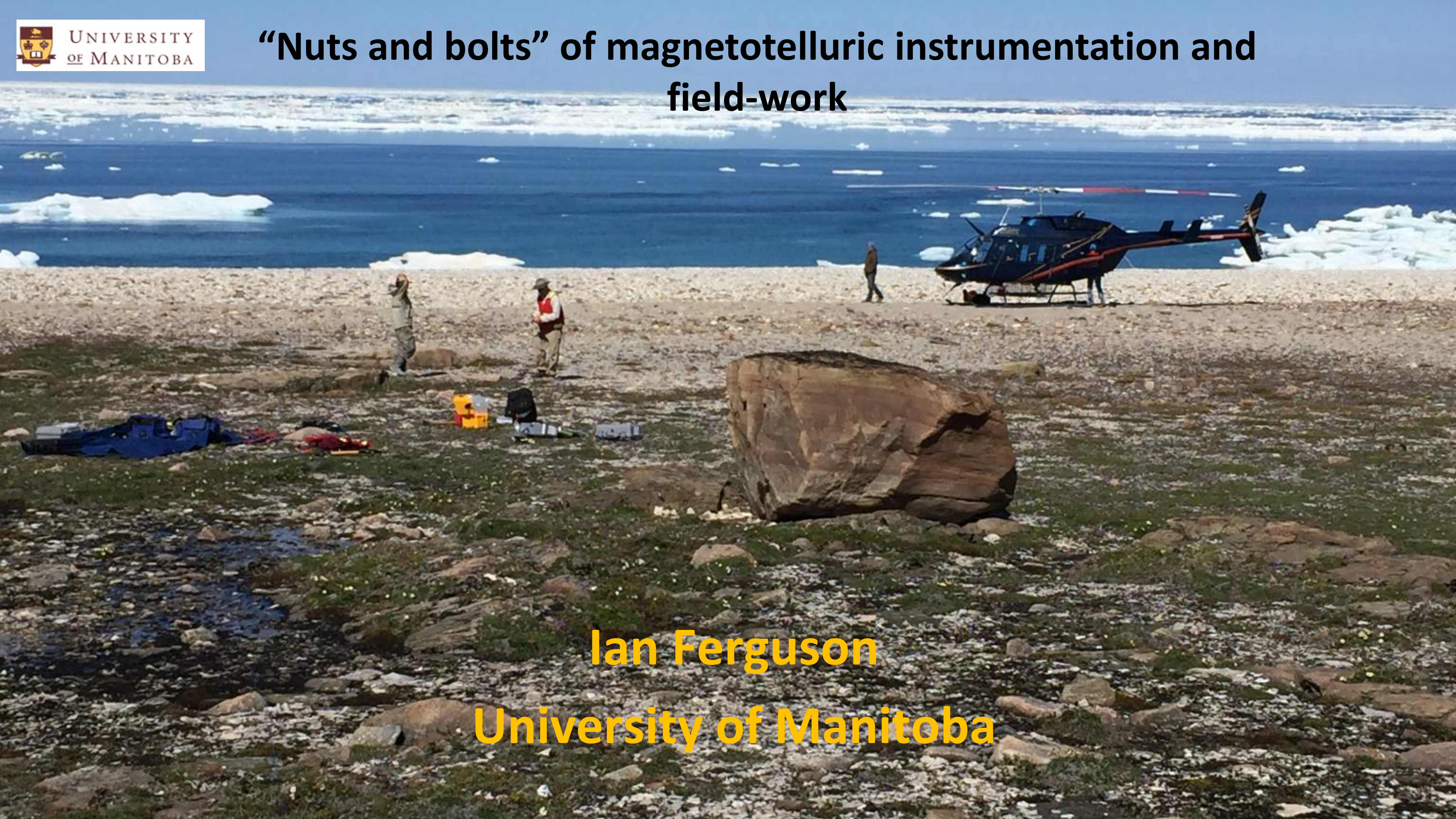
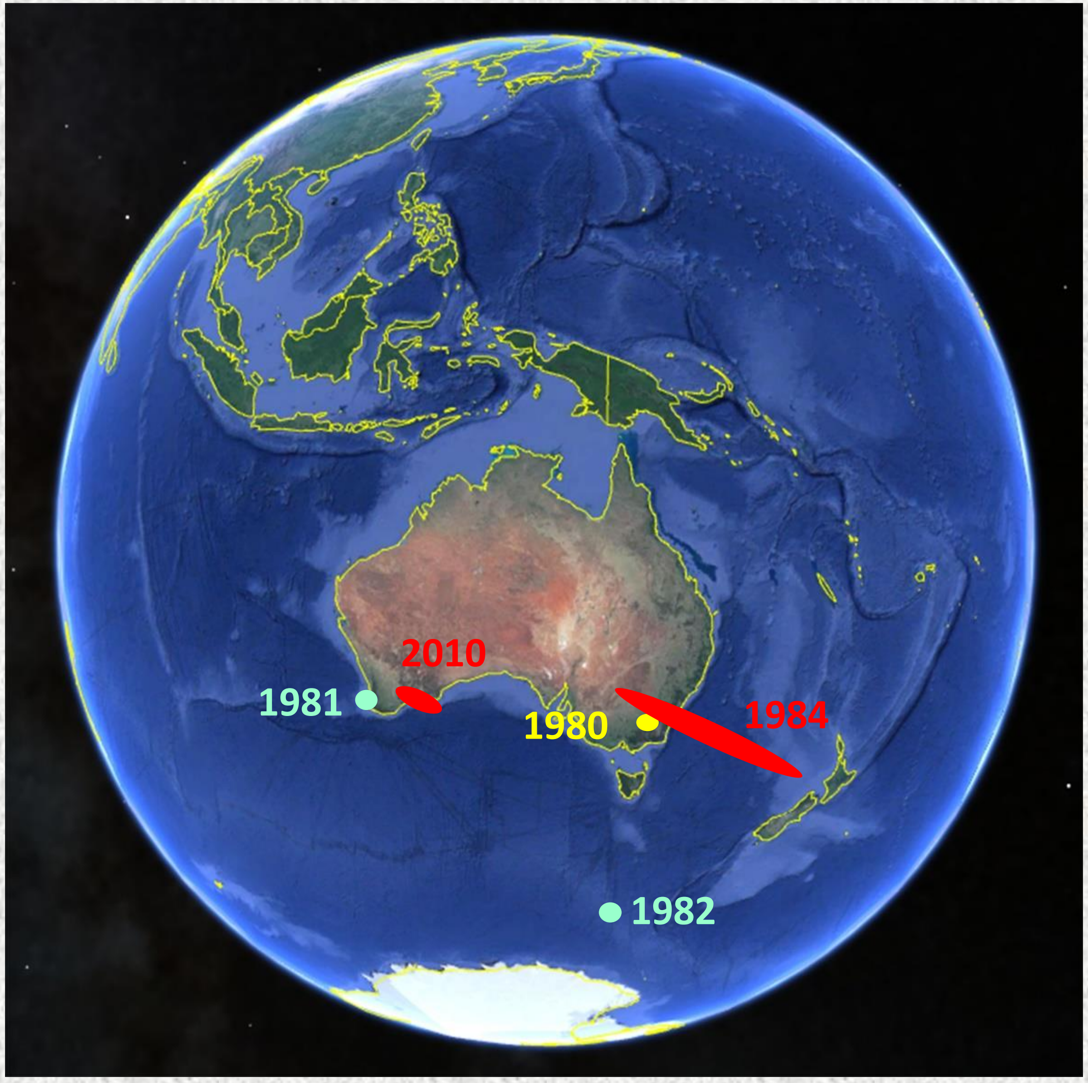
“Nuts and bolts” of magnetotelluric instrumentation and field-work

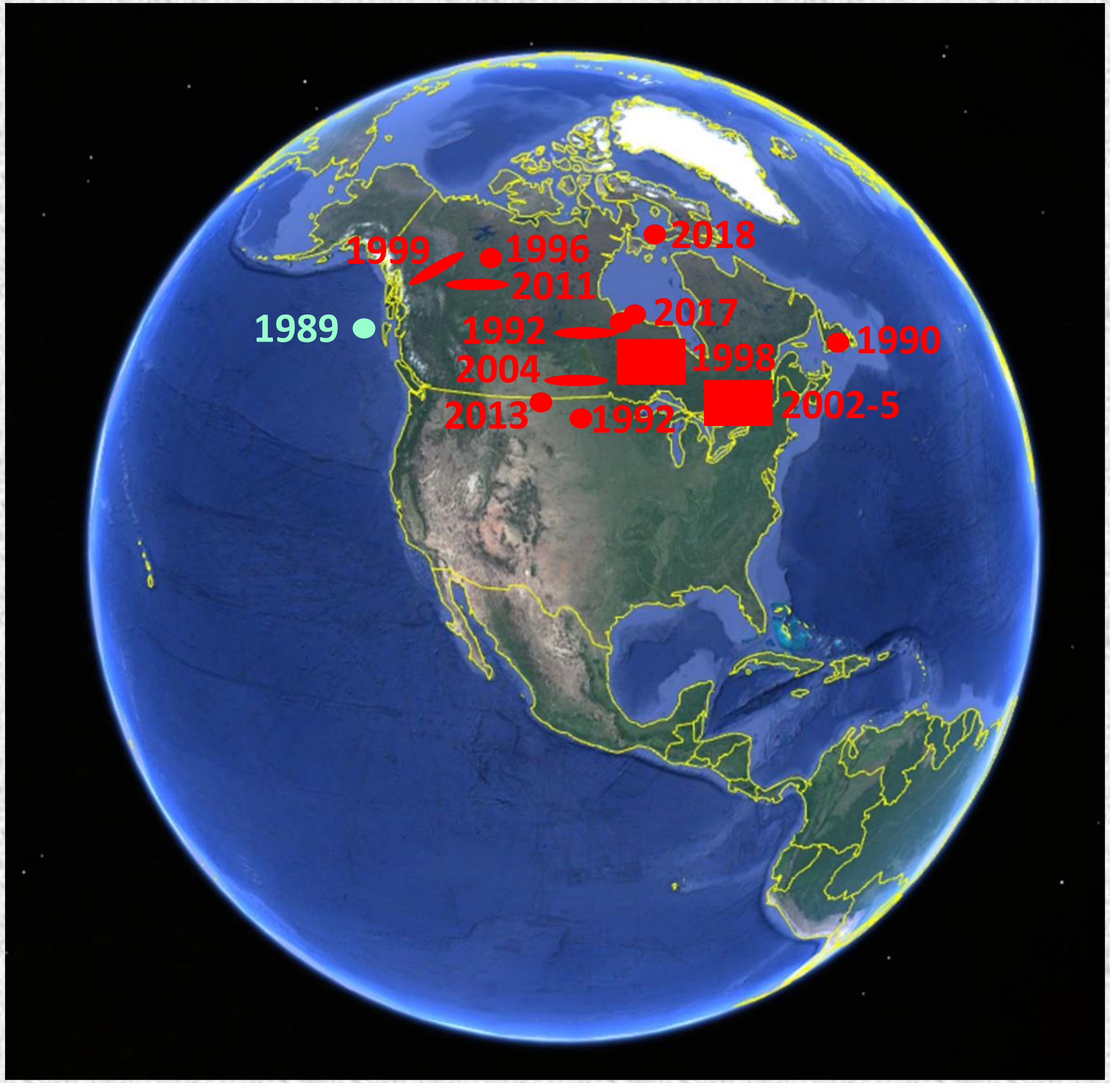


Ian Ferguson

University of Manitoba

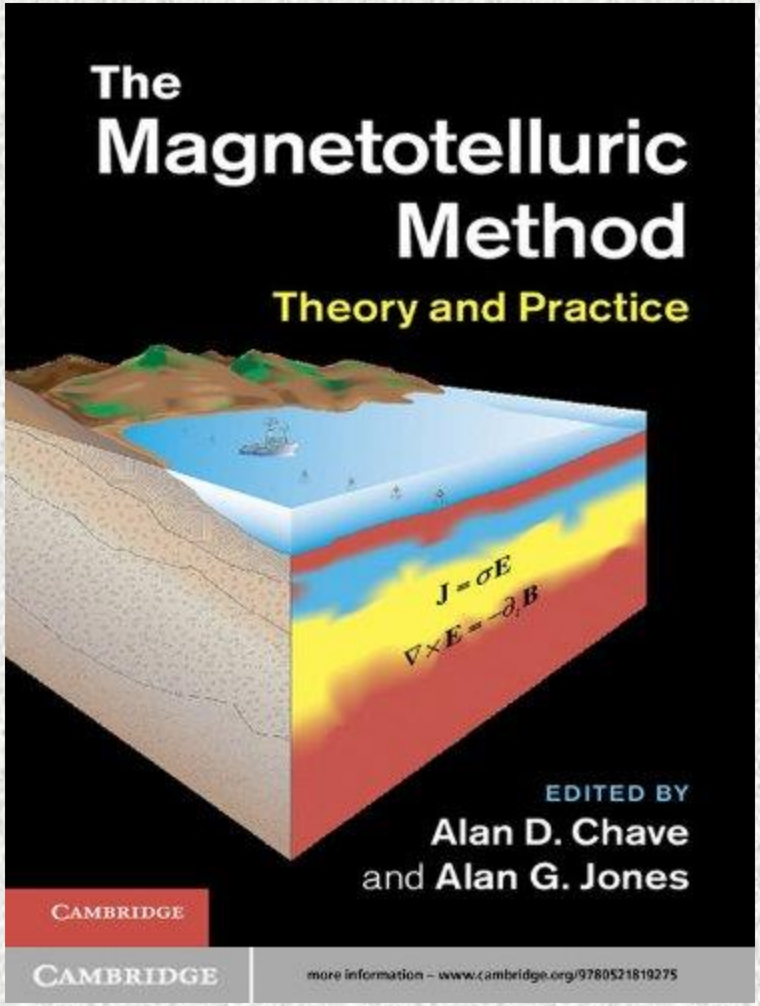
MT and related field experience



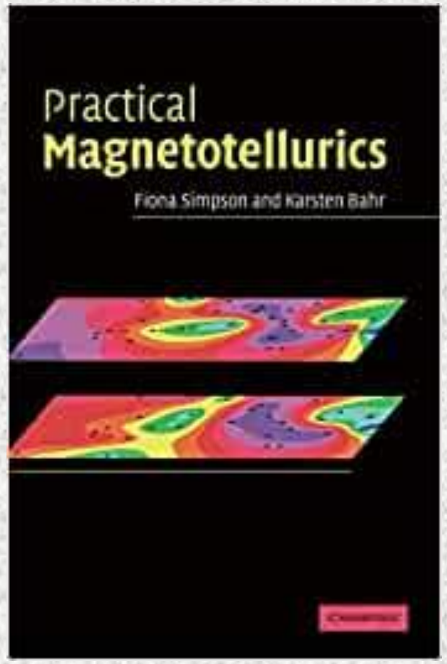


Magnetotelluric measurements   Telluric measurements   Magnetic measurements

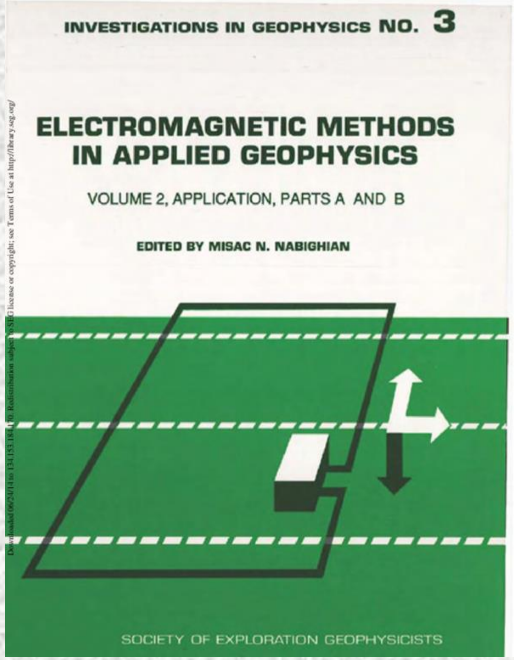
“Nuts and bolts” of magnetotelluric instrumentation and field-work



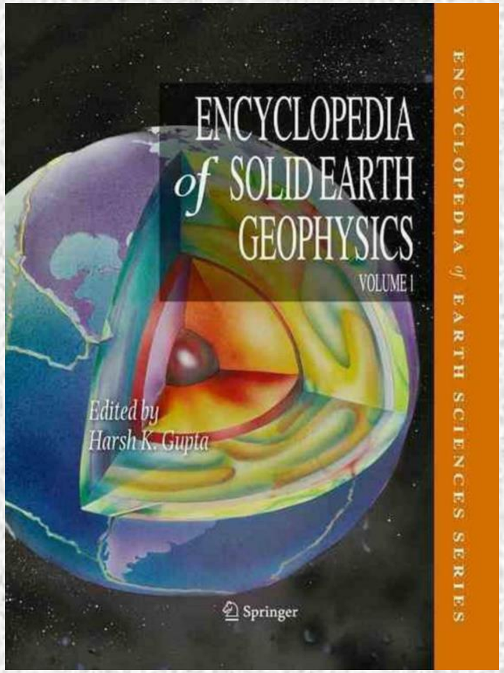
Chave & Jones (2012)



Simpson & Bahr (2005)



Vozoff (1991)



Constable (1989)

Geophysical Prospecting, 1980, 28, 792–804.

NOISE, TEMPERATURE COEFFICIENT, AND LONG TIME STABILITY OF ELECTRODES FOR TELLURIC OBSERVATIONS*

G. PETIAU and A. DUPIS**

Abstract

Petiau G. and Dupis A. 1980, Noise, Temperature Coefficient, and Long Time Stability of Electrodes for Telluric Observations, Geophysical Prospecting 28, 792–804.

Numerous electrodes, already used in geophysics or just perfected by us, have been compared by measuring the three main characteristics which interest the user: noise spectrum, temperature coefficient and polarization with its stability versus time.

Among the most used unpolarizable electrodes, silver–silver chloride (Ag–AgCl) are the best ones. But a systematic research of all different possible metal-salt couples, have led us to use lead–lead chloride ($Pb–PbCl_2$) for the following reasons: noise as low as the one of Ag–AgCl at 1 Hz and even lower for the low frequencies (0.4 μV at 1 Hz and 1.2 μV at 0.01 Hz for peak to peak value and $\Delta F = F$), temperature coefficient about ten times weaker (−40 μV/°C instead of −450 μV/°C) and also better long time stability of the polarization (1 mV/month instead of 2 at 10 mV/month).

We have been using these electrodes since 1977 as “tube” electrodes which are very easy to use. They allow us to record correctly the fast variations thanks to their low noise, the very slow variations, their low temperature coefficient and their stability, and this with telluric lines only about 100 m long.

The Effect of Electrode Contact Resistance On Electric Field Measurements

Kenneth L. Zonge and Larry J. Hughes

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Submitted for presentation at the 55th Annual SEG Convention
Washington, D.C. October 6-10, 1985

ABSTRACT

A simple equivalent circuit model and field measurements show that dipolar electric field measurements can be changed by up to 50% due to the effects of electrode contact resistance (R_C). The equivalent circuit model shows that a high R_C enhances the effective wire-to-ground capacitive coupling, leading to a complex dependence of received voltage on frequency, electrode contact resistance, wire length, and wire capacitance. The model shows that measured electric field voltages will fall between a perfectly grounded asymptote ($R_C \to 0$) and an ungrounded asymptote ($R_C \to \infty$). Field tests were made of this model using the controlled source audio-frequency magnetotelluric (CSAMT) technique. By varying the effective R_C and the signal frequency, the behavior predicted by the model was confirmed. The tests indicate that electrode contact resistance or ECR effects cannot be ignored in CSAMT data, and that they may influence complex resistivity measurements in certain conditions.

A simple, workable solution to the ECR problem was devised by inserting a high-impedance amplifier in series with the electrodes and by shielding the lead wires, grounding the shield to a common-mode reference pot. Measurements using this configuration show that ECR effects virtually can be eliminated even at high R_C values.

