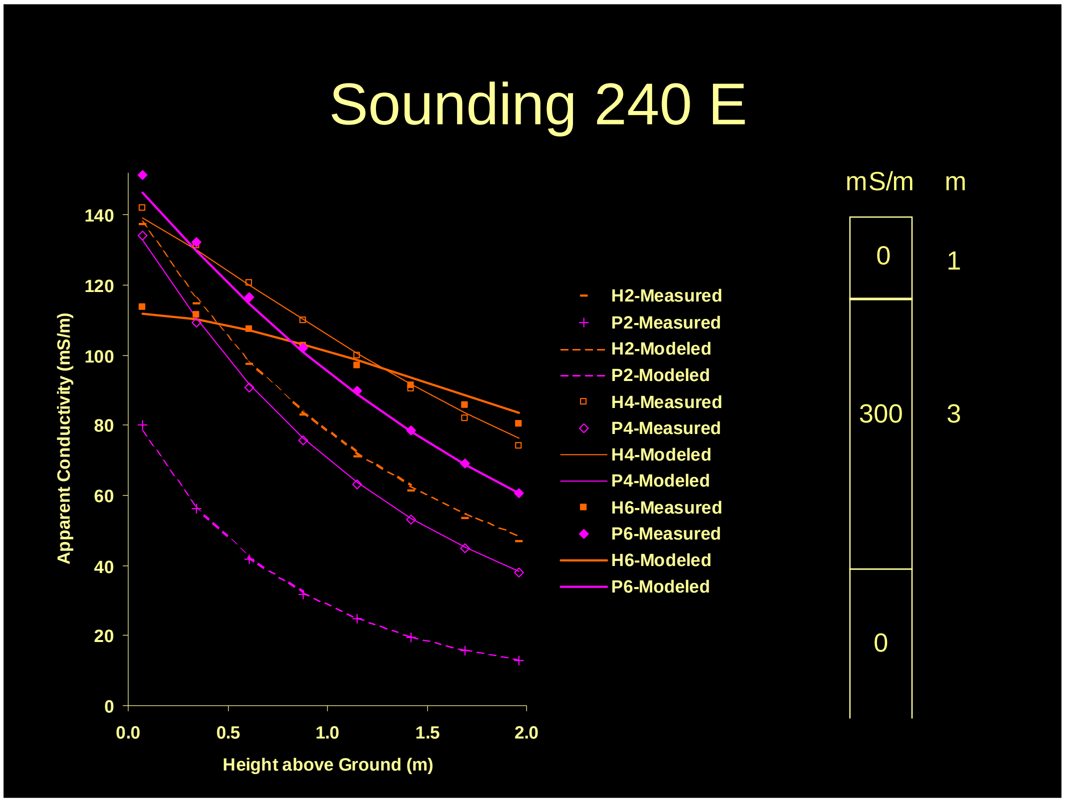
The plotted curves show apparent conductivities that would be observed from on-ground to 2-m height over a model layered-earth with the parameters shown to the right. The plot shows that there is very close agreement between the modeled and measured apparent conductivities.

The model has a surficial layer with 30 mS/m conductivity and 0.7 m thickness, a lower layer with 80 mS/m conductivity and 3 m thickness, and an underlying earth with 7 mS/m conductivity.

The 0.7-m thickness of the surficial layer is somewhat greater than the ice thickness of about 0.5 m at the sounding sites as determined by auger. The surficial conductivity of 30 mS/m is greater than a value of less than 10 mS/m that might be expected for a combination of ice and fresh water.

The lower layer has a conductivity of 80 mS/m and a thickness of 3 m. The hydrographic chart indicates that water depth at this location is less than 2 m, so the lower layer appears to combine about 1-m of water and 2-m of bay-bottom material. Conductivity of 80 mS/m suggests the fluid in the layer contains a significant amount of dissolved solids.

The underlying earth has 7 mS/m conductivity, which suggests the material at this depth is sediment saturated with relatively fresh lake-water, or low-porosity bedrock.



