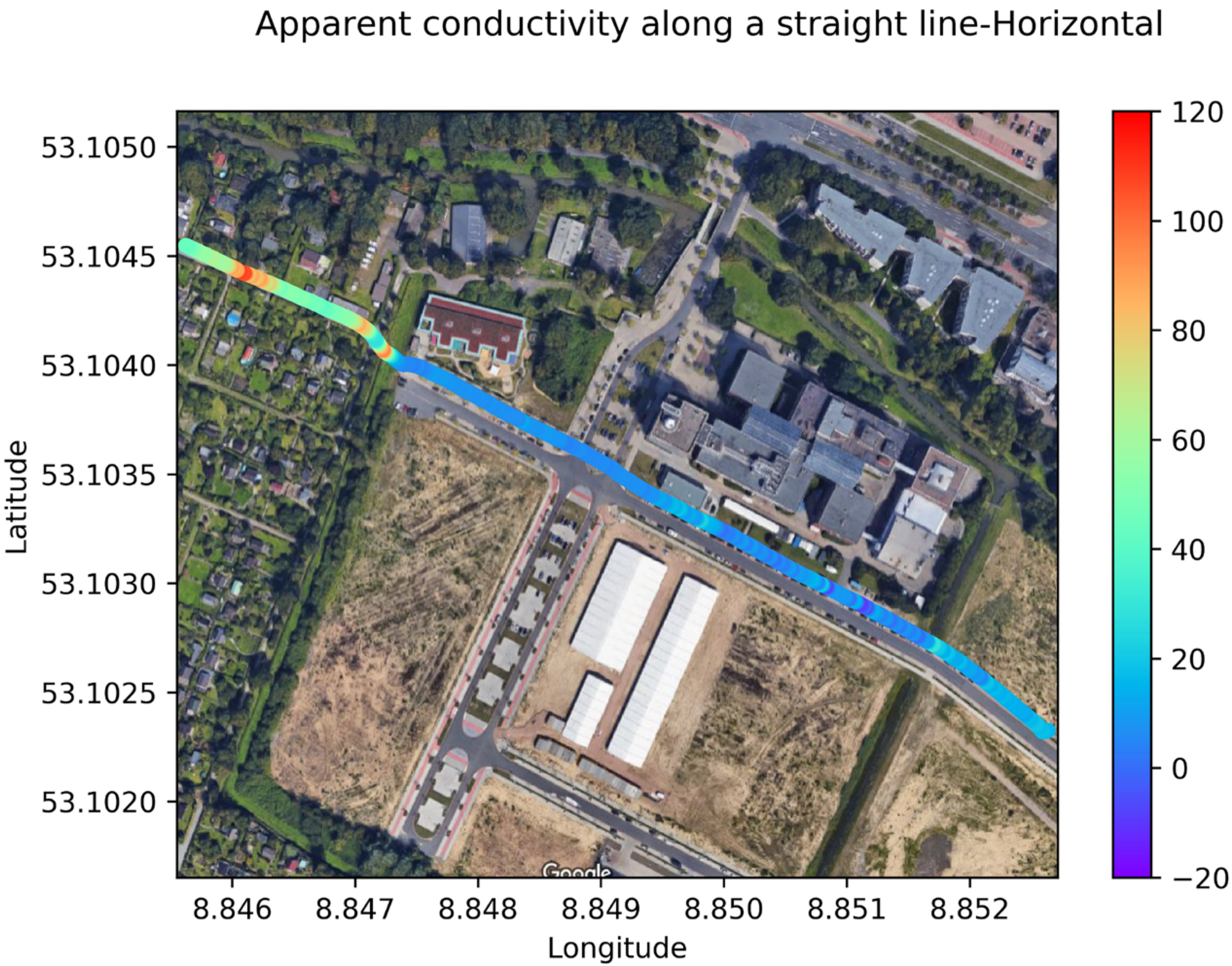
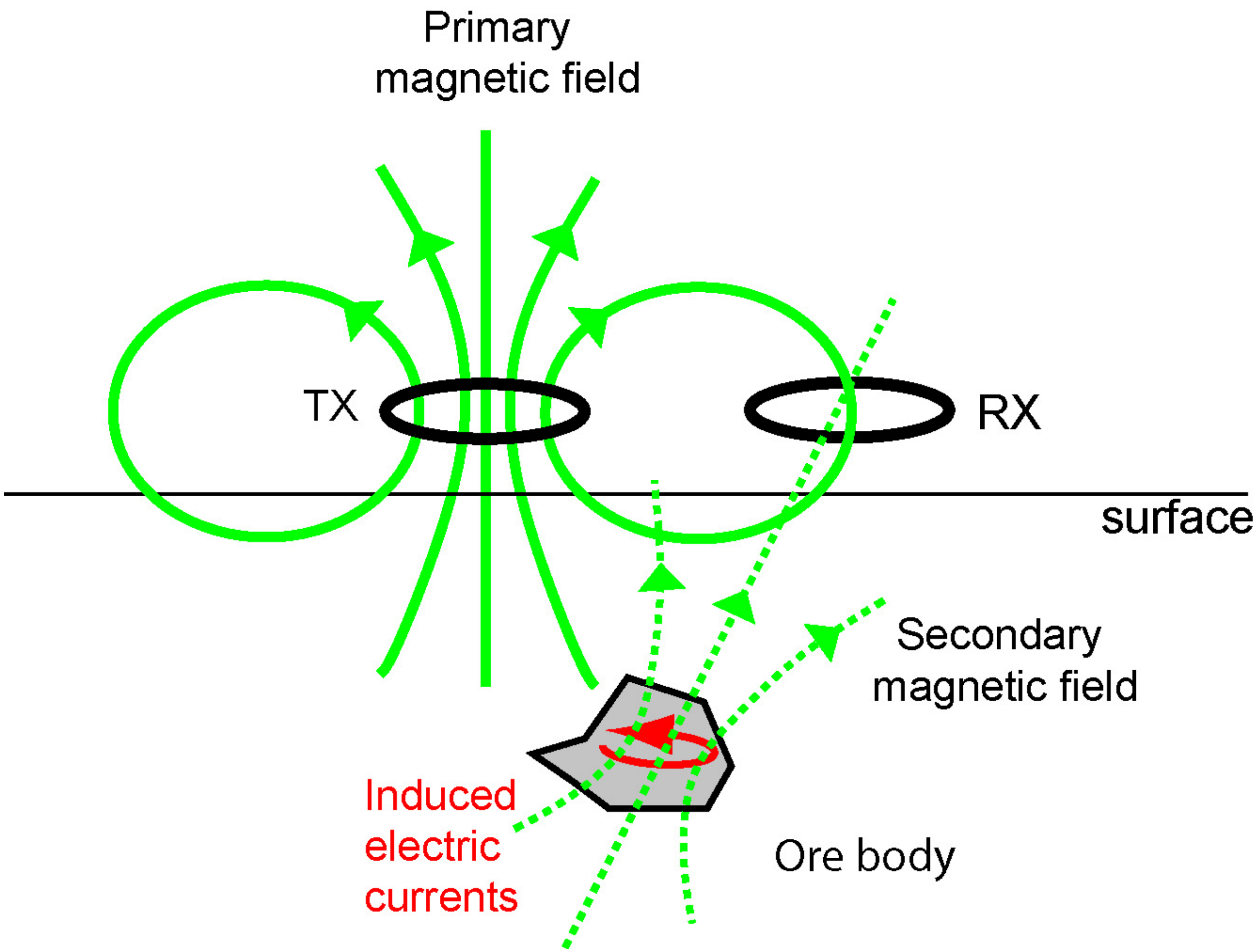
Electromagnetic ice thickness measurements

Prof. Dr. Christian Haas, IUP (PEP) & AWI



Apparent conductivity along a straight line-Horizontal
Latitude
53.1050
53.1045
53.1040
53.1035
53.1030
53.1025
53.1020
Longitude
8.846
8.847
8.848
8.849
8.850
8.851
8.852
120
100
80
60
40
20
0
−20
Google

Electromagnetic (<u>induction</u>) sounding



Observables in Geophysics

- Seismics: Travel time of seismic waves
- DC Resistivity: Voltage and current between electrodes
- EM induction: Amplitude and phase (and direction) of an induced electromagnetic (EM) <u>field</u>
- Magnetics: Strength and direction of magnetic field
- Radar: Travel time of electromagnetic <u>wave</u>

- Important information is obtained from measurements of these observables with different source-receiver spacings

Electromagnetic induction sounding

- Sensitive to distribution of conductivity/resistivity in the underground
- Same principles of rock conductivity mechanisms (e.g. Archies Law) as with DC Resistivity sounding.
- However, currents are generated by induction rather than by generating a potential difference (voltage)
- Therefore, EM sounding does not require contact with the underground

Maxwell’s equations

- Describe the propagation of EM waves
- Provide solutions for low frequency EM: Diffusive equations, i.e. the EM field can be considered as static, slowly time varying, no propagation with time
- High frequency EM (radar): wave equations, i.e. dynamic, propagation of EM signals with time

Faraday’s Law of EM induction

- Time variation of a magnetic field generates a voltage.
- This can cause electric current to flow.

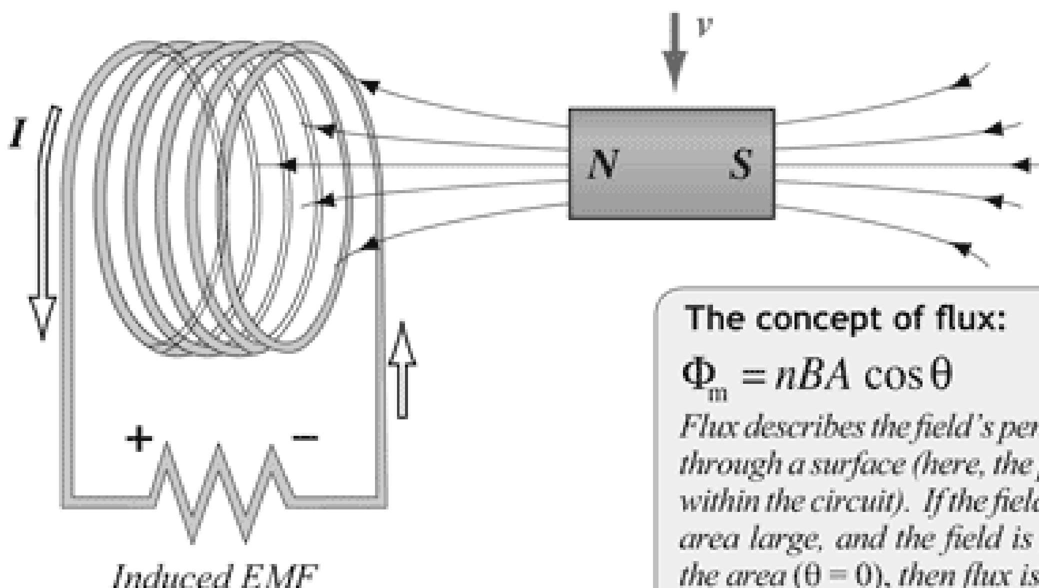
$$\text{curl } E = -\frac{\partial B}{\partial t}$$

$$\varepsilon = -\frac{\Delta\Phi_m}{\Delta t}$$

ε = induced emf

$\frac{\Delta\Phi_m}{\Delta t}$ = rate of change of magnetic flux through the circuit

- E = Electric field
- B = Magnetic flux
- t = Time



The concept of flux:

$$\Phi_m = nBA\cos\theta$$

Flux describes the field’s penetration (or flow) through a surface (here, the plane of the loops within the circuit). If the field is strong and the area large, and the field is perpendicular to the area ($\theta = 0$), then flux is high. Each turn in the coil (n) adds more area.

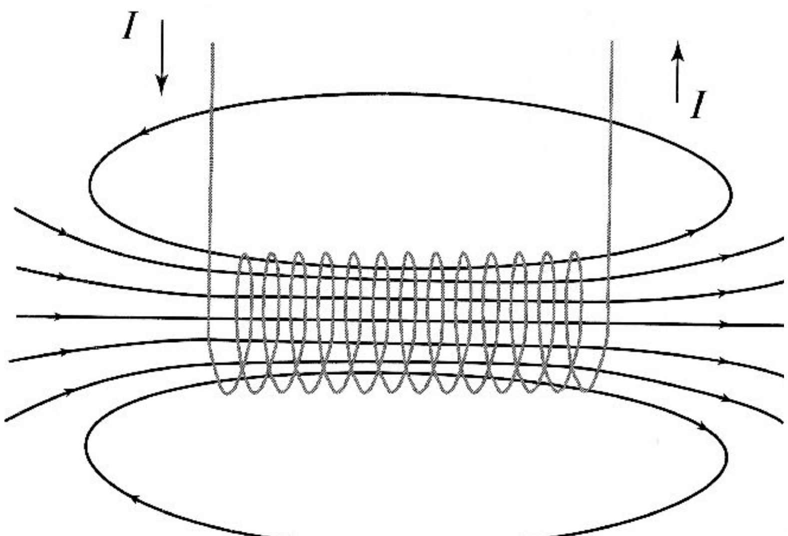
http://phet.colorado.edu/sims/faradays-law/faradays-law_en.html

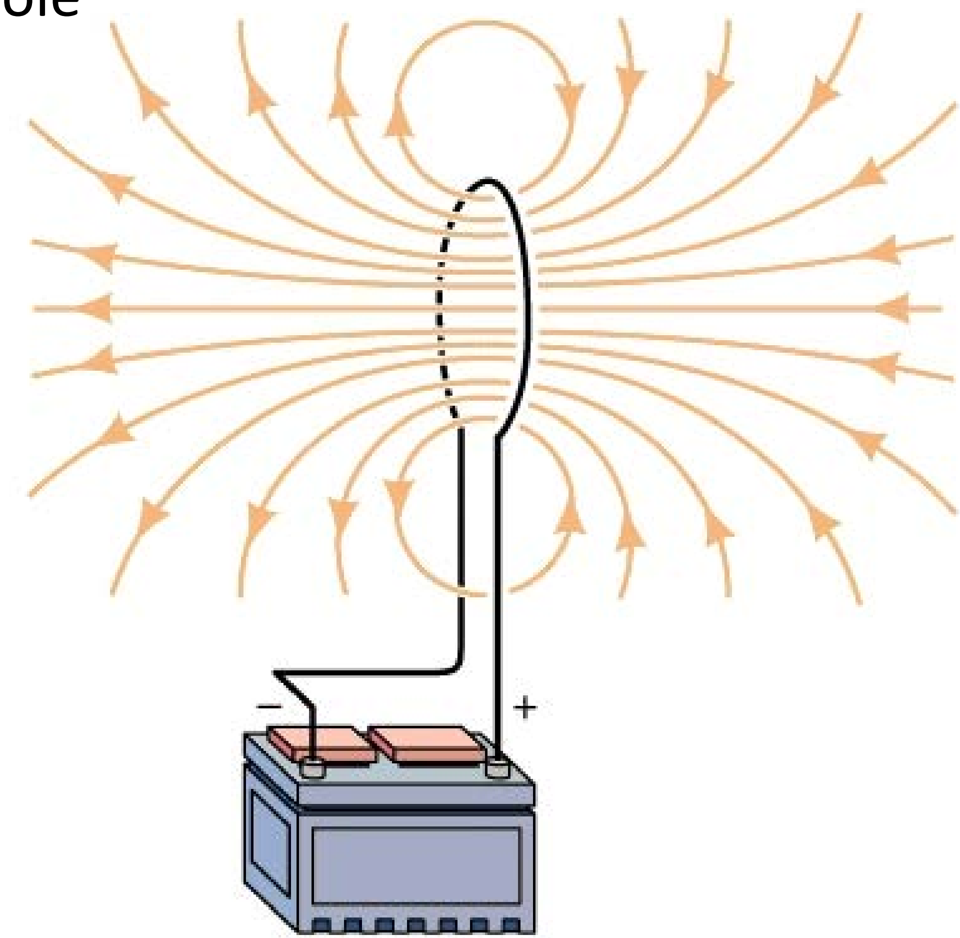
Magnetic field created by current loop (coil)

- The magnetic field is a dipole field
- Example shows a horizontal dipole
- Magnetic Dipole Moment

  μ = IA or μ = NIA ,

  with Current I, Area A, and number of turns N
- Magnetic dipoles are vectors (direction matters)!

