Detailed Low-Induction-Number EM Sounding to 9-m Depth

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

SAGEEP, Charleston SC, April 2011

On behalf of my co-authors Scott Holladay and Dave Lalonde, let me express thanks to the organizers of SAGEEP for accepting our abstract as the basis of this presentation.

This presentation uses data that supercede those shown in the expanded abstract. The new data were gathered at the same site but with augmented instrumentation.

Preview

Instrumentation

Site of Plume

Profile and Soundings

LIN Interpretation

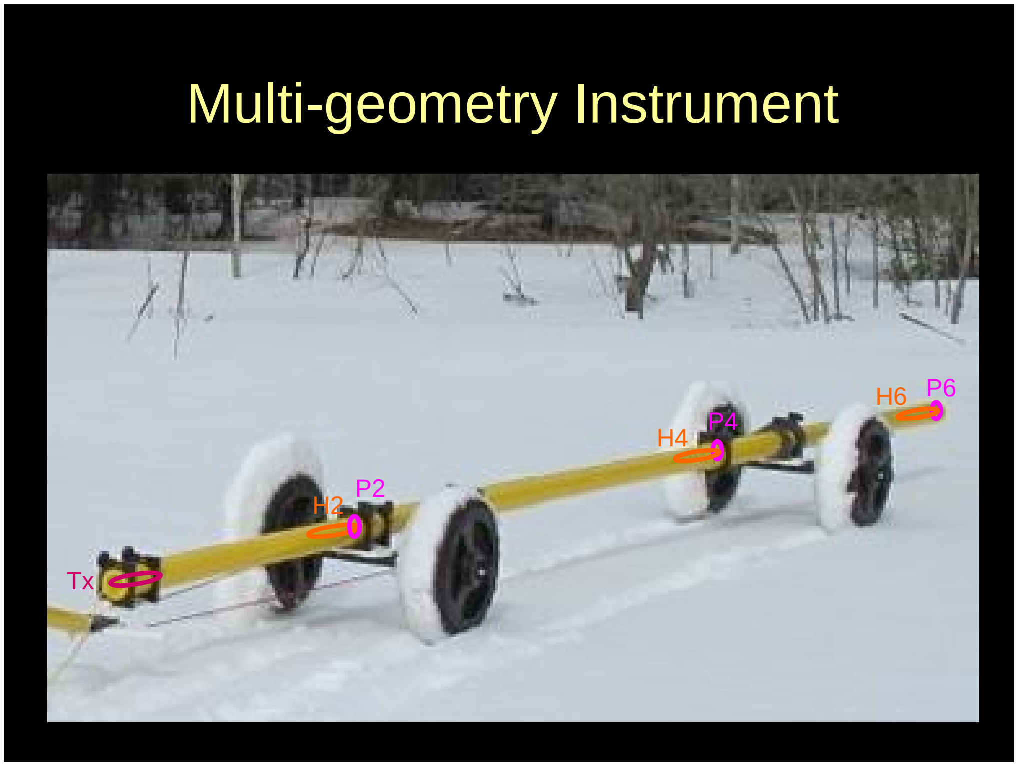
Compare to measured elevation

Our presentation will begin with a description of the EM instrumentation used to gather data at Canadian Forces Base (CFB) Borden.

The base has a contaminant plume in groundwater, over which we took profile- and sounding-measurements.

From these, we interpreted the conductivities of the vadose layer and the saturated layer, and the depth to the saturated layer.

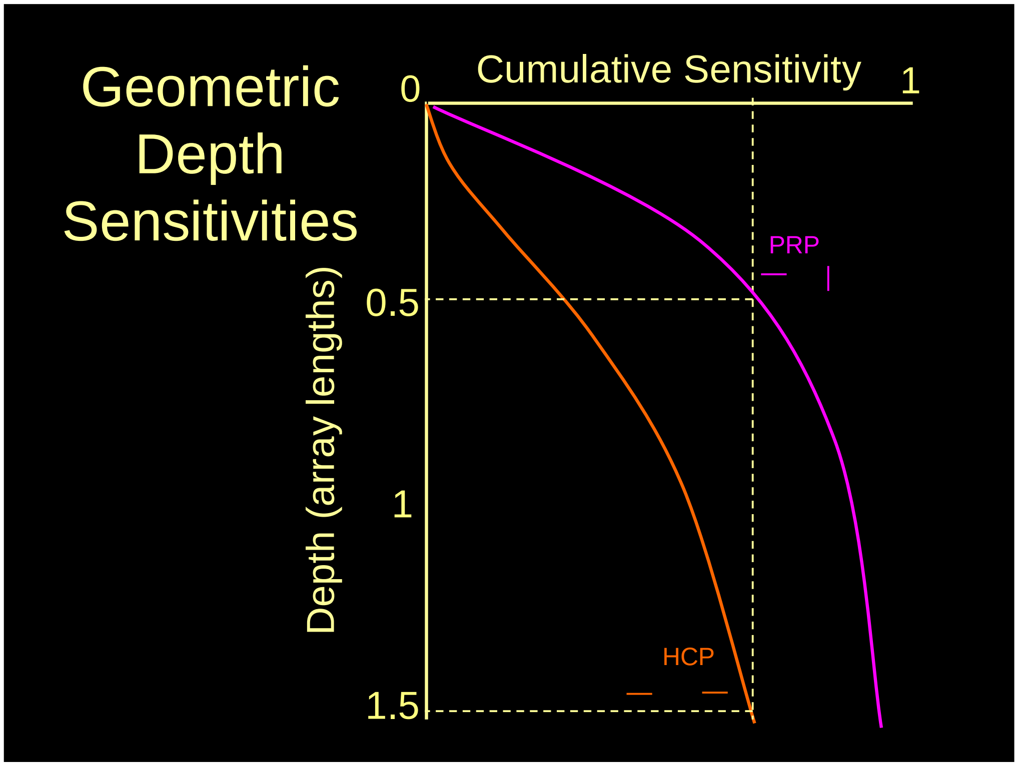
Borehole data from 1983, and elevations measured along the profile in 2000 provide a basis for assessing the interpretations.