For the sounding at 240 E, in the zone of elevated conductivity, on-ground measurements ranged from 80- to 150-mS/m. The lowest value was measured by the shallowest-sounding 2-m PRP array. The highest values were measured with the 2-m HCP, 4-m HCP and 6-m PRP arrays, which have intermediate depths of sounding.

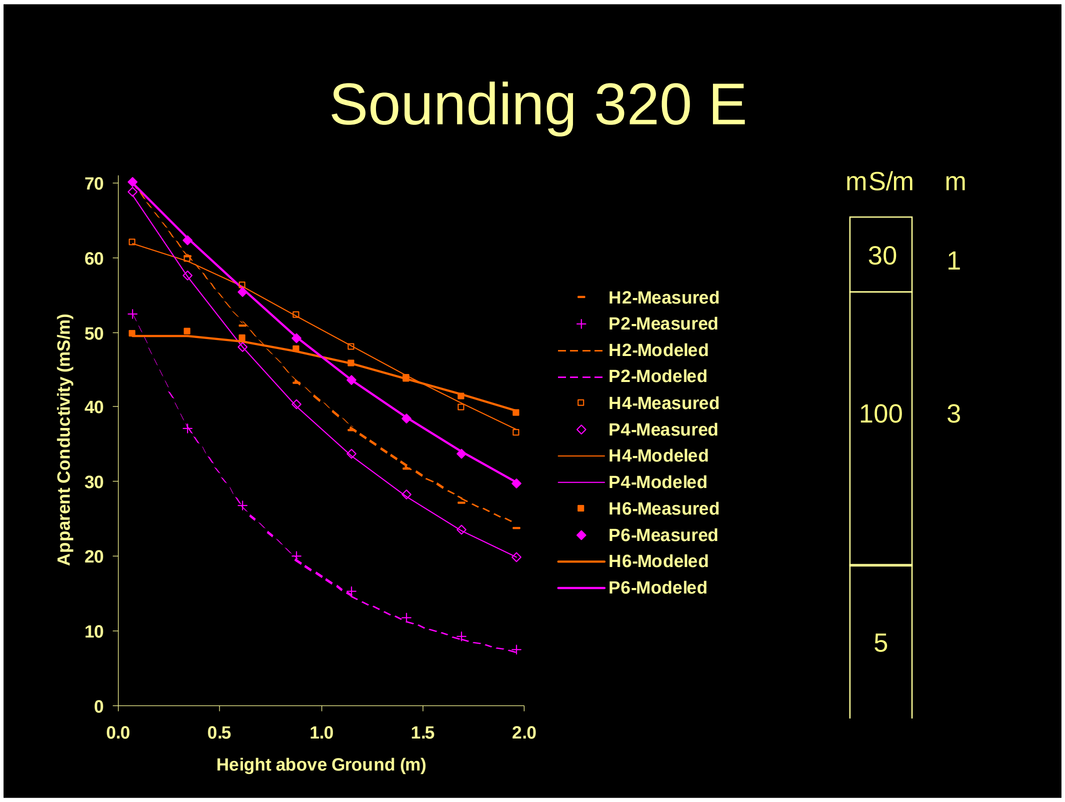
The plot, with measurements displayed as symbols and model output displayed as curves, shows that there is very close agreement between the modeled and measured apparent conductivities.

The model has a surficial layer with 0 mS/m conductivity and 1 m thickness, a lower layer with 300 mS/m conductivity and 3 m thickness, and an underlying earth with 0 mS/m conductivity.

The model suggests that a lower layer of high conductivity and substantial thickness dominates the response. Constraining the conductivities of the upper layer and underlying earth to a minimum of 10 mS/m has no significant effect on the fit of model-output to measurements.

