Magnetotellurics (and other EM Geophysics)

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GEOL/PHYS 6650

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Maxwell's Equations

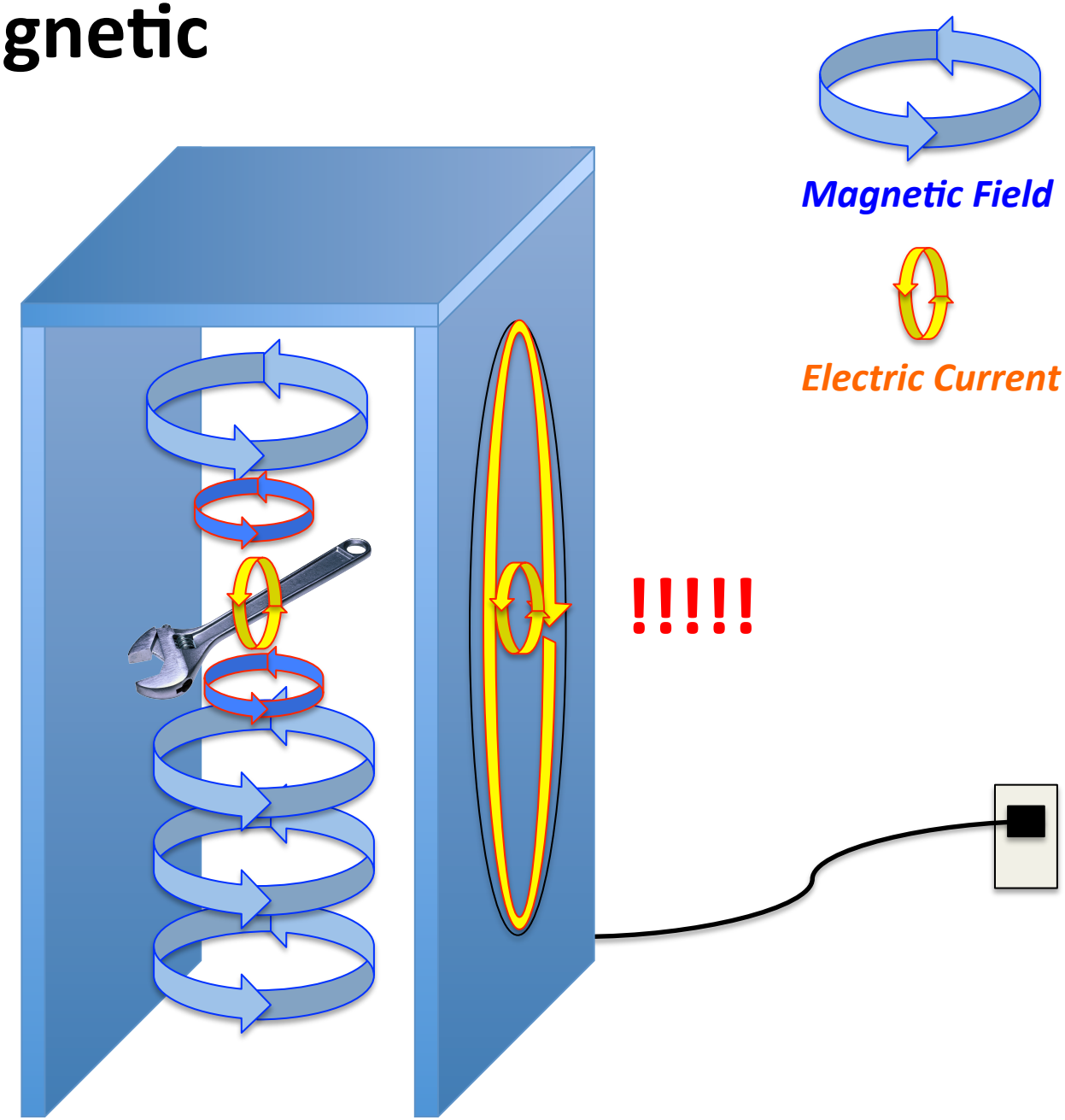
Faraday's Law: $$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