Surv Geophys (2012) 33:1059–1079
DOI 10.1007/s10712-012-9197-8

Flux-Gate Magnetometers Design Peculiarities

Valery Korepanov · Andriy Marusenkov

Received: 30 May 2011 / Accepted: 14 May 2012 / Published online: 1 June 2012

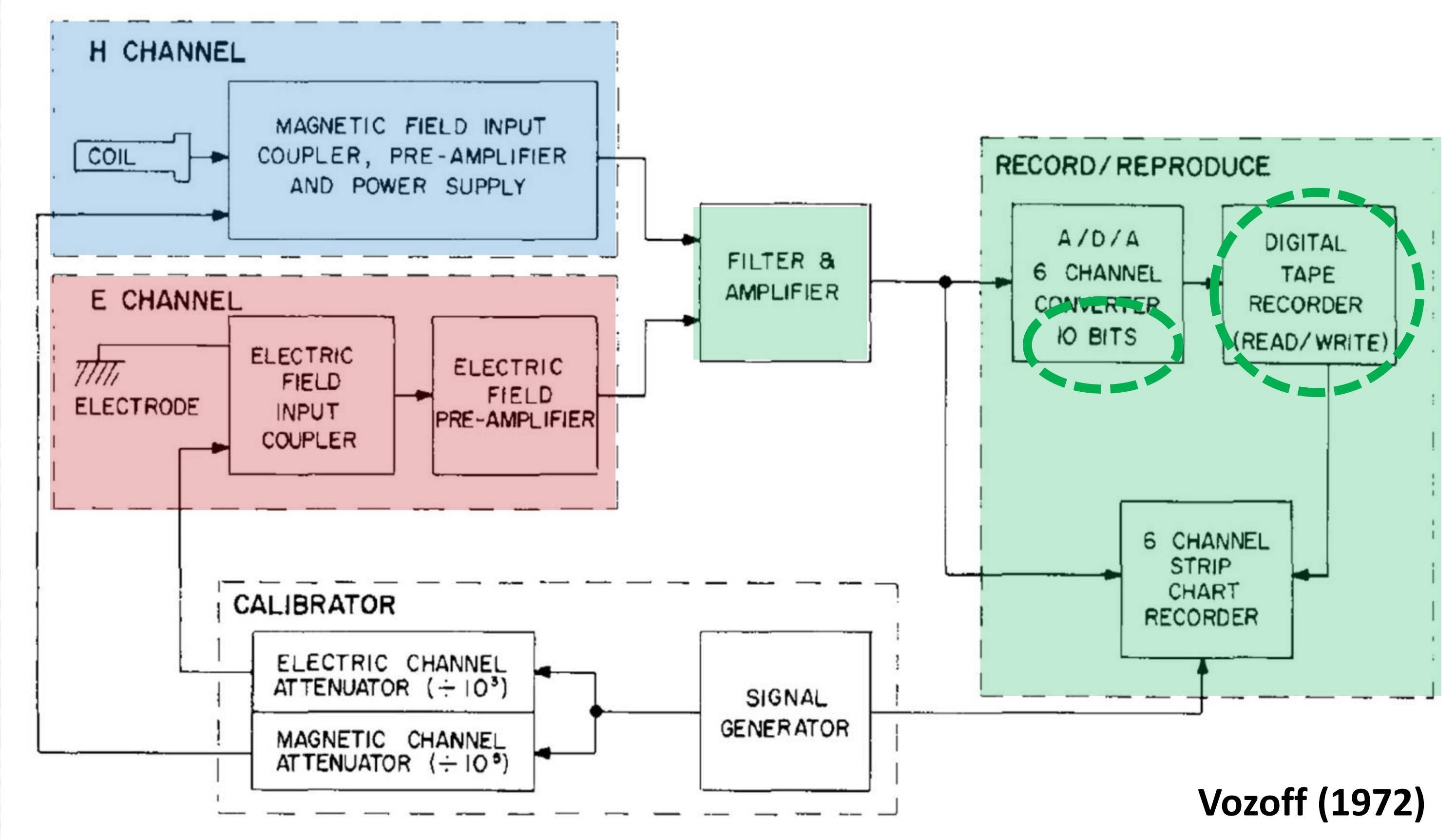
Abstract The most widespread instrument used today for the measurement of quasi-stationary and slowly fluctuating vector magnetic fields is a flux-gate magnetometer (FGM). The most important parameter characterizing the magnetometer quality is its magnetic noise—its threshold sensitivity or its own noise level (NL). Based on the results of experimental research, we may state that the FGM NL mainly depends on the quality of the magnetic material used for FGM sensor core. The “solid liquid” model explaining the nature of magnetic noise is proposed and substantiated. It is demonstrated that special attention has to be paid to the annealing of the core. A new effect—termed gamma-magnetic normalization—is discovered and discussed. It is shown that the magnetometer NL depends not only on the core length and volume but also on the excitation mode of the core. Besides, the ways to improve other factors, such as power consumption and thermal drift which must be taken into account in order to create a FGM with the highest possible performance, are discussed. Some examples are given of the parameters of present advanced FGMs for geophysical uses.

1. **Requirements of MT measurements**
2. **Electric field sensors**
3. **Magnetic field sensors**
4. **MT recording devices**

Related EMinars:

- **Alan Jones, 2020-2021 series: *MT acquisition, from survey design to field procedures***
- **Adam Schultz, Feb. 2022: *Faster, lighter, cheaper: developing new instrumentation to broaden access to MT***

Conceptual diagram of MT system from 50-years ago remains (mostly) accurate



Vozoff (1972)

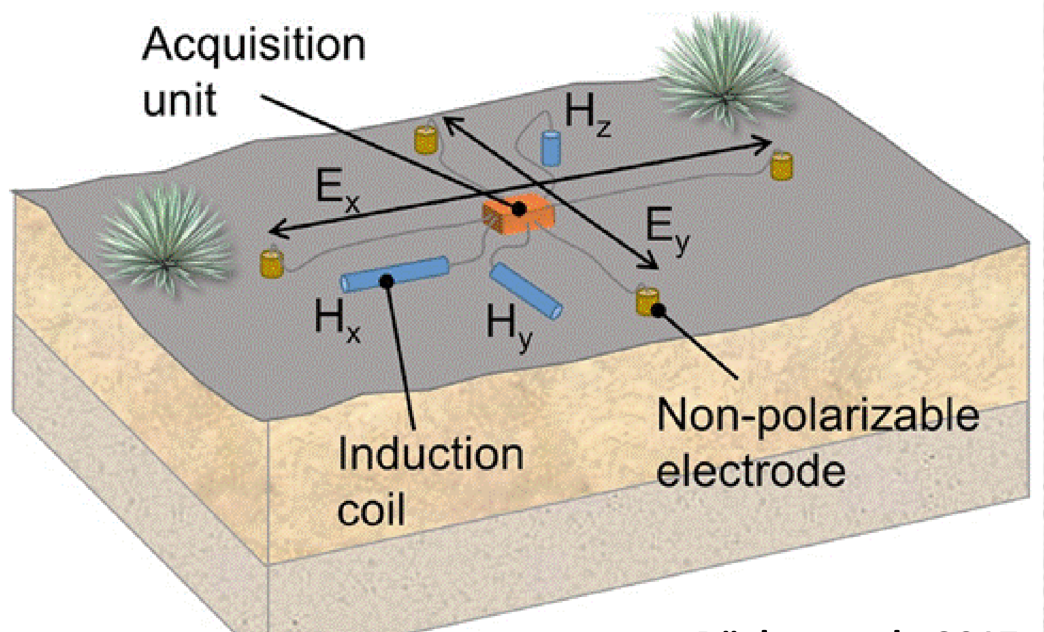
1. Requirements of MT measurements

- Record time-series of B_x, B_y, (B_z), E_x and E_y (or equivalent) plus two remote components R_x and R_y, with high SNR, for signals over a broad period range.

- Recordings must allow computation of unbiased, low-variance, four-component impedance (±tipper) responses over target period range.

- The signal at the remote reference site must be coherent with the signal at the main site and the noise must not be coherent. The remote reference is usually a pair of horizontal magnetic field recordings, but electric field recordings are sometimes as effective.

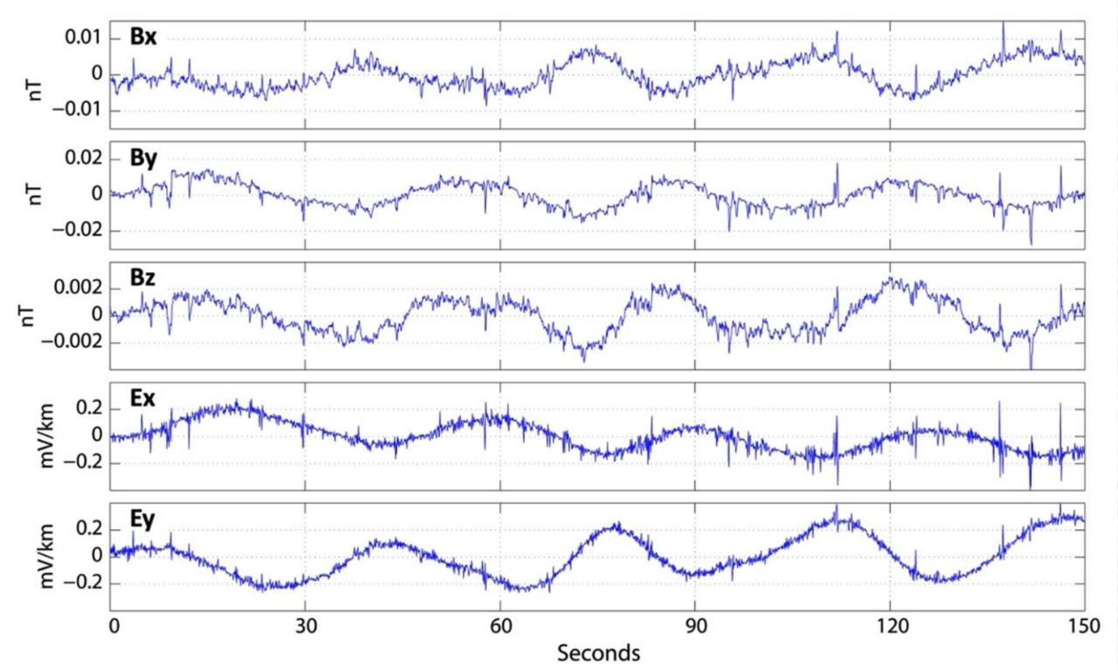
- The computed responses should correspond to zero-wavenumber geomagnetic sources.



Bücker et al., 2017

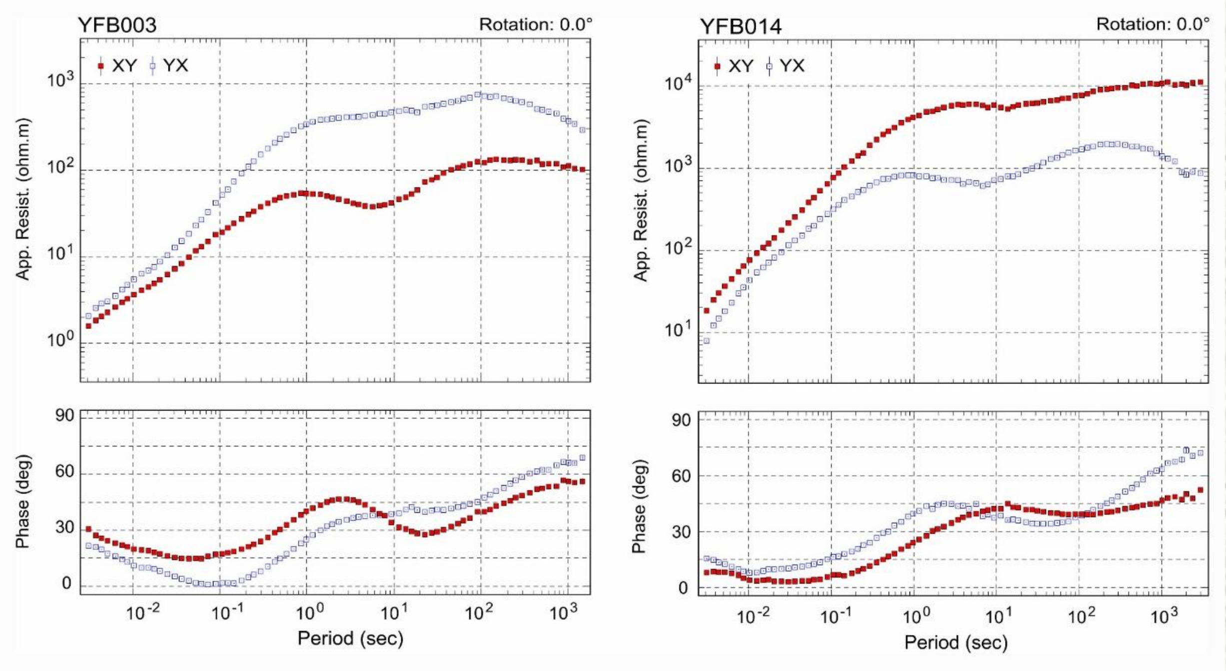
1. Requirements of MT measurements

MT time series



MT time series from the central Andes (Comeault, 2015)

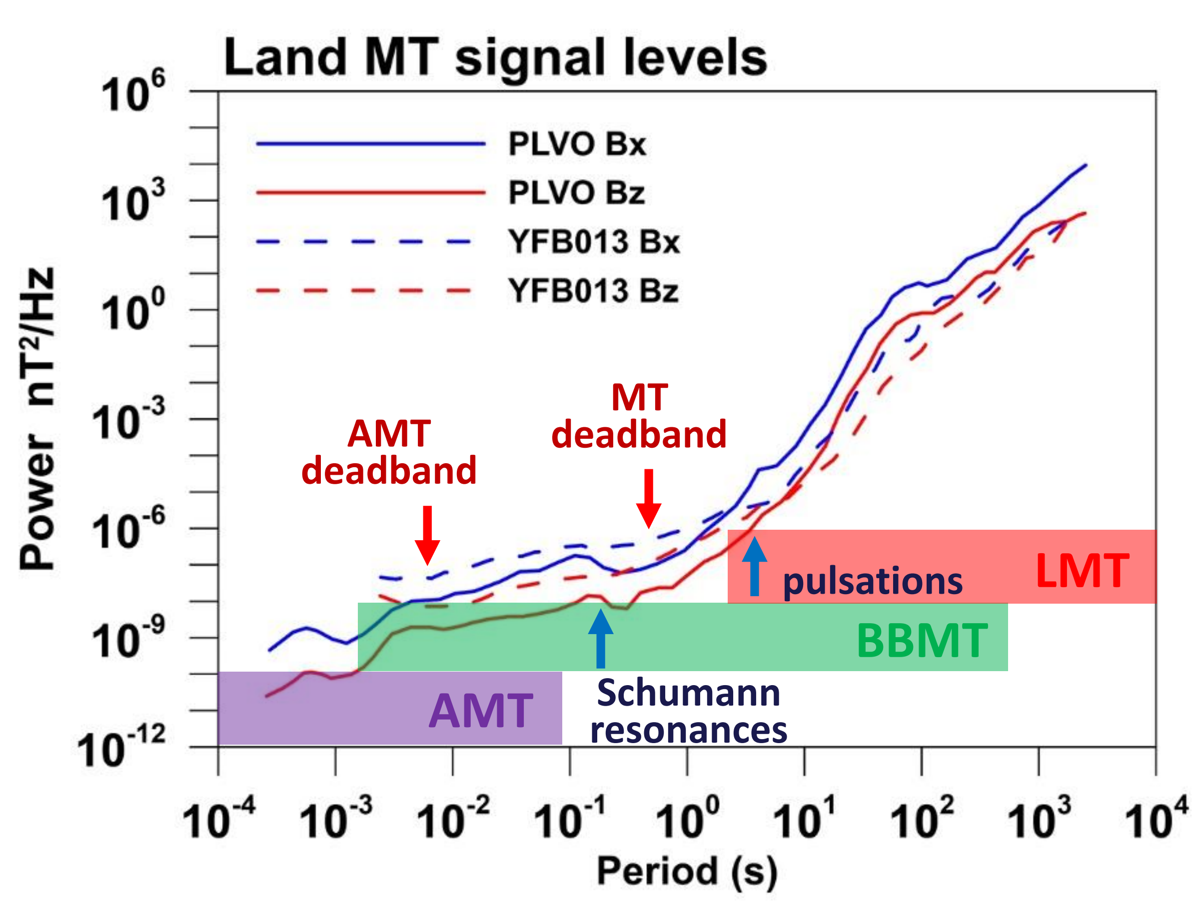
MT responses



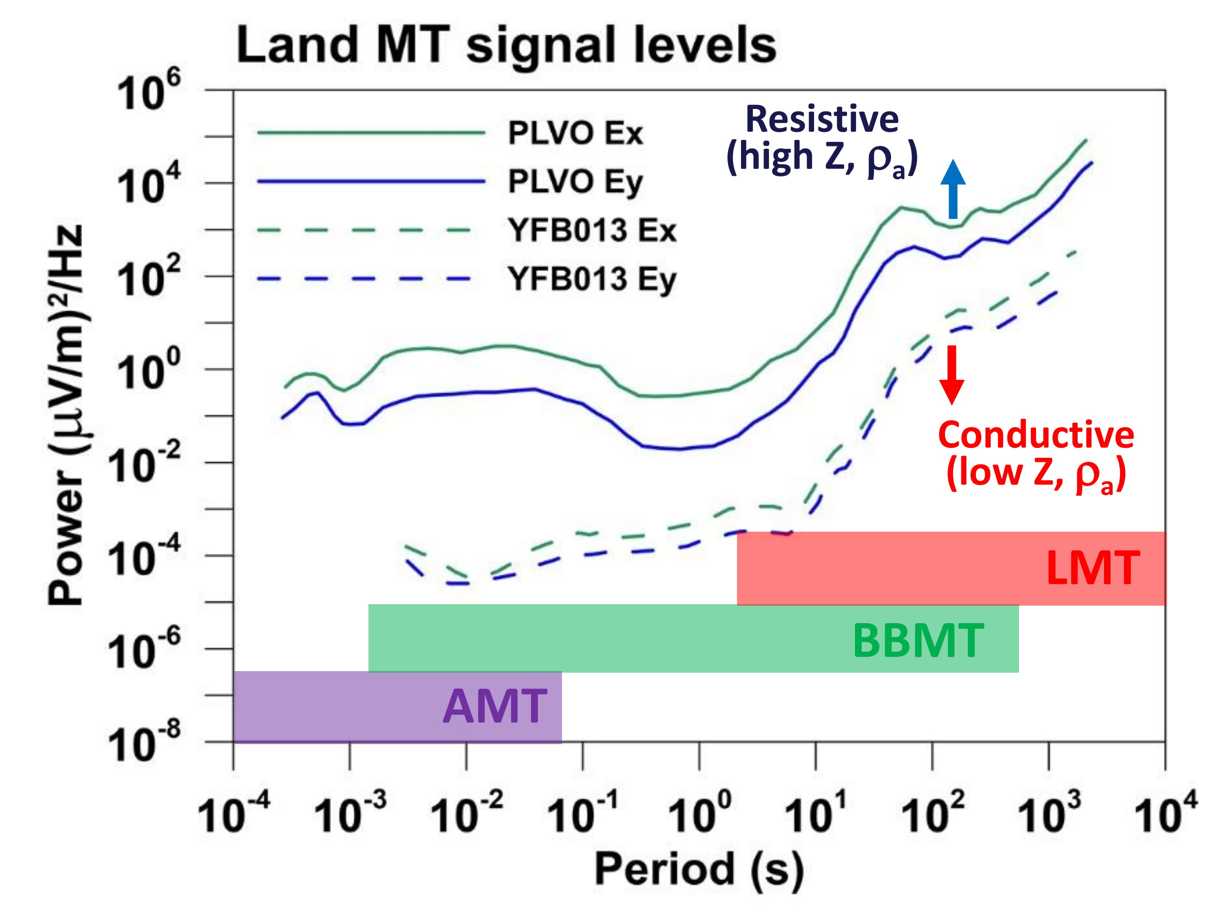
BBMT response from remote area in southwestern Australia

MT signal levels

Magnetic field signal levels



Electric field signal levels



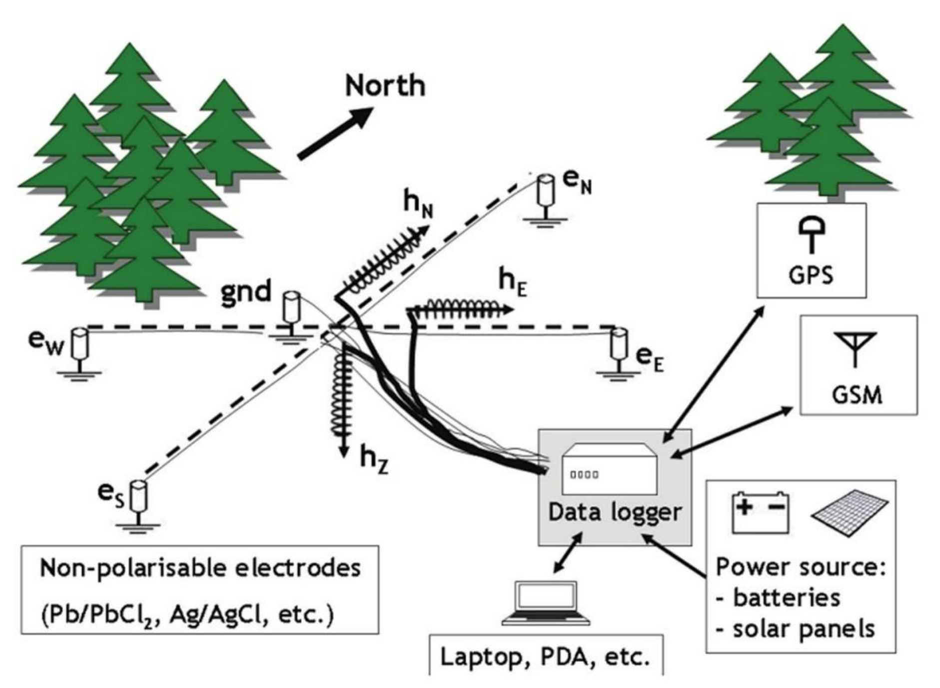
Power spectra of MT signal levels. Land data are from a relatively resistive region in central Canada (PLVO) and a relatively conductive site in southwestern Australia (YFB013).