Again, the 1-m thickness of the upper layer corresponds the augered thickness of the ice plus some underlying fresh water. The high conductivity of the lower layer likely results from dissolved solids in brine that has ponded at depth in the lagoon. The hydrographic chart indicates water depth at this site is about 3 m, so the highly conductive layer seems to extend somewhat into sediments.

As at the previous site, the low conductivity of the underlying earth might be due to fresh, cold porewater and/or decreased porosity.

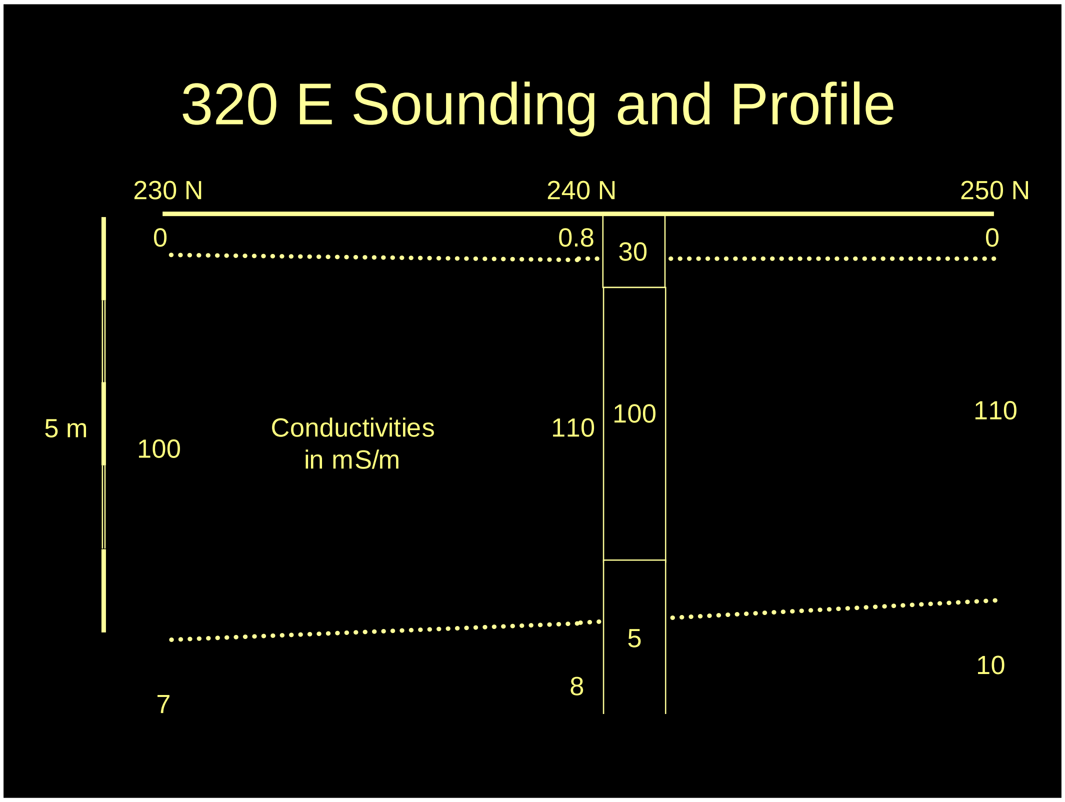


For the sounding at 320 E, at the southern edge of the zone of elevated conductivity, on-ground measurements ranged from 50- to 70-mS/m. The lowest value was measured by the deepest-sounding 6-m HCP array, followed closely by the shallowest-sounding 2-m PRP array. The highest values were measured with the 6-m PRP and 2-m HCP arrays, which have intermediate depths of sounding.

The plot shows that there is very close agreement between the modeled and measured apparent conductivities.

The model is very similar to that for the sounding on the western edge of the highly conductive zone. Here, a surficial layer of 30 mS/m conductivity has 1-m thickness, a lower layer of 100 mS/m conductivity has 3-m thickness, and the underlying earth has 5 mS/m conductivity.