Ampere's Law w/ Maxwell's correction:

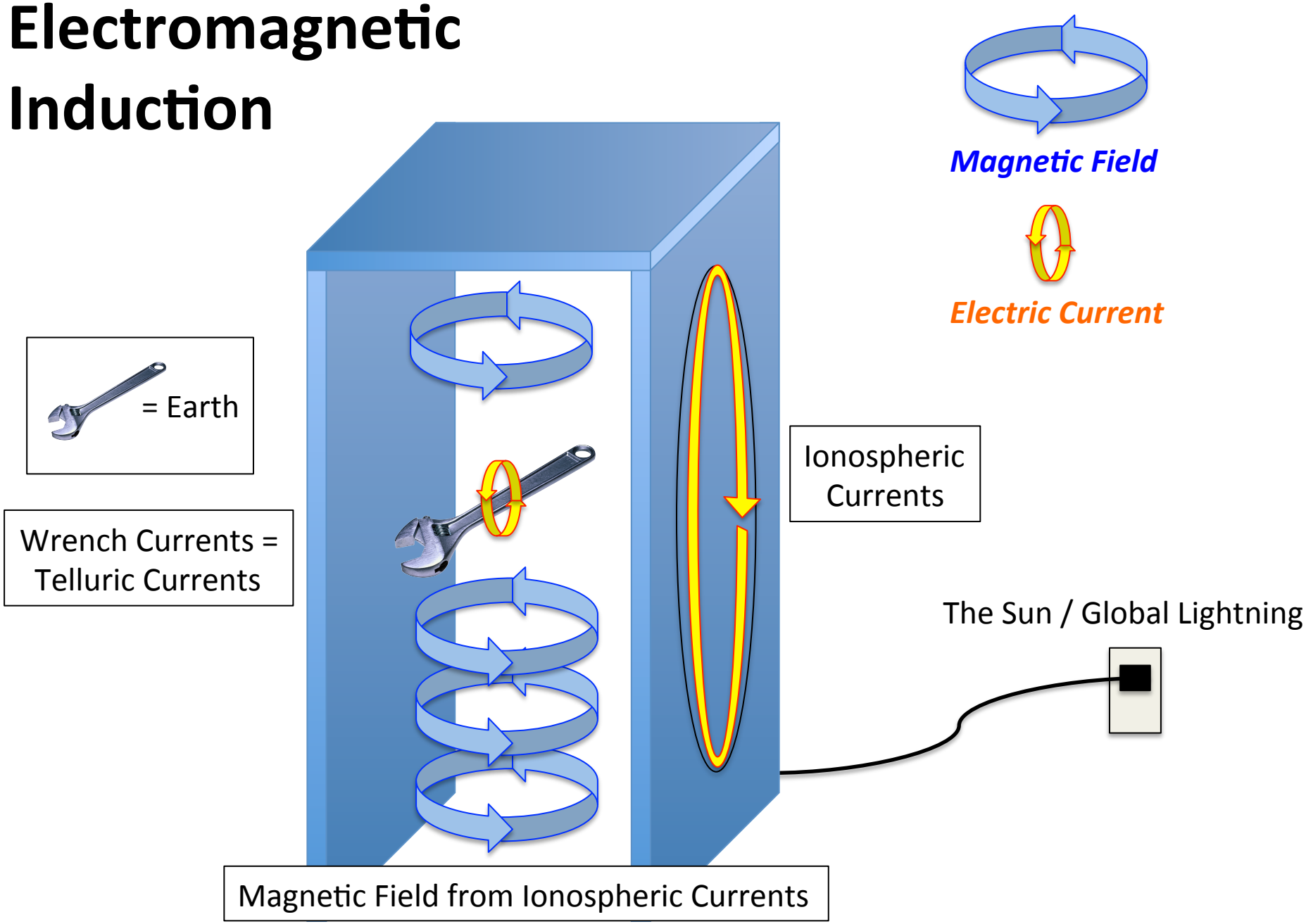
$$\vec{\nabla}\times\vec{B} = \mu_o\vec{J} + \mu\varepsilon\partial_t\vec{E}$$