Here is the multi-geometry instrument, mounted on wheels, in a clearing at the CFB Borden survey site.

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.

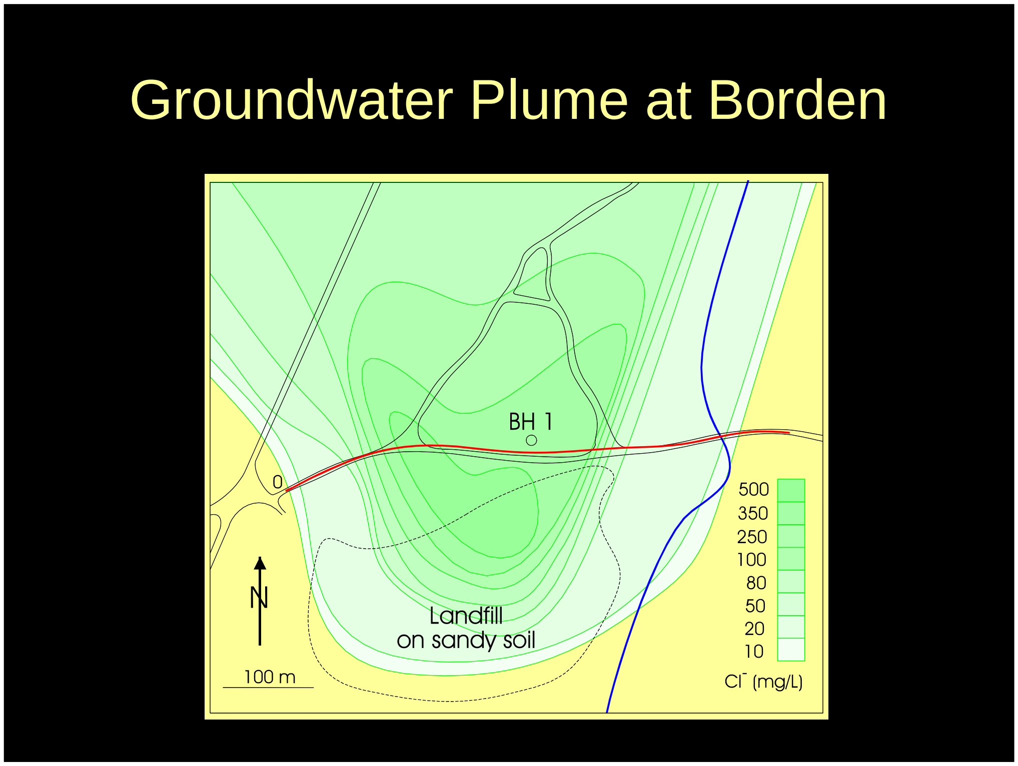
Thus, the instrument contains 6 arrays, (i) 2-m horizontal coplanar (HCP), (ii) 2-m perpendicular (PRP), (iii) 4-m HCP, (iv) 4-m PRP, (v) 6-m HCP and (vi) 6-m PRP.



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 ½ the array length, and the DOE of an HCP array is about 1½ array lengths.

Accordingly, the instrument used here has 6 distinct LIN DOEs, ranging from 1 m for the 2-m PRP array to 9 m for the 6-m HCP array.