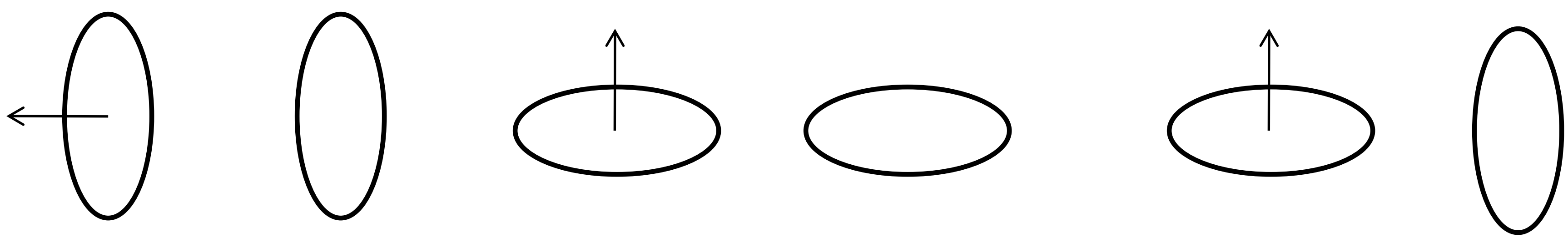




Importance of coil orientation for induction

- Induced voltage is maximal if flux trough coil is maximized
- Therefore crossed coils are not coupled

Examples:

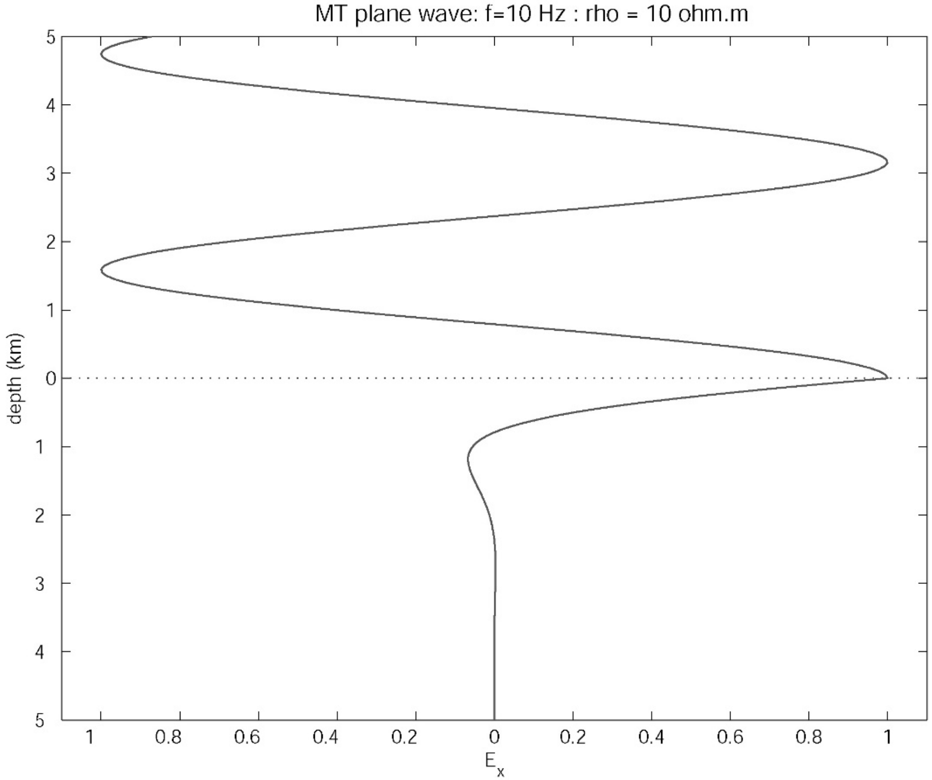


Maximum coupling

Medium coupling

Zero coupling

Electromagnetic wave propagation and diffusion

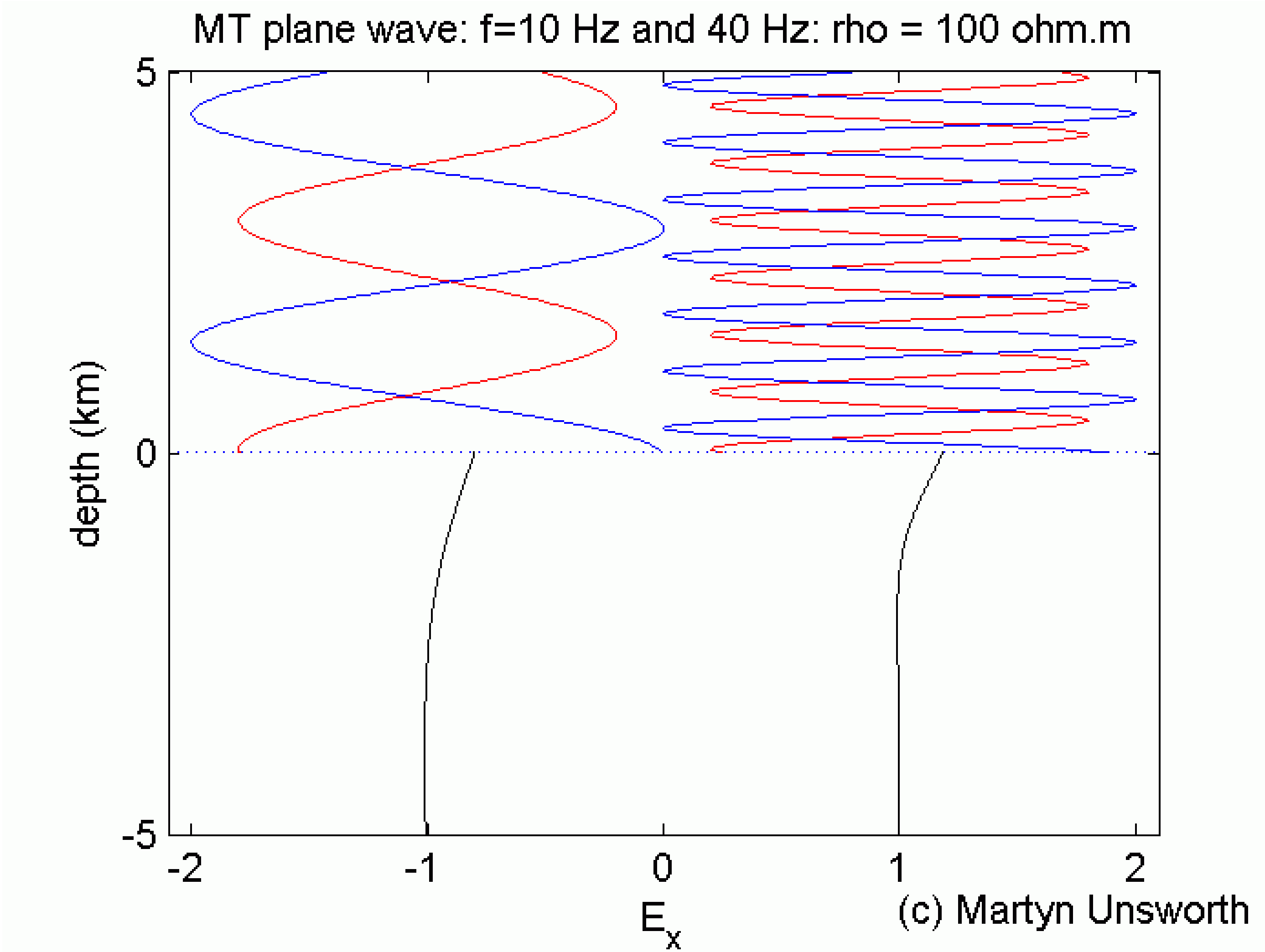


$$E(z) = E_o e^{-\frac{z}{\delta}}$$ EM field amplitude

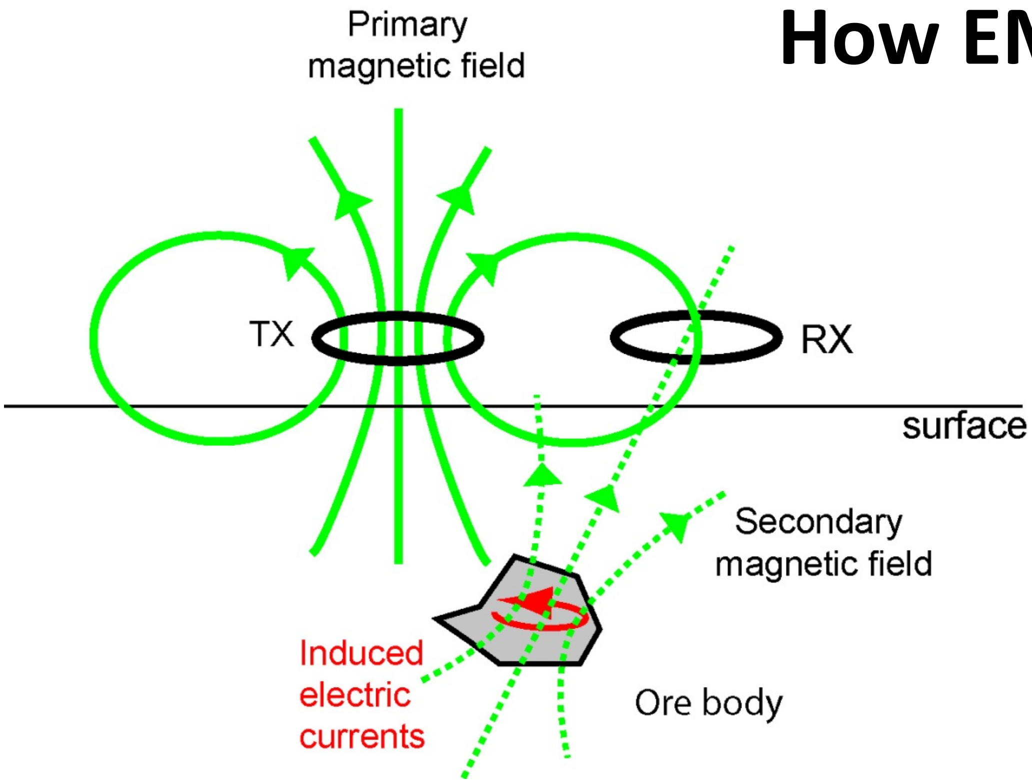
$$\delta = \frac{500}{\sqrt{\sigma f}}$$ Skin depth (m)

Depth at which signal amplitude has dropped to 1/e (one third)

- When low-frequency electromagnetic signals ($f<10^5$ Hz) enter the Earth, they propagate by **diffusion** ($\sigma^2/\varepsilon^2\omega^2 >> 1$)
- The time-varying magnetic field induces an oscillating electric current in the Earth.
- As this electric current flows, energy is converted to heat.
- This energy cannot be converted back into electric or magnetic fields and is lost from the signal
- This causes the amplitude of the EM signal to decrease


MT plane wave: f=10 Hz and 40 Hz: rho = 100 ohm.m
depth (km)
5
0
-5
-2
-1
0
1
2
E
x
(c) Martyn Unsworth

How EM methods work



(1) A **primary magnetic field** is generated by electric current flowing in the transmitter loop (TX).

(2) The transmitter current oscillates with time to produce a primary magnetic field that also oscillates with time.

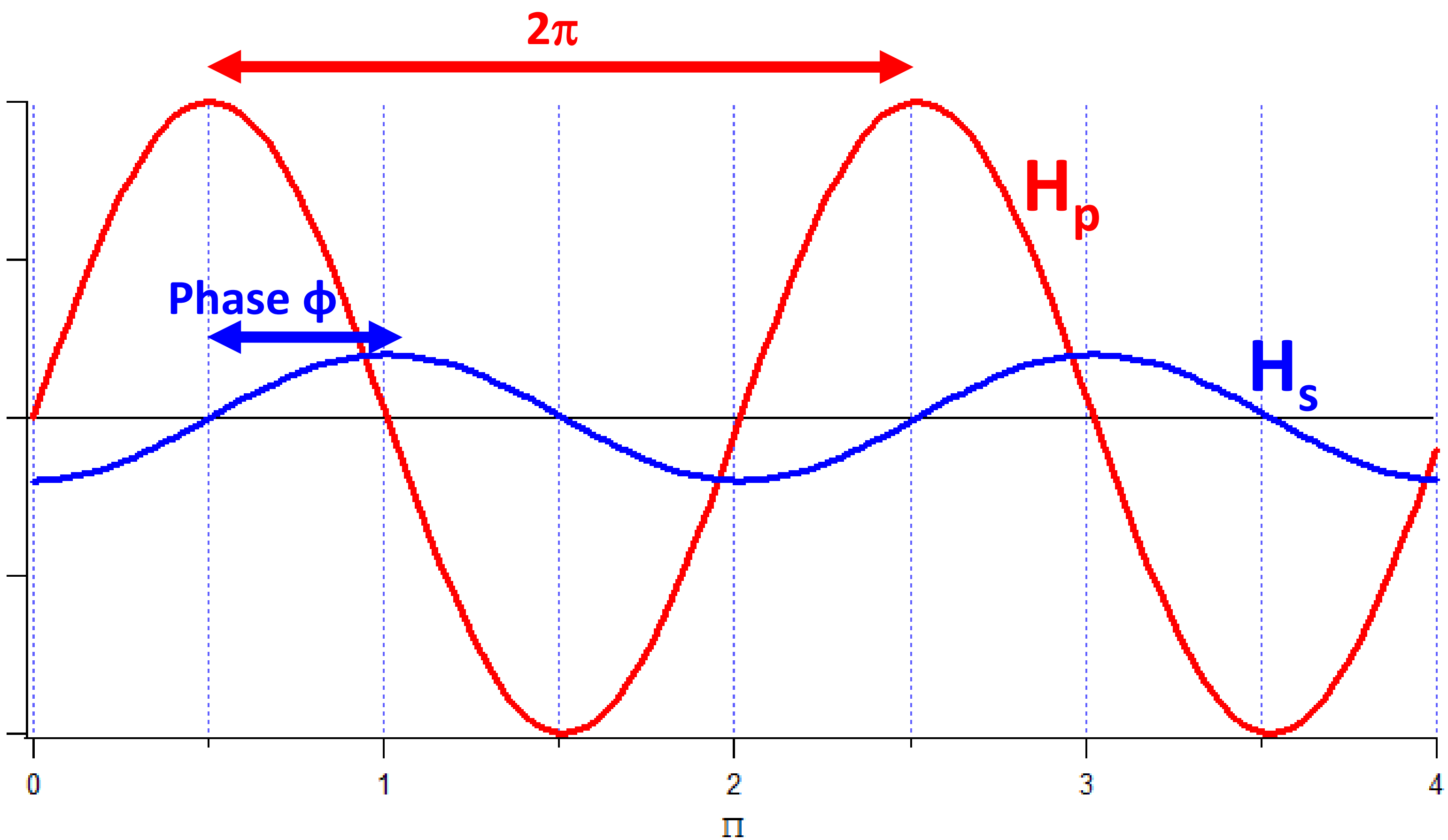
(3) Time variations of the primary magnetic field induce **secondary electric currents** in a conductor (ore body).

(4) The secondary magnetic field passes through the RX, which is also a loop of wire. Time variations (oscillations) in the secondary magnetic field generate a **secondary voltage in the RX**.

(5) Measurement of the secondary voltage gives information about the size and location of the conductor.