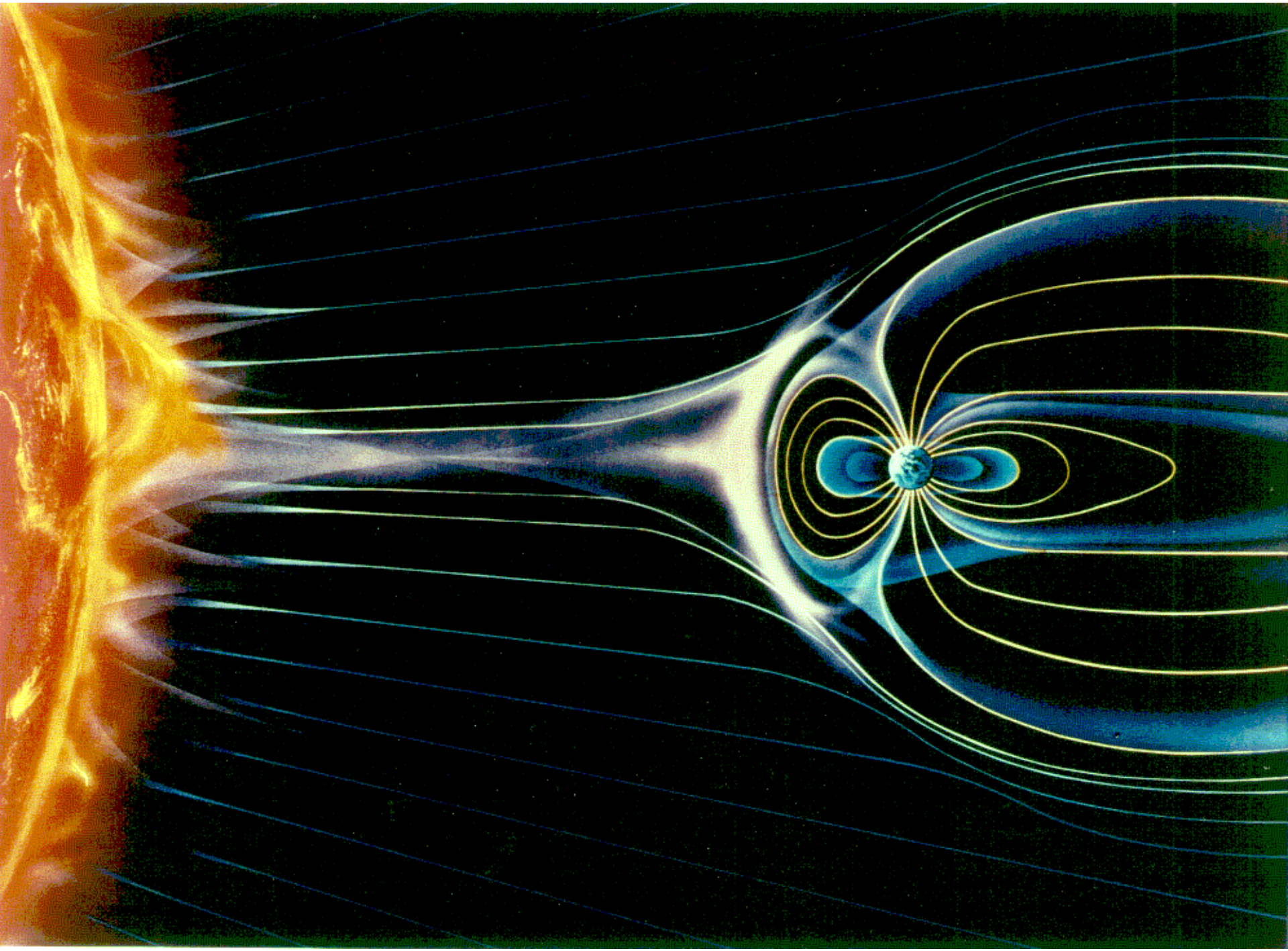
ProVision
ATD
3
4

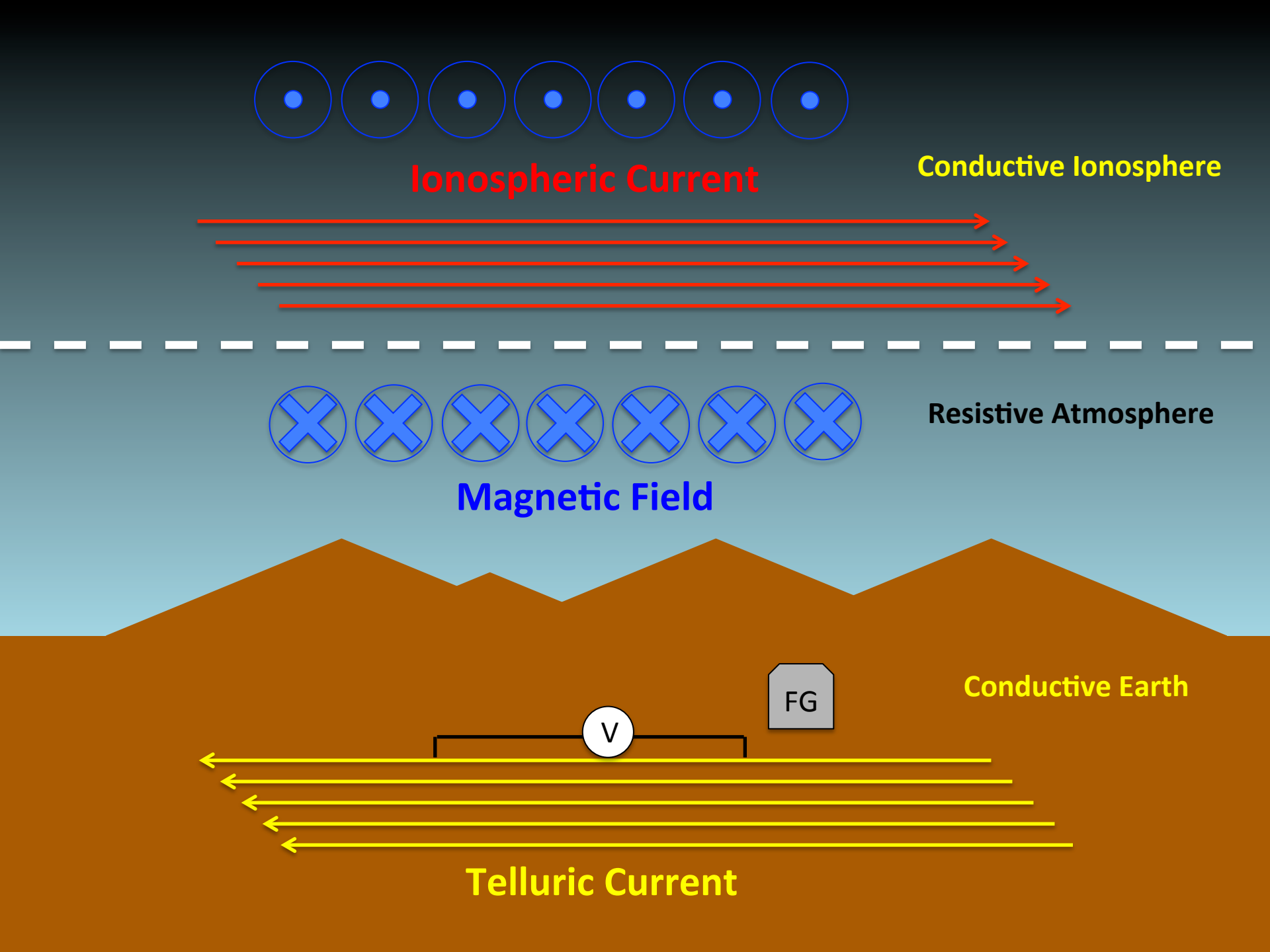
Electromagnetic Induction