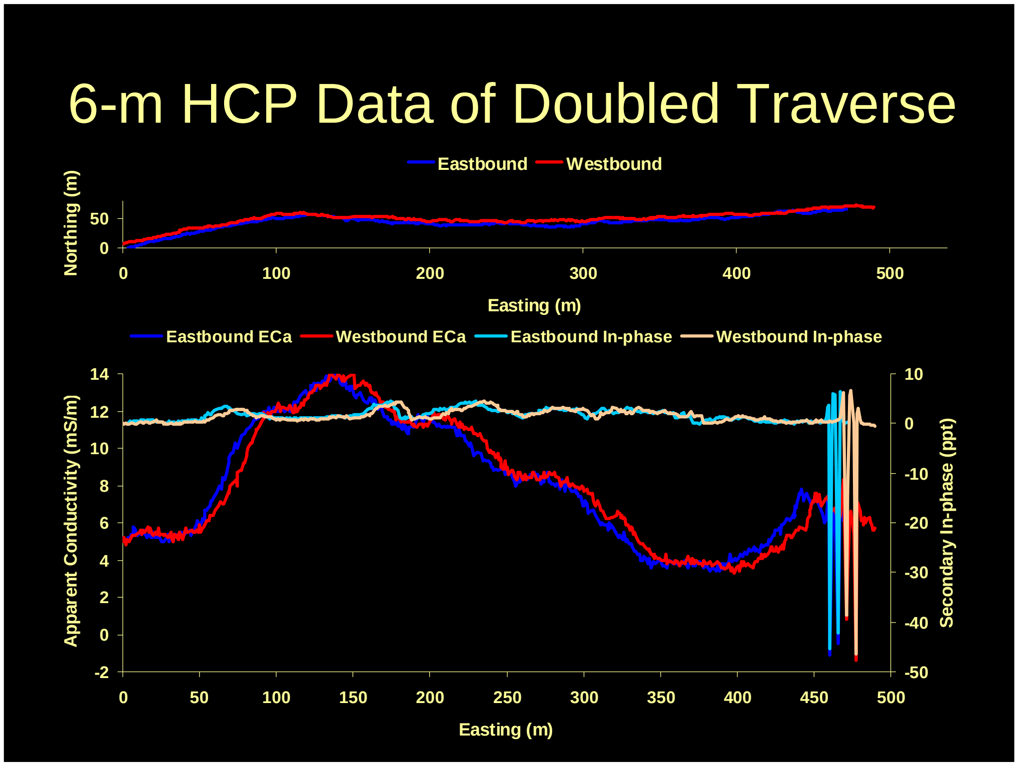


A disused landfill at CFB Borden received ash, wood, debris and some food waste between 1940 and 1976. There is a stream to the east of the landfill that flows northerly.

The landfill sits on about 20 m of sandy soil, which decreases in thickness to about 10 m at the northern edge of the area shown. An aquiclude of clay underlies the sandy soil.

In 1983, contours of chloride concentration in the aquifer were drawn (Sweeney, 1983) from analysis of well samples. An induction log was also made of (borehole) BH1. The induction log showed negligible conductivity to 6.5-m depth, below which conductivity ranged between 20- and 45-mS/m.

On March 15 of this year, we traversed with the multi-geometry instrument on a gravel road across the historical location of the plume. We traversed west-to-east, then east-to-west, to assess the repeatability of measurements.

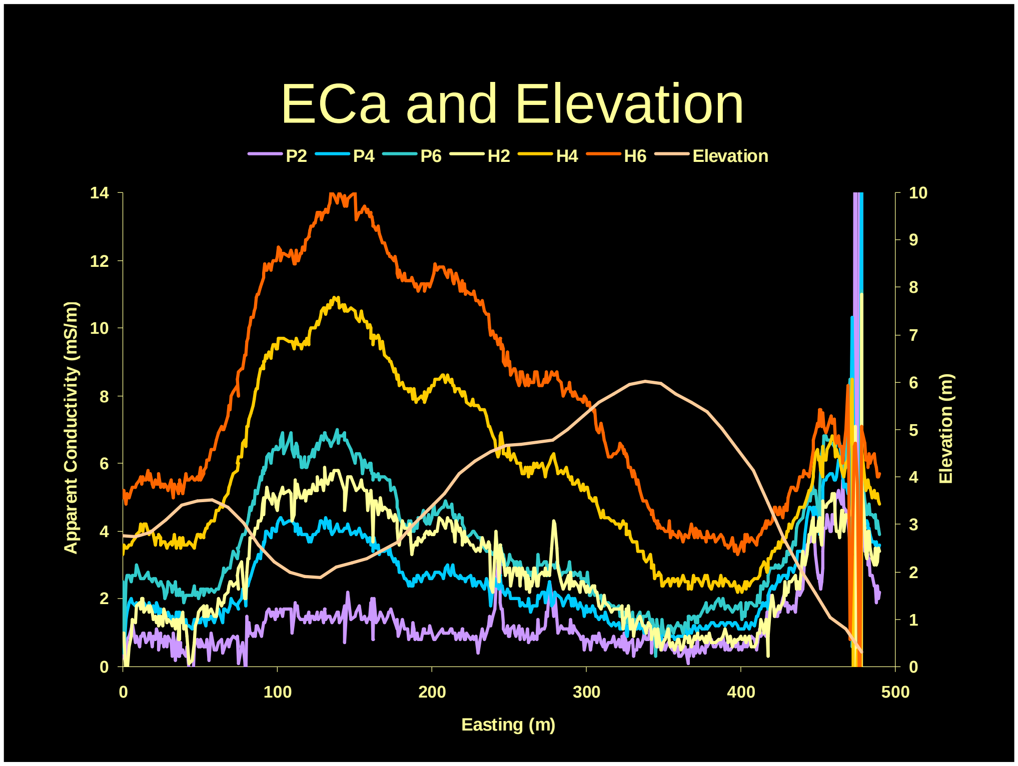


The upper chart shows positioning of the data on the doubled traverse according to the GPS receiver inside the instrument. Wide-area differential correction was generally available, but in this wooded area we observed about a 10-m east-west dislocation between the eastbound and westbound passes. Positions and measurements were recorded at 1-s intervals. The instrument did not smooth consecutive measurements.

Perhaps the slight dislocation in positioning makes it easier to assess the repeatability of measurements; for example, measurements of the 6-m HCP array are shown in the lower graph. The blue and red profiles show apparent conductivity, scaled linearly from quadrature, and the cyan and tan profiles show in-phase.

The most striking features in all profiles are the strong and sharp in-phase responses at the location of the stream. These responses, along with similar responses in apparent conductivity, arise from metal culverts buried in the stream bed.