2. Electric field sensors

- **The MT electrometer measures the electric field in two horizontal orthogonal directions. In land MT, this is usually done by measuring potential difference between grounded electrodes spaced by a known distance.**

- **For most MT installations, electrode separation is 25 m (AMT) to 200 m (BBMT/LMT).**

- **Most MT systems use a ground electrode near the recording unit, which serves as the grounding electrode for the electronics.**



MT configuration (Smirnov et al., 2008)

- **Most land MT surveys use non-polarizing porous-pot Cu-$CuSO_4$, Pb-$PbCl_2$, Cd-$CdCl_2$ or Ag-AgCl electrodes. Some high-frequency surveys use metal rod or plate electrodes. High frequency RMT and AMT studies may use capacitive electrodes.**

Porous pot electrode (Phoenix Geophysics)

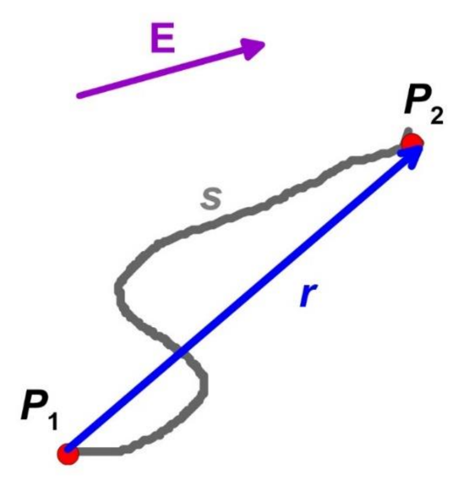
Metal plate electrode (Quantec Geoscience)

Capactive electrode (Groundmetrics)

Physical Principles

- The electric field considered in MT can be expressed in terms of a scalar electric potential and vector magnetic potential:

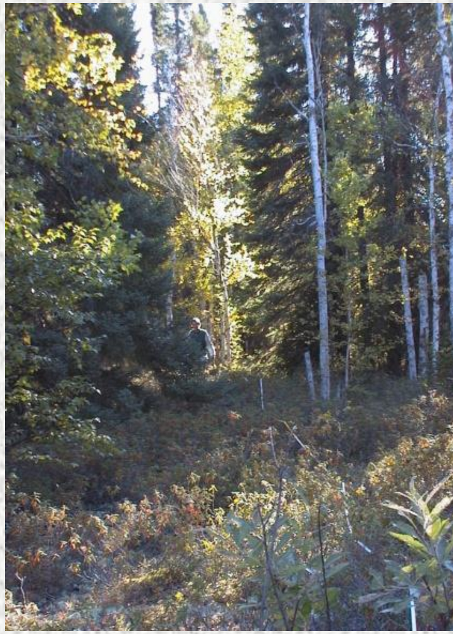
$$\mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t} \quad \text{where} \quad \mathbf{B} = \nabla \times \mathbf{A}$$



- The second term means that the field is non-conservative and potential difference $\phi_{12}=\phi(P_1)-\phi(P_2)$ between two points therefore depends on the path.

$$\phi_{12} = \int_{P_1}^{P_2} \mathbf{E} \cdot d\mathbf{s}$$

- For a measurement of potential difference to provide a measure of the electric field in a direction, it is necessary for the wire joining the electrodes to be straight.
- Errors from non-straight wires are greatest at higher frequencies and can involve a few percent in apparent resistivity or few degrees in phase when average deviation from straight is a small fraction of the skin depth (Gomez-Trevino, 1987).
- In the extreme case of a large circular loop in the wire, the time variations in the vertical magnetic field will induce a spurious voltage proportional to the area enclosed by the loop.

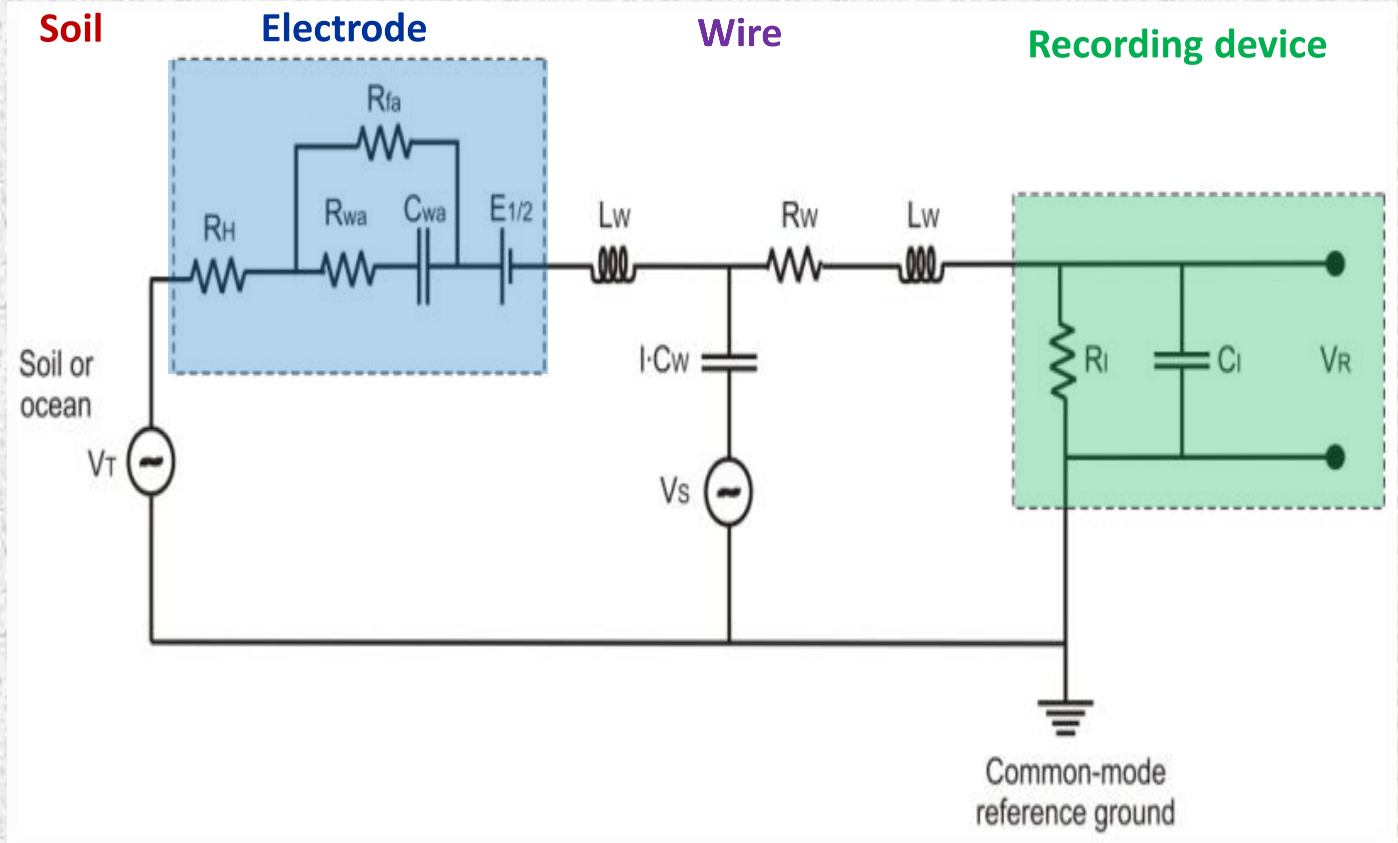


Installing an e-line in northern Manitoba

Equivalent circuit

- Measurement of the telluric voltage V_T can be affected by the soil in which the electrode is buried, the electrode, the wire, a preamplifier, and the recording unit yielding V_s.
- It is desirable for half-cell potential to be as low as possible; series resistance, capacitance and inductance to be as low as possible; and parallel input impedance of the measuring device to be as high as possible.

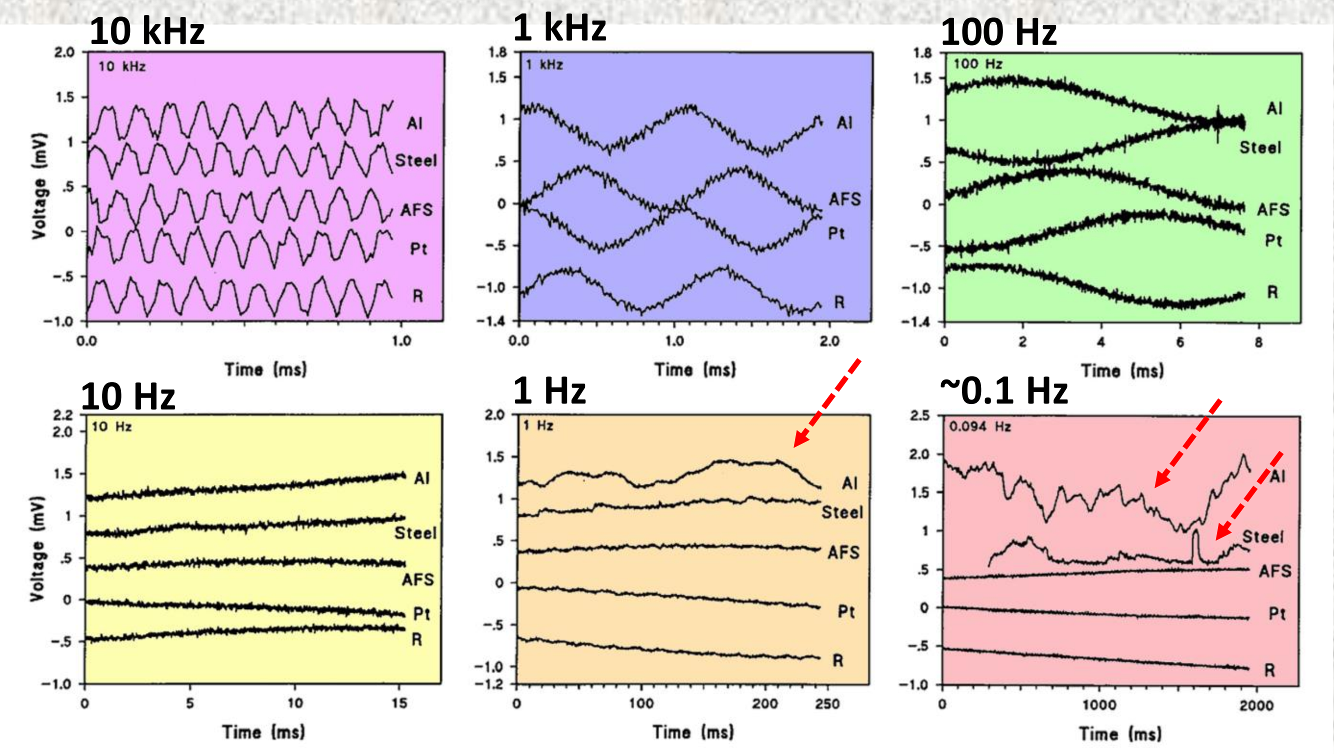
Installed porous pot electrode



Circuit representation of a telluric measurement (modified from Zonge & Hughes 1985).

Half-cell potential

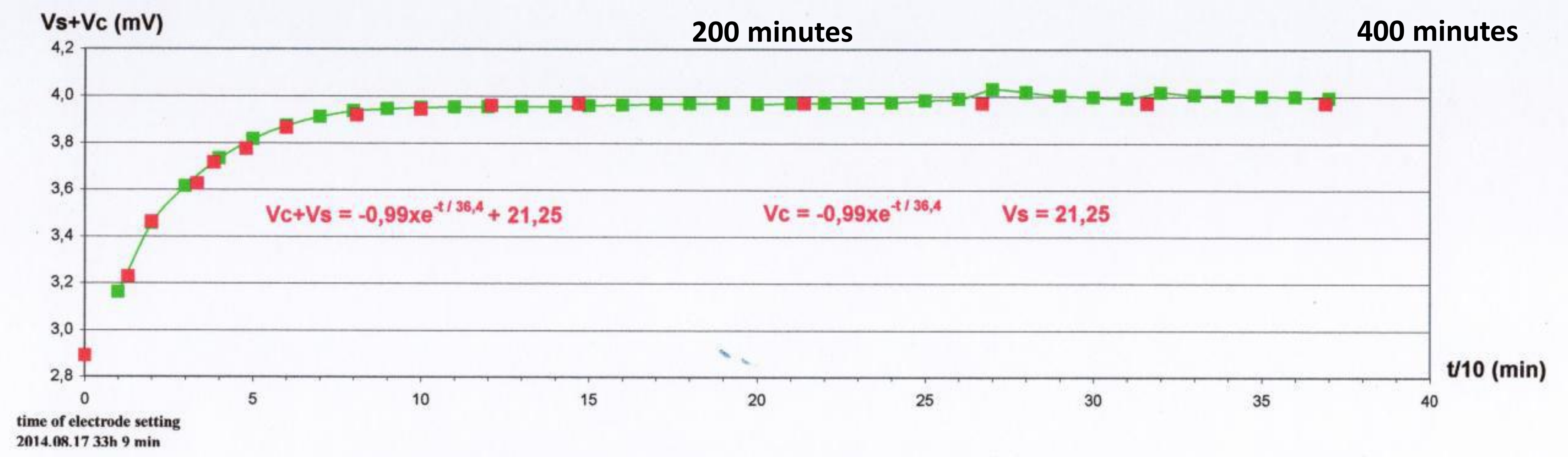
- Time-variations in half-cell potential under constant ambient conditions include deposition of metal-ion salt on the metal interface, and physical degradation of metal surfaces.
- Spontaneous changes for metal electrodes, which be as large as 20 mV, may be due to reaction charge release.
- Time-frequency characteristics of the noise are different for different types of electrode. Electrochemical processes are complicated and depend on frequency, current density, and ambient conditions (temperature, fluid chemistry).
- In metal electrodes stainless steel provides the lowest noise levels, followed by iron, copper, lead, and brass with intermediate noise levels, and aluminum and graphite with highest noise levels.
- For at least some electrodes, the level of noise increases with increasing self potential of the electrodes.



Metal electrode noise at different frequency in 60 Ωm tap water (Vanhala & Soininen, 1995)

Half-cell potential

- In the case of metal-metal ion electrodes the half-cell potential is mainly due to the potential between the metal and the surrounding salt solution V_s.
- A contact potential V_c of several millivolts develops between the electrode and ground on installation but this normally dissipates within a few hours of the installation.
- The contact potential is caused by liquid junction and diffusion potentials (as observed in SP logging) and develops because of the different salt concentrations in the electrode and soil.



An example of the observed decay of a contact potential (S. Andras, "Results of test measurements"
http://www.nonpolarizingelectrode.com/results_of_test_measurements_long_time_variation_of_self_potential_resistance_contact_liquid_junction_and_diffusion_effect)

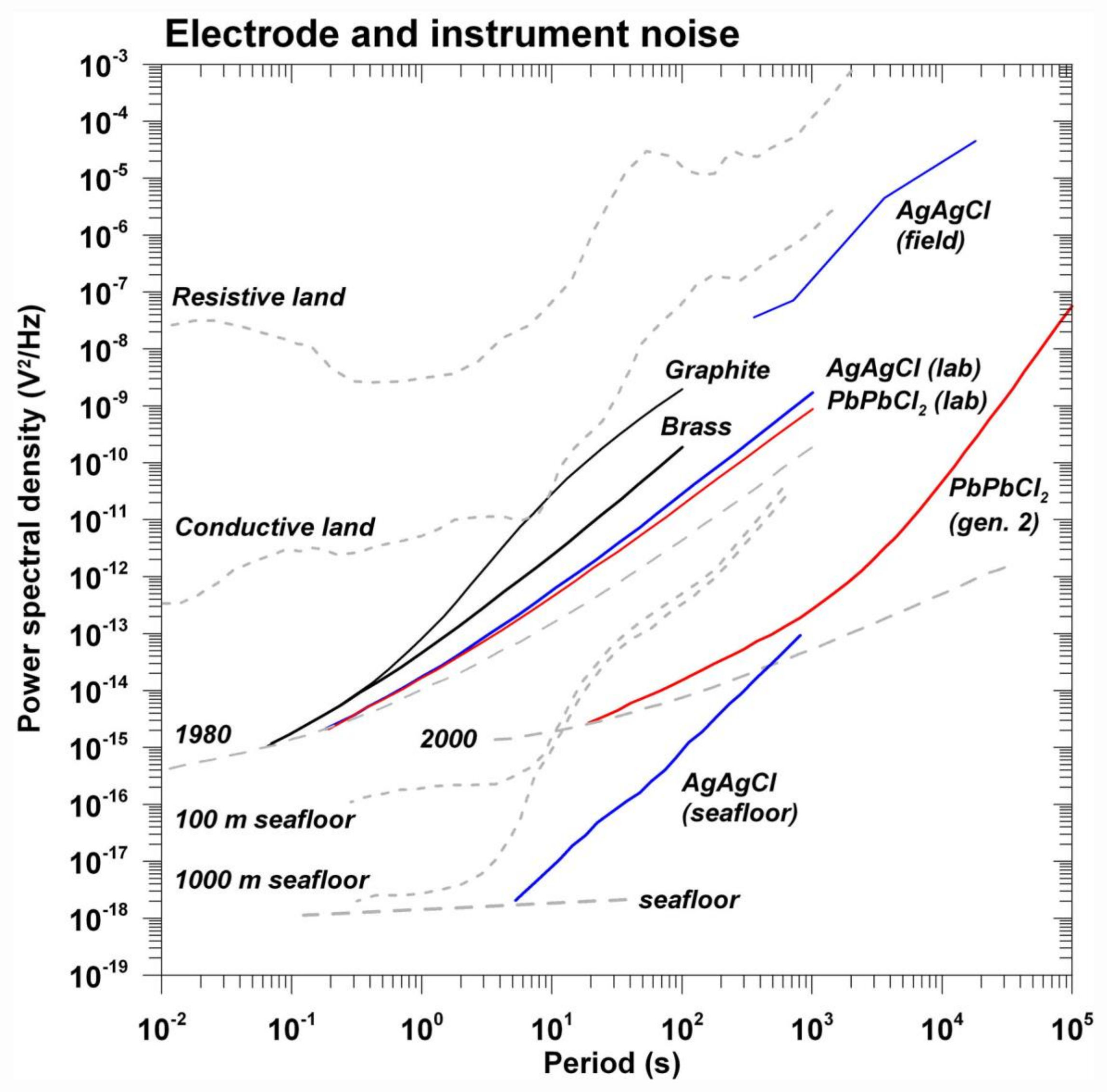
Electrode noise

- **Electrode noise will have the greatest impact on the signal to noise ratio at periods of 1 to 10 s.**

- **Noise of MT electrodes increases with increasing period and, at long-period, is larger for metal electrodes than for metal-metal ion electrodes.**

- **Relative performance of metal electrodes improves at shorter periods.**

- **At 1 s period poor metal electrodes are less than a factor of 10 noisier than metal-metal ion electrodes and at 0.2 s there is little difference for stainless steel, iron, and metal-metal ion electrodes.**



Comparison of noise levels of electrodes and telluric recording instrumentation with signal levels. Signal levels are for 100 m long dipoles.