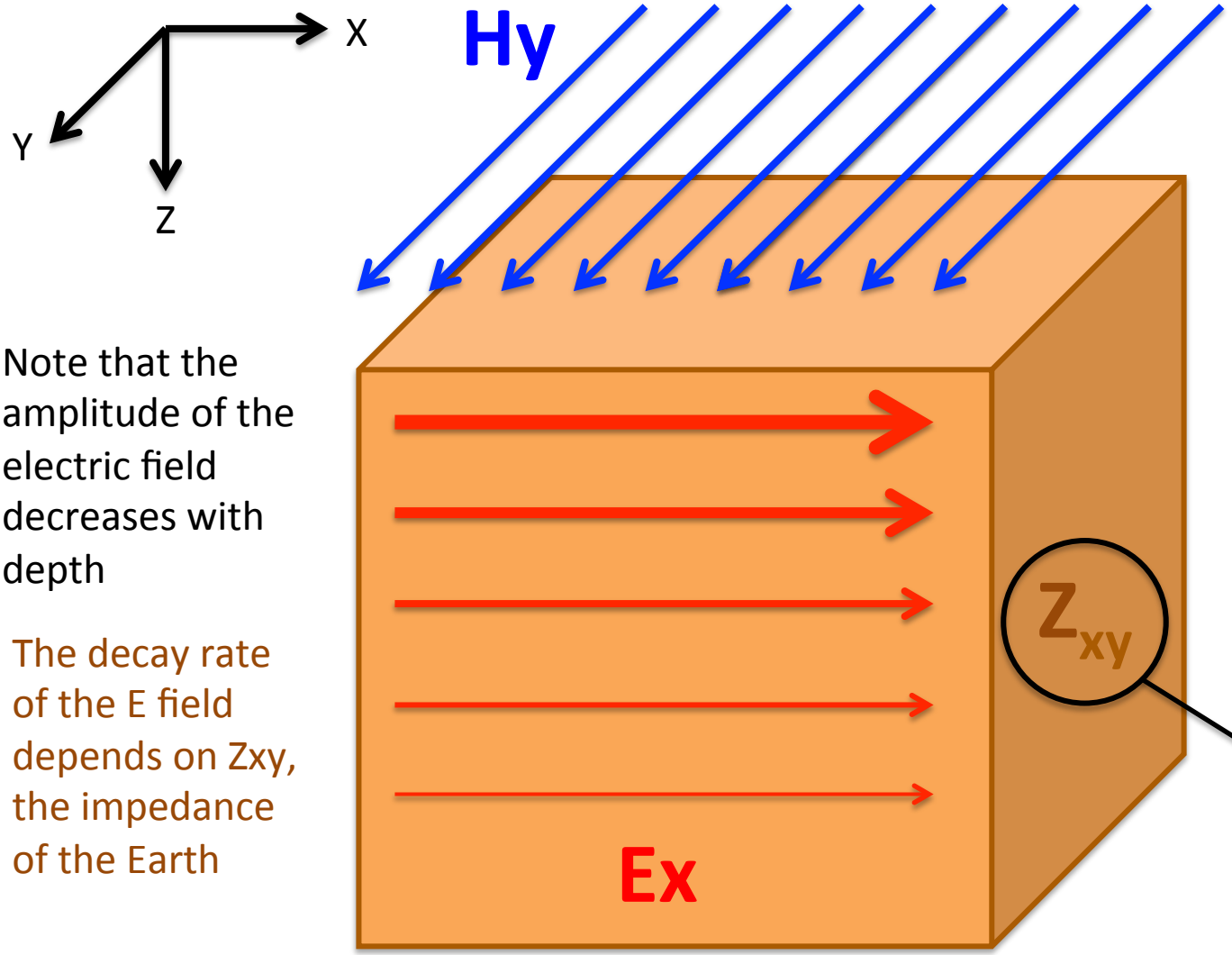
Electromagnetic Induction






Ionospheric Current
Conductive Ionosphere
Resistive Atmosphere
Magnetic Field
FG
V
Conductive Earth
Telluric Current

Electromagnetic Induction



horizontal magnetic field induced by time-varying ionosphere currents