As at previous sites, the upper layer seems to incorporate ice and some fresh water, and the underlying earth likely corresponds to a horizon of fresh, cold porewater and/or decreased porosity. The hydrographic chart gives 1.2 m as the water depth at this site, so the lower layer of elevated conductivity seems to be mostly sediment, topped by some brackish water.

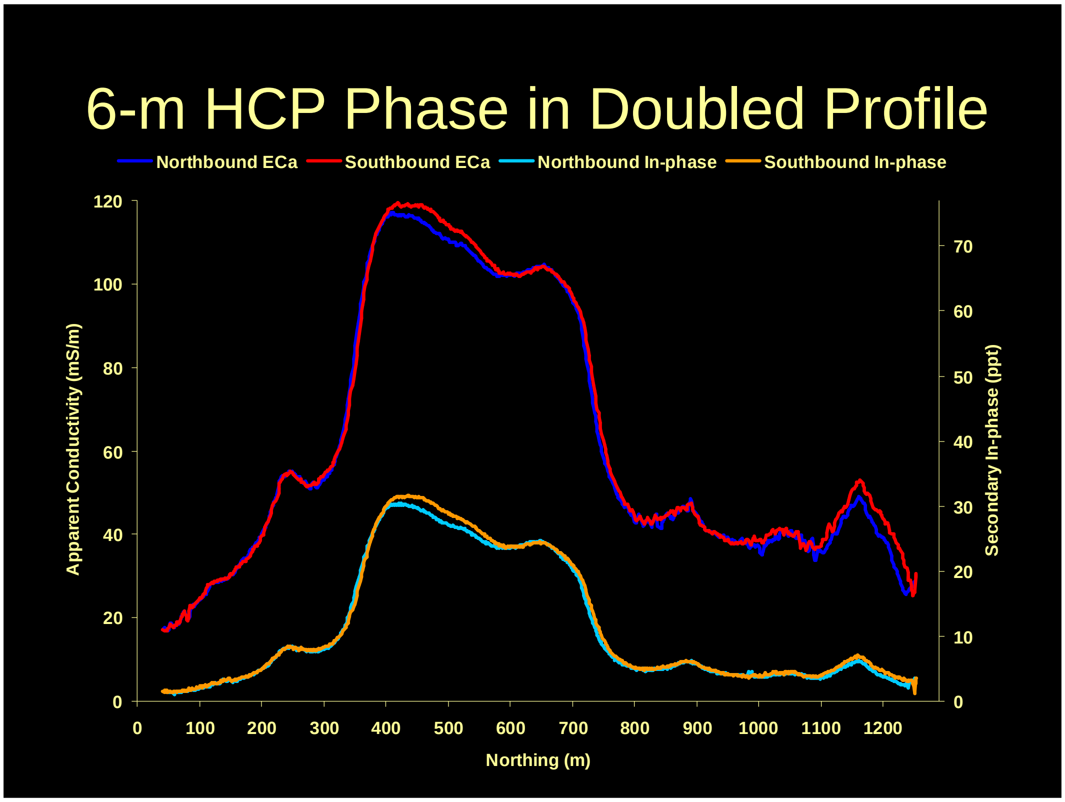


The sounding at 320 E lies essentially along the 315 E profile, at 241 N. The model for the sounding is plotted again here, along with the models for profile values at 230 N, 240 N and 250 N.

The estimates of the sounding model are likely to be more refined and robust than those of the profile models, as the sounding has the benefit of measurements at 8 heights, both above and below the traverse height.

The sounding model seems to incorporate about equal amounts of ice and water in the upper layer, for which it estimates a conductivity of 30 mS/m. The profile models estimate thickness and conductivity for the upper layer closer to what we might expect for ice-only.

While the profile models assign less conductivity and thickness to the upper layer, they estimate slightly higher conductivities for the lower layer and underlying earth, and slightly greater thickness to the lower layer. Furthermore, the sounding estimates provide about as good a fit as the profile estimates to the profile measurements, suggesting that the profile models are substantially equivalent to the sounding model.