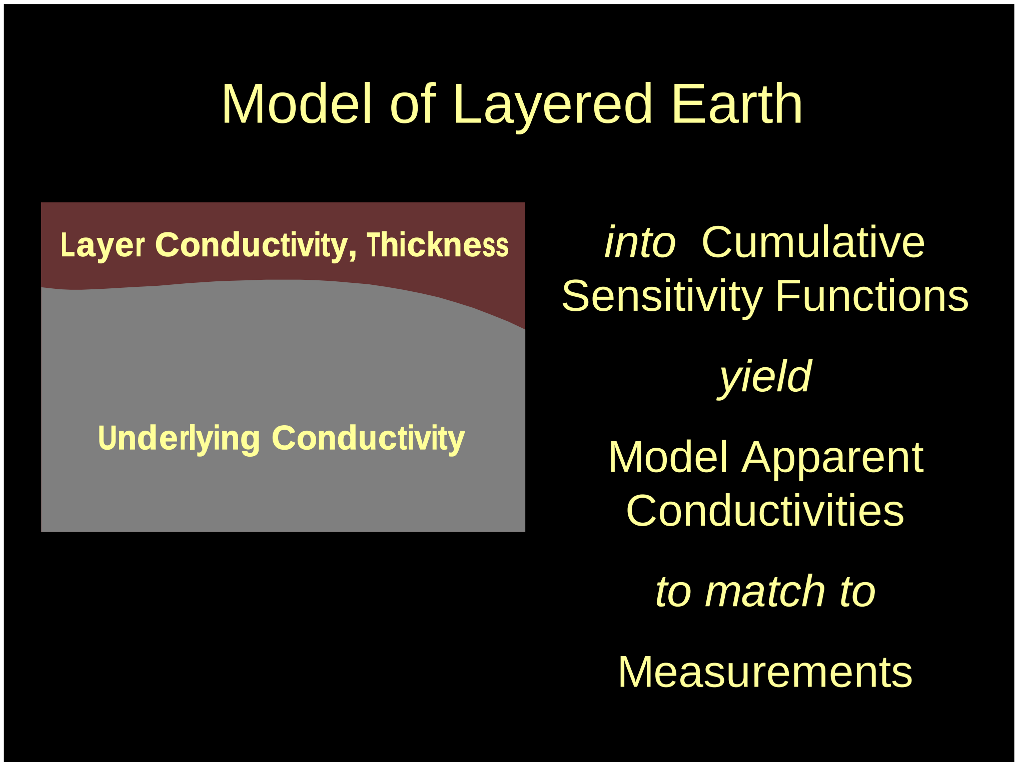
In general, corresponding measurements on the two traverses agree to well-within 1 mS/m in apparent conductivity, and 1 ppt in in-phase.



Here are the apparent conductivities measured by all-6 arrays on the east-to-west traverse, along with surface elevation measured by rod-and-level in 2000.

Apparent conductivity increases with the DOE of the array. Over the historical location of the plume, for example, peak values in mS/m are about 2 for the 2-m PRP array, 4 for the 4-m PRP array, 6 for the 2-m HCP array, 7 for the 6-m PRP array, 11 for the 4-m HCP array and 14 for the 6-m HCP array. Increasing apparent-conductivity with DOE suggests that a conductive feature lies beneath less-conductive surficial material.

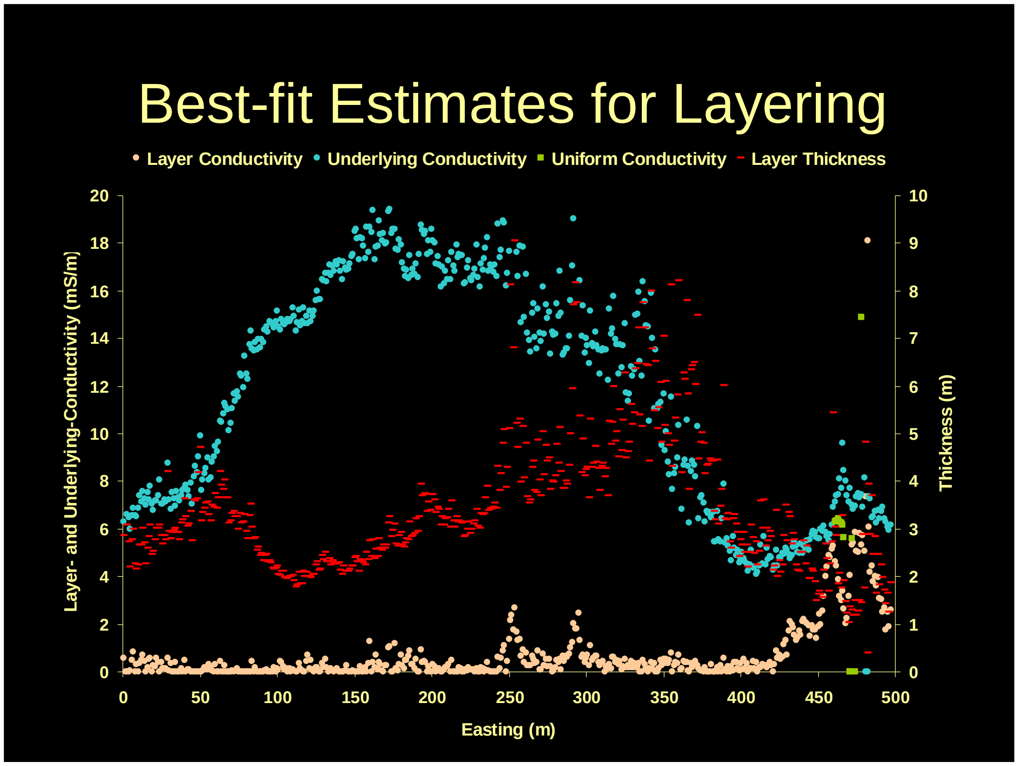
Topographic relief over the 500-m traverse is about 6 m, with the stream at the topographic low. An inverse relationship between elevation and apparent conductivity is evident for all arrays. This might be explained by a water table that is essentially flat in its sandy host, where the conductivity of the overlying sand is low and uniform, and where elevation controls the height of the instrument above the conductive aquifer.