Electrode noise

- Quality metal-metal ion electrodes have noise:
  10^{-14} V^2/Hz at 1 s
  10^{-9} V^2/Hz at 100 s
  10^{-5} V^2/Hz at 10^5 s

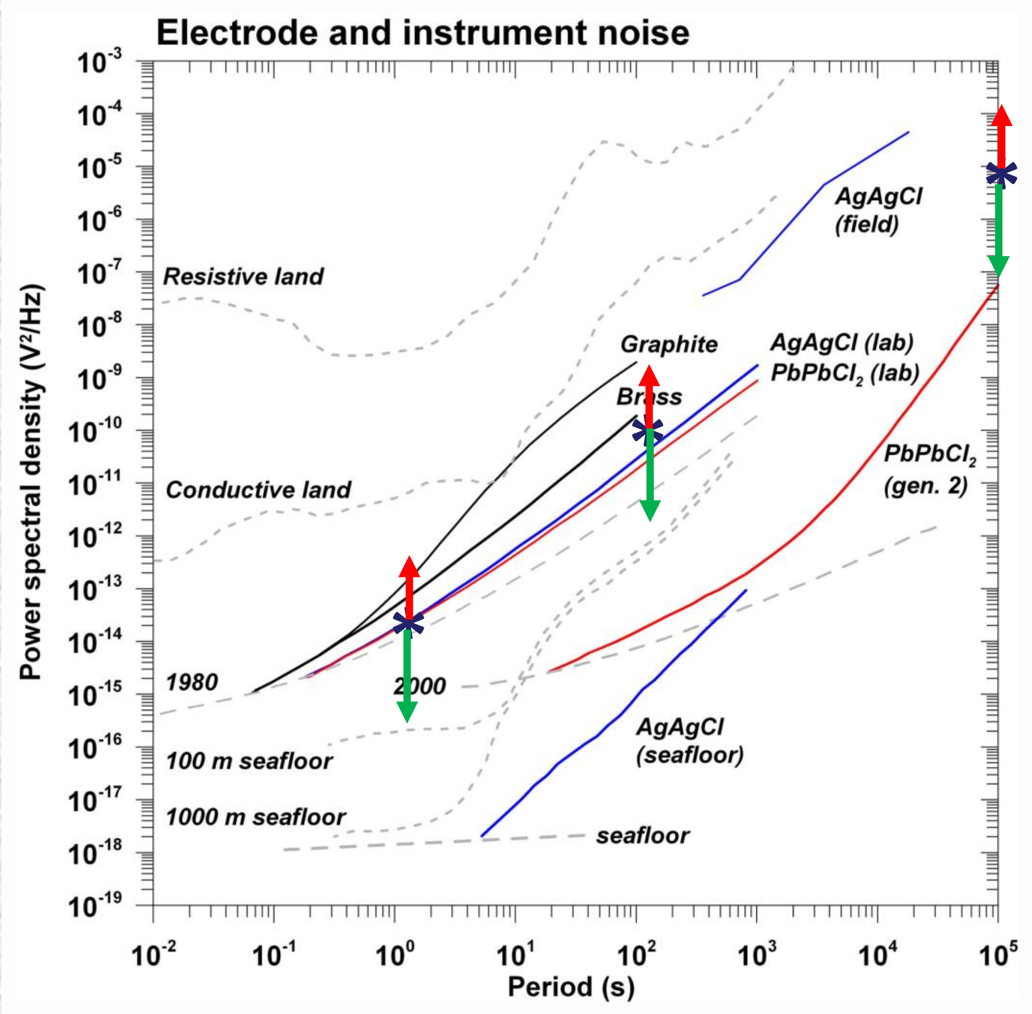
corresponding to mean peak-to-peak fluctuations of 0.3 µV, 3 µV, 100 µV.

- Exceptional electrodes may have noise power levels 50 or more time lower, and poor electrodes may have noise levels a factor of 10 or more times higher.

- The distribution of self-potential of electrodes of one design is approximately Gaussian.

- Use of pairs of electrodes with similar self potential can further minimize differential potential during recordings.

- Changes in ambient physical and chemical conditions mean that electrode noise is higher in land field deployments than in the lab.



Comparison of noise levels of electrodes and telluric recording instrumentation with signal levels. Signal levels are for 100 m long dipoles.

Electrode drift and temperature dependence

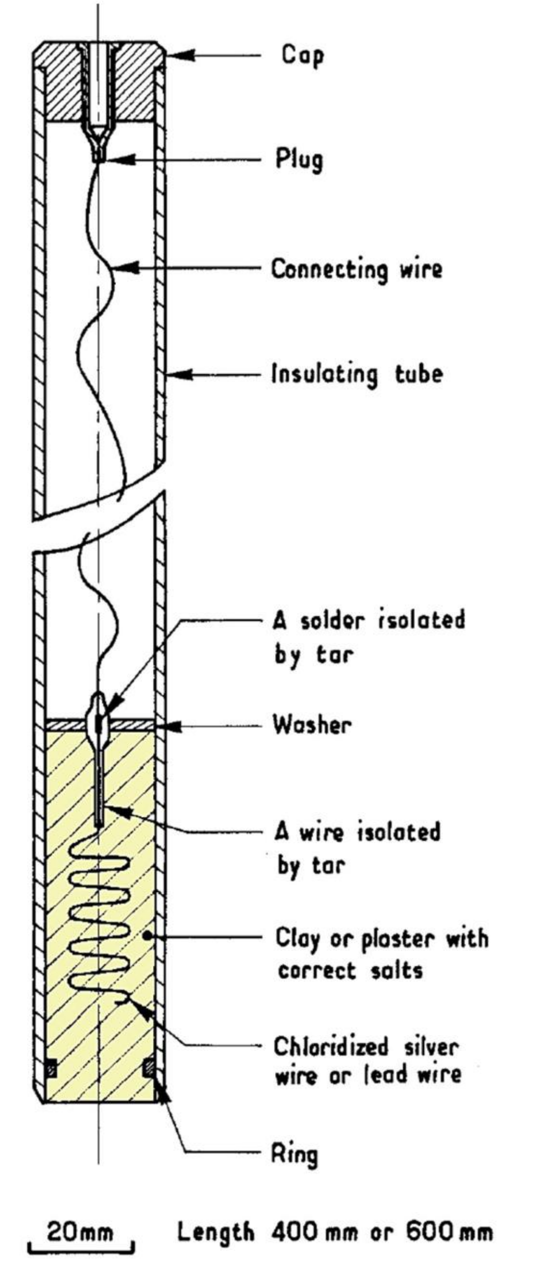
- Changes in soil chemistry and moisture cause long-term change in electrode potential. Following installation, there is stronger drift over minutes to tens of minutes as the electrode-soil system reaches equilibrium.

- Temperature dependence of electrodes is most important in long-duration surveys, which expose electrodes to the largest temperature variation.

- At onset of freezing large changes in potential occur as salinity of the remaining unfrozen pore fluid increases.

- At colder temperatures, potential and contact resistance of electrodes increase considerably as both the ground and possibly the electrode freeze. Electrodes used in MT deployments on ice have included copper and titanium sheets and require changes to the measurement design.

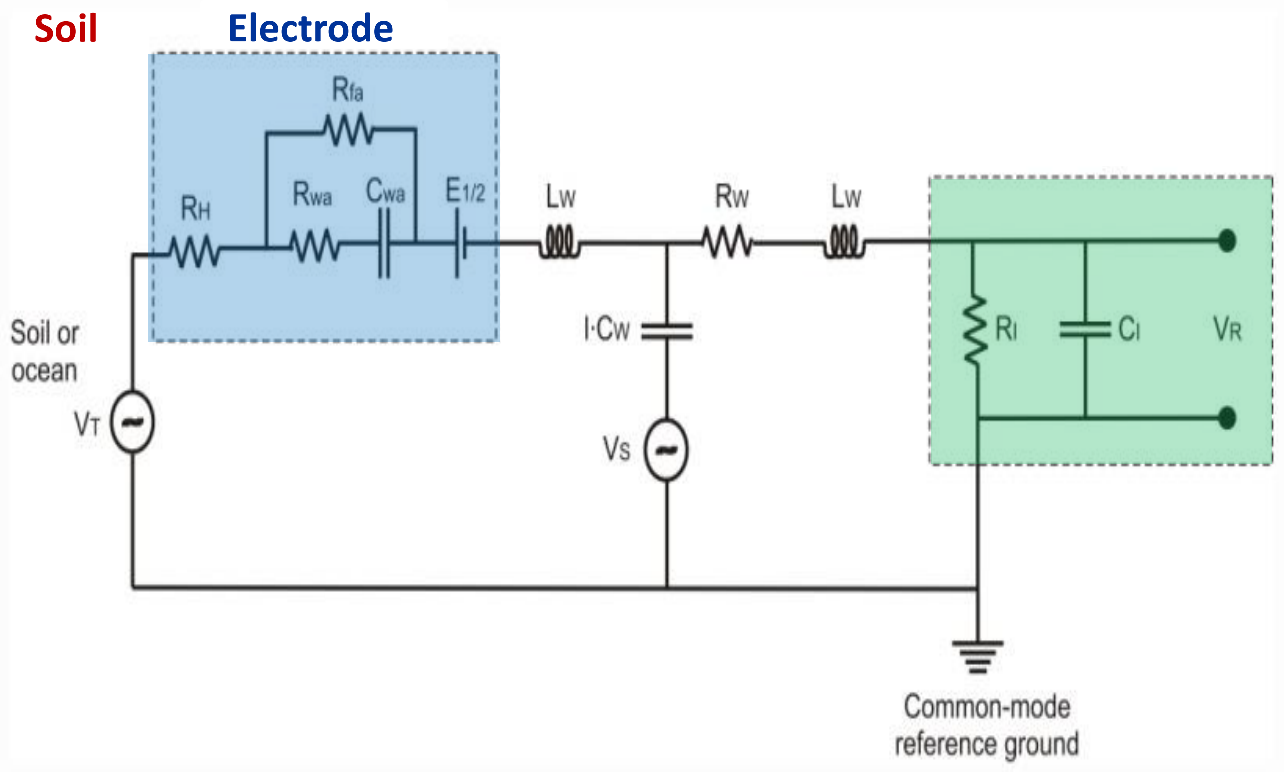
- Undesirable electrode drift also occurs because of aging and deterioration of electrodes. Processes include changes to concentration of metal ions, corrosion of wire in the electrode and exposed wire in the vicinity of the electrode.

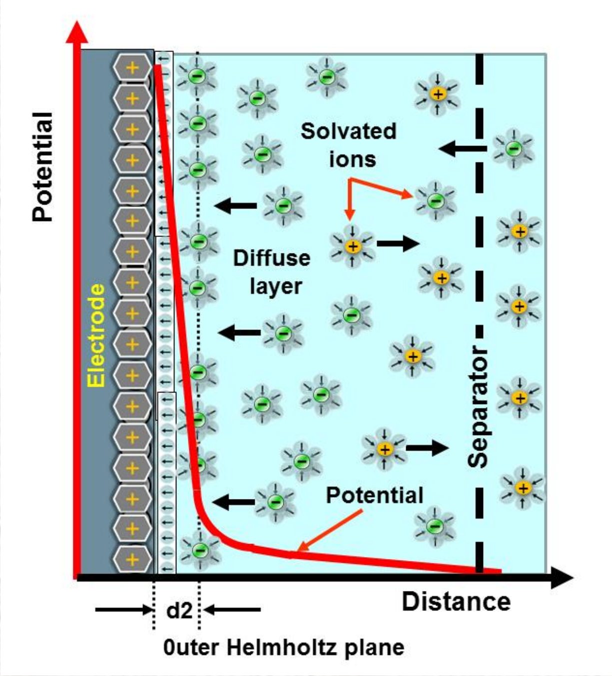


Tube electrode (Petiau & Dupis, 1980)

Electrode impedance (resistance)

- Electrode impedance/resistance is often modelled in terms of an equivalent Randles circuit.
- It can include a Faradaic charge transfer resistance, a Warburg impedance associated with the transfer of ions to the electrode surface by diffusion, and a capacitance associated with the charging and discharging of the electric double layer (associated with the organization of ions at the electrode and grain surfaces).
- The overall electrode impedance is frequency-dependent and to an extent current- and voltage-dependent.

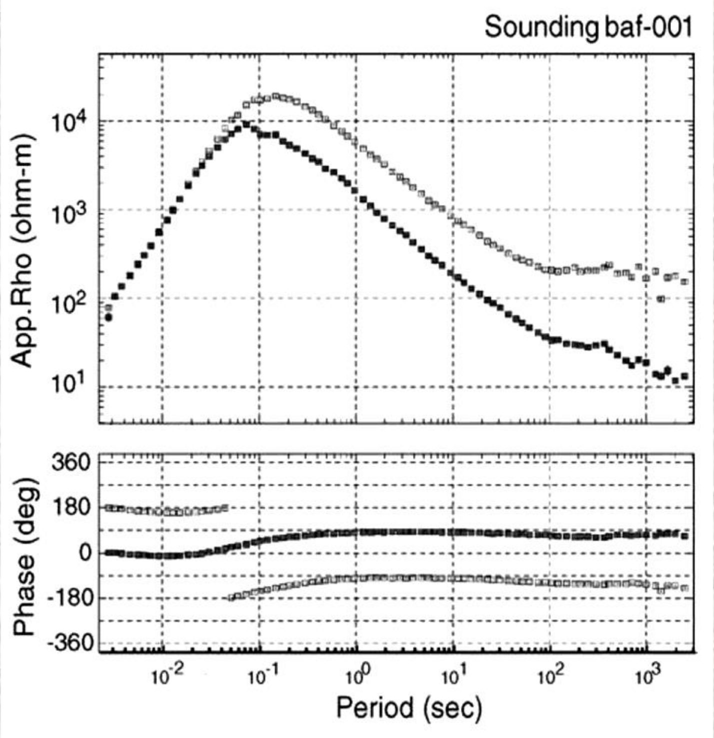


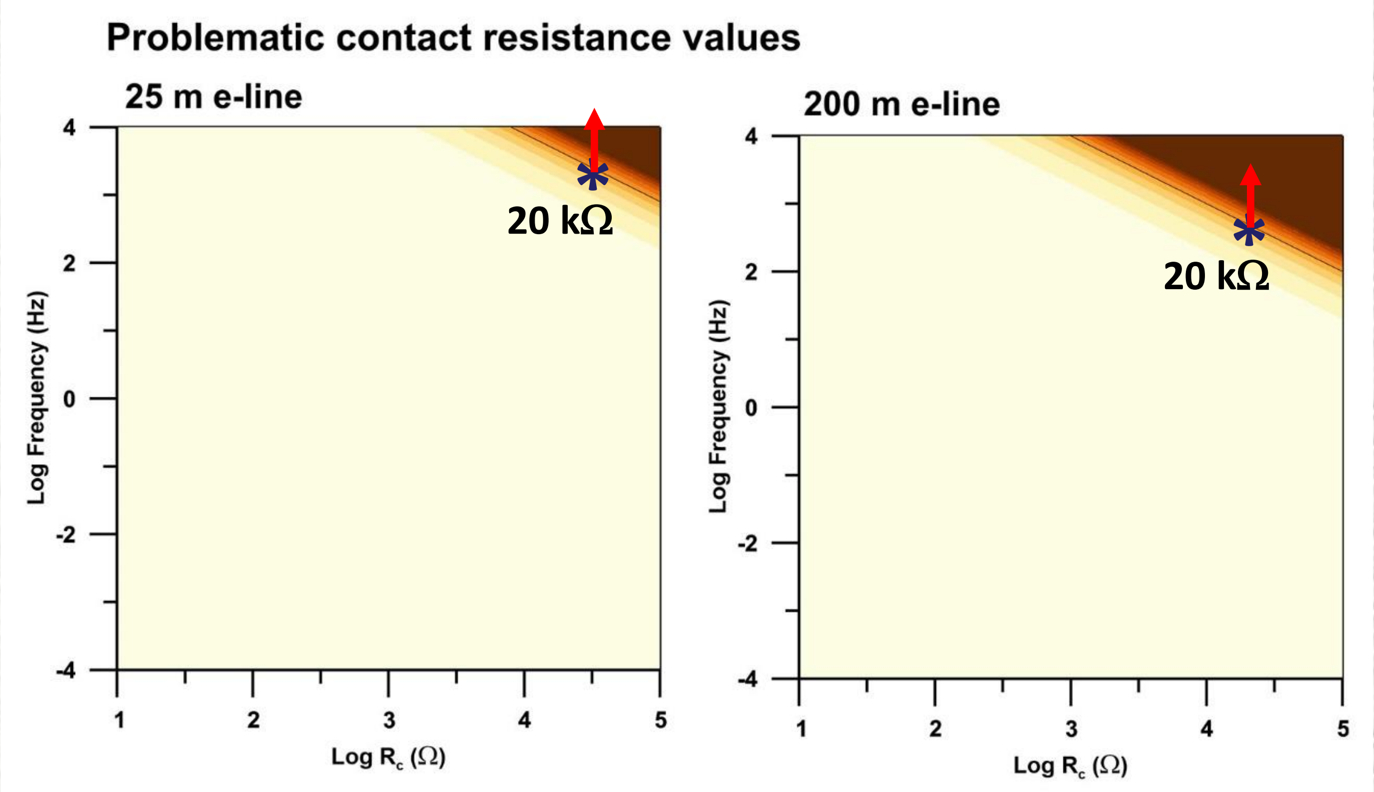


Elcap, accessed February 2022
https://commons.wikimedia.org/w/index.php?curid=25771148

Electrode impedance (resistance)

- **Accurate measurement of potentials requires electrode contact impedance to be small. Large values of electrode contact resistance can couple with the distributed capacitance of dipole wires to alter the shorter period telluric response.**
- **Zonge & Hughes (1985) indicate that as a rule-of-thumb this effect becomes significant if the product LfR_c of dipole wire length L (in km), frequency f (kHz), and electrode contact resistance R_c (kΩ) exceeds 2.0.**





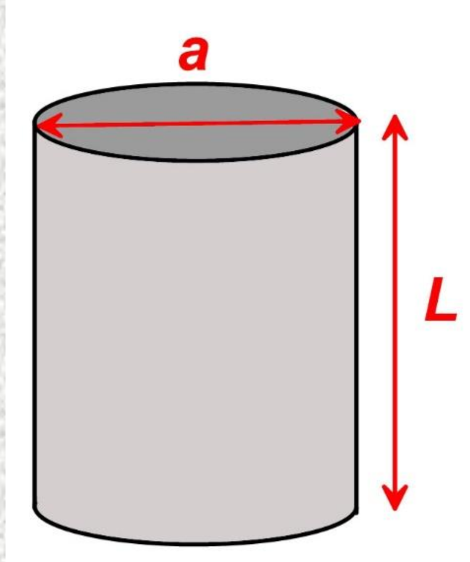
MT response from Baffin Island, northern Canada (Evans et al. 2003). Solid symbols are the xy- and open symbols are yx-component. Response at <0.1 s are affected by high contact resistance causing the earth-electrode-recording system to act as an low-pass filter.