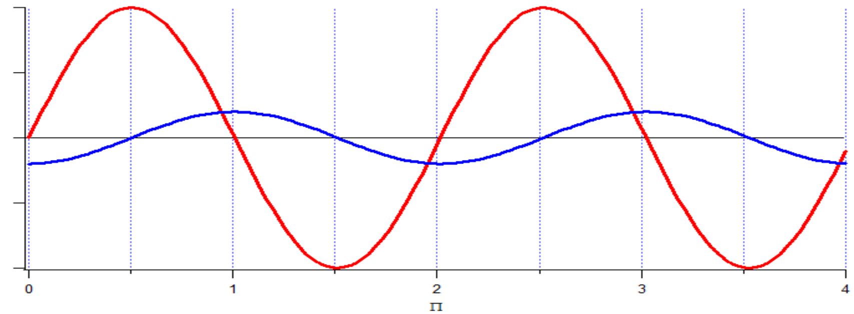
The secondary EM field H_s

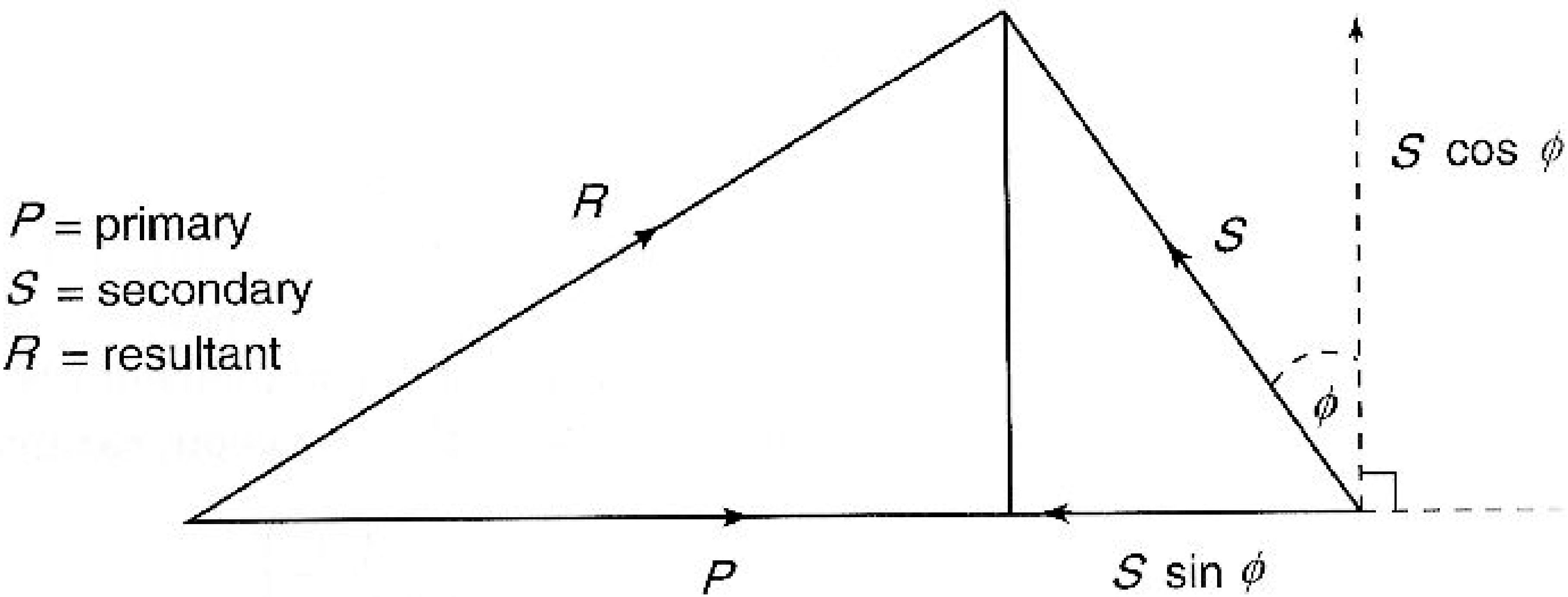
- Characterized by amplitude and phase relative to primary field H_p



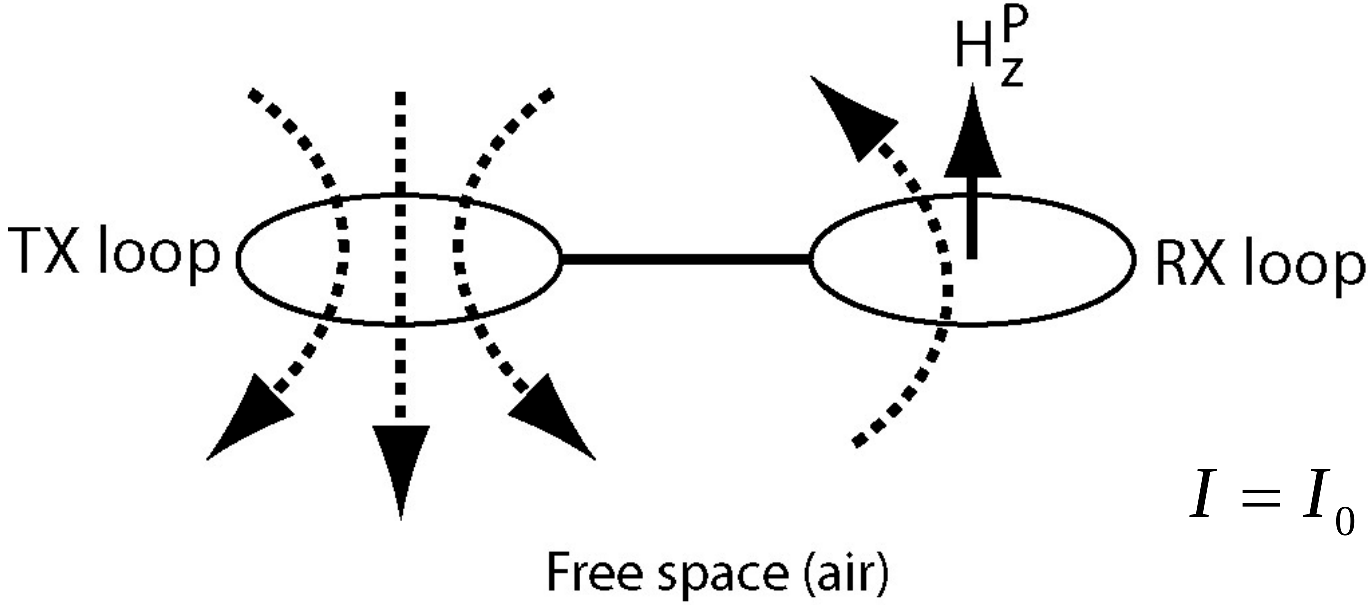
Phase diagram

- EM surveys often measure the real (In-phase) and imaginary (Out-of-phase / “Quadrature”) component of the secondary field
- Inphase = S sin(ϕ)
- Quadrature = S cos(ϕ)





Primary magnetic field



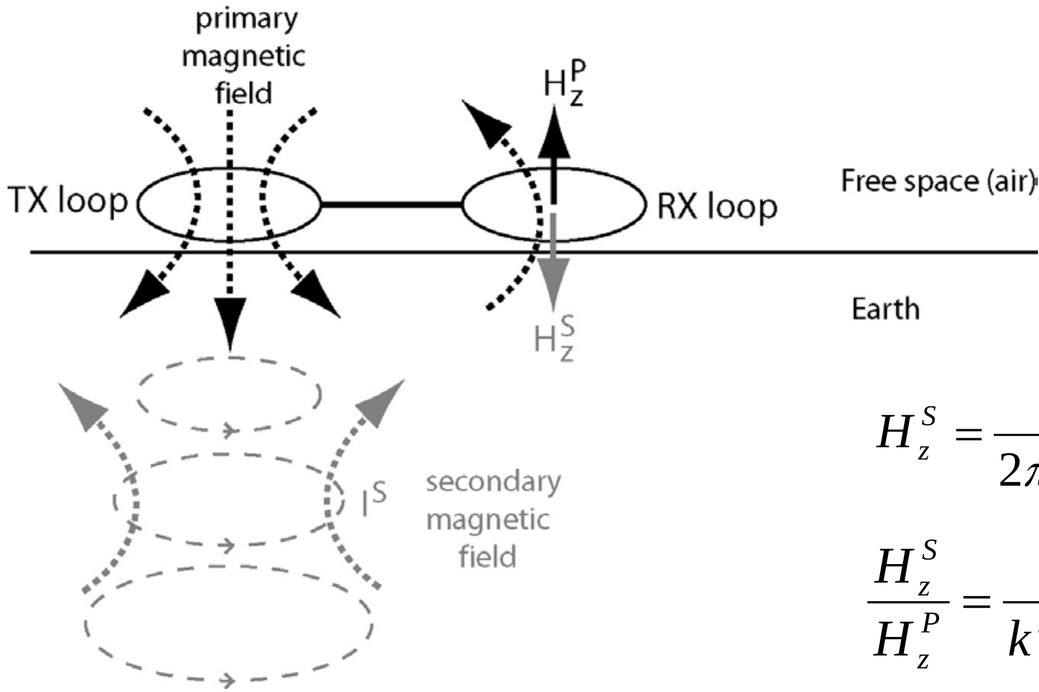
$$I = I_0 \sin(\omega t)$$

$$H_z^p = -\frac{I_0 A}{4\pi s^3}$$

- The strongest signal experienced by the receiver (Rx) coil is the Primary Field H^p
- Increases with coil area / number of turns
- Decreases with coil spacing ($\sim s^{-3}$)

I – Current
A – Coil area
s – Coil spacing

Secondary magnetic field



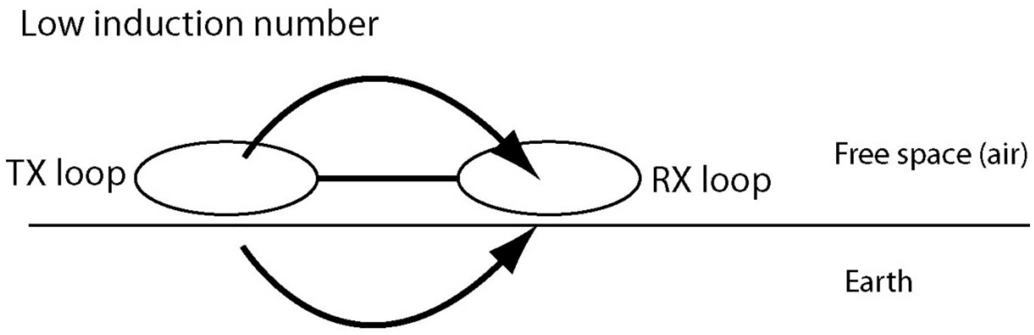
$$H_z^S = \frac{IA}{2\pi k^2 s^5}\{9-(9+9iks-4k^2s^2-ik^3s^3)e^{-iks}\}$$

$$\frac{H_z^S}{H_z^P} = \frac{2}{k^2s^2}\{9-(9+9iks-4k^2s^2-ik^3s^3)e^{-iks}\}$$

wave number $k=\sqrt{i\omega\mu\sigma}$

- In the presence of conductors, Rx experiences an additional secondary field
- Total magnetic field = primary magnetic field + secondary magnetic field (with vector properties!)
- Secondary field is measured relative to primary field $\frac{H_z^S}{H_z^P}$

Apparent conductivity of a halfspace



$$Induction\ Number\ B = \frac{s}{\delta} << 1$$

s = TX-RX distance
δ = skin depth

- Low induction number: s << δ, i.e. coil spacing << skin depth
- Then $\frac{H_z^S}{H_z^p}$ simplifies:

$$\frac{H_z^S}{H_z^p} = 1 - \frac{k^2 s^2}{4} = 1 - \frac{i\omega\mu\sigma s^2}{4}$$

Imaginary part (Quadrature):

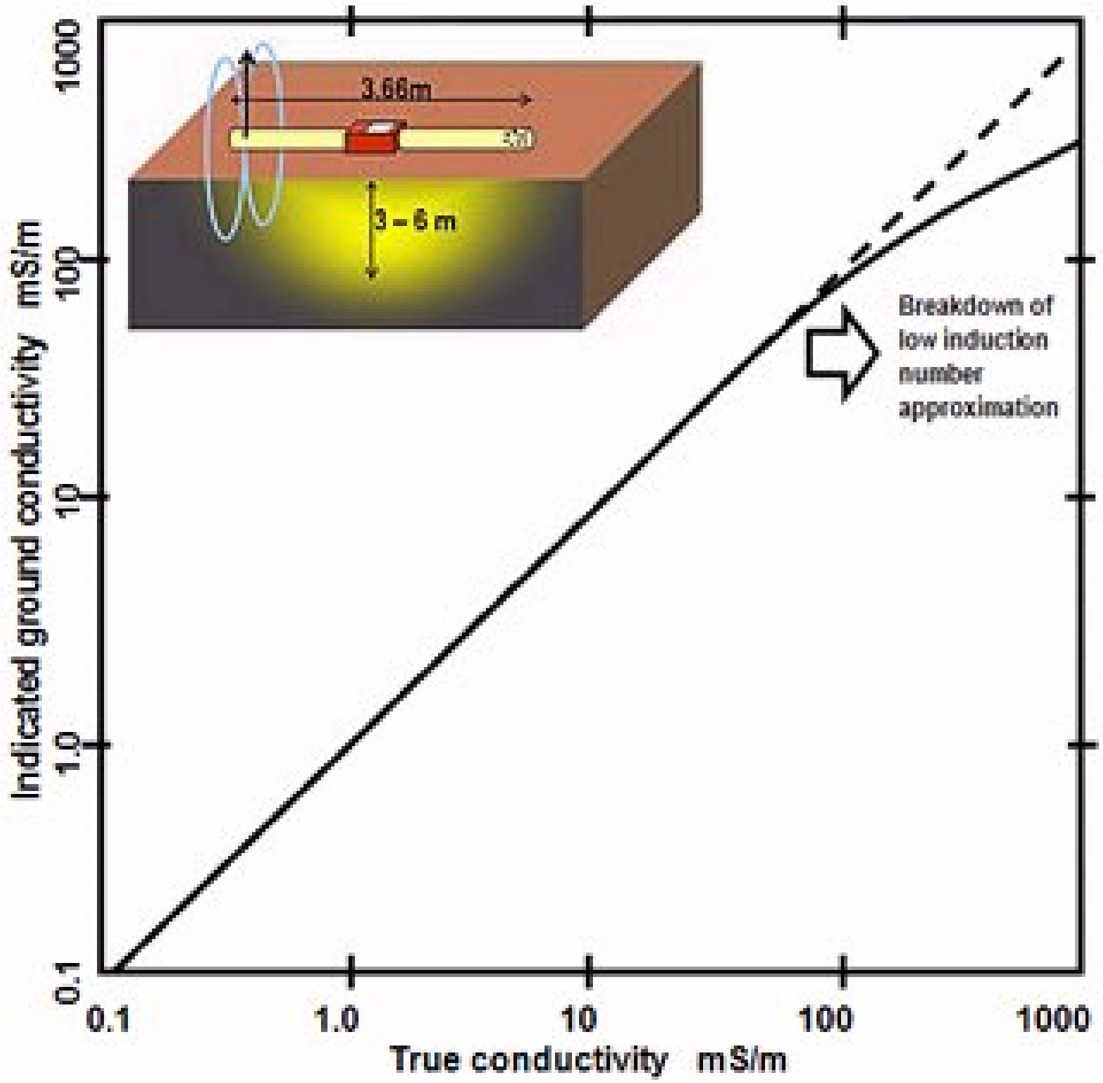
$$\mathrm{Im}(\frac{H_z}{H_z^p}) = \frac{\omega\mu\sigma s^2}{4}$$

- i.e. for low induction numbers, Hs/Hp is proportional to halfspace conductivity

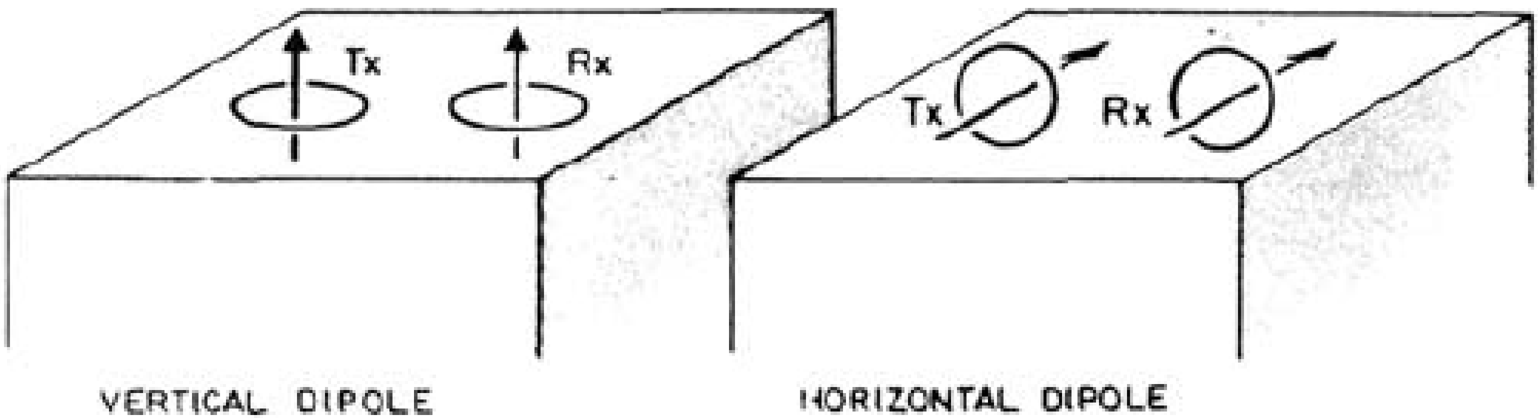
$$\sigma = \frac{4}{\omega\mu s^2}\mathrm{Im}(\frac{H_z}{H_z^p})$$