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 3 parameters, i.e. conductivity of a surficial layer, thickness of the layer, and conductivity of the earth underlying the layer.

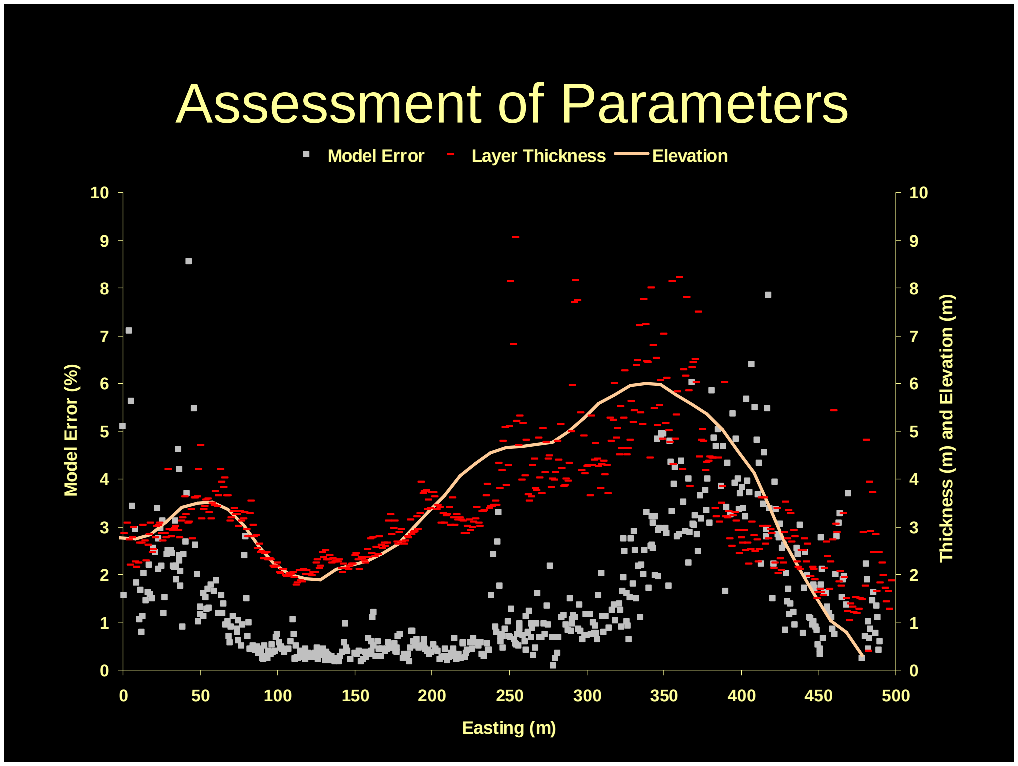
To estimate realistic values for these 3 parameters, we search for parameter values that, when plugged into our cumulative sensitivity functions, yield apparent conductivities that most closely match the apparent conductivities we measured.



Here are the parameter values that yield apparent conductivities that fit best to our measurements. Estimates of the conductivity of the surficial layer are typically less than 1 mS/m, except near the stream where they rise to several mS/m.

Estimates of layer thickness are relatively low near the stream and around 130 E, with values around 2 m. At a few locations near the stream the thickness estimates are zero, implying that the surficial layer has disappeared. With no layer present, the best we can do is estimate the conductivity of a uniform earth. The largest estimates of thickness, around 8 m, lie between 250 E and 370 E.

Estimates of the conductivity of the underlying earth peak at about 19 mS/m at the historical core of the plume, and fall away to about 6 mS/m at the historical edges.



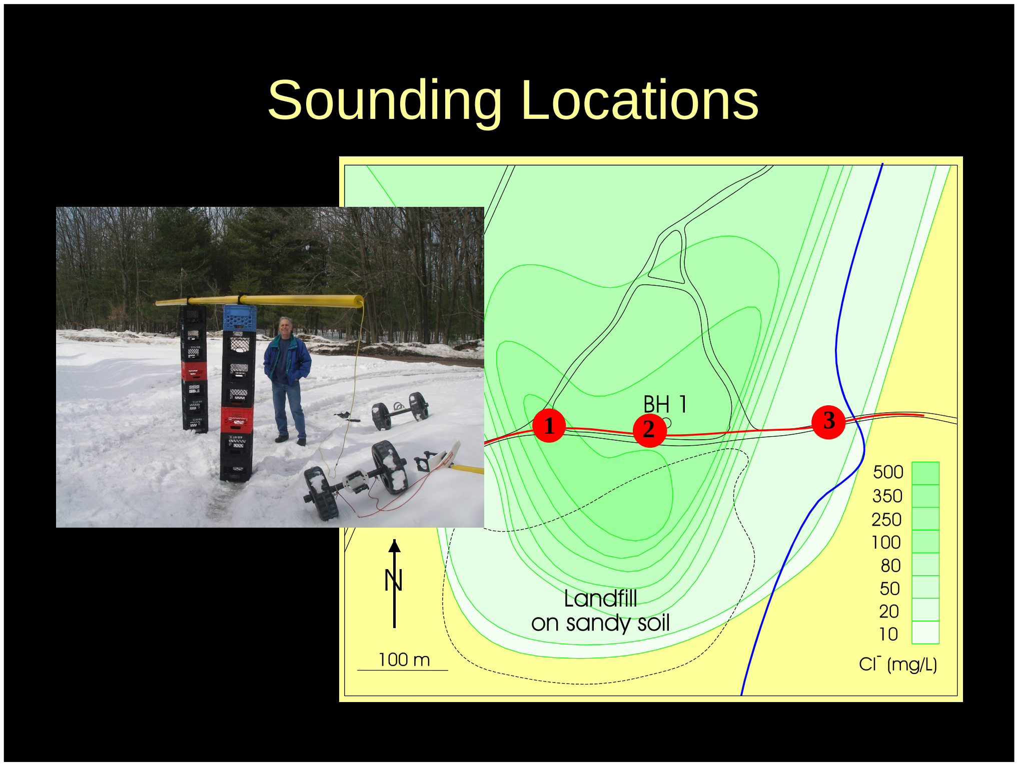
Model error and comparison with independent data allow us to assess the reasonableness of parameter estimates. Model error measures the discrepancy between measured apparent conductivities and those generated by the model with given sets of parameter values.