Electrode impedance (resistance)

- Contact resistance of metal electrodes depends on the shape and size and on the resistivity of the surrounding material.

- For rod-shaped electrodes, Faradaic contribution to contact resistance for a cylindrical rod of length *L* and diameter *a* in half-space of resistivity ρ is:

$$R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{2L}{a}\right) - 1\right]$$



- A 1 cm diameter rod buried to 50 cm depth in half-space of 1000 Ω·m will have contact resistance of 1150 Ω.

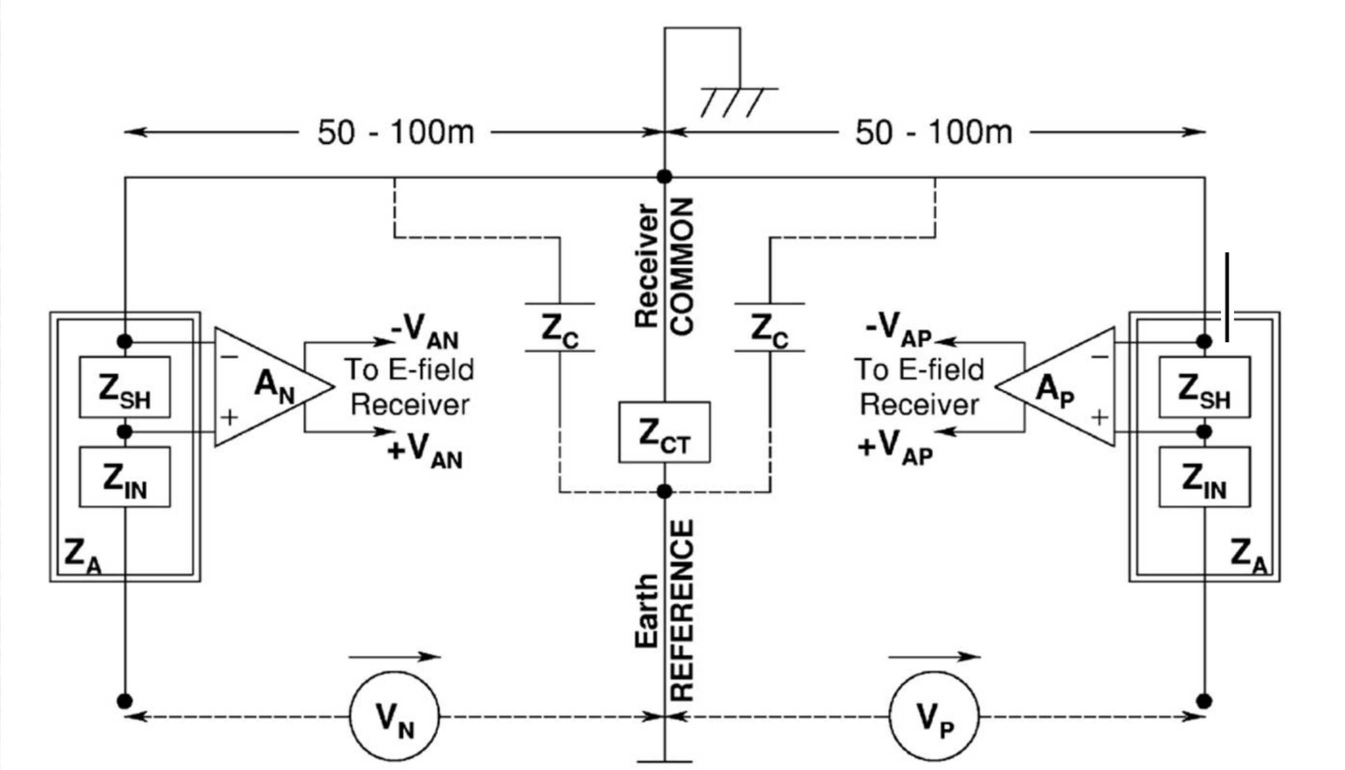
- For the dimensions of metal electrodes used in many land MT surveys, contact resistance will be 0.75 and 2 times the numerical value of the resistivity in the near-surface material.

- In metal metal-ions electrodes there is an internal resistance between the metal and salt, ideally less than several hundred ohms, and a contact resistance between the base of the electrode and the ground. The contact resistance is often the smaller term but can become larger in dry sandy soils (S. Andras).

- Contact resistance can be reduced by using twin electrodes connected in parallel.

Electrode impedance (resistivity)

- It is possible to overcome high contact resistance issue, e.g., in Antarctic surveys, using active electrodes that include a high impedance amplifier near the electrode and shielding the lead wires from amplifier to receiver.



Active electrode configuration used in Antarctic surveys (Wannamaker et al., 2004).

Ti-plate and preamp, Kerry Key, Electromagnetic Geophysics Lab, Lamont-Doherty Earth Observatory, Columbia University

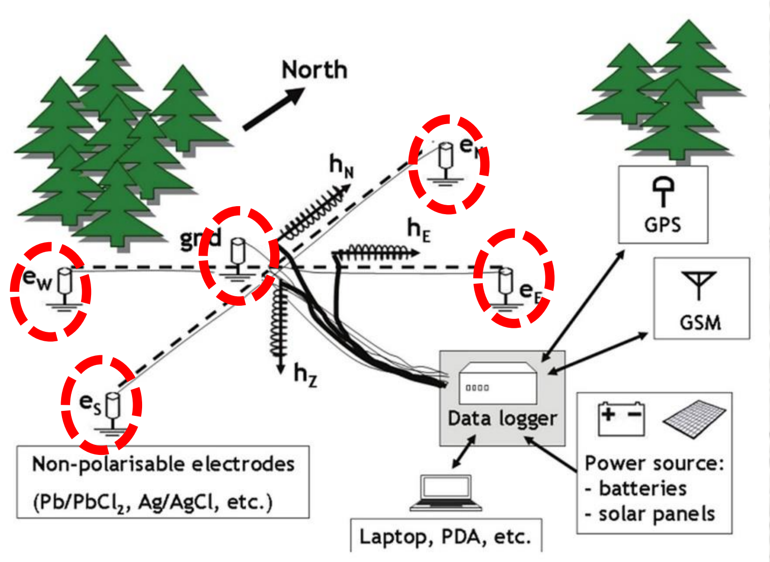
Electric field amplifiers and filtering

- **Telluric amplifiers are differential amplifiers designed to multiply the voltage difference between two channels by an appropriate gain factor.**

- **Some systems amplify the differential signal between the individual main electrodes and ground before combining the signals, while others amplify the differential signal between the two main electrodes.**

- **In the first case, it is important to use ground electrodes of comparable quality to the main electrodes to minimize risk of saturation due to drift, saturation, or other electrode noise from the ground electrode.**

- **Amplifiers must have impedance characteristics matched to electrode impedance, a linear response over the range of input voltages and required frequency band, low noise relative to electrode noise, low temperature dependence, and moderate power consumption.**

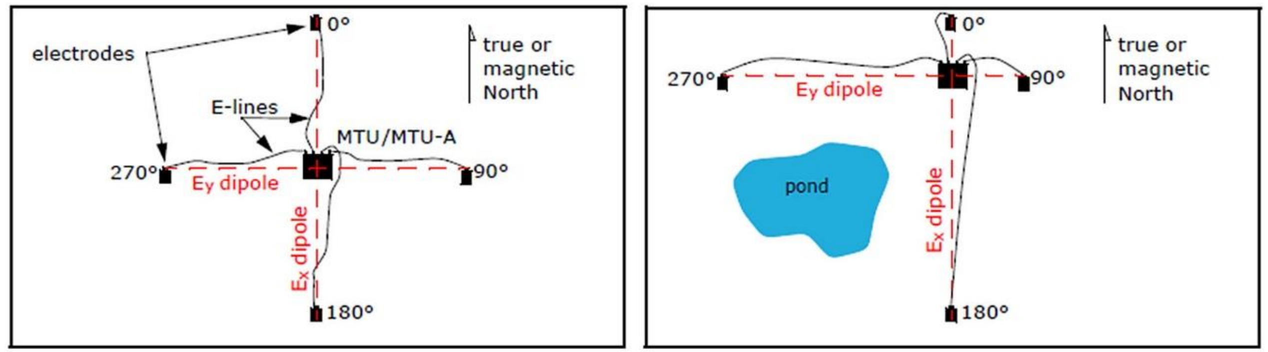


MT configuration (Smirnov et al., 2008)

- **Noise can be minimized by chopping amplifiers in which the output is obtained from an input signal reversed in sign at a short period and integrated. A chopping amplifier will reduce drift and remove DC offset between channels, allowing measurement of the long-period response, but reduces the frequency-bandwidth of the output.**

Electrometer field deployments

- Electric dipoles are usually installed in a cross- or L-shape, aligned with geomagnetic or geographic coordinates. With the possibility of accurate GPS positioning the latter is becoming more common.



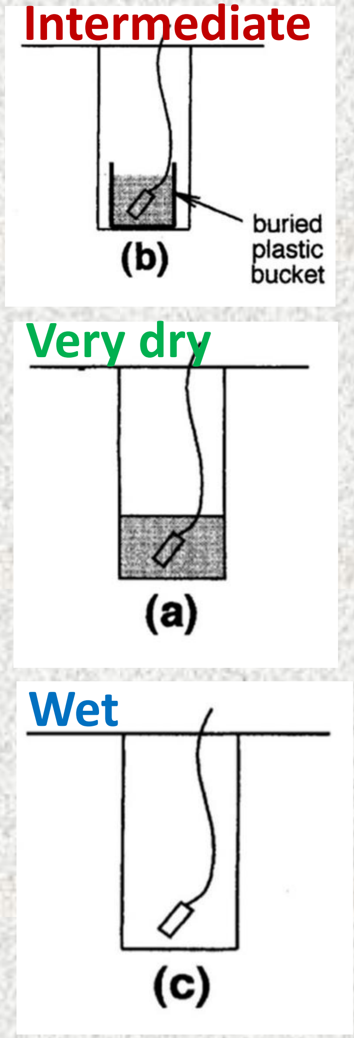
MT site configurations (Phoenix Geophysics)

- In land surveys, electrodes are optimally deployed in moist, salted, kaolinitic mud or bentonite. The saline fluid helps reduce the overall contact resistance, and the clays help retain the moisture.

- In soils with an intermediate moisture level, long term drift can be reduced by deploying electrodes in non-metallic buckets ("Russian bucket configuration"; Lu & Macnae 1998)

- In very dry soils, it may be better to install the electrodes directly in the soil to allow the hydroscopic properties of the salted clay to attract moisture from the surrounding soil.

- In wet soils, no bucket is required as adequate moisture is present. It is sometimes best to not use salt as advection of water around the electrode after rainfall can change the salt concentrations, leading to changes in electrode potential (Perrier et al. 1997)



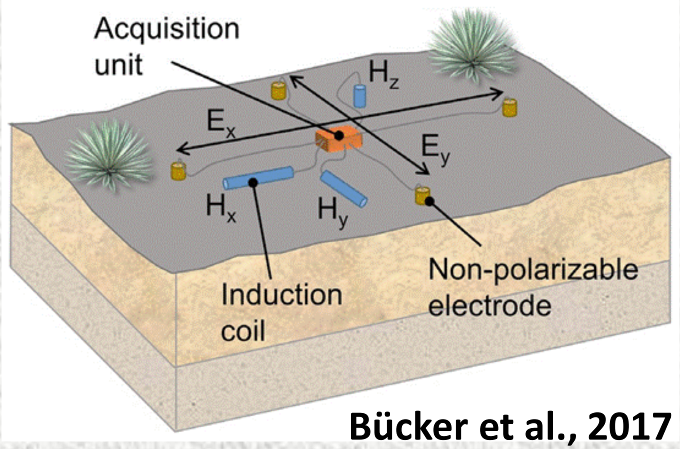
Electrode burial styles (modified form Perrier et al., 1997)

3. Magnetic sensors

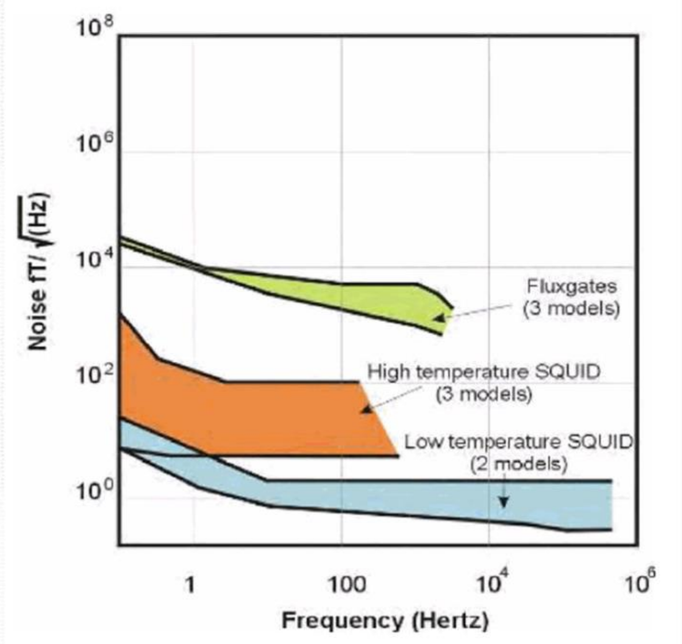
- In MT the magnetometer in MT senses time-variations of the magnetic field H, or more strictly the magnetic induction B, in the two horizontal orthogonal directions or the three orthogonal directions.

- In modern systems, measurements are usually made with induction coil sensors for AMT/BBMT and fluxgate sensors for LMT.

- A large volume of LMT data has been collected in the past using torsion-fibre magnetometers based on observing or nulling the deflection of suspended magnets.



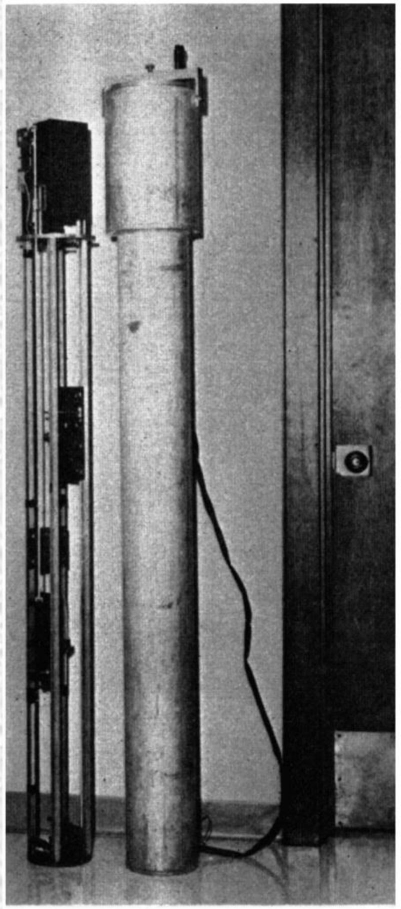
Bücker et al., 2017



SQUID noise levels (Le Roux, 2005)

- The noise level of SQUID magnetometers is comparable or significantly superior to that of many induction coils in the 10^{-2} to 10^{2} s period range.

- High-temperature SQUIDs require only liquid nitrogen rather than liquid helium, providing greater portability than low temperature SQUIDS, but have higher noise levels.



Gough Reitzel magnetometers (Alan Jones, Ingo Richter)

Induction coil sensors

- The EMF induced in an idealized coil of negligible resistance, capacitance, and inductance by a time-varying magnetic induction B is given by:

$$EMF = nAa\frac{dB}{dt}$$

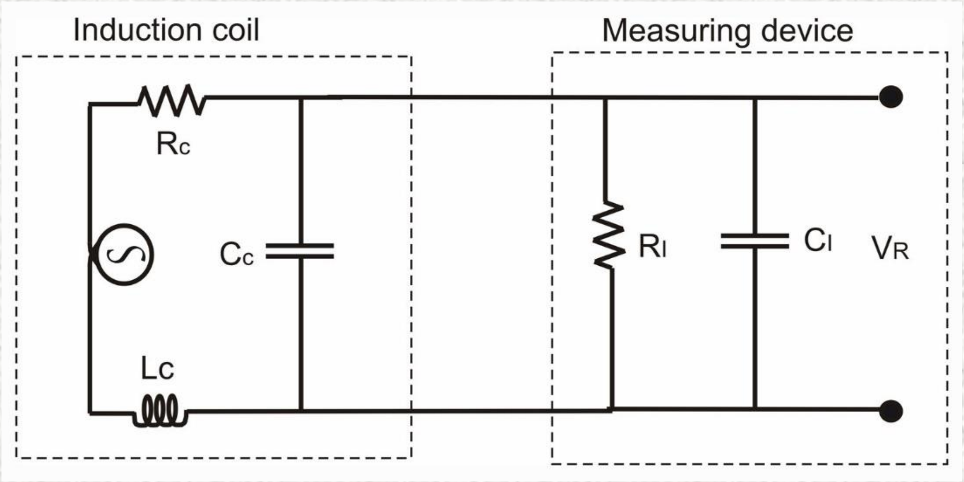
where *n* is the number of turns of wire in the coil, *A* is the area of the coil, and *a* is the unit vector parallel to the axis of the coil.

- The response of a practical induction coil will depend on the lumped resistance R_c, capacitance C_c, and inductance L_c, of the coil. If the input resistance of the coil is much less than that of the measuring device R_i, the corner frequency will be given by:

$$\omega_{max} = \sqrt{\frac{1}{L_c C_c}}$$

- For the roll-over frequency to be high, it is desirable for capacitance, which depends on coil geometry, wire diameter, insulation characteristics, and the sequence of winding of turns, to be as low as possible.

- In order to minimize noise levels, it is also desirable for the resistance, which depends on the gauge of the wire and the metal used, to be as low as possible.



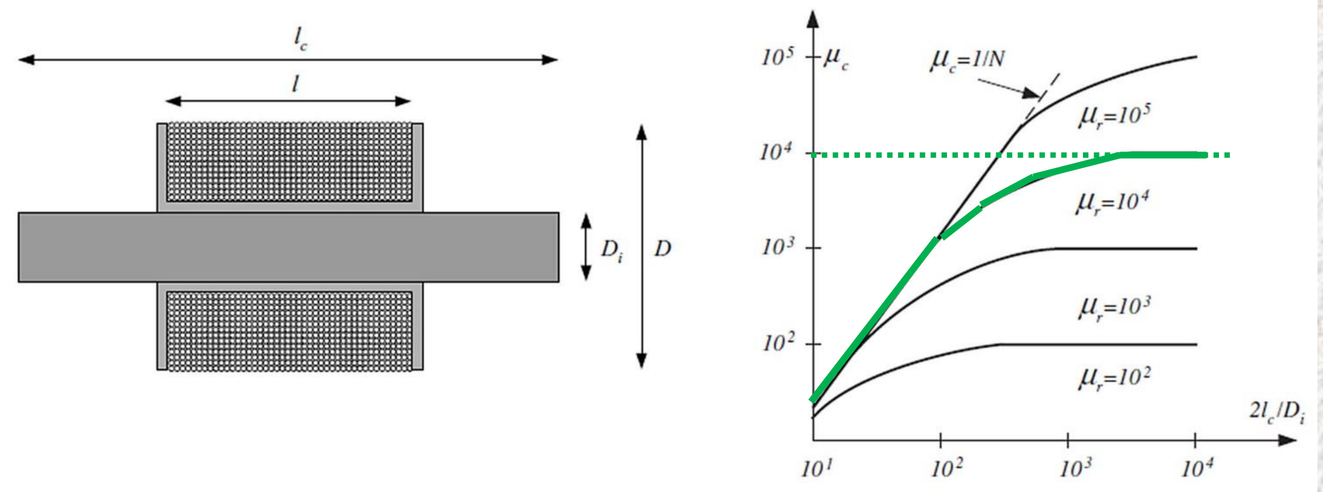
Equivalent electrical circuit to an induction coil sensor.