Indicated vs. true conductivity

- 1:1 agreement for low conductivities (s/δ<<1)
- Measured conductivity < true conductivity for higher ground conductivities, when s/δ<<1 becomes invalid
- Example shown for EM31, with s = 3.66 m and f = 9.8 kHz
- Induction number depends on coil spacing and signal frequency

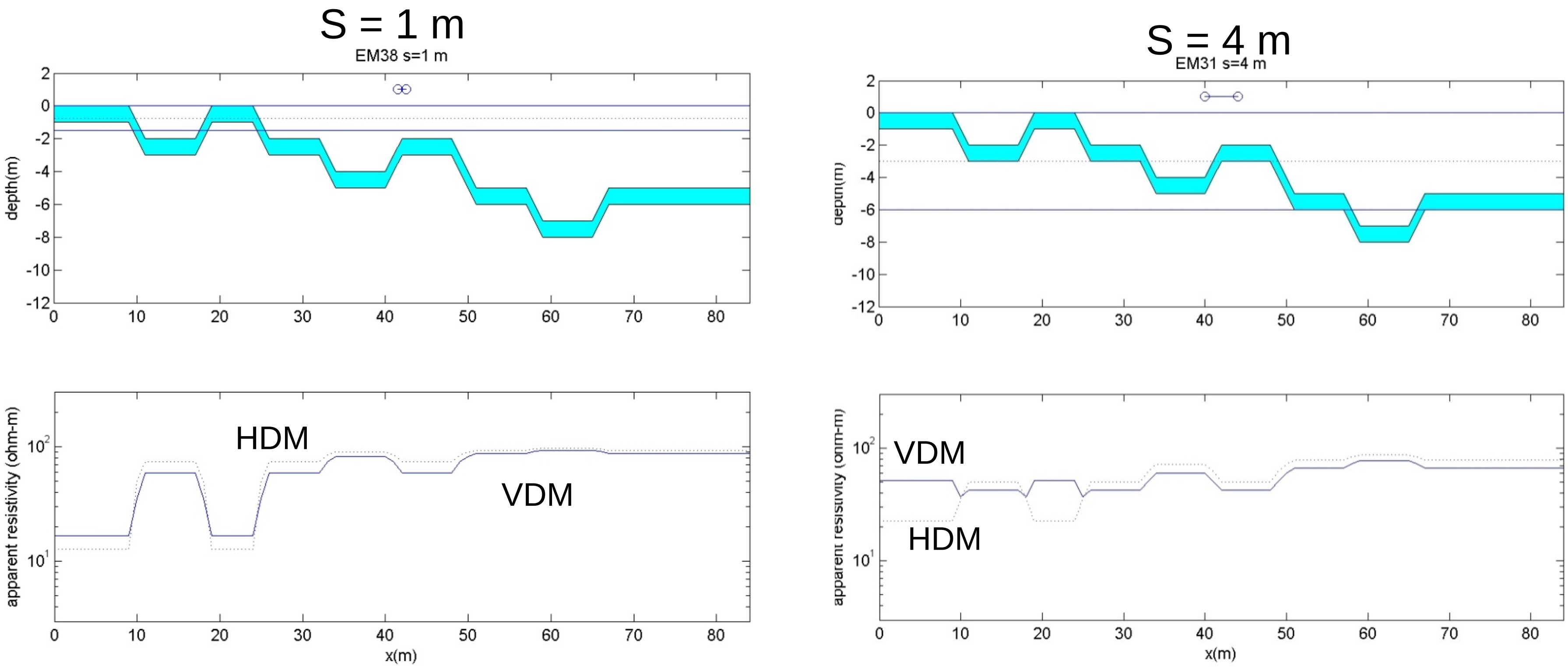


Vertical and horizontal dipole mode (VDM/HDM)



- Most EM instruments can be used in either vertical (VDM) or horizontal dipole mode (HDM)
- These couple differently with the underground and have different penetration characteristics
- Also called horizontal co-planar (HCP) or vertical co-planar (VCP)

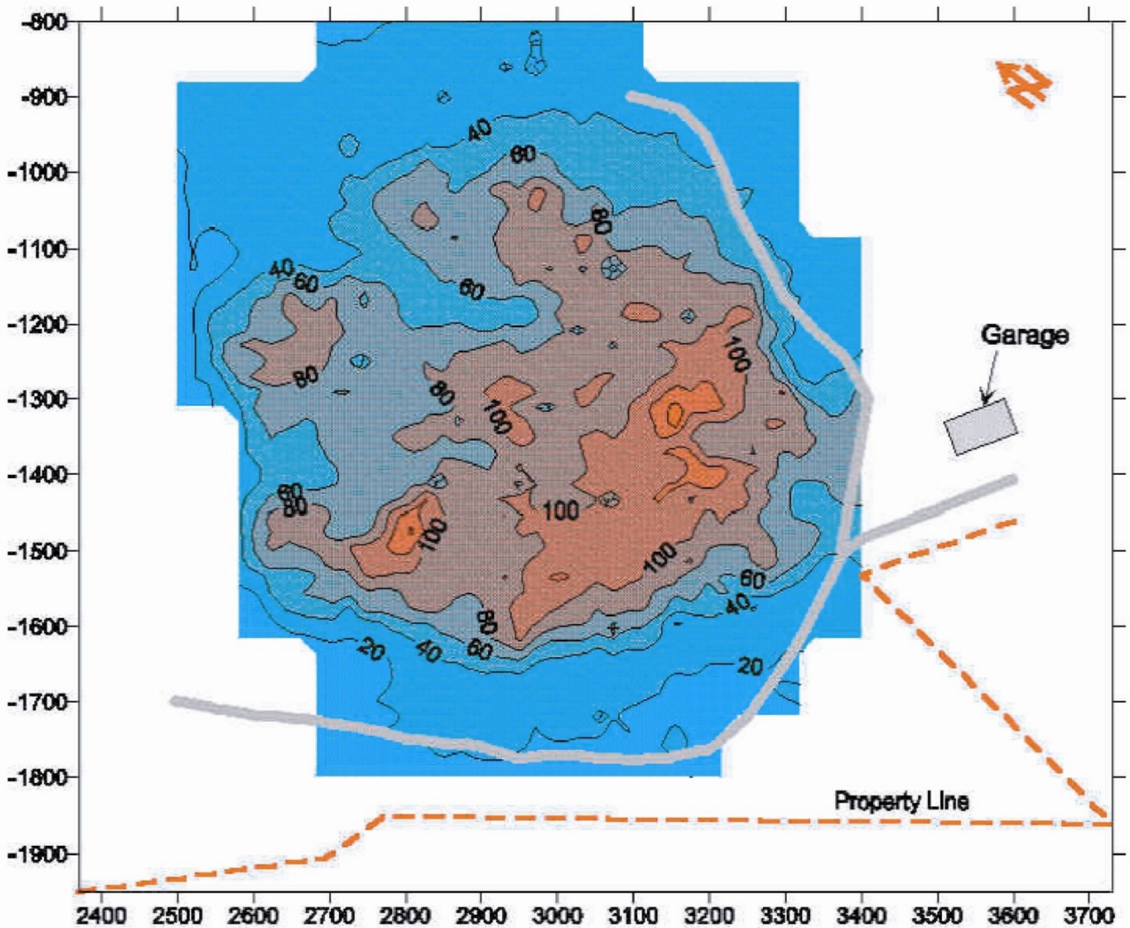
Profiling



White half space: 100 Ωm; Blue layer: 10 Ωm

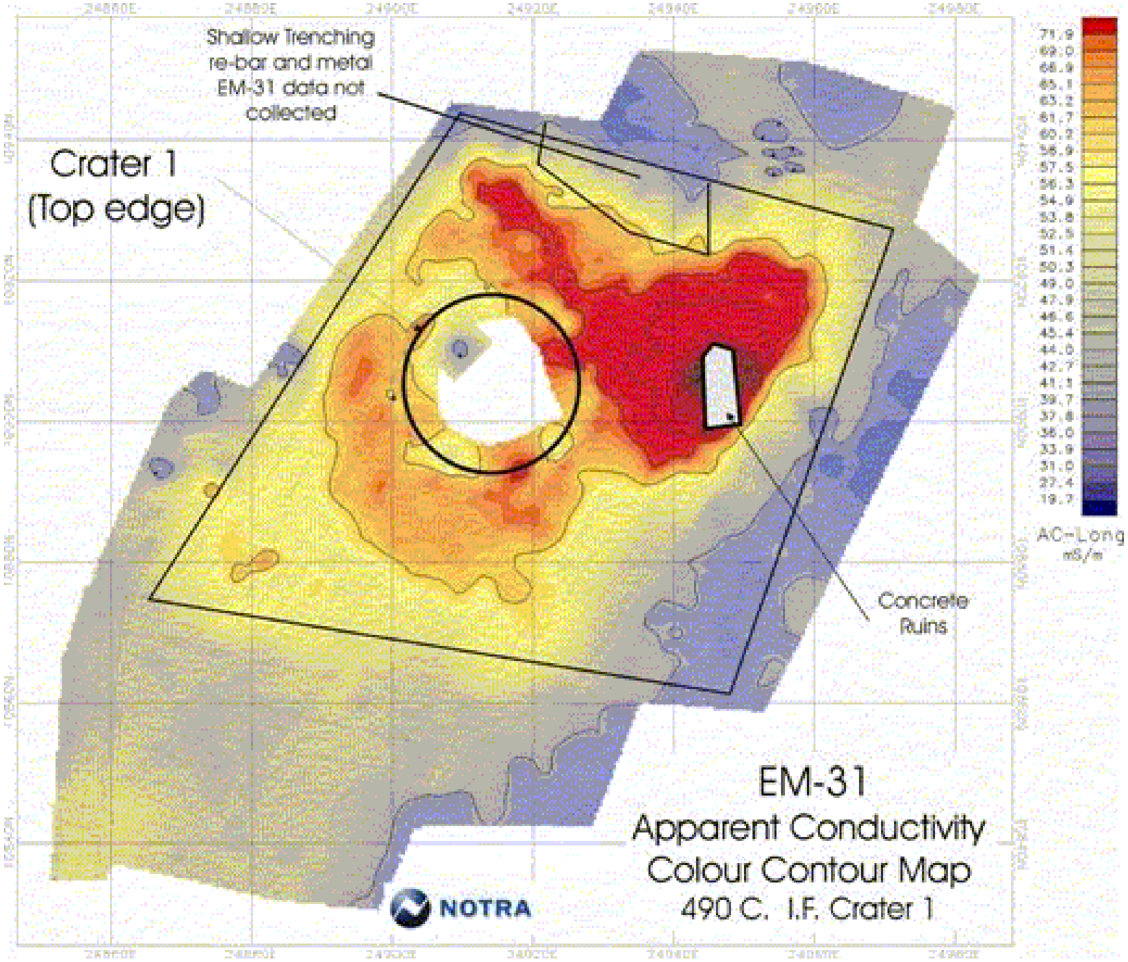
- Instrument with small coil spacing more sensitive to high-conductivity layer near surface
- HDM (dashed) more sensitive to near-surface
- Note ambiguity between layer depth and conductivity

Conductivity survey over buried landfill



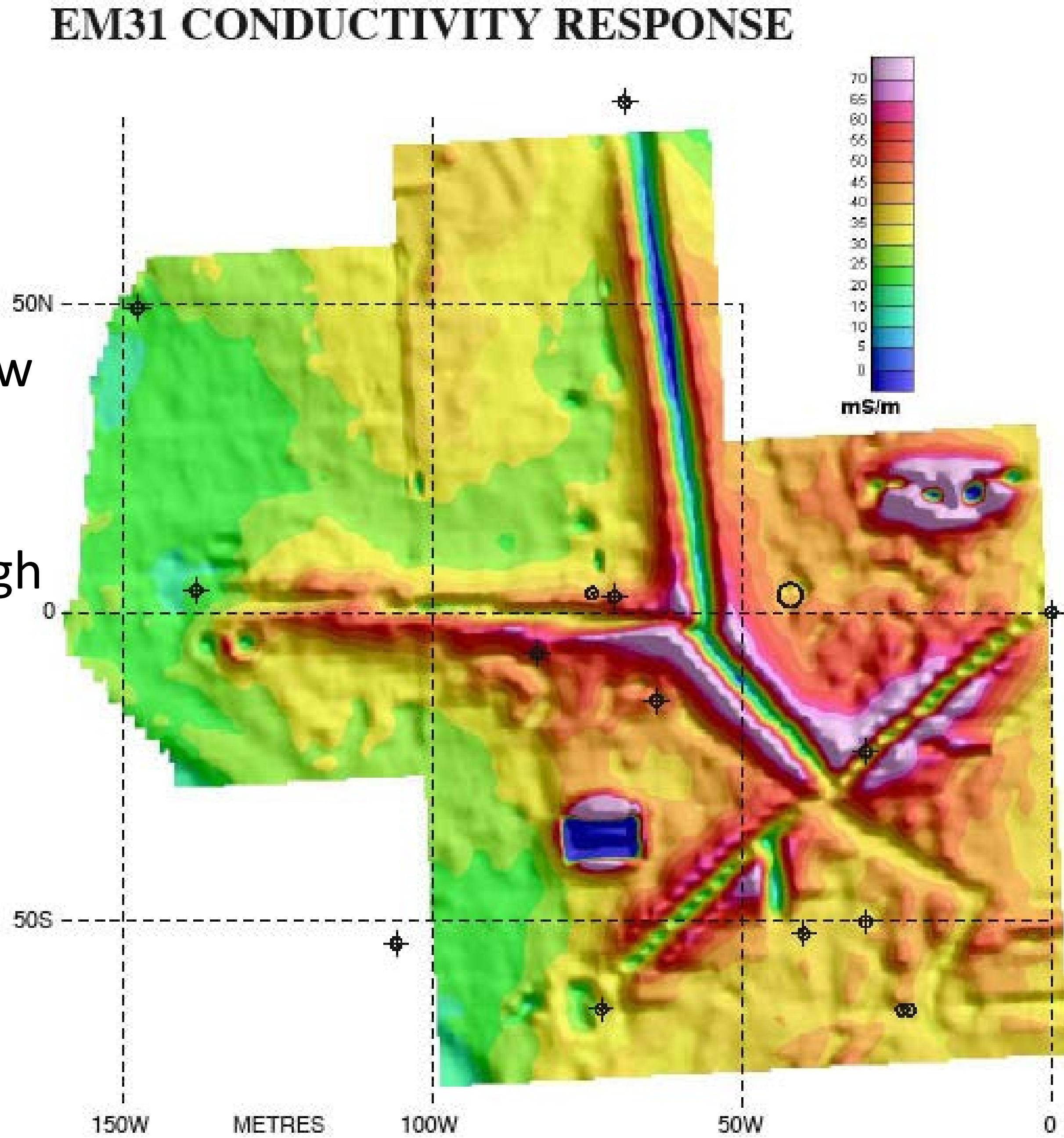
Electromagnetic terrain conductivity map (in mS/m) of Laurel Ridge Landfill, Lily, Kentucky (in feet). The higher conductivity values (>40 mS/m) represent areas of buried waste.