Model error along the traverse was 1 % or less from about 90 E to 220 E, over the historical core of the plume where the conductivity contrast between the surficial layer and the underlying earth is relatively strong. Through this interval, depths to the underlying earth were less than 4 m.

At the ends of the traverse, where the layer contrast is less strong, model error ranges up to 4 %. Error increases by a few percent more around 400 E, perhaps due to lower contrast, greater elevation, and possible geological complexity in this sloping area.

A comparison of layer thickness and topography might be a more meaningful test of model validity. If the water table is essentially horizontal and a major factor of conductive layering, estimates of layer thickness should correspond closely to elevation above the water table.

The chart shows, again, measured elevations relative to stream level as the tan line. Layer-thickness estimates correspond within a few dm over the historic core of the plume, within a m or so at the western end of the traverse, and within a few m through the higher elevations and lower contrasts of the eastern portion.

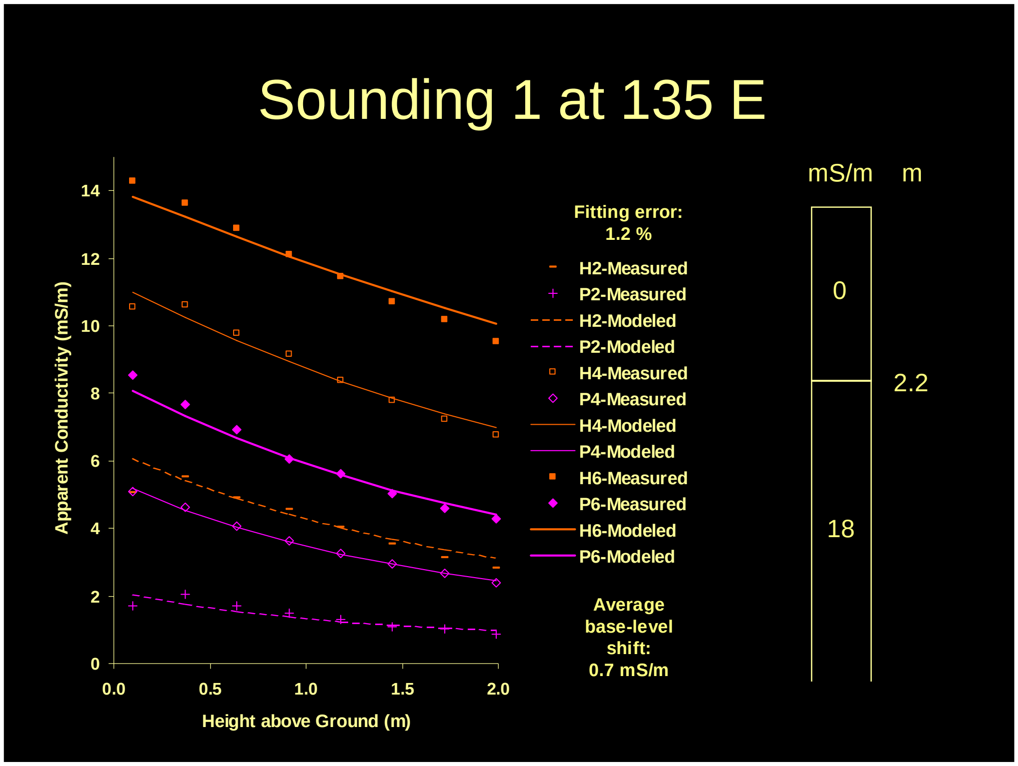


We performed 3 vertical soundings to acquire detailed and low-noise data at 135 E, 260 E and 460 E.

For each sounding, 20 1-s measurements were made at each of 8 heights, ranging from 0.1 m to 2 m. The measurements at each height were averaged.

Site 135 E is in a topographic low over a portion of the plume that, historically, is high in chloride. Site 260 E is about half-way up the topographic rise, in the vicinity of historic BH 1. Site 460 E is well past the topographic high, on a gentle slope approaching the western bank of the stream.

The photo shows the instrument at 2 m height at the 135-E site. The photo also shows ruts and ridges in the snow, which may have caused some noise in the traverse measurements.