Induction coil sensors

- Sensitivity of induction coil sensors can be increased by the addition of magnetically permeable material within the core of the coil.

- Materials such as permalloy and supermalloy have very high magnetic permeability and can greatly amplify the response. However, because of geometrically-controlled demagnetization, the effective magnetic permeability of the core will be less than the true material permeability.

- Demagnetization is minimized when the core has a long rod-like form.



Dependence of core permeability on dimensions and material permeability (Tumanski, 2007)

- The response also depends on characteristics of the measuring electronics. If the ratio of the coil resistance to the load resistance R_c/R_i is significant, the response will have a flat peak with corner frequencies.

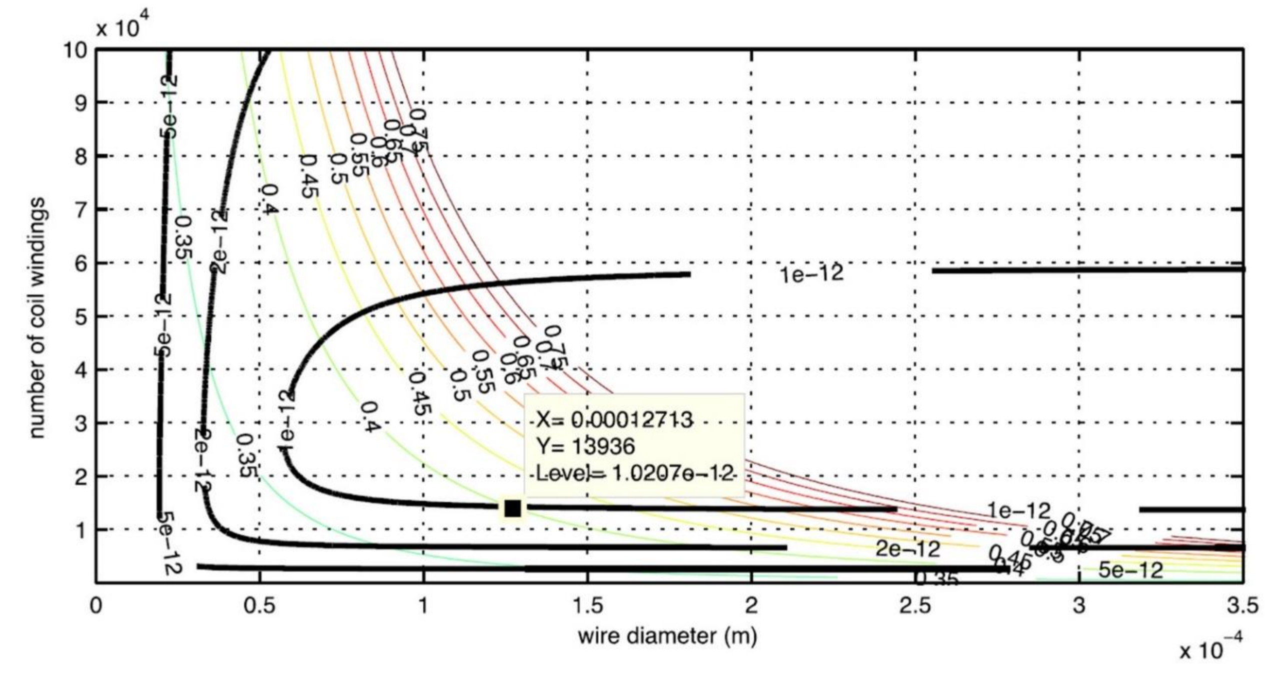
$$\omega_{low} = \frac{R_c + R_i}{L_c} \quad \text{and} \quad \omega_{high} = \frac{1}{R_i C_C}$$

- Preamplifiers must be well-matched to the coils to provide a relatively flat response in the target period band, and in modern MT systems are constructed as part of the coils.

Induction coil sensors

- There are numerous factors that are balanced in induction coil design to produce the desired system response, low noise levels, and required functional aspects such as the coil dimensions and mass.

- There has been considerable effort made in recent years to produce coils with broad frequency ranges to permit AMT-BBMT recordings and sometimes LMT using a single coil. A number of manufacturers now provide coils with a period range of 10^{-4} s to 10^{4} s.



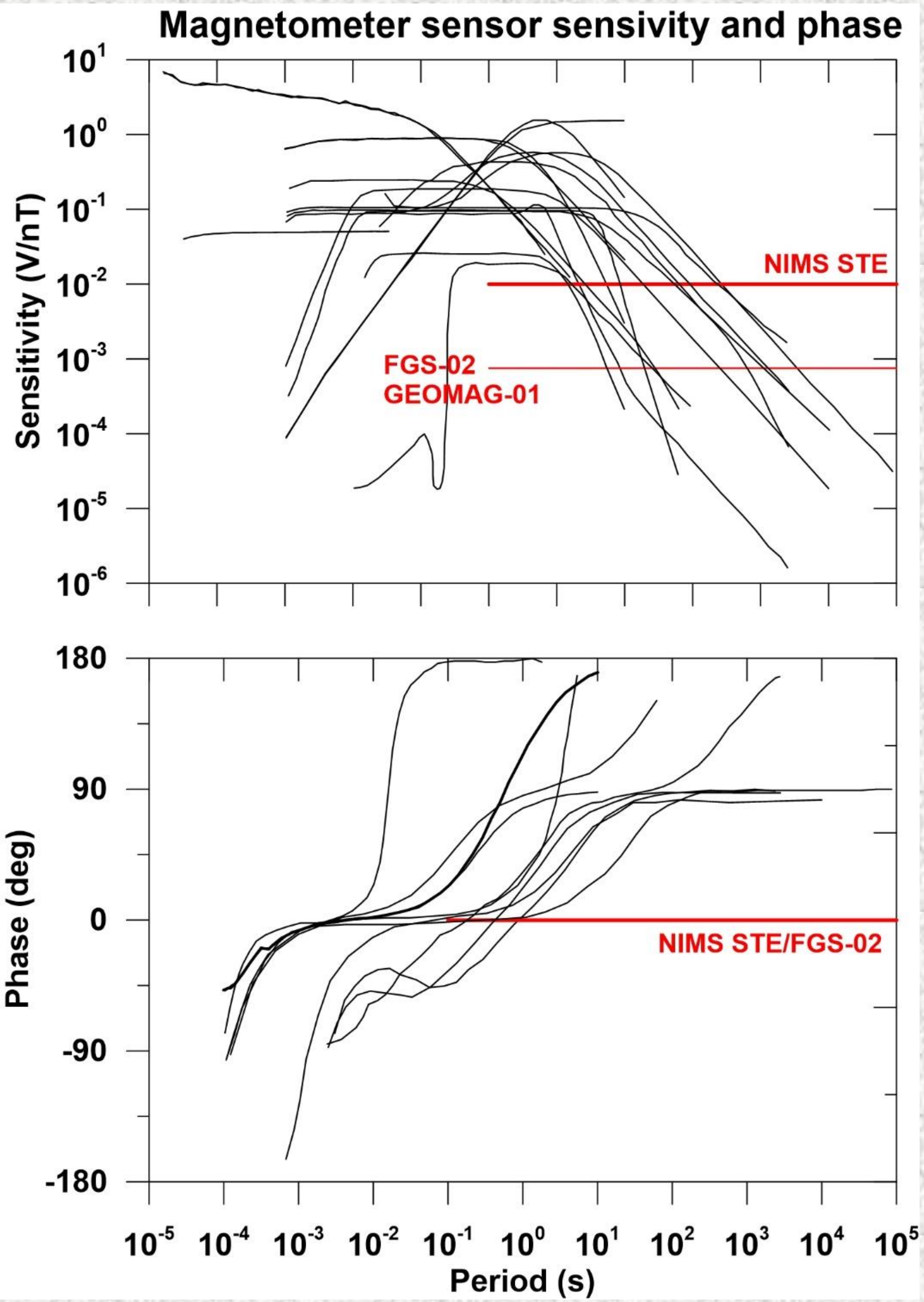
Optimizing mass and noise levels of coil (Hamad & Macnae, 2014) showing noise level in T at 1 s in black and coil mass in kg in colour.

- However, there are sometimes advantages in using multiple sensors with narrower bandwidth, including greater sensitivity and a flatter response in the desired period band, minimization of noise outside this band, sometimes smaller coils, and sometimes lower power consumption.

- The properties of coils are typically examined in terms of the amplitude and phase response and the noise spectrum (or equivalently the mean peak-to-peak amplitude at specified frequencies).

Induction coil sensitivity

- The maximum sensitivity of common MT induction coil sensors is between about 0.1 V/nT for smaller RMT and AMT coils rising to 1 to 10 V/nT for larger BBMT coils.
- The amplitude response versus period is variable (cf. fluxgates) but is relatively flat over the target period band.
- The phase difference of the output and the input signals passes through zero in the target period band, with negative phase response occurring at shorter periods and positive phase response at longer periods.
- Inclusion of integrating circuitry reduces the fall off in the long-period response and reduces the maximum phase difference at these periods from 180^{o} to 90^{o}.



Range of induction coils compared with fluxgates

Induction coil sensitivity

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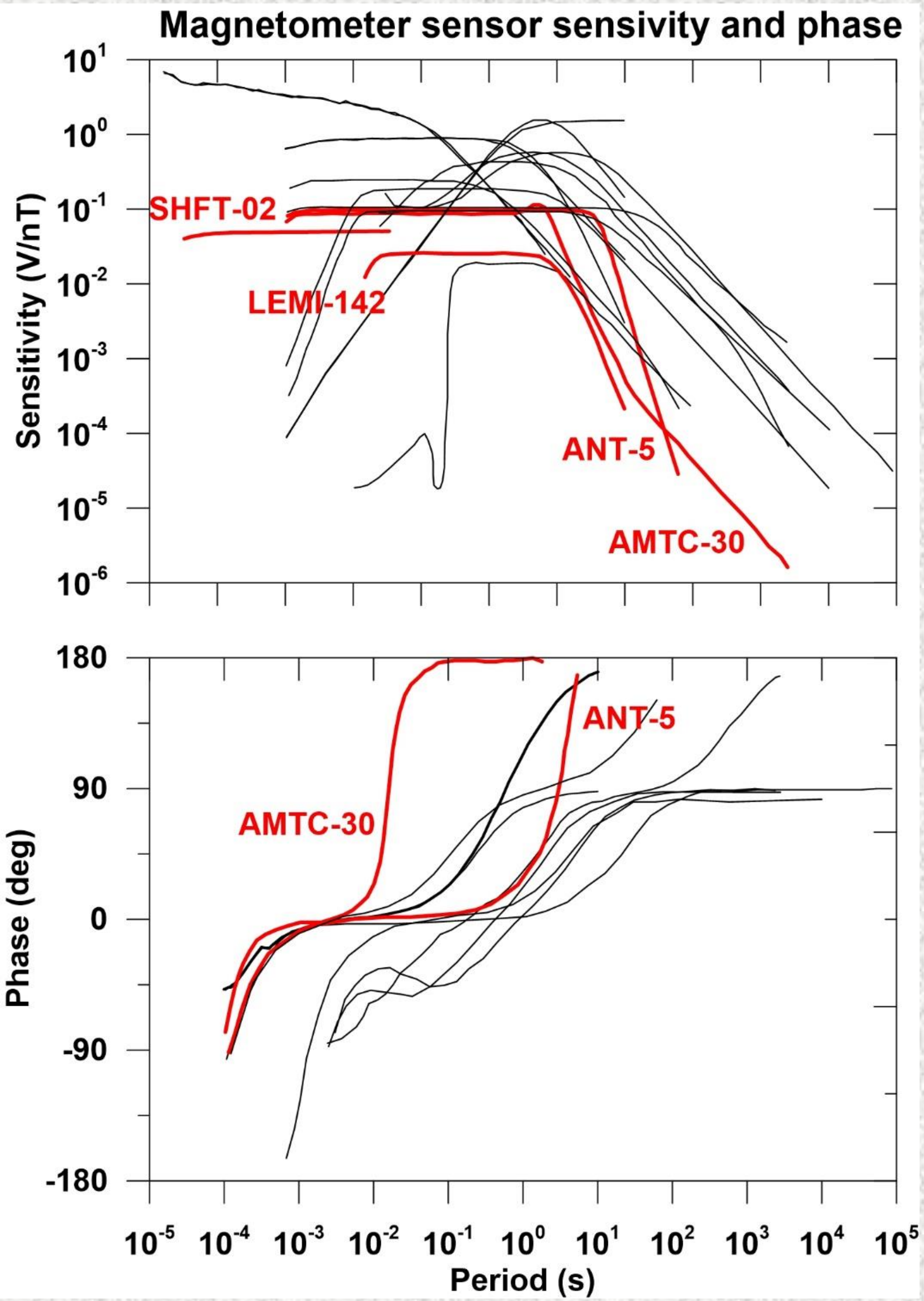

Induction coils with RMT and AMT focus

Induction coil sensitivity

- **The maximum sensitivity of common MT induction coil sensors is between about 0.1 V/nT for smaller RMT and AMT coils rising to 1 to 10 V/nT for larger BBMT coils.**

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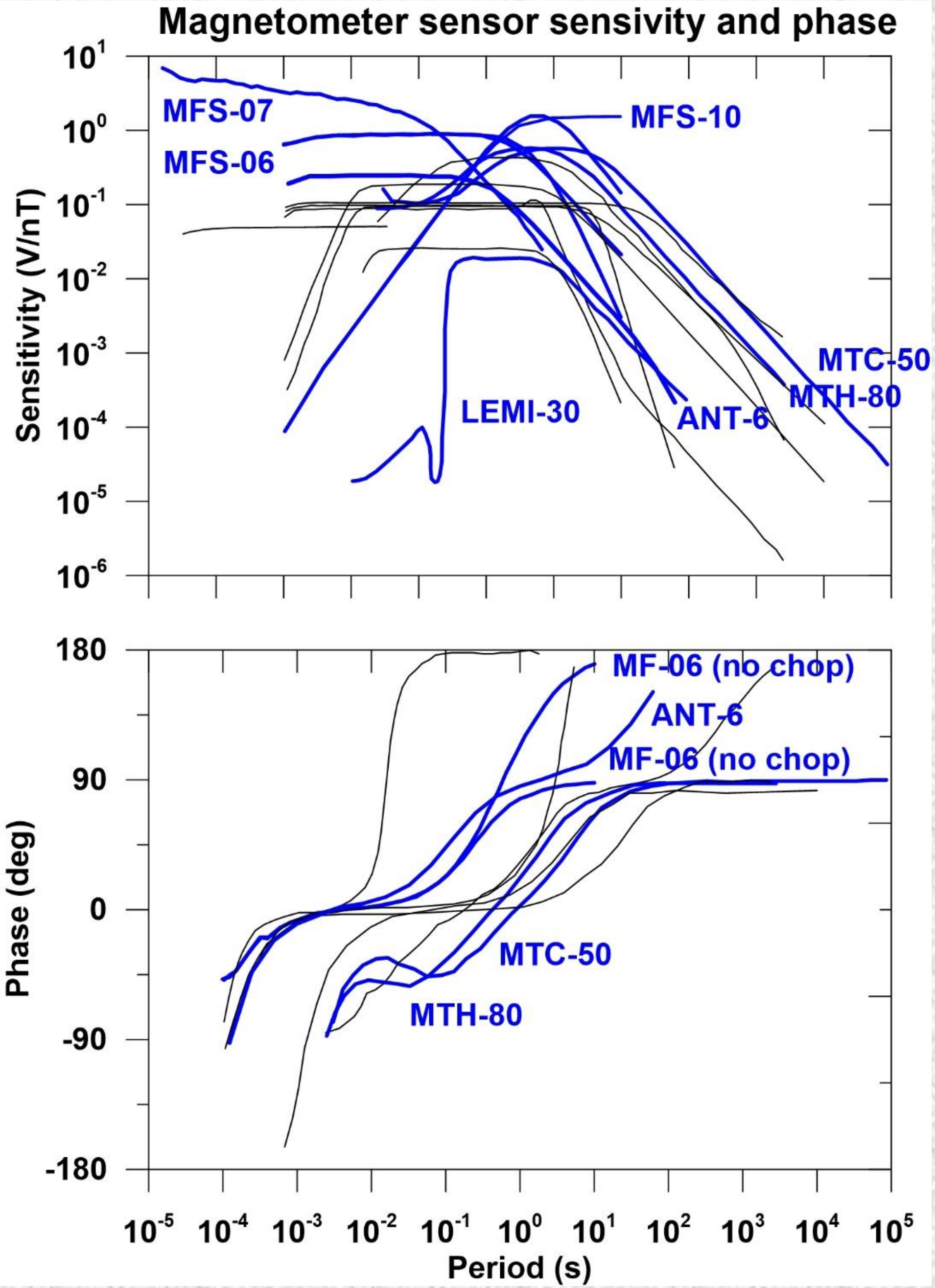


Induction coils with mainly MT (±AMT) focus

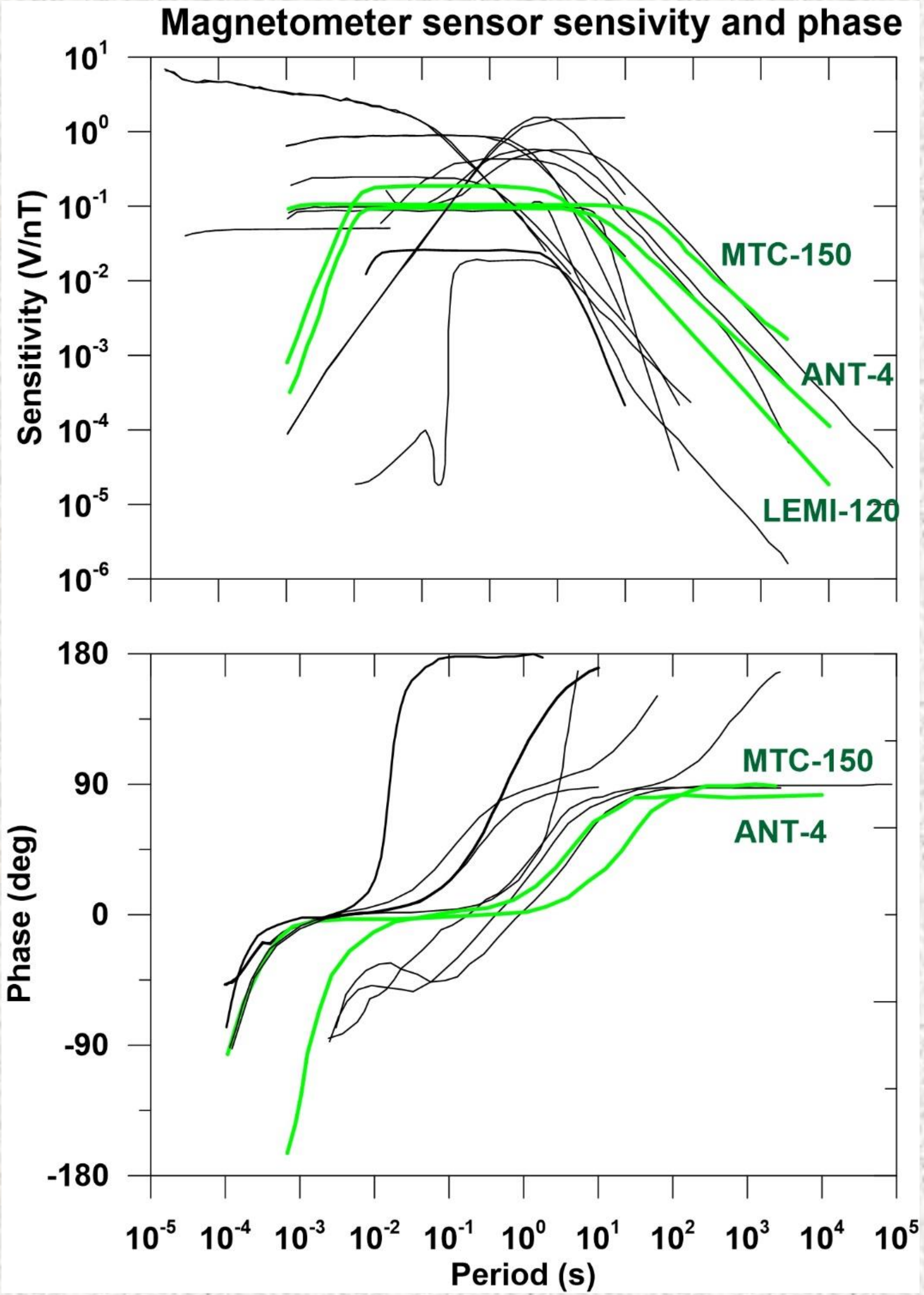
Induction coil sensitivity

- The maximum sensitivity of common MT induction coil sensors is between about 0.1 V/nT for smaller RMT and AMT coils rising to 1 to 10 V/nT for larger BBMT coils.