Unexploded ordnance UXO

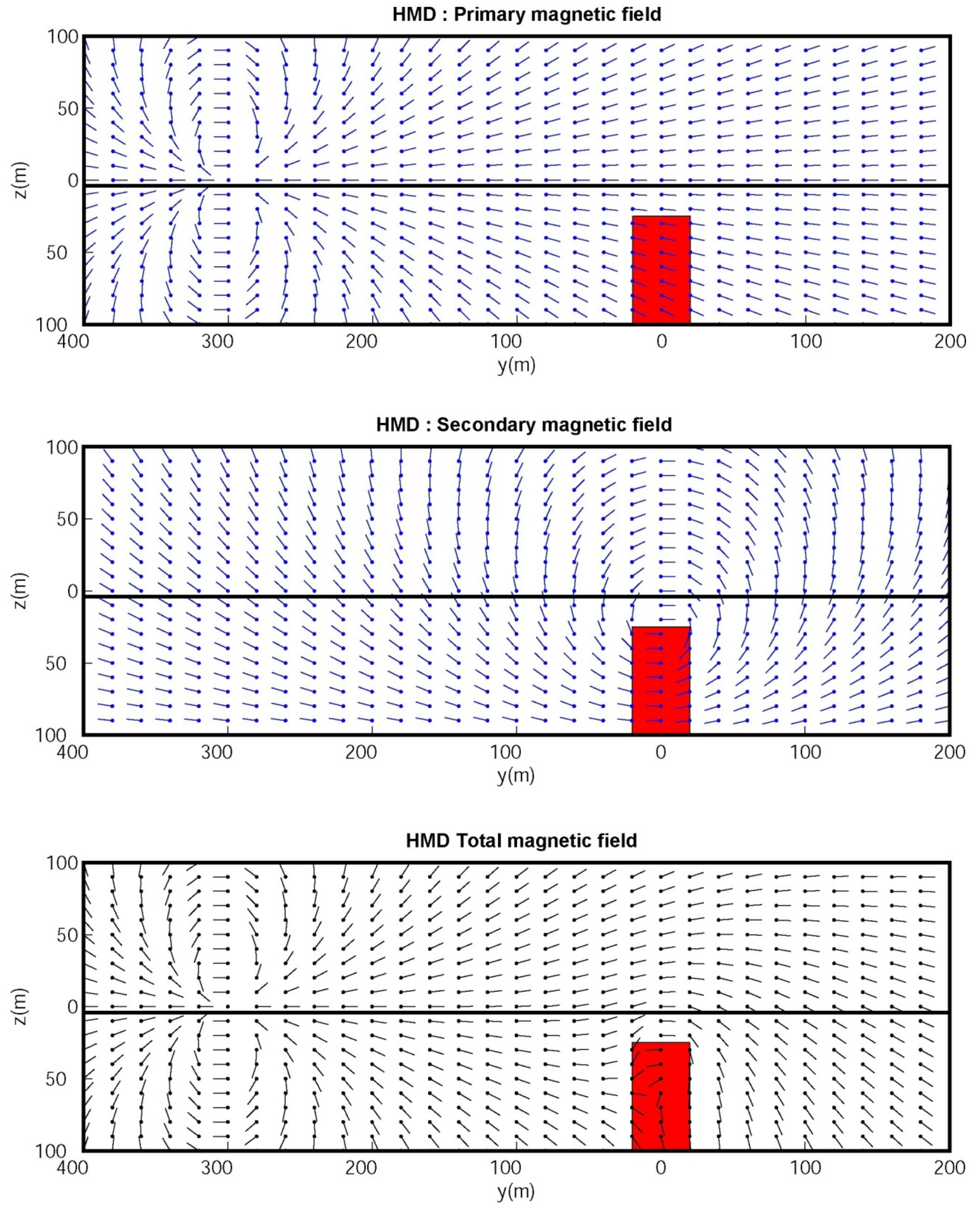


Apparent conductivity (EM31) and metallic (EM61) surveys to help define the extent of possible contamination. At many of the locations an elevated conductive trend was noted in the field. CFB Suffield, Alberta

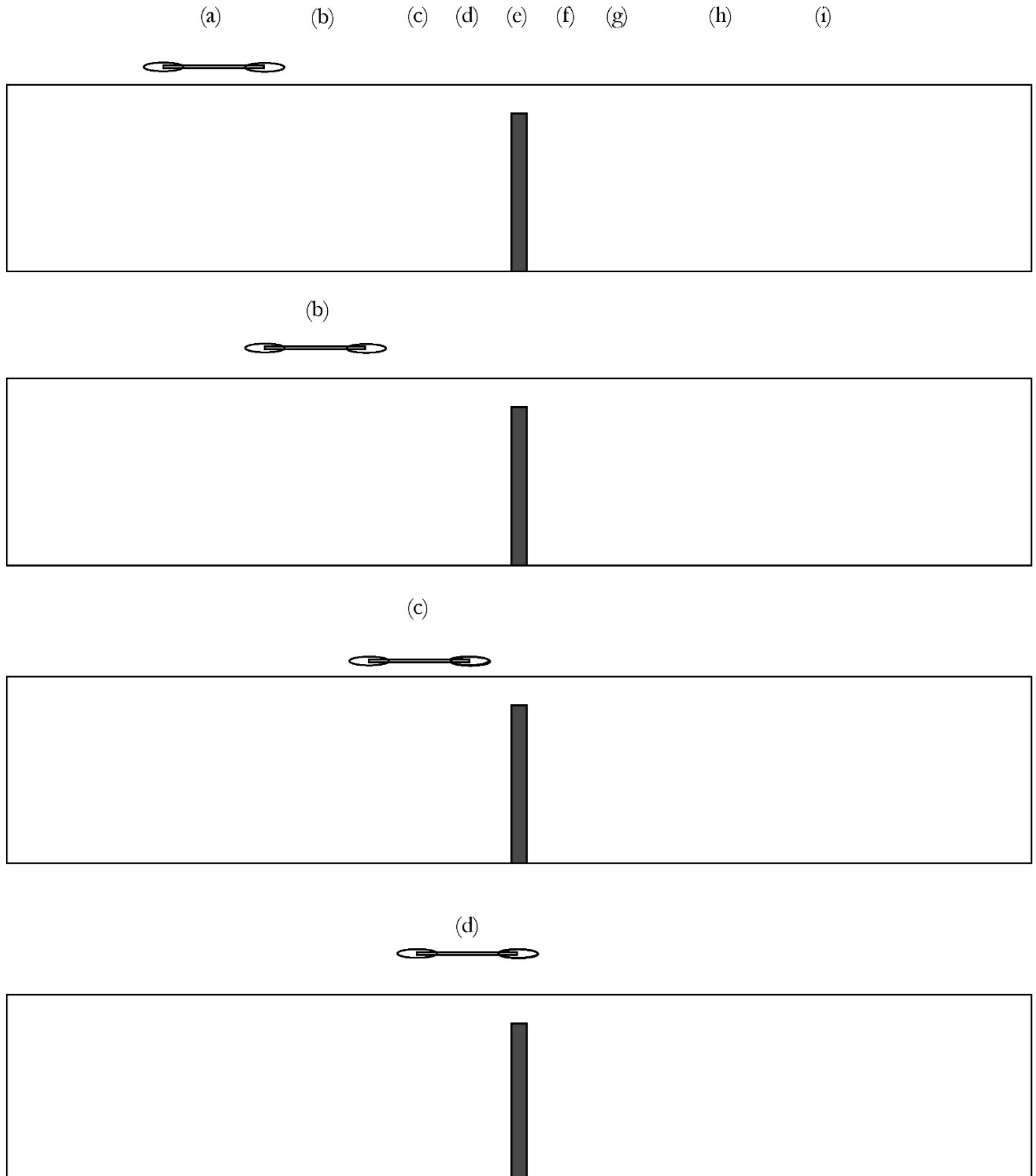
- Over small, anomalous bodies, EM response (apparent conductivity) can be negative!
- This occurs when the low induction number approximation is invalidated (e.g. very high conductivity with small skin depth close to instrument)



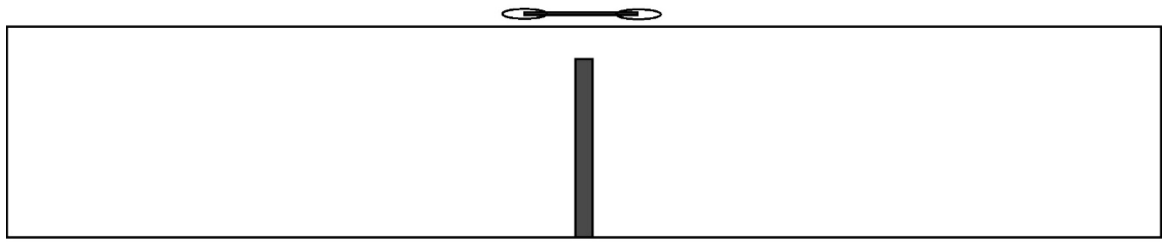
- The measured total EM field (a Vector!) is a superposition of Primary and Secondary field vectors



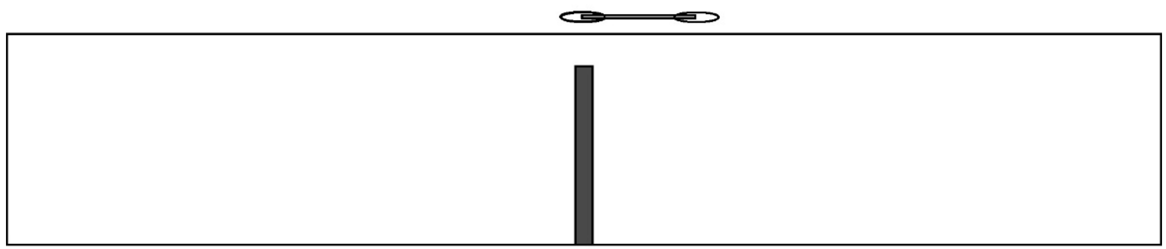
Measurements over small-scale anomalous bodies



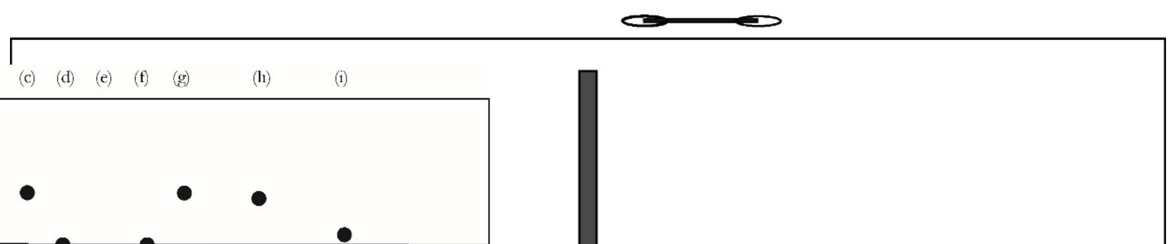
(e)

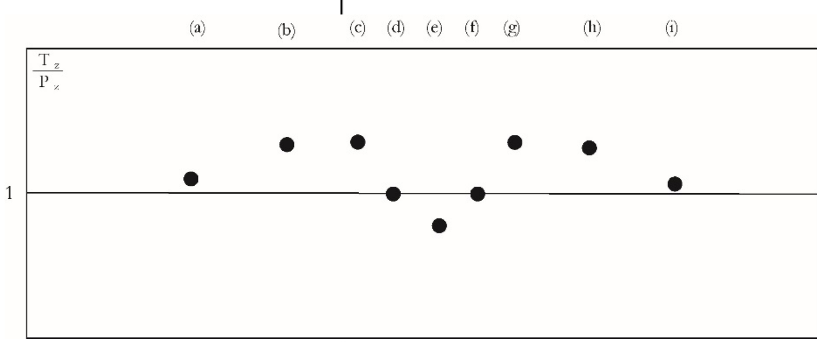


(f)

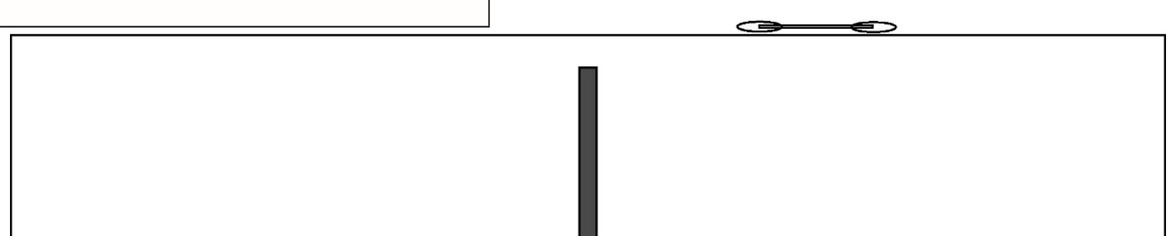


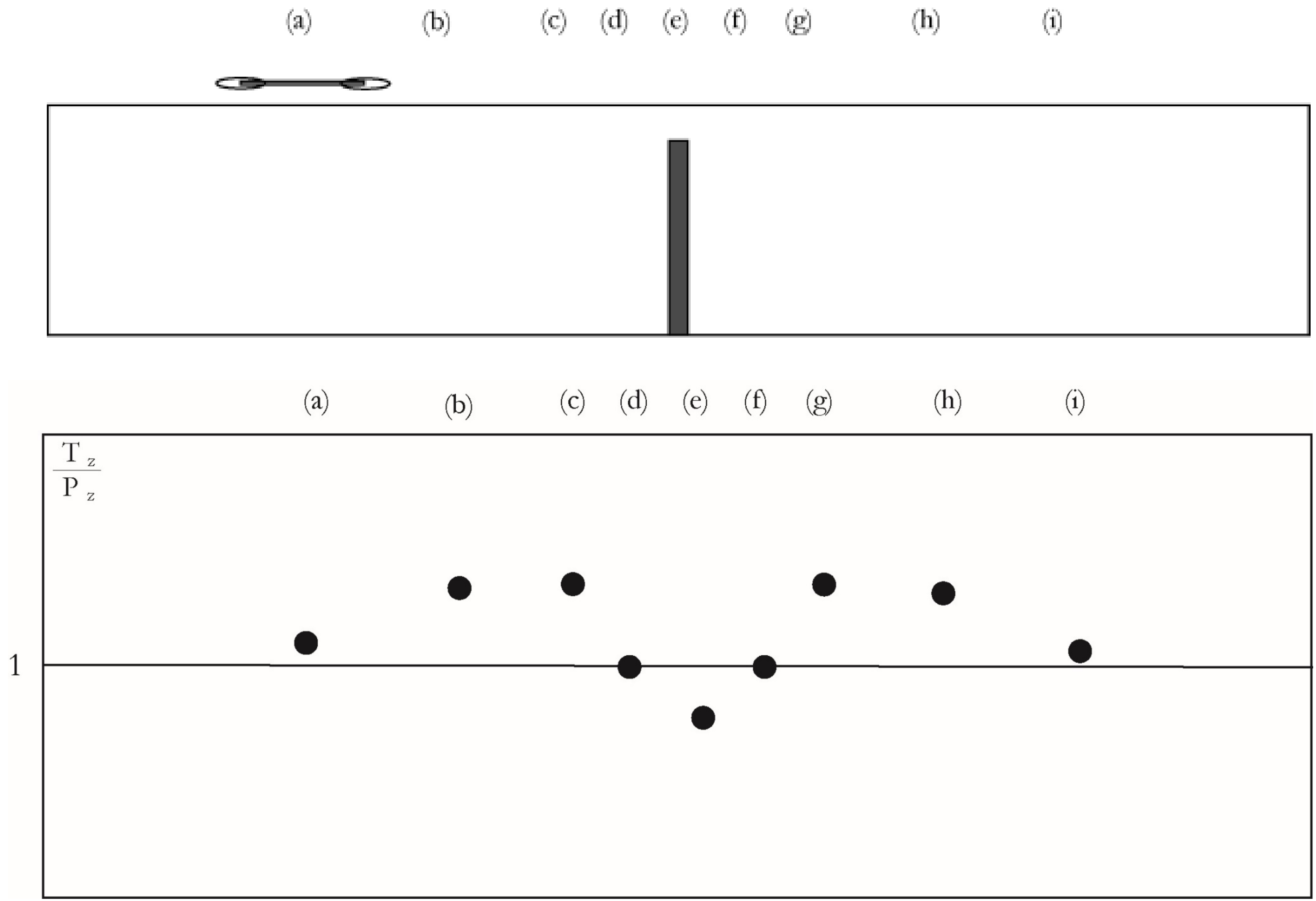
(g)





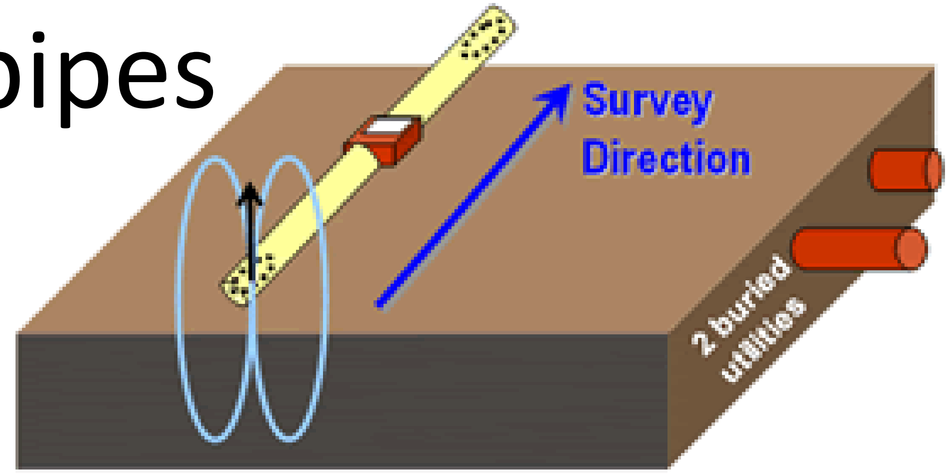
(h)