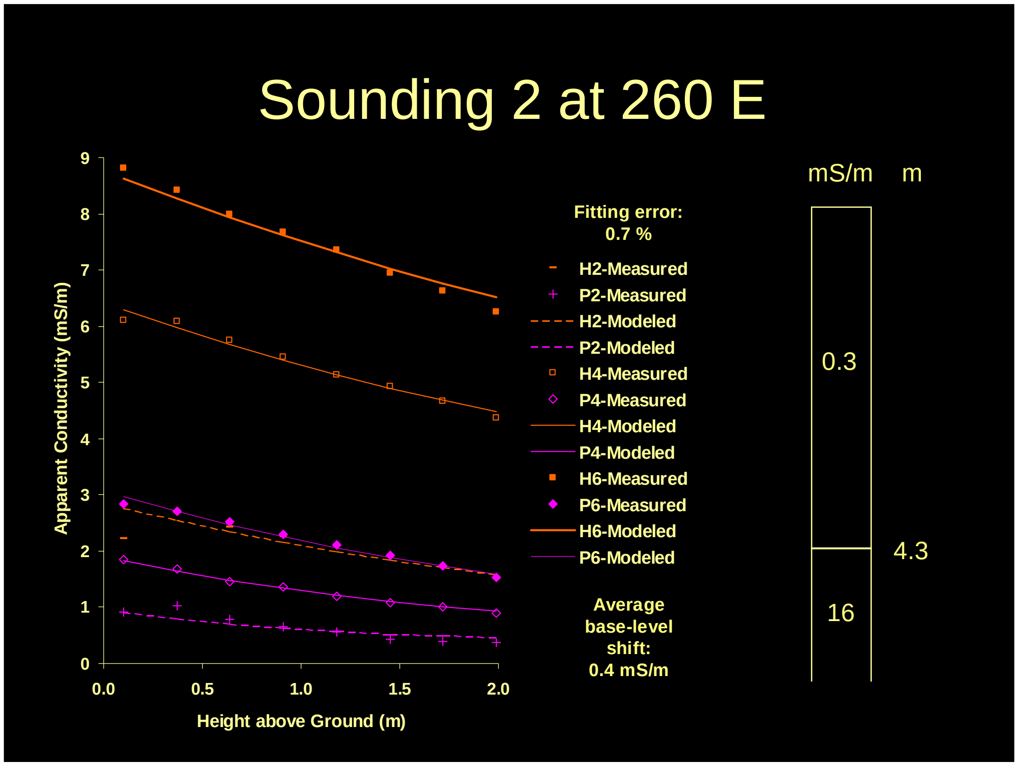


The chart on the left shows the sounding measurements as individual symbols, and the apparent conductivities of the model as curves.

In addition to searching for parameter values for a layered earth, the modeling routine also was able to adjust the base level for each array by up to 1 mS/m. Fitting error between measured and modeled apparent conductivities was minimized at 1.2 % with 0 mS/m as the conductivity of the layer, 2.2 m as the thickness of the layer, and 18 mS/m as the conductivity of the underlying earth. The average base-level adjustment was 0.7 mS/m.

On-ground measurements vary by up to 1 mS/m from the modeled apparent conductivities. These minor variances might be caused by several factors related to the road surface, its maintenance, and the incipient thawing at the surface during this late-winter survey.

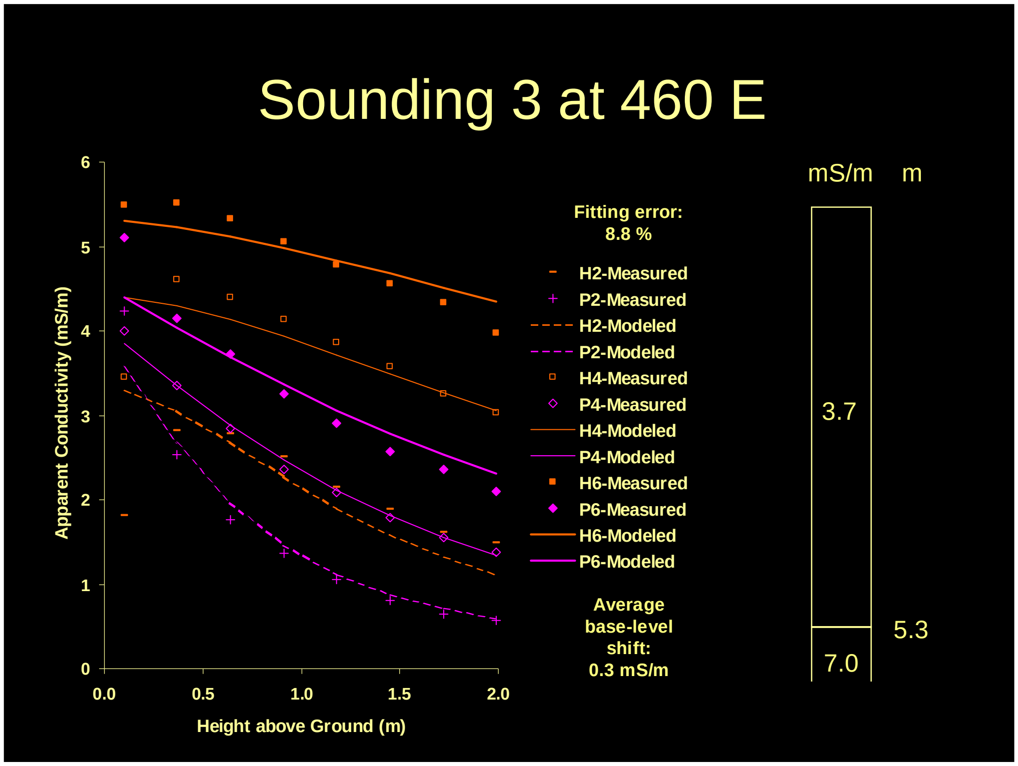
Overall, the excellent fit allows us to conclude that at 135 E over the historical core of the plume, there is negligible conductivity to 2.2 m depth, below which conductivity is about 18 mS/m. Since the elevation at 135 E is about 2.1 m above the stream elevation, we might conclude that the layer of negligible conductivity is representative of the vadose zone, and the 18 mS/m underlying earth is representative of the contaminated aquifer.