- The amplitude response is variable (cf. fluxgates) but is relatively flat over the target period band.

- The phase difference of the output and the input signals passes through zero in the target period band, with negative phase response occurring at shorter periods and positive phase response at longer periods.

- Inclusion of integrating circuitry reduces the fall off in the long-period response and reduces the maximum phase difference at these periods from 180^o to 90^o.



Induction coils with larger bandwidth

Induction coil noise

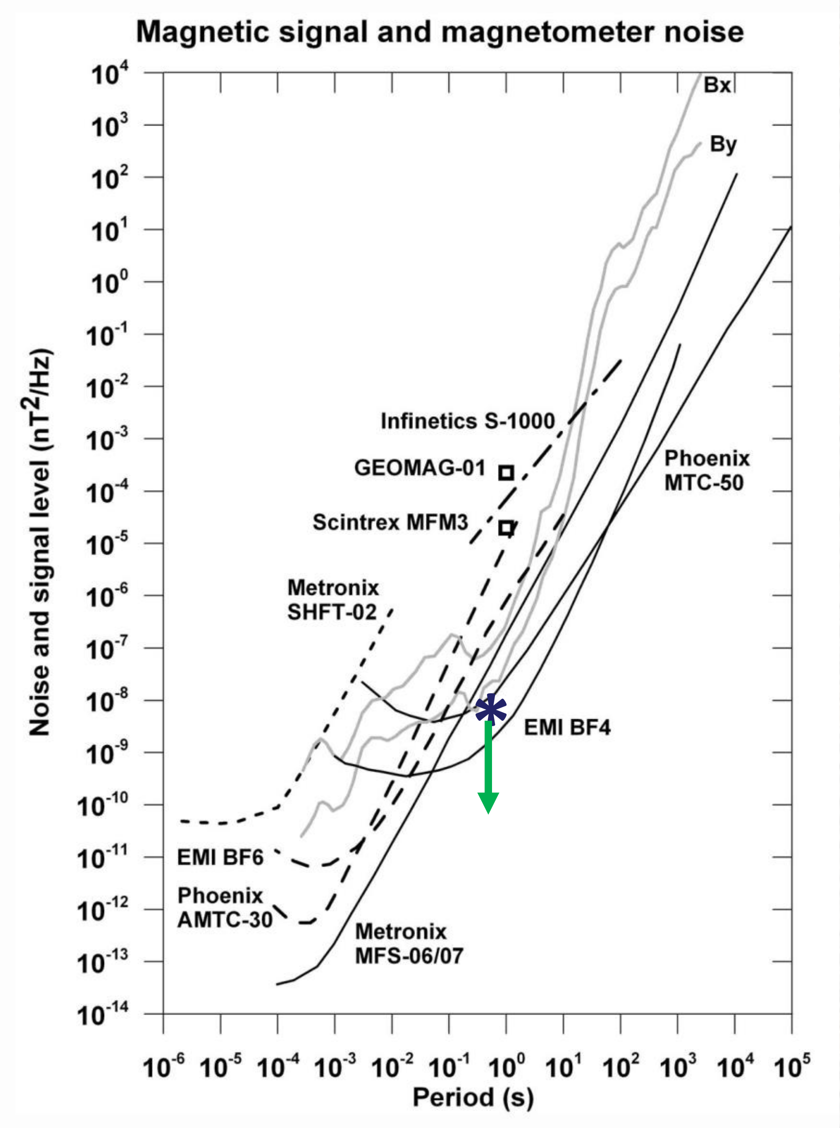
- The noise in induction coil magnetometers arises from the coil itself and from the electronic circuitry including the amplifier.

- The major source of coil noise at higher frequencies is the thermal resistance (Johnson noise) of the coil wiring. This noise has a white spectrum and increases with resistance of the wire.

- At high frequencies, current noise in the amplifier becomes the most significant source of noise. At very low frequencies the noise spectrum is dominated by 1/*f* noise from semiconductors in the electronic circuitry.

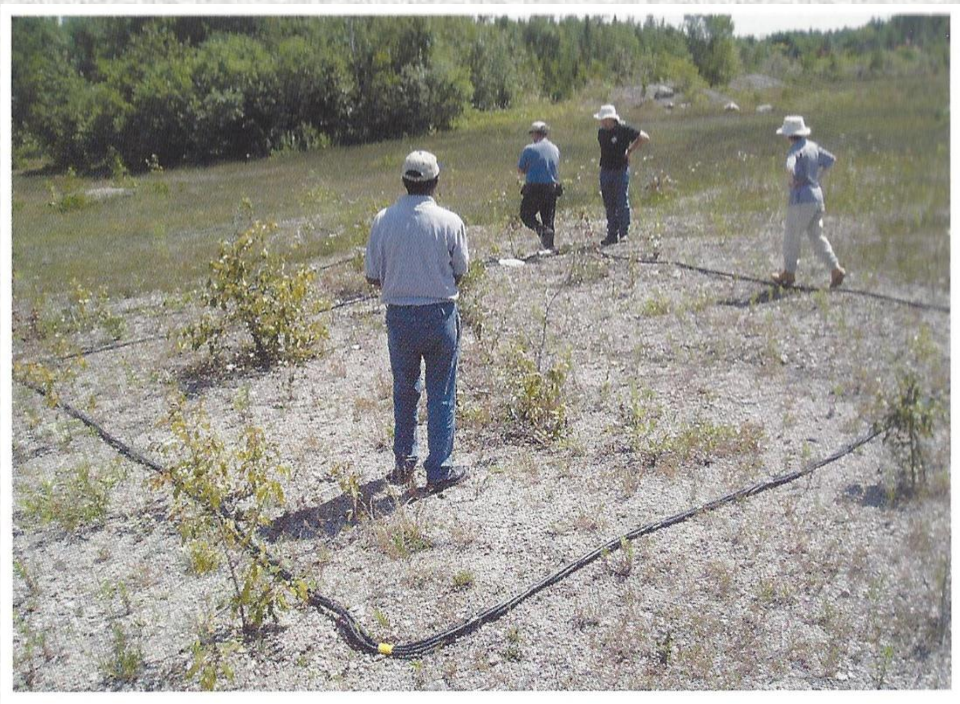
- A good induction coil sensor has a noise level of less than 10^{-8} nT^2/Hz at a period of 1 s, corresponding to mean peak-to-peak fluctuations of less than a picotesla.

- The response of an induction coil may change with time due to aging of high permeability cores, changes of the permeability as a function of Earth's field strength, changes in the core material due to changes in temperature and moisture, and changes in geometry (e.g., bending, distortion). Coils should be calibrated regularly!

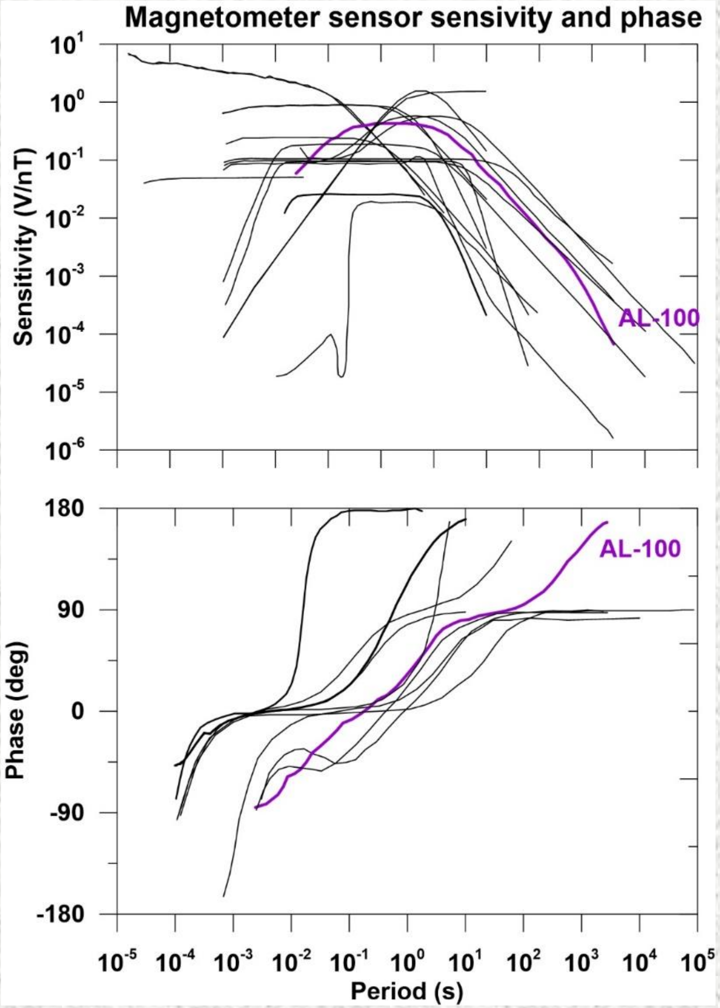


Induction coil sensors

- **An additional type of induction coil sensor in common use is the air-loop. This is a large-diameter multi-turn loop deployed flat on the ground and used to measure the vertical field in locations where a coil cannot be installed.**
  - **The response of an air-loop MT sensor has similar characteristics to other induction coils, but it generally exhibits a lower overall sensitivity.**



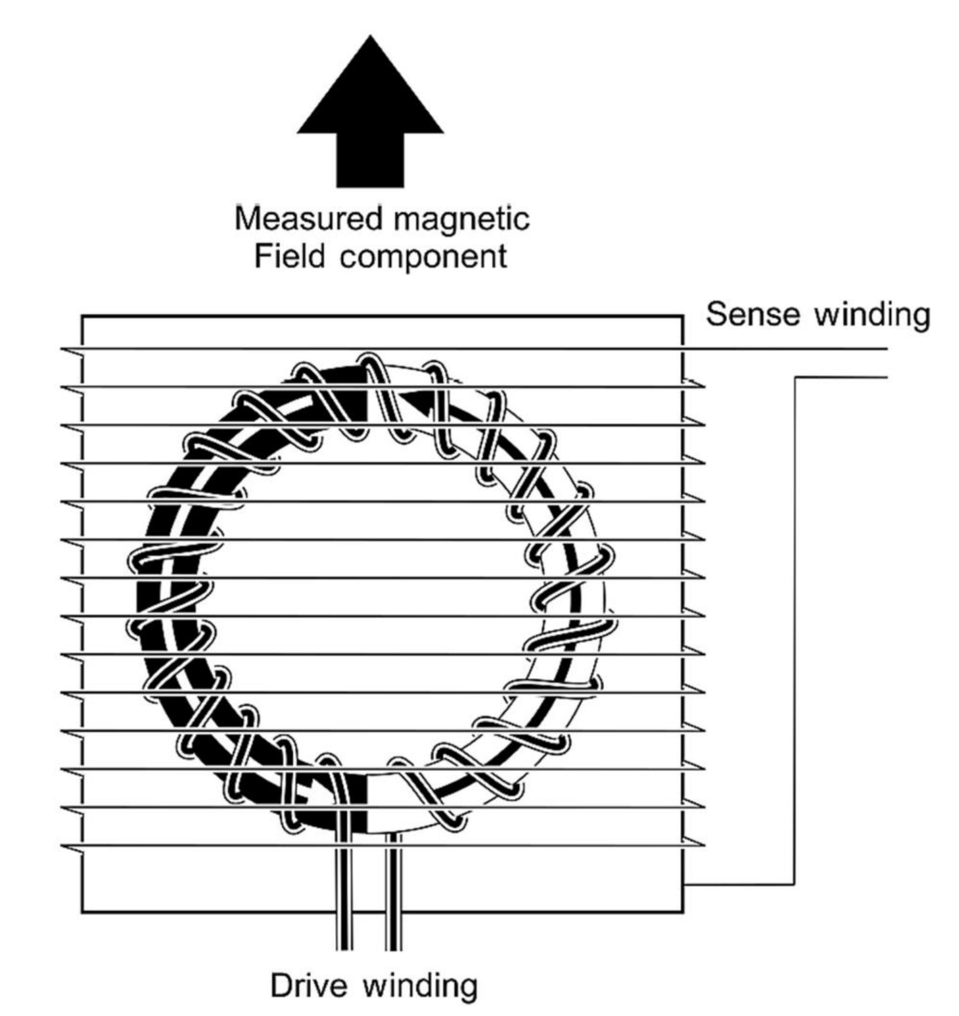
Installation of an air loop in southern Ontario (P. Fernberg)



Response of Phoenix Geophysics AL-100 air-loop sensor

Fluxgate sensors and sensitivity

- Fluxgate sensors consist of an excitation coil, carrying an alternating current, wound around a magnetically permeable body and a detector coil.
- The differential magnetic saturation in directions parallel and antiparallel to B_E provides a measure of the field magnitude.
- The sensitivity of fluxgate sensors is flat and zero-phase at periods significantly longer than that of the measurement cycle, and the amplitude response of sensors used in geophysics is commonly in the range 0.5 to 10 mV/nT.
- This value is restricted by dynamic range constraints of the amplifier and recording electronics rather than the sensor itself.



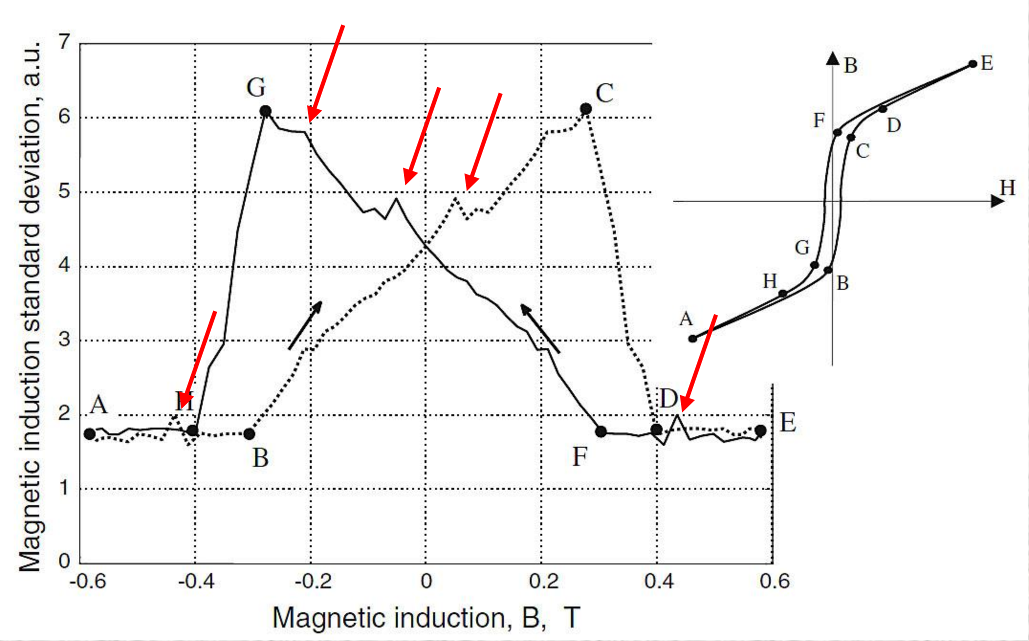
Ring-core fluxgate sensor (Miles et al., 2017)

- Comparison of the sensitivity of fluxgate and induction coil sensors, shows that induction coil sensors will generally provide greater sensitivity at periods of less than about 10^3 s, and fluxgate sensors will have superior sensitivity at longer periods.

Fluxgate sensor noise

- **Sources of instrumental noise in a flux-gate magnetometer can be divided into sensor noise, thermal drift, and long-term drift.**

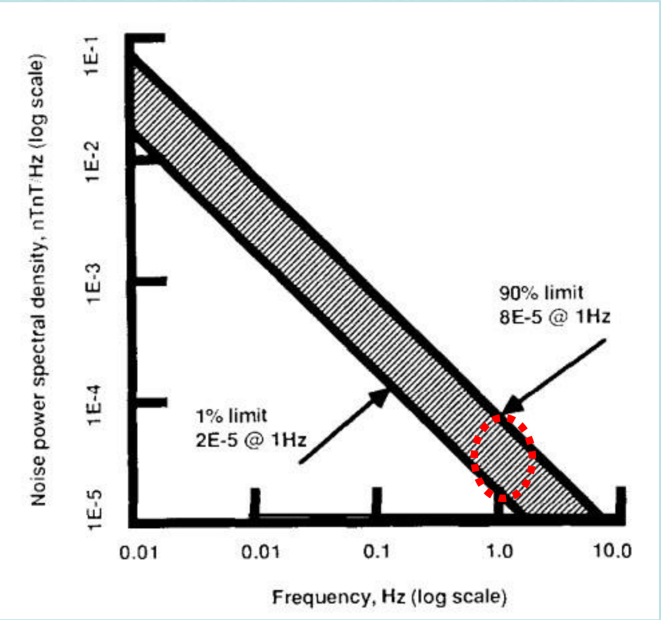
- **Sensor noise arises in large part because ferromagnetic materials undergo magnetization changes in a series of small, discrete Barkhausen steps caused by magnetostriction. This noise can be minimized by an appropriate choice of core material.**



Irregularity of hysteresis (Korepanov & Marusenkov, 2012)

- **Researchers have investigated optimal materials for reducing this noise in ring-core sensors, and have found that metallic glasses consisting of alloys of Fe, Co, Si and B have suitable properties.**

- **Cores of such material show a 1/*f* spectral characteristic and most of the ring cores have noise levels between $2{\cdot}10^{-5}$ and $8{\cdot}10^{-5}$ nT^2/Hz at 1 Hz frequency.**



Typical fluxgate noise (Narod & Bennest, 1988)

Fluxgate sensor noise

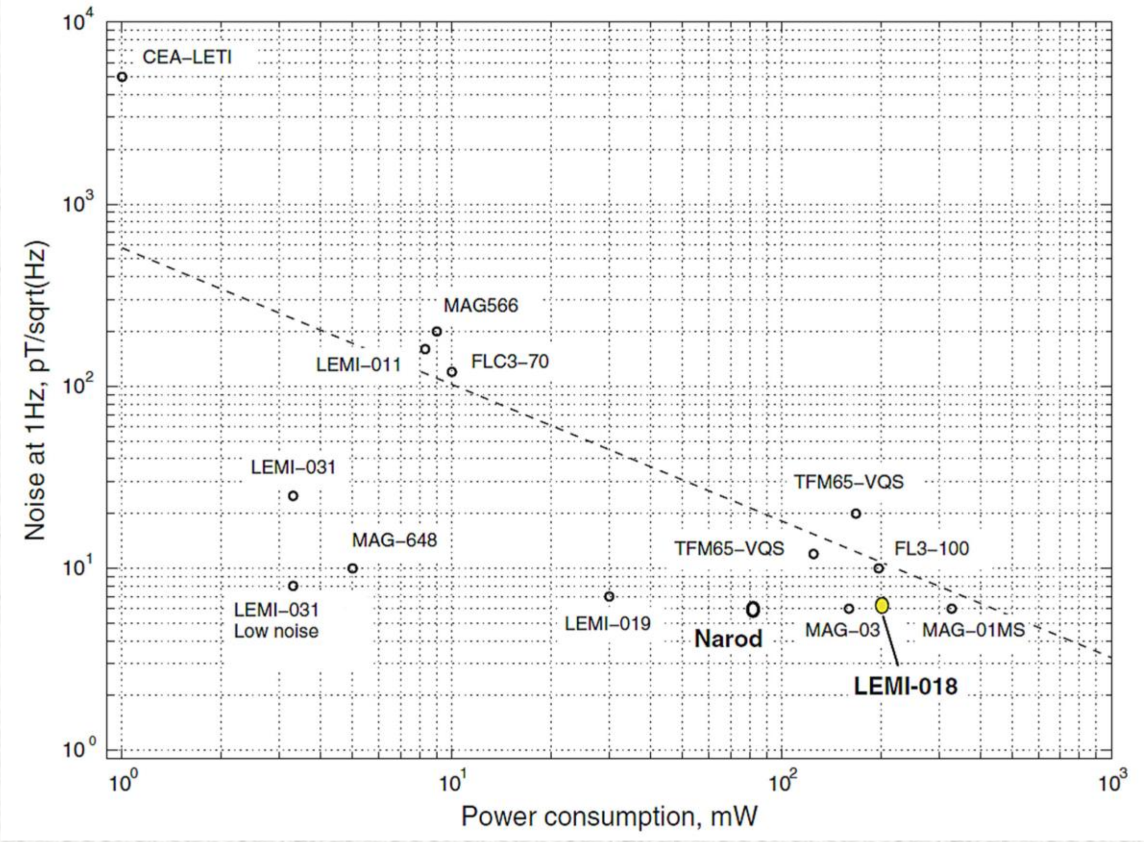
- Thermal sensitivity of fluxgate magnetometers arises mainly from the electronic circuitry including the voltage reference.