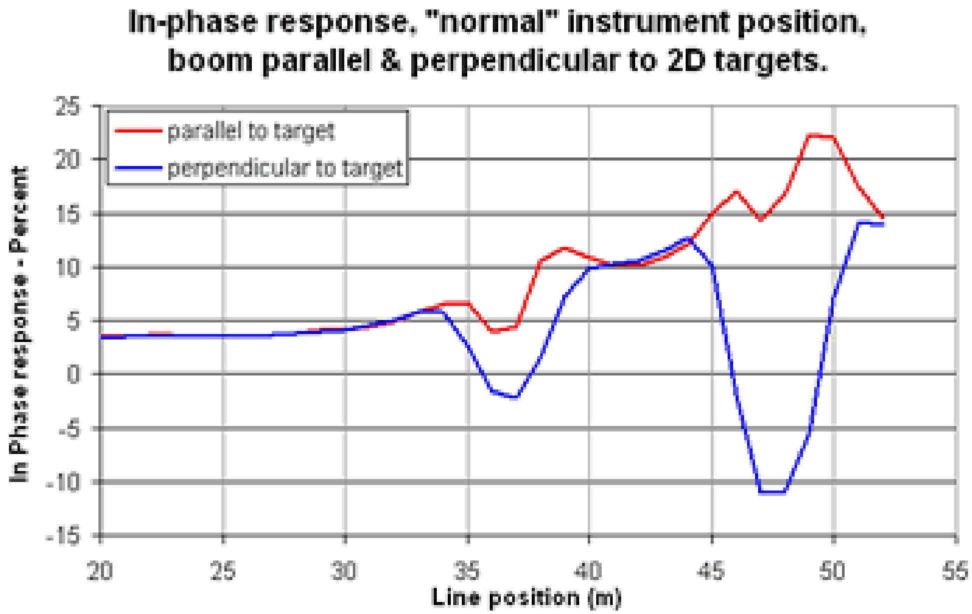


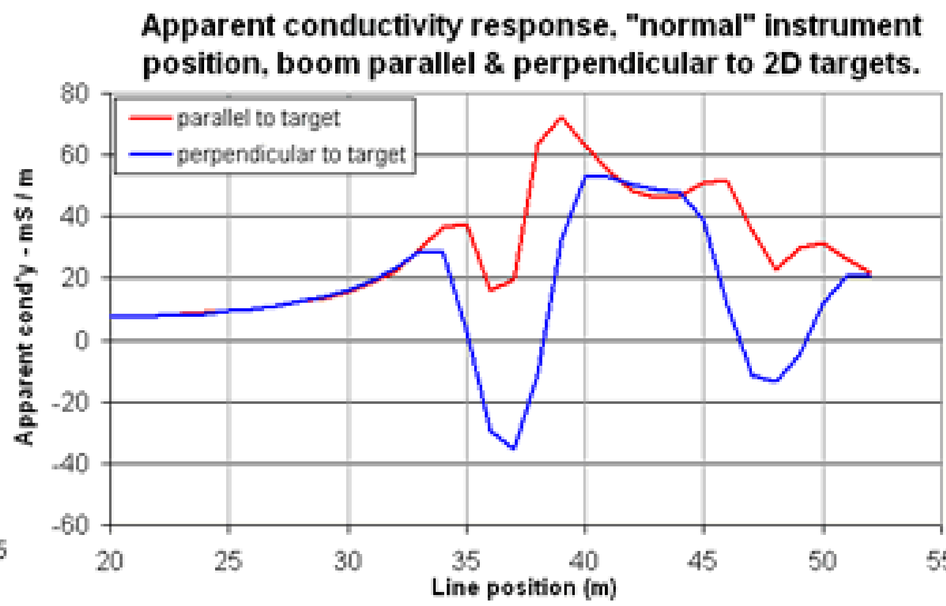

(a) (b) (c) (d) (e) (f) (g) (h) (i)
(a) (b) (c) (d) (e) (f) (g) (h) (i)
Tz / Pz
1

EM31 over buried pipes

- Response depends on instrument orientation relative to buried object's orientation
- Quadrature and Inphase show strong anomalies



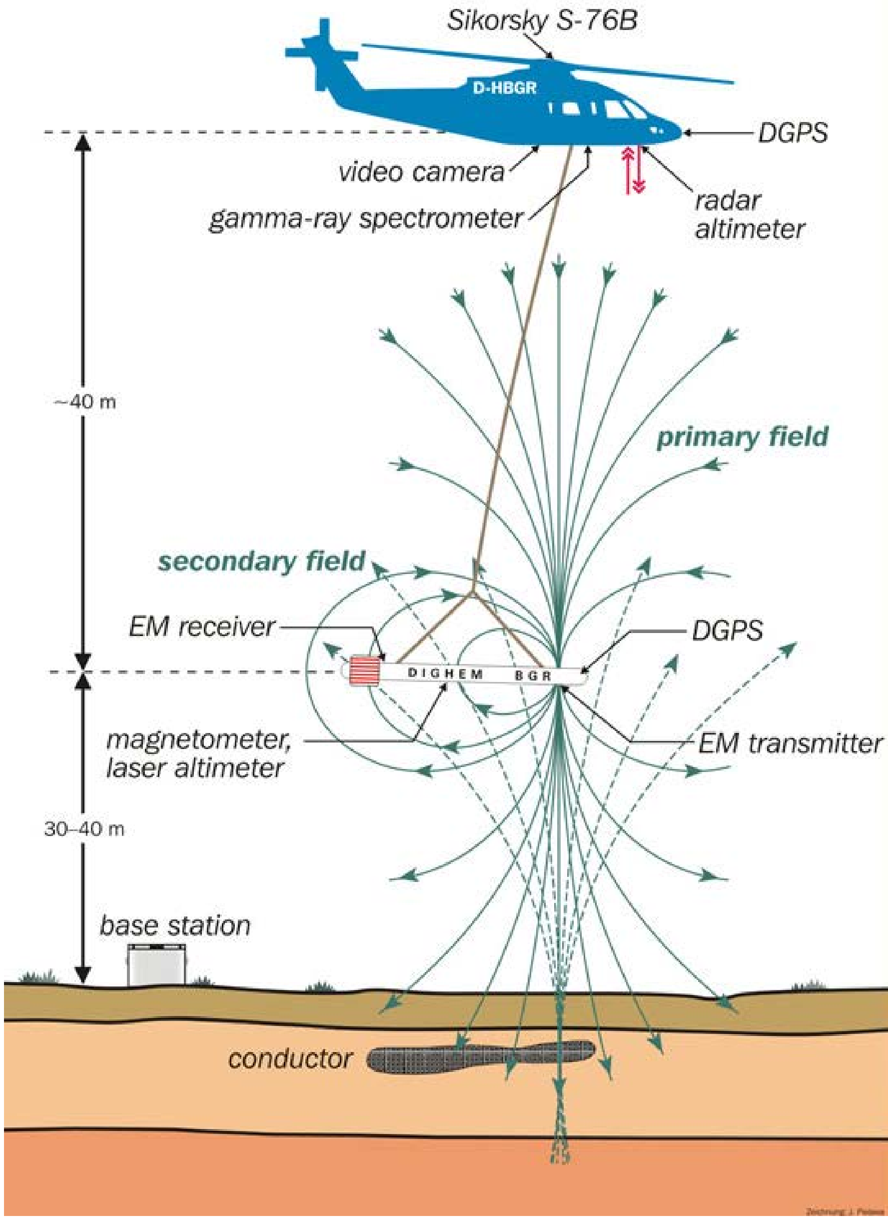




http://www.eos.ubc.ca/ubcgif/iag/foundations/method-summ_files/em31-notes.htm

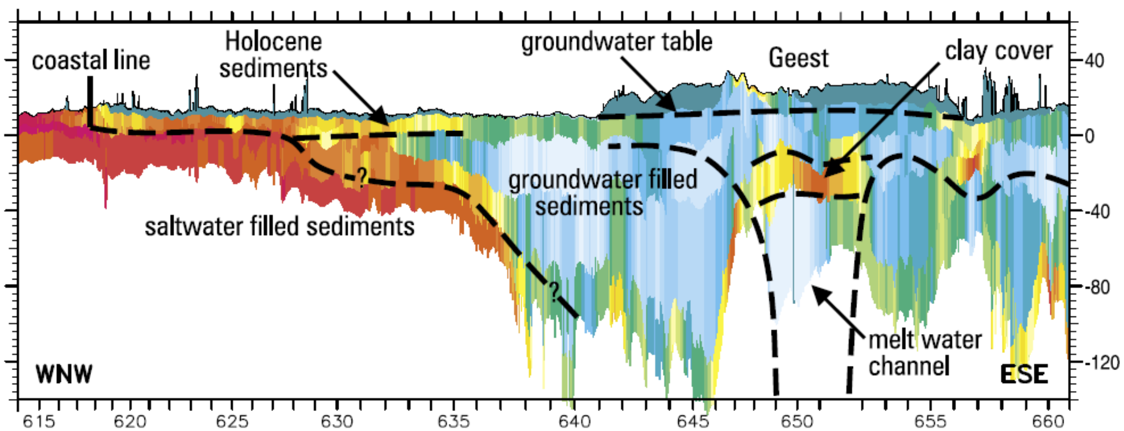
Airborne EM sounding (AEM)

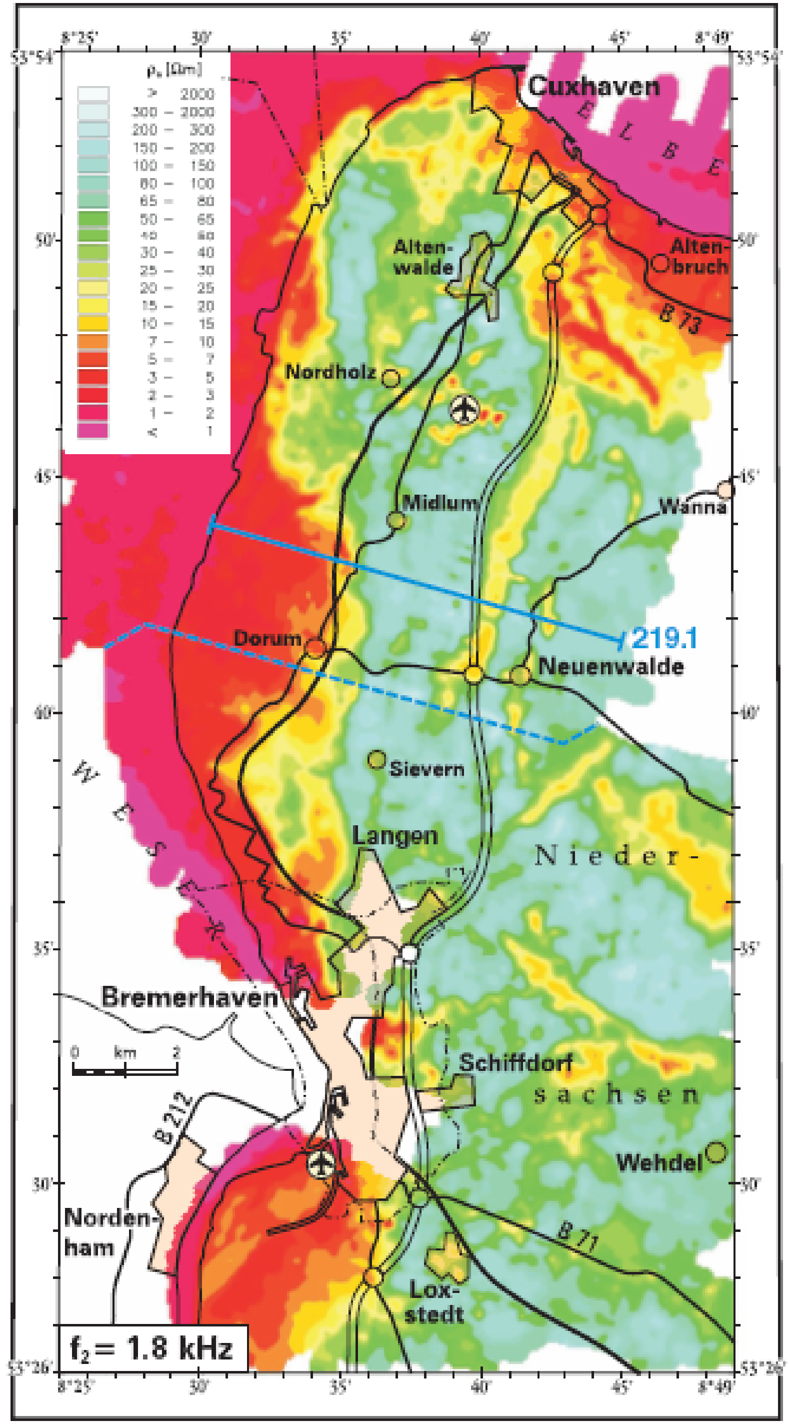
- Many EM instruments use only one signal frequency, i.e. they can only reveal limited information about the depth distribution of conductivity
- Many airborne EM systems utilize up to 5 frequencies to overcome these limitations
- Involved inversion of data required to derive conductivity-depth sections



http://www.bgr.bund.de/nn_335476/EN/Themen/GG__Geophysik/Aerogeophysik/Aeroelektromagnetik/aeroelektromagnetik__inhalt__en.html

Mapping of buried valleys

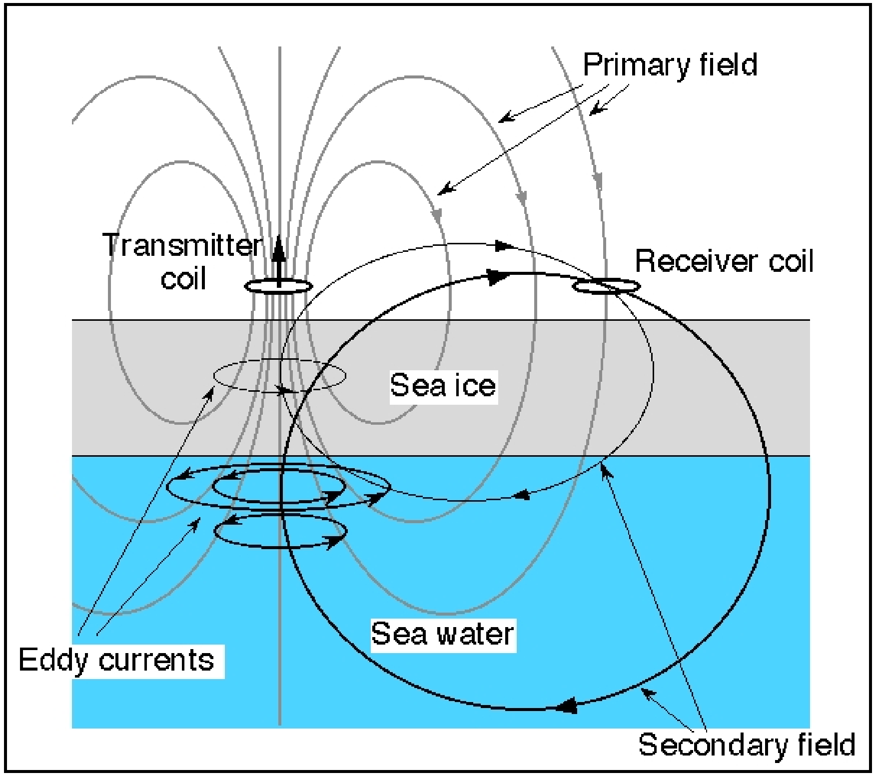




- Glacial meltwater channels are often filled with clay and possess higher conductivity than surrounding sediments

EM sounding of sea ice thickness

Uses assumption of negligible ice conductivity ("like air") and known water conductivity



σ = 0-50 mS/m

σ = 2500-2700 mS/m

Apparent conductivity $\sigma_a \equiv \frac{4}{\omega \mu_0 r^2} \cdot \mathrm{Im}(H_s / H_p)$

H_s, H_p: secondary and primary magnetic field

EM yields snow-plus-ice thickness, i.e. "total thickness"