At 260 E, a model with layer conductivity of 0.3 mS/m, layer thickness of 4.3 m and underlying conductivity of 16 mS/m fits the sounding measurements with an error of 0.7 %. Average base-level shift was 0.4 mS/m

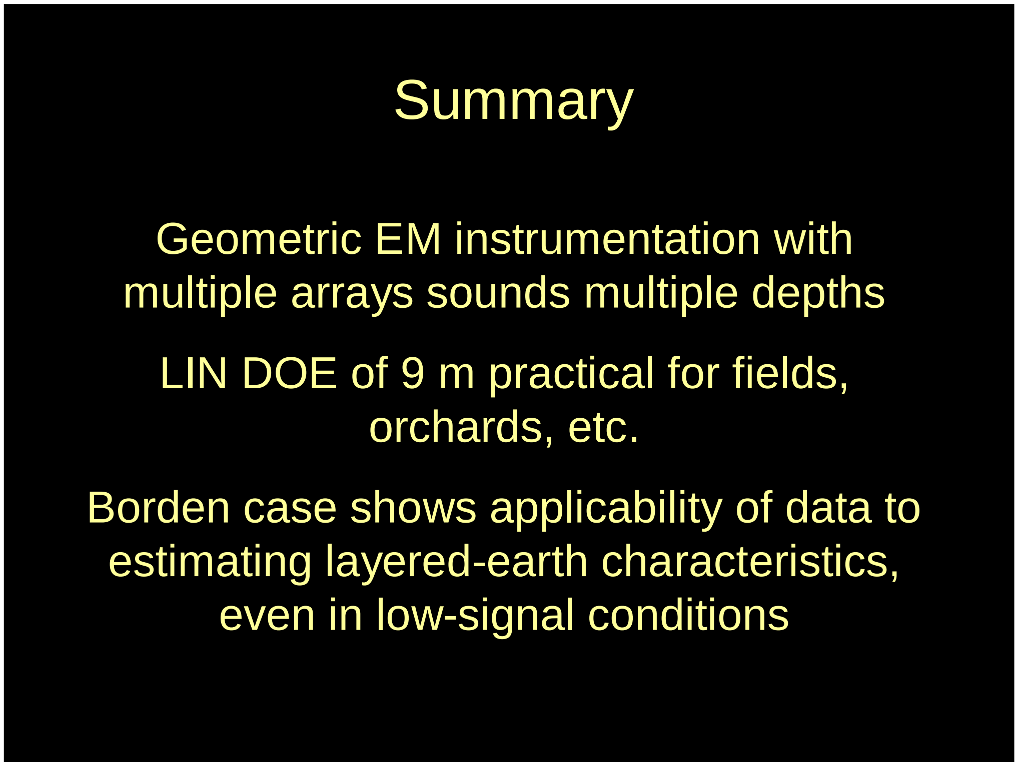
As with the previous sounding, the on-ground measurement shows slight variance to the model values.

The elevation at 260 E is about 4.7 m above stream-level. With layer thickness at 4.3 m, we might conclude the water table is slightly above stream-level, the conductivity of the vadose zone is represented by the layer value, and the conductivity of the contaminated aquifer is represented by the underlying value.



The best-fit model for the sounding at 425 E has 3.7 mS/m as the conductivity of the surficial layer, and 7 mS/m as the conductivity of the underlying earth. Layer thickness is estimated at 5.3 m. Since the elevation at 460 E is about 1 m above stream-level, the model layer incorporates several metres of aquifer.

Low conductivity-contrast at 5.3-m depth would contribute to the model-fitting error of 8.8 %. As with the other soundings, the on-ground measurements show minor variance with model values, at most approaching 2 mS/m for the 2-m HCP array.



In summary, geometric EM instrumentation with multiple arrays can sound to multiple depths. The instrumentation featured here provides LIN DOE to 9-m in a configuration that is suitable for sites that are reasonably clear and have low-to-moderate relief, such as fields and orchards.

The conductivity measurements presented from CFB Borden have a maximum amplitude of 14 mS/m, which is atypically low for surveys with agricultural application. Even in such low-signal conditions, the multi-geometry measurements provided a basis for layered-earth analysis. The analysis was consistent with site topography, and compatible with historical measures of groundwater contamination.

References

Sweeney, S.J., 1983, Concentration, distribution and time variations of a contaminant plume in an unconfined sand aquifer: B.Sc. Thesis, University of Waterloo.

Taylor, R.S., 2000, Mapping sites of environmental contamination with a dual-geometry electromagnetic system: Society of Exploration Geophysicists 2000 Technical Program Expanded Abstracts, 70th Annual Meeting.

www.dualem.com

has supplementary information

This presentation drew information from the two references listed here. The Dualem website contains further information that might be of interest.

Thank you for your attention.