Magneto-telluric and Very Low Frequency EM methods

In this lecture, we discuss two EM techniques using almost plane waves (recall the end of the preceding lecture) from natural and artificial sources

- **Magneto-telluric (MT) method**
  - Telluric currents
  - Instrumentation

- **Very Low Frequency (VLF) method**
  - VLF sources

- **Interpretation**
  - Apparent resistivity
  - VLF tilt angle

**Reading:**
- Reynolds, Chapter 12
- Dentith and Mudge, online appendix 4 at [www.cambridge.org/dentith](http://www.cambridge.org/dentith) (MT only)
- Telford et al., Chapter 6
Magneto-telluric (MT) method

- Uses naturally occurring electromagnetic waves generated by electrical currents within the ionosphere, electric storms, lightning
- Relatively low-frequency EM waves bouncing back and forth between the Earth’s surface and ionosphere
  - Frequencies $10^{-5}$ to $10^5$ Hz ($10^{-3}$ to $10^3$ Hz used in MT work)
  - Mostly vertically-propagating EM waves. i.e. both $E$ and $H$ are near-horizontal

Patterns of telluric currents
Telluric currents - amplitudes

- Plot below shows MT amplitudes at 15-min intervals at several frequencies, relative to their average levels.
- Note that higher-frequency MT signal is below 50% from about 10 am to 8 pm.
  - This may be good for lower-frequency MT work.

![Graph showing MT amplitudes at different frequencies.](image)
Telluric currents – azimuthal variations

- Azimuthal variations of amplitudes are also lower at around 2 pm
- Thus, 6 to 8 hours around 2 pm is a convenient window for MT measurements
Magneto-telluric measurements

- Reference (similar to “base” in gravity) site is usually needed to measure time variations (drift) of telluric currents
- Magnetic coils are usually buried to avoid shaking
- Audio-frequency range MT (AMT) can also use a controlled source in the form of a grounded electric dipole

Setting up an $H_x$ coil in 2019 Geophysics Field School (Phoenix Geophysical)
VLF method

- Powerful radio transmitter (Tx) with vertical antenna creates horizontally-polarized magnetic field at low frequency (figure below). This is the primary VLF field.
  - As in most EM methods, the wave propagates away from the source, but the wavelength is long (~15 km), and the field can be viewed as spatially uniform.

- The field is polarized with $E$ (electric) field oriented vertically, and $H$ horizontally sideways from the direction to the transmitter.
  - Therefore, VLF surveying is done in a direction perpendicular to the direction to the Tx (figure).

- Thus, a conductor oriented along the direction toward the Tx supports currents induced both by $E$ and the oscillating $H$.
  - These currents create secondary magnetic and electric fields that are measured by the VLF receiver.
VLF transmitters

- There are currently about 11 powerful (> 1 MWt) VLF transmitters around the world, operating at 15-24 kHz
  - Their primary designation is of course not for geophysics but for marine navigation and communication with submarines

Signal strength > 54 dB is good for VLF imaging
MT and VLF interpretation

- Interpretation of MT and VLF is often based on the relation for apparent resistivity from horizontal components of $E$ and $H$ fields.

- Recall from the preceding lecture that, for example, $E$ and $H$ fields on the surface of a conductor are orthogonal, and their amplitudes are mutually related due to the skin-layer effect.
  - This relation is caused by the resistivity of the medium.
  - From the ratio of $E$ and $H$ amplitudes, the apparent resistivity is:

$$\rho_a = \frac{1}{\omega \mu_0} \frac{\langle E_x^2 \rangle}{\langle H_y^2 \rangle} = \frac{1}{\omega \mu_0} \frac{\langle E_y^2 \rangle}{\langle H_x^2 \rangle} \approx 0.2T \frac{\langle E_H^2 \rangle}{\langle H_H^2 \rangle}$$

- When evaluated for different orientations, this $\rho_a$ can actually be different (plot on the right).

MT example

- To display apparent-resistivity MT section, the frequency is plotted in descending order and logarithmic scale downward and often viewed as “pseudo-depth”
- The pseudo-depth is the skin depth at some reference resistivity $\rho_0$:

\[
\text{pseudo-depth } = \delta(f) = \sqrt{\frac{\rho_0}{\pi\mu_0}} \cdot f^{-1/2}
\]

- Figures on the right show such a pseudo-depth $\rho_a$ section and a geological section of Coxwell dome in northern Saskatchewan

From Telford et al. text
MT and VLF depth sounding

- The apparent resistivity $\rho_a$ in MT and VLF depends on frequency. This dependence allows constraining true conductivity variations with depth.
- For example, for a single layer over a half space (Cagniard, 1953), the apparent resistivity scaled by resistivity of the layer is a function of scaled frequency $\gamma = 2z \sqrt{\frac{\omega \mu}{2\rho_1}} = \frac{2z}{z_s} \approx 0.004z \frac{f}{\rho_1}$:

$$\frac{\rho_a}{\rho_1}(\gamma) = \frac{\alpha^2 e^{2\gamma} + 2\alpha e^\gamma \cos \gamma + 1}{\alpha^2 e^{2\gamma} - 2\alpha e^\gamma \cos \gamma + 1}, \text{ where } \alpha = \sqrt{\frac{\rho_2/\rho_1 + 1}{\sqrt{\rho_2/\rho_1} - 1}}$$

- Thus (similar to resistivity in a two-layer medium), we can invert $\rho_a(f)$ data for a two-layer model like this:
  1. Precompute master curves of $\rho_a(\gamma)/\rho_1$
  2. Plot the measured $f$ and $\rho_a$ on log-log scales
  3. By shifting the measured curves and matching the master curves, find $\rho_1$ and $\rho_2/\rho_1$
  4. Find in the graphs $f_s$ for which $\gamma = \pi/2$ (this basically means that $z$ is the skin depth at frequency $f_s$; see next slides). From this $f_s$, depth of the resistivity contrast $z$ is estimated:

$$z \approx 250\gamma \sqrt{\frac{2\rho_1}{f_s}} \approx 400 \frac{2\rho_1}{f_s}$$
AMT master curves ($\rho_2 < \rho_1$)

$\gamma = \pi / 2$
AMT master curves ($\rho_2 > \rho_1$)

$\gamma = \pi d^2$
VLF tilt angle

- Due to dense profiling, “tilt angle” interpretation is also convenient for VLF
  - Tilt angle ($\theta$ in the figure) is a convenient indicator for locating conductive anomalies when using a uniform primary field (such as in VLF)
- Tilt angle can be obtained by taking ratio of $H_z$ to $H_x$ amplitudes or by tilting Rx coil to obtain a minimum signal
- $\theta$ changes from downward to upward over an anomaly
  - $\theta = 0$ indicates the conductive anomaly