When James R. Wait quantified LIN depth sensitivity, he suggested that it would be valid if in-phase amplitude was no more than 10 % of quadrature amplitude.

Here are the apparent-conductivity and in-phase measurements from the 6-m HCP array along the doubled profile. As customary, apparent conductivity has been scaled linearly from quadrature amplitude, and on this chart the scaling of apparent conductivity and in-phase are the same in ppt.

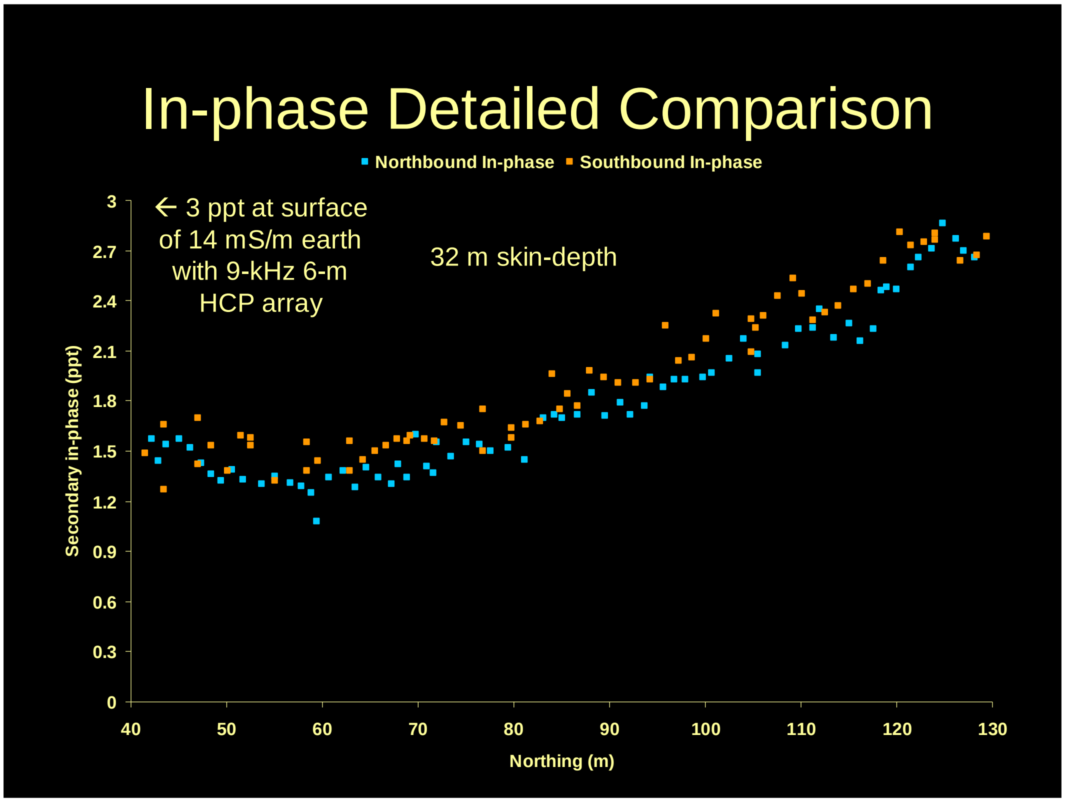
Along the profile, in-phase ranges from 12- to 41-% of quadrature. Thus, all the 6-m HCP measurements exceed Wait's LIN guideline, with the following two consequences:

1. Apparent conductivity scaled from quadrature will significantly understate actual conductivity, and;

2. Interpretation of depth based on the LIN sensitivity function may be distorted.

Interpretation of conductivity and depth using both in-phase and quadrature would be more accurate, provided that the quality of the in-phase- and quadrature-data are comparable.

Visual inspection of the doubled-profile data suggests that the in-phase measurements are as repeatable as the quadrature measurements. To get a better idea of in-phase repeatability, let's look in detail at the southernmost measurements, where the northbound- and southbound-traverses effectively overlap.