„Geonics EM31“

Ice thickness and apparent conductivity

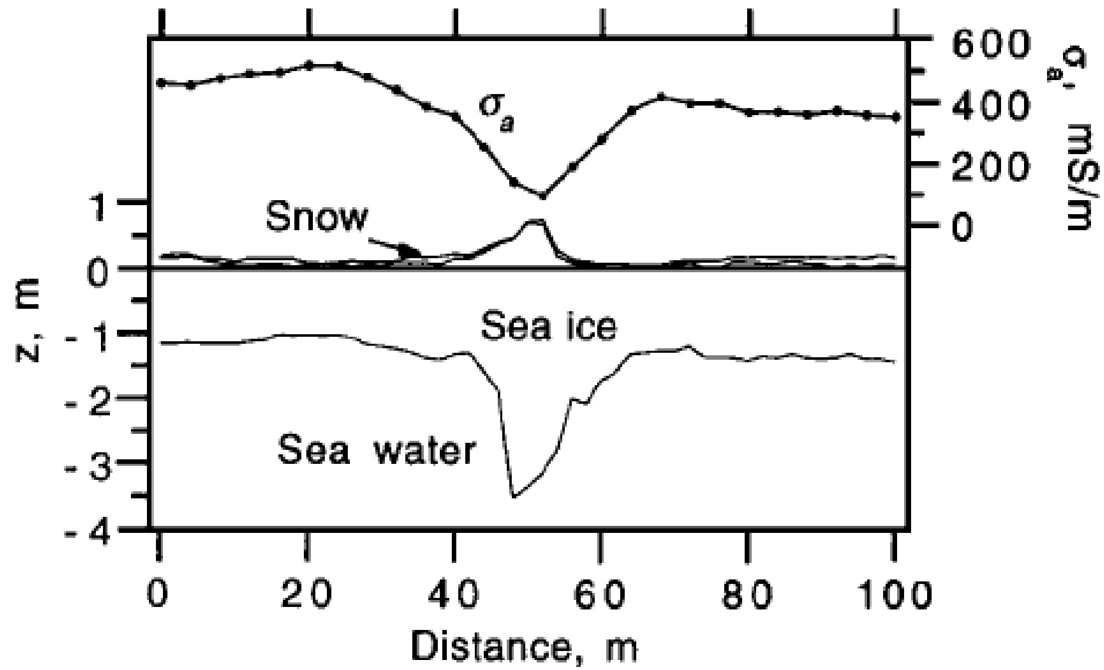


FIG. 2. 100 m long profiles of snow and ice thickness and apparent conductivity σ_a as measured in the horizontal dipole mode with the instrument placed on the ice surface (summer, profile S3). The zero line on the left axis marks the sea level. Spacing of drillholes is 2 m; that of EM measurements is 4 m.

GEOPHYSICS, VOL. 62, NO. 3 (MAY-JUNE 1997); P. 749–757, 8 FIGS., 1 TABLE.

Comparison of sea-ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device

Christian Haas*, Sebastian Gerland‡, Hajo Eicken*, and Heinz Miller*

ABSTRACT

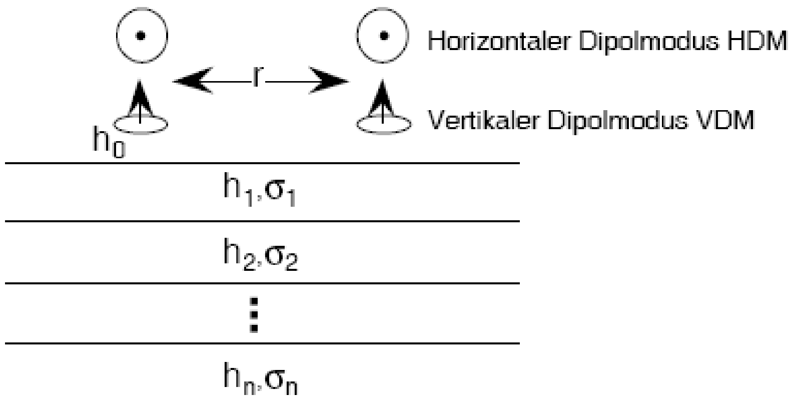
Drillhole-determined sea-ice thickness was compared with values derived remotely using a portable small-offset loop-loop steady state electromagnetic (EM) induction device during expeditions to Fram Strait and the Siberian Arctic, under typical winter and summer conditions. Simple empirical transformation equations are derived to convert measured apparent conductivity into ice thickness. Despite the extreme seasonal differences in sea-ice properties as revealed by ice core analysis, the transformation equations vary little for winter and summer. Thus, the EM induction technique operated on the ice surface in the horizontal dipole mode yields accurate results within 5 to 10% of the drillhole determined thickness over level ice in both seasons.

The robustness of the induction method with respect to seasonal extremes is attributed to the low salinity of brine or meltwater filling the extensive pore space in summer. Thus, the average bulk ice conductivity for summer multiyear sea ice derived according to Archie's law amounts to 23 mS/m compared to 3 mS/m for winter conditions. These mean conductivities cause only minor differences in the EM response, as is shown by means of 1-D modeling.

However, under summer conditions the range of ice conductivities is wider. Along with the widespread occurrence of surface melt ponds and freshwater lenses underneath the ice, this causes greater scatter in the apparent conductivity/ice thickness relation. This can result in higher deviations between EM-derived and drillhole determined thicknesses in summer than in winter.

1D-Model of layered underground

- <u>Simple formulas (R-terms) cannot be applied</u> because low-induction number approximation does not apply due to high seawater conductivity
- Full solutions have to be calculated involving “Hankel Transforms” and Bessel functions



$$H_s/H_p = -r^2 \int_0^\infty \lambda R_0 \cdot \exp(-2\lambda h_0) \cdot f(\lambda r)\, d\lambda \qquad 3.9$$

berechnen (z.B. Mundry, 1984; Ward und Hohmann, 1988; Verma und Sharma, 1995). Dabei ist λ die Integrationskonstante und f eine vom Dipolmodus abhängige Funktion:

$$f(\lambda r) = \lambda\, r\, J_0(\lambda r), \quad \text{vertikaler Dipolmodus (VDM)}$$

$$f(\lambda r) = J_1(\lambda r), \quad \text{horizontaler Dipolmodus (HDM)},$$

mit den Besselfunktionen erster Gattung nullter und erster Ordnung J_0 und J_1. R_0 ist eine rekursive Funktion der Untergrundparameter:

$$R_{n-1} = K_{n-1}$$

$$R_{i-2} = (K_{i-2} + R_{i-1}\, u_{i-1})/(1 + K_{i-2}\, R_{i-1}\, u_{i-1}) \qquad 3.9a$$

mit:

$$u_i = \exp(-2\, h_i\, v_i),$$

$$v_i = (\lambda^2 + j\omega\mu_0\sigma_i)^{1/2}$$

$$K_{i-1} = (v_{i-1} - v_i)/(v_{i-1} + v_i)$$

Apparent conductivity vs. Thickness: Drill-hole comparison

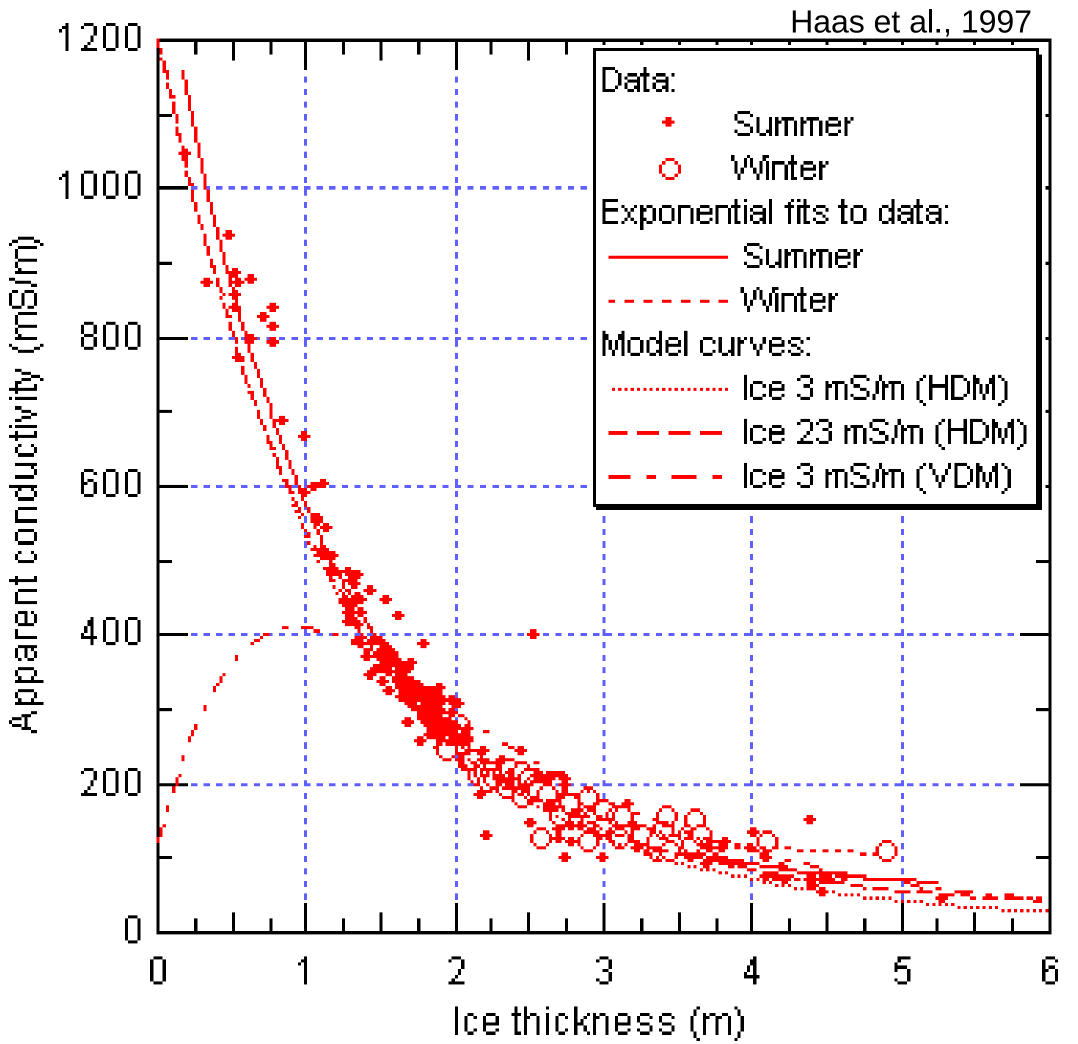
• Data follow negative exponential relation of the form:

$$\sigma_a = c_0 + c_1 e^{(-c_2 h_i)}$$

c_i = coefficients
h_i = ice thickness

• This can be solved for ice thickness:

$$h_i = -\frac{1}{c_2} \ln\left(\frac{\sigma_a - c_0}{c_1}\right)$$



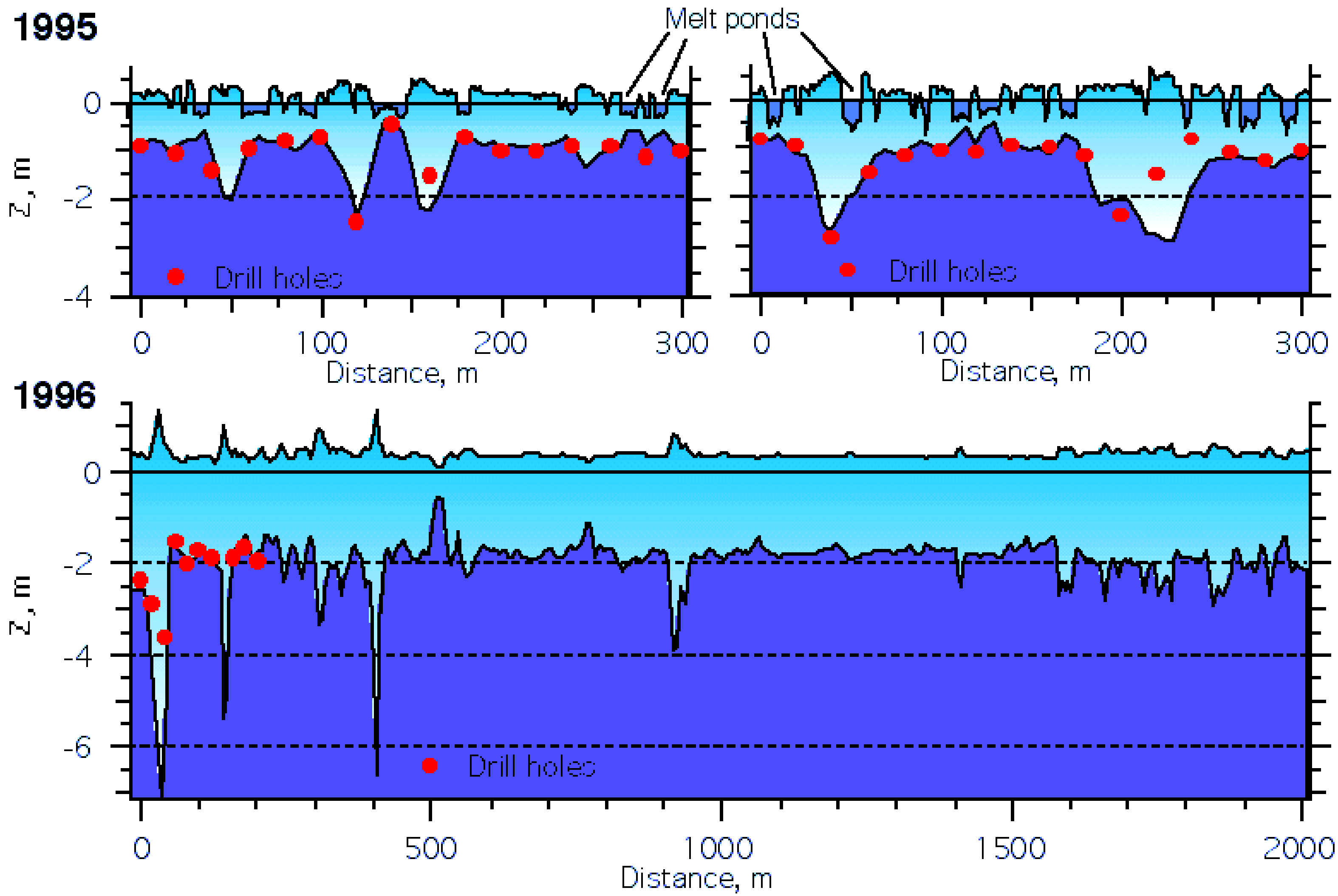
• Very little variation between summer and winter