- Field-based instruments designed to use lower power components may have corresponding values of 10 ppm.deg^{-1} and 0.5 nT.deg^{-1}. In comparison, the sensor itself typically has a sensitivity of better than 0.1 nT.deg^{-1}.

- Long-term drift arises from aging of sensor windings and other electronic components.

- Engineering data suggests that this drift may be around 50 ppm.yr^{-1} or 3 nT.yr^{-1} in a 60,000 nT field, but instrument tests have suggested that values of 1 nT.yr^{-1} may be possible.

- Overall, fluxgate sensors provide excellent noise levels at a particular level of power consumption. There is a general correlation between decreasing noise level and increasing power.



Fluxgate power consumption versus noise level (Korepanov & Marusenkov, 2012)

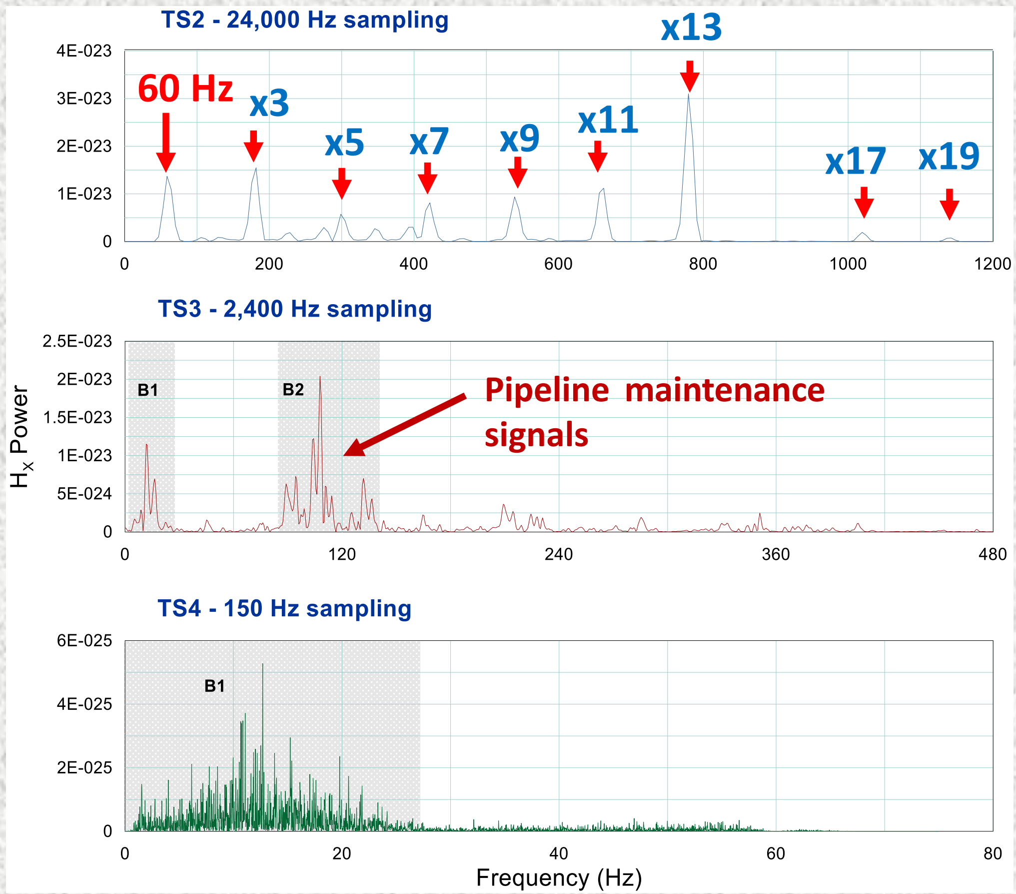
Other components of magnetometers

- Noise associated with 50 or 60 Hz powerline signals and their harmonics occurs within the AMT and BBMT frequency ranges. For symmetric clipping of the fundamental signal, only odd harmonics will occur.

- Powerline noise is usually removed using comb filters acting on the primary frequency and its harmonics.

- Low pass filters are used to remove high frequency noise, such as VLF radio-frequency signals, from magnetic data. The roll-off of the filters may be weaker for BBMT and LMT recordings.

- For AMT recordings made within about 100 km of a VLF transmitter, it is important for the filters to have a steep roll-off in order to record signals at periods at, or smaller than, 10^{-4} s.



No filter

60 Hz + harmonic comb filter

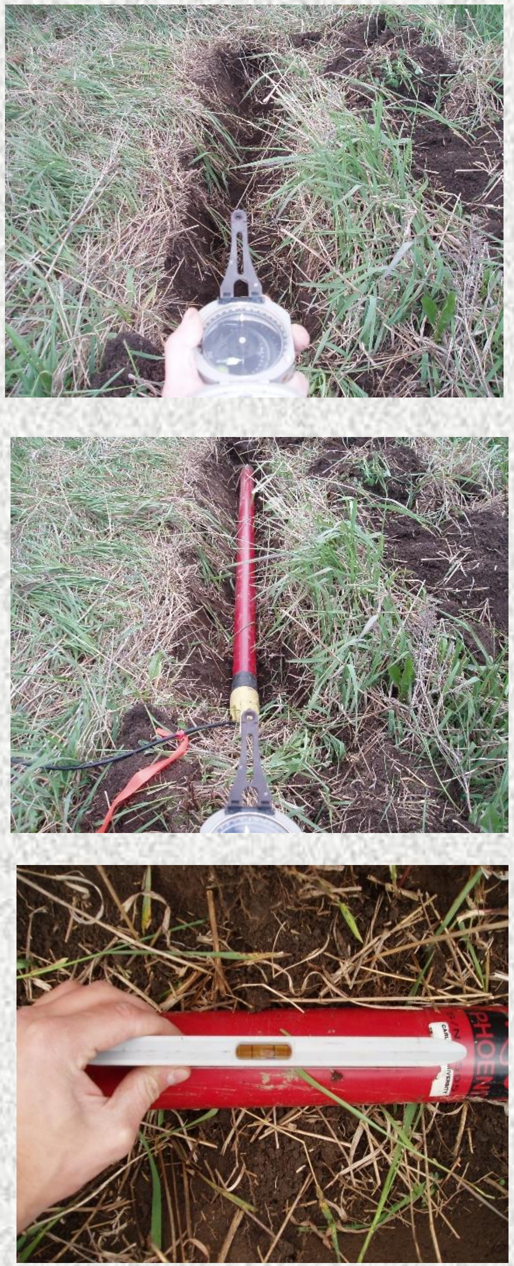
60 Hz + harmonic comb filter

H_x spectra for each of three MT data sampling frequencies recorded on November 10, 2014 at site aqi08 near the Boundary Dam Power station, Saskatchewan (McLeod, 2016).

Magnetometer deployment

- In most MT surveys, magnetic sensors are buried at a depth of between 20 cm and 1 m to minimize temperature variation, microseismic shake, and wind noise.
- Two sensors are usually aligned in magnetic or geographic north and east with the third vertical. Compasses, levels, and surveying methods should be used to ensure that the sensors are aligned to within 1^{o} of the required azimuth.
- In LMT and BBMT surveys, it is critical for the sensors to be installed in firm soil to minimize long-term drift due to changes in sensor orientation.
- An instrument rotation of 0.1^{o} can produce spurious signals of up to 100 nT in a 60,000 nT field.
- Installing a vertical coil may be a challenge (but not compared with a Gough-Reitzel instrument)

Vertical coil



Induction coil installation

Fluxgate installation

4. MT recording devices

Digitization and dynamic range

- The number of bits in data digitization and recording affects the dynamic range. Modern broadband MT systems have 24-bit or 32-bit resolution providing a dynamic range (in terms of signal power) of over 130 dB. Older digital systems are 16-bit or less with a maximum dynamic range of 90 dB.

- For LMT, dynamic range of >24-bit systems allows recording of the total magnetic field without removal of a baseline value. For a total field value of 100,000 nT, a 24-bit system allows a least count of 6 pT. This value corresponds to a noise level of $5{\cdot}10^{-6}$ nT^2/Hz at a period of 1 s, just lower than the inherent noise of good fluxgate sensors, providing optimum data.

- AC coupling of induction coils means B_E is not a constraint. Recording of the time-derivative also flattens the spectrum, so spectral variation in $(nT/s)^2/Hz$, is less than several decades. So 24-bit systems allow accurate recording of narrow band noise superimposed on the background, and recordings during disturbed and quiet field variations.

- Dynamic range of land LMT electric recordings should enable an accuracy at 1 s period of 10^{-15} V^2/Hz, or better, corresponding to fluctuations of 0.1 μV. For a least-count of 0.1 μV, a 24-bit system provides a maximum of 1700 mV, large enough to accommodate most changes in electrode self-potential.

LEMI 423 MT system

KMS MT system

Data acquisition control and storage

- Data acquisition is controlled by an on-board microcomputer. For each acquisition run, the program to be executed and/or a table of acquisition parameters is downloaded from a PC, memory card, or other storage device.

- One of the most important advances in MT instrumentation in the last two decades is GPS synchronized data acquisition. All commercial land MT systems now use a clock system synchronized by GPS signals. This system provides a time accuracy of ±340 ns.

- MT data are now recorded with solid-state memory such as SD memory cards, and are retrieved by removal of the memory cards or uploading the data to a field computer. Telemetry is of growing importance (see A. Schultz Eminar).

- Many BBMT and AMT surveys now involve several hundred Mb or more of MT time series at each site. LMT surveys with 1 to 10 Hz sampling and recording durations of up to one month involve data collection of close to 1 Mb per site.

Phoenix MTU system

Metronix ADU-08e

Data acquisition control and storage

- Most LMT instruments record continuous time series with a fixed sampling interval typically between 0.1 and 1 s. There is little to be gained by using shorter sampling periods.

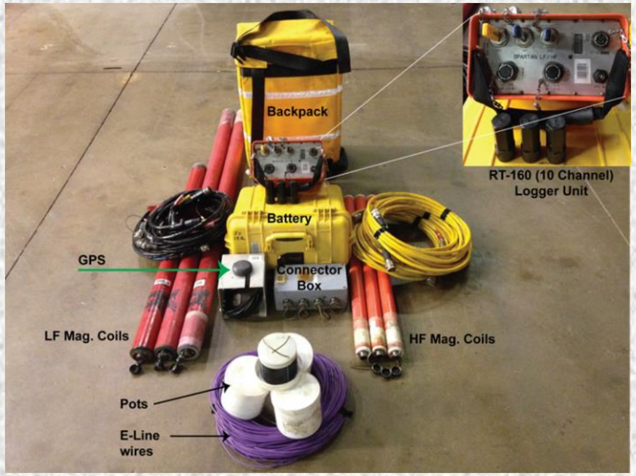
- AMT and BBMT systems typically use advanced recording arrangements involving two or more frequency ranges. Recording in each frequency range uses different base-frequency sampling rates and recording windows, and sometimes different amplifier and A/D boards.

- Background signal levels in the AMT dead-band between 1 and 5 kHz is typically one or two orders of magnitude less than the sensitivity of most AMT field sensors. Strategies for optimizing AMT data collected, include acquisition of data in night-time hours when AMT signals are stronger and threshold triggering of buffered recordings.

- In CSAMT and RMT recordings, the MT response is usually measured at a series of discrete periods. The MT impedance can be computed directly by the microprocessor on the instruments, removing the need for a permanent recording of the time series.

Zonge portable AMT system

Chongqing Gold Mechanical and Electrical co.



Quantec Geoscience Spartan system

Power requirements and batteries

- Most commercial land BBMT and AMT systems have typical power consumptions of between 5 and 15 W and draw around one amp with a 12 V supply. They are typically operated for one to two days using one or two good quality wet cell car-type batteries with capacity of 45 Ah or greater.

- In contrast, LMT systems use a maximum of 1 to 2 W, drawing 1/10 amp, and must be able record without service visits for one week or longer. These systems typically require one wet cell battery per week of recording. Typically, batteries at LMT installations are larger (up to 120 Ah) and are the marine deep-cycle type to give maximum performance.

- Use of solar panels to power LMT systems is becoming more common, particularly in long duration and remote recording locations in which weekly service visits would be difficult or expensive. Solar power has its own set of attendant problems, including noise generation and security issues.

MT site with battery

MT site with solar panel power (Kirkby, 2019)

MT instrument calibration and instrument noise evaluation

- MT equipment must be accurately calibrated. For BBMT and AMT surveys, it is necessary to conduct a frequency-dependent calibration. For LMT surveys, the system response often has a negligible period dependence in the period range of interest, so it is possible to calibrate at a single period such as the DC response.

- MT instrument calibration first requires that the recording unit respond correctly to input signals. This involves checking that a known reference voltage input, representing a sensor output, is recorded at the correct level.

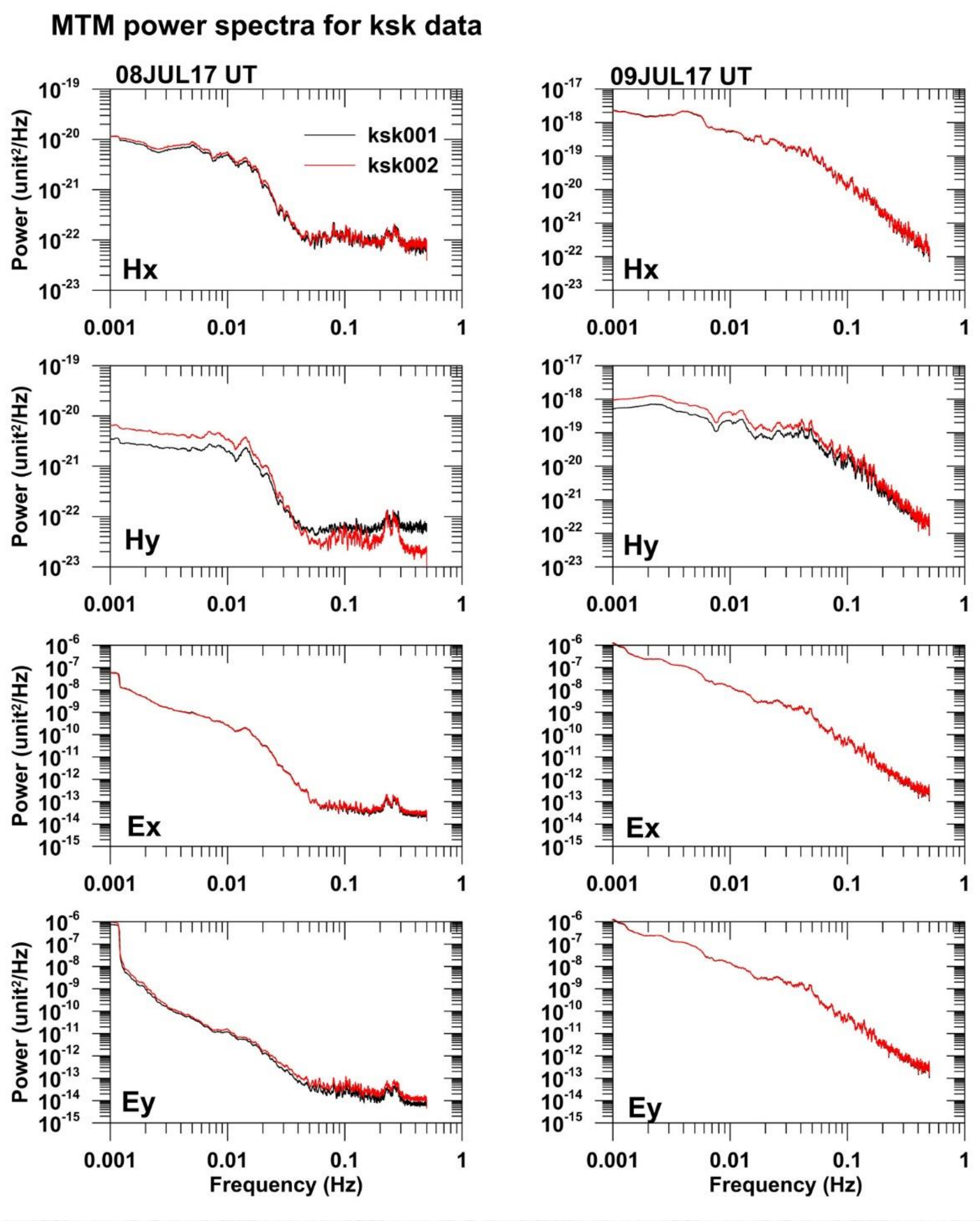
Calibration of coils for Winter survey (Phoenix Geophysics)

- The second part of the calibration involves defining the response for each sensor including any associated preamplifiers and filters. Magnetic induction coil sensors are usually calibrated using a secondary coil that creates an accurately known magnetic field.

- For BBMT and AMT systems, and LMT systems with significant period-dependence of the response, the calibrations are usually applied to the frequency-domain response during data processing.

MT instrument calibration and instrument noise evaluation

- It is important for MT systems to be tested for instrumental noise levels prior to their use.
- First, the system can be used to make recordings in an area in which EM noise sources are at a relatively low level. Spectra derived from the recorded time series can be examined for indications of noise.
- Second, in side-by-side coil tests, the difference between the spectra of time series recorded by closely spaced parallel coils is evaluated and provides an indication of the frequency-dependent noise level of the coils. Electrode noise is often assessed using a DC approach with the voltage measured between electrodes placed side-by-side on cloth or paper moistened with a saline fluid.
- Finally, the full response of an MT system can be assessed by comparing the full impedance response measured by two instruments at the same location.



Examples of spectra during extremely low signal levels showing recording system limits.

Assorted recommendations

1. Talk to the MT instrument engineers and those experienced in MT field operations. For good results, MT equipment needs to be more than a “black box” to the user.
2. Don’t ignore electrodes. They are the critical part of the electrical sensing system, and not part of the “disposable” equipment in the same way as wires and batteries are.
3. Electric field recordings sometimes make a good remote reference.
4. Good site selection and site installation is critical. It is rarely possible to use MT processing methods to get a good response from a poor site. Take detailed field notes.
5. Whenever possible, look at the basic MT data (especially time series and spectral edi files).

Kaskattama Highland MT survey, NE Manitoba