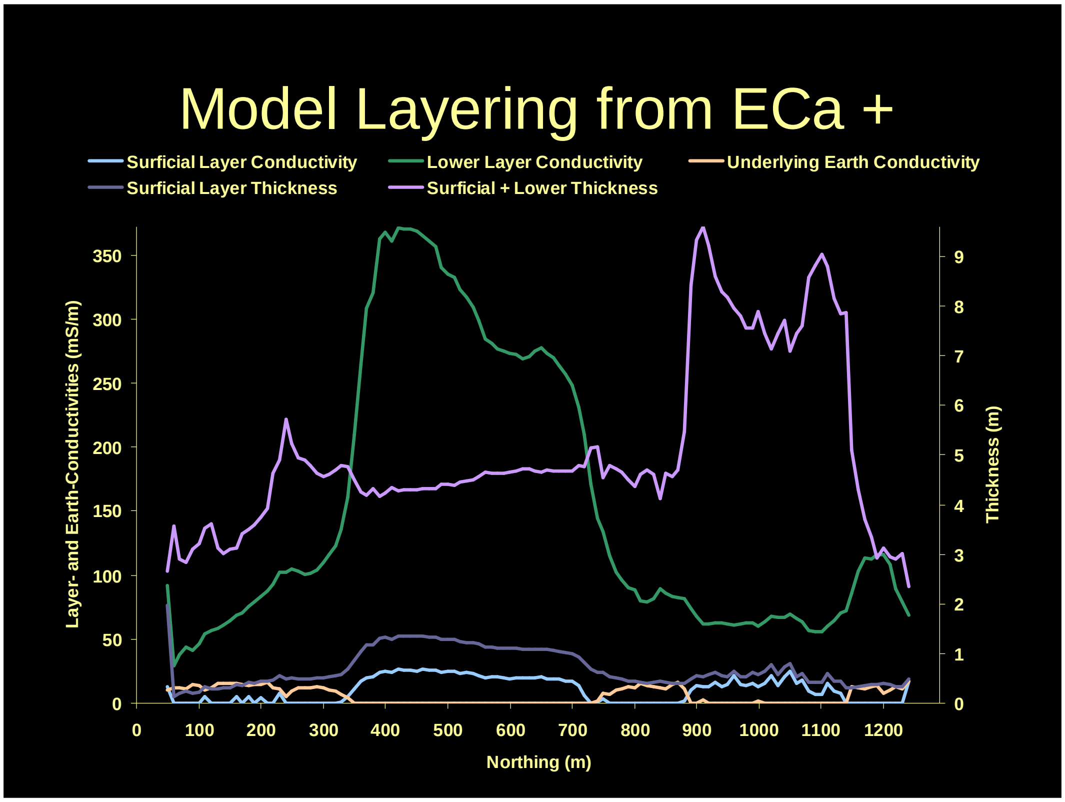


The northbound measurements were taken at the start of the doubled traverse, and the southbound measurements were made at the end, about half-an-hour later.

The error-envelope incorporating all environmental and instrumental factors appears to be about 0.3 ppt.

For perspective, a signal of 3 ppt would be about 10-times the noise level. The 6-m HCP array used here, at its operating frequency 9 kHz, would elicit a 3 ppt in-phase response from the surface of a 14 mS/m earth. The skin depth of the 9 kHz field in an earth of such conductivity would be 32 m.

Thus, we might expect this array to provide useable in-phase if ground conductivity is at least 14 mS/m, and the depth of exploration using in-phase will be substantial. For example, the skin depth remains greater than 10 m for an earth of 140 mS/m conductivity.