• Note odd VDM behavior
→ HDM is used for thin ice

EM thickness validation by drill-holes

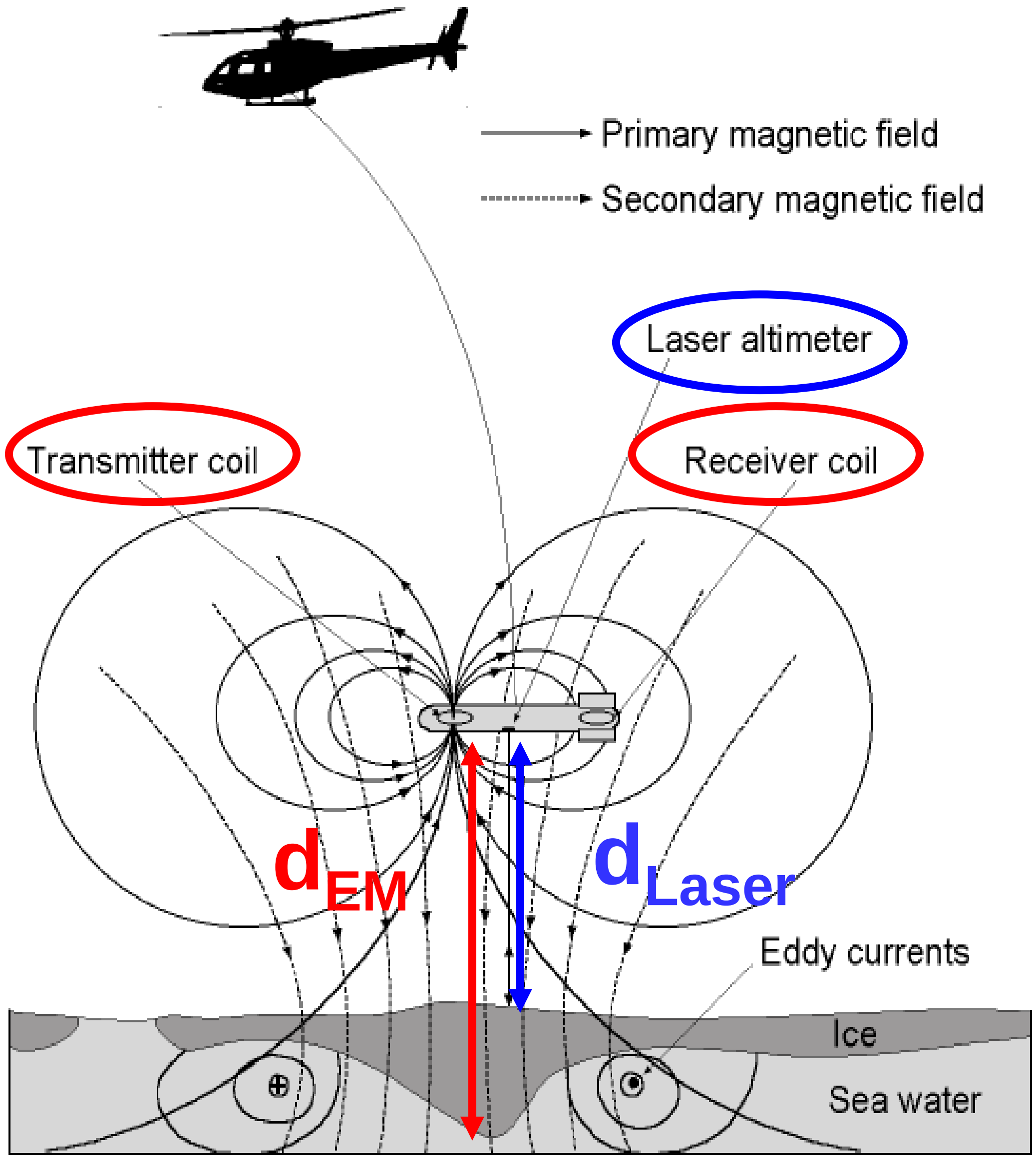
Summer

Winter



- Good agreement within +/- 10 cm with drill-hole data over level ice
- Significant deviations over rough ice due to EM footprint

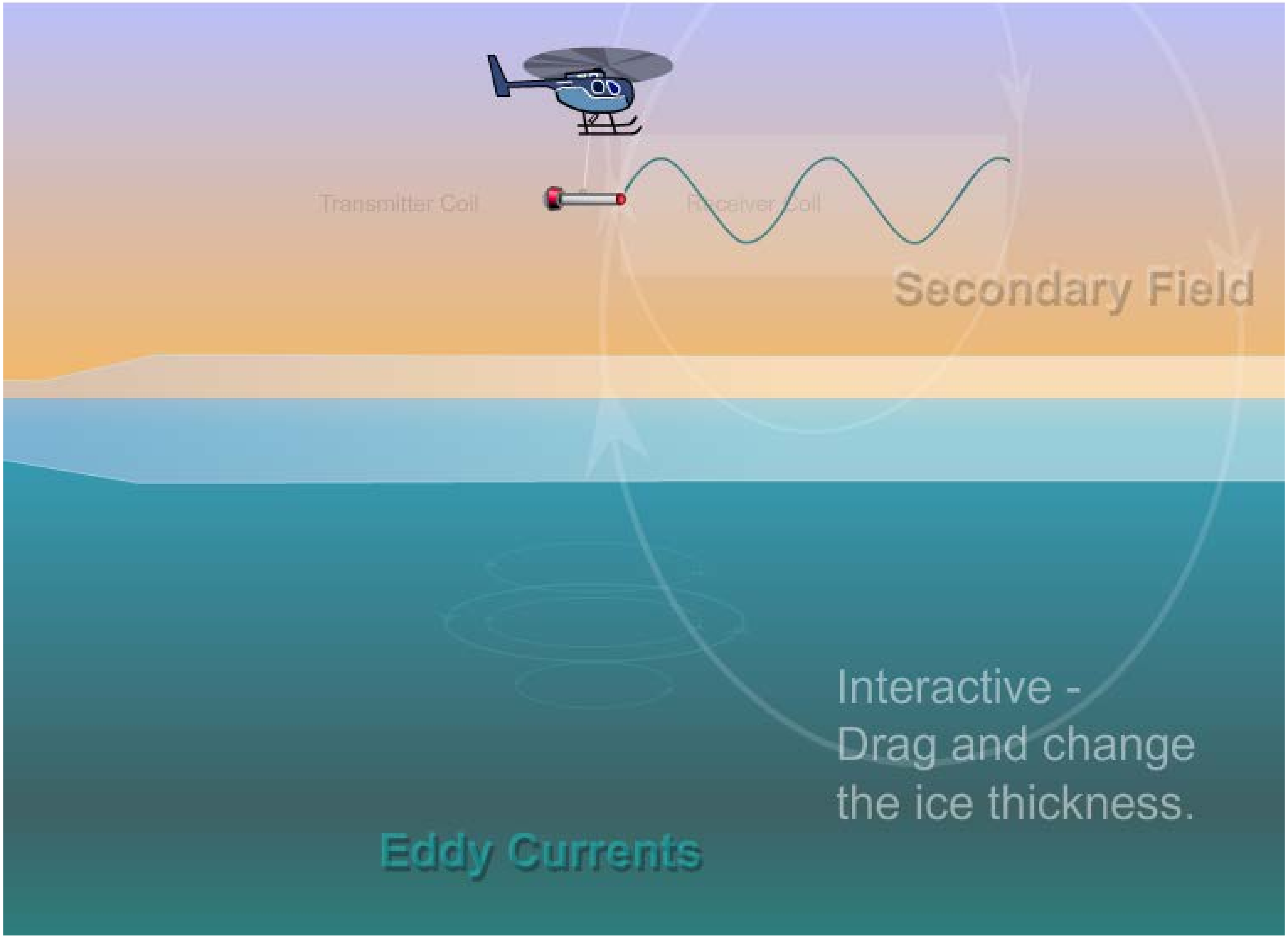
EM induction sea ice thickness sounding



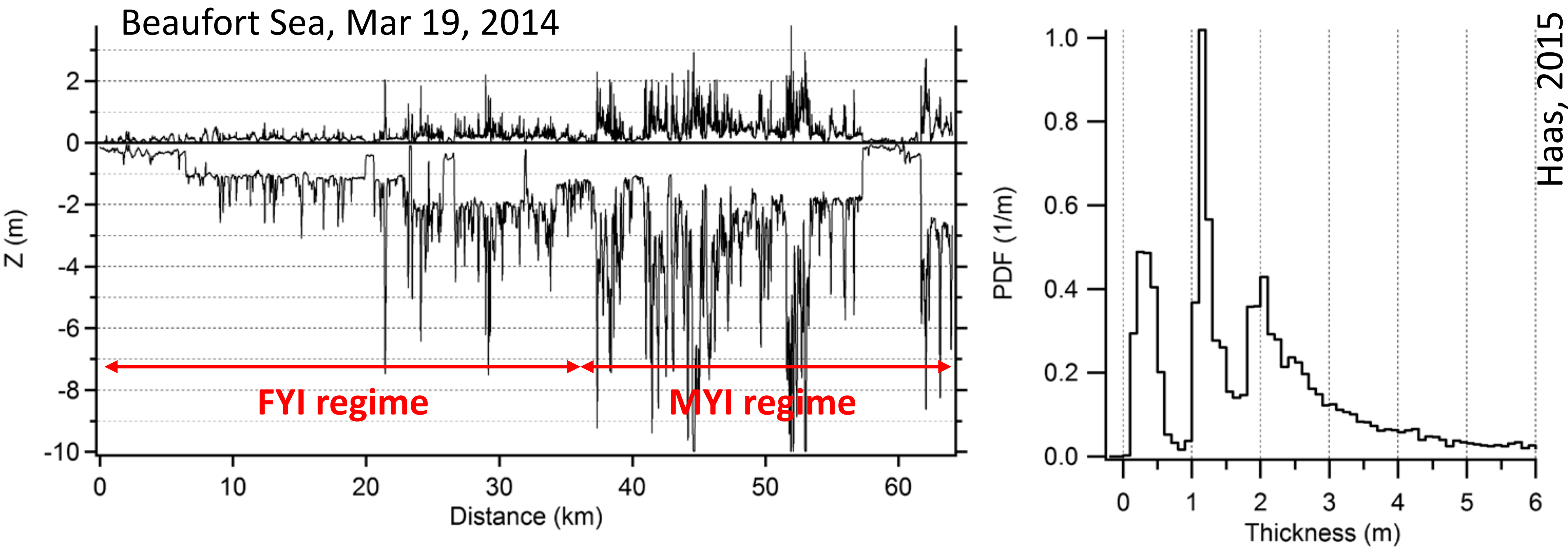
$$Z_i = d_{EM} - d_{Laser}$$

(snow + ice)

$$\sigma_{Ice} << \sigma_{Sea\ water}$$

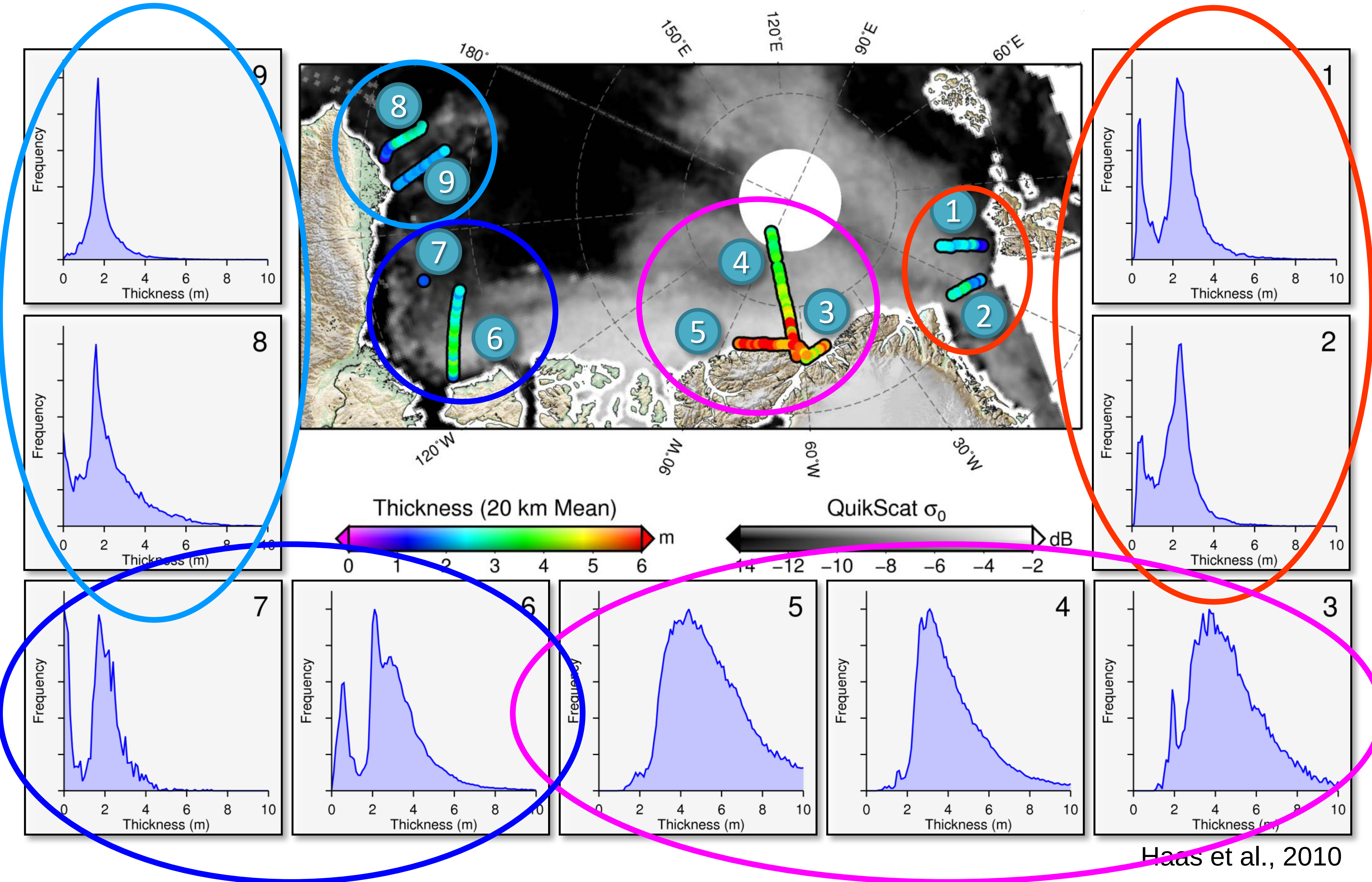

Transmitter Coil
Receiver Coil
Secondary Field
Interactive -
Drag and change
the ice thickness.
Eddy Currents

Typical AEM thickness profile



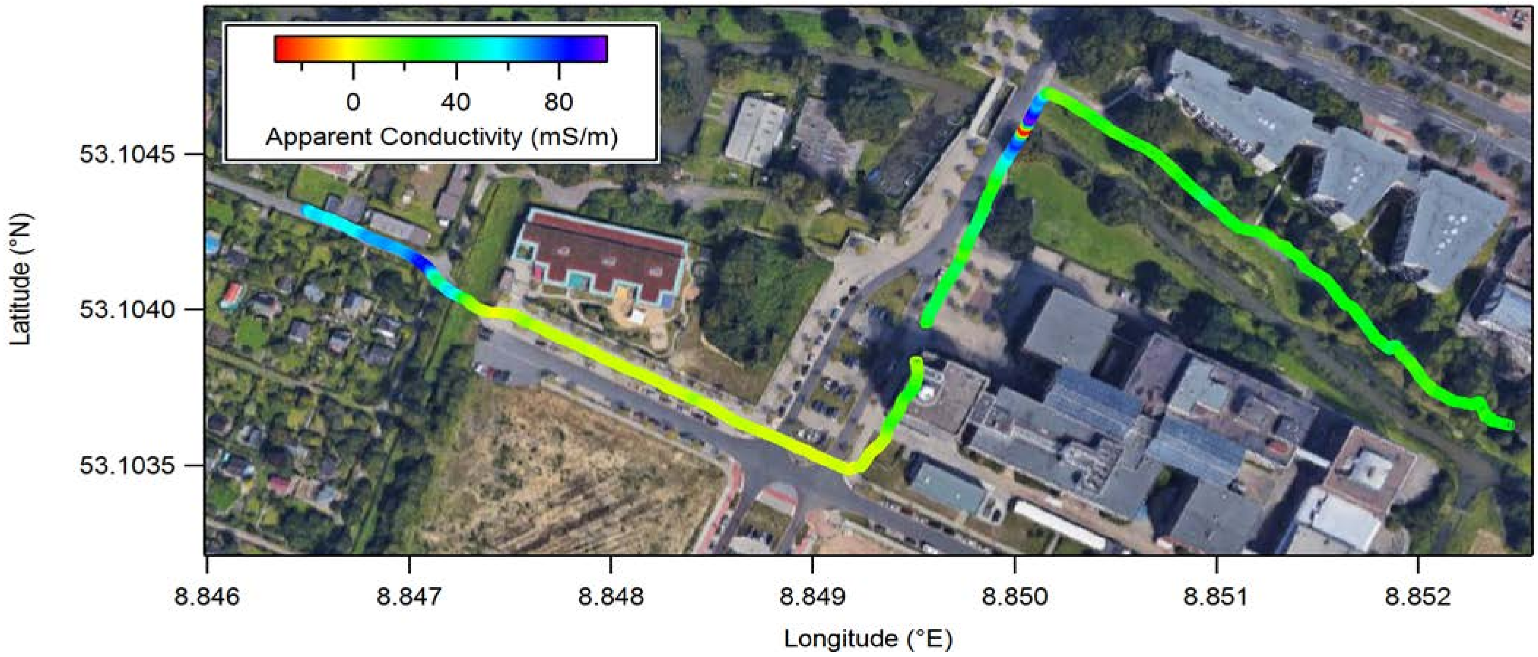
- Ice thickness (incl. bottom and keel morphology) from AEM (smoothed by footprint)
- Surface morphology (incl. ridge distributions) from laser altimetry
- Note mix of different FYI and MYI thickness classes and overlapping ranges of ridges and level ice

Thickness Fingerprints of Arctic Ice Regimes



Haas et al., 2010

The Bremen experiment



- Profile campus in VDM and HDM
- Georeference and resample data
- Convert to ice thickness