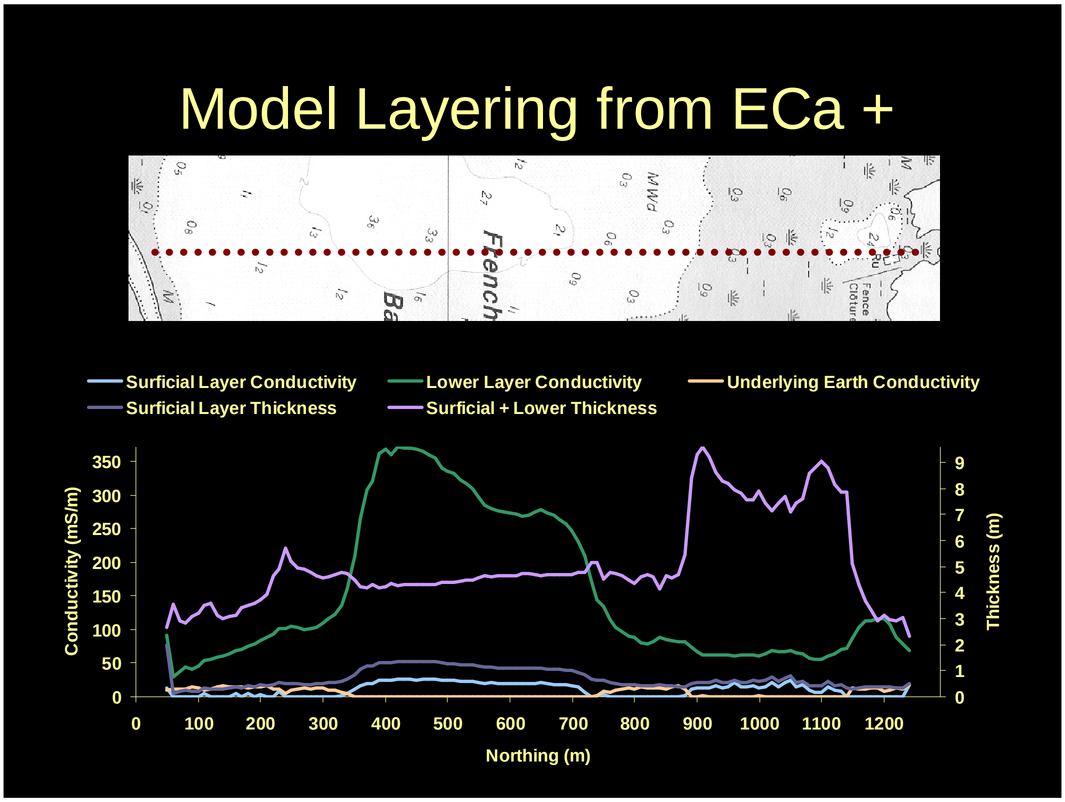
Layered-earth analysis using both in-phase and quadrature is much more complex than LIN analysis using only quadrature, and is beyond the scope of this presentation.

However, a sense of the benefits of such analysis can be gained by using in-phase in a crude but simple way. As previously mentioned, one consequence of operating above LIN is the understatement of apparent conductivity by linear scaling of quadrature. A rough correction for such understatement consists of scaling apparent conductivity from a vector sum of in-phase and quadrature.

Here are the best-fit model parameters for our profile at 315 E, after 6-m HCP apparent conductivity has been augmented by vector addition. Two improvements are apparent by comparison to the quadrature-only analysis shown previously:

1. Conductivities for the lower layer remain more realistic for brackish water and sediment, with a maximum conductivity of 370 mS/m instead of 630 mS/m.

2. Estimation of layer thickness is more stable where conductivities are high, and where thickness is greatest.



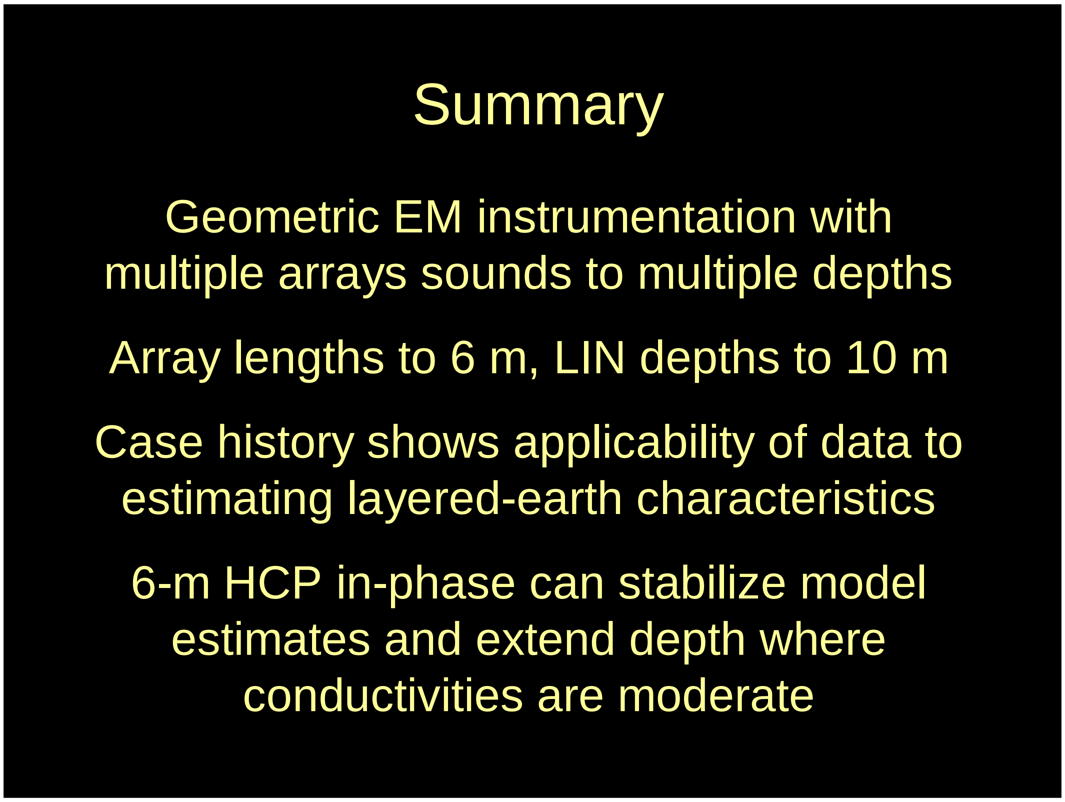
So how do our layer parameters fit with known features along the profile?

As noted previously, the conductivity and thickness of the surficial layer are suggestive of the ice covering on the lagoon, especially away from the zone of high conductivity.

For the lower layer, the highest conductivities coincide with the deepest portion of the lagoon, consistent with the possible pooling of saline water at depth, but above an underlying earth that seems to be consistently low in conductivity.

The thickness of the lower layer increases from about 3 m at the southern end of the profile to about 4 m at 250 N. From 250 N to 850 N, thickness remains at about 4 m even as water depth fluctuates by about 3 m. From the southern end to 850 N, the topographic chart gives the bottom condition as muddy with weeds (“MWd”).

North of 850 N, the condition is given as swamp, and the lower layer thickness increases to 7 m or more. Over the local deepening of the lagoon near the northern end of the profile, the bottom condition returns to muddy, layer thickness decreases to slightly more than water depth, and layer conductivity increases.



In summary, we have described a geometric EM instrument with 6 arrays that sound to 6 distinctive depths.

Depths of exploration range from 1 m for the 2-m PRP array to 10 m for the 6-m HCP array.

Data gathered at Frenchman's Bay show the applicability of multi-array data to estimating the conductivity and thickness of layering in the earth.

In-phase data from the 6-m HCP array may be useful in stabilizing estimates of conductivity and thickness, and extending the depth range of such estimates.

Supplementary material regarding the instrumentation and measurements at Frenchman's Bay can be found at the Dualem website.

Thank you for your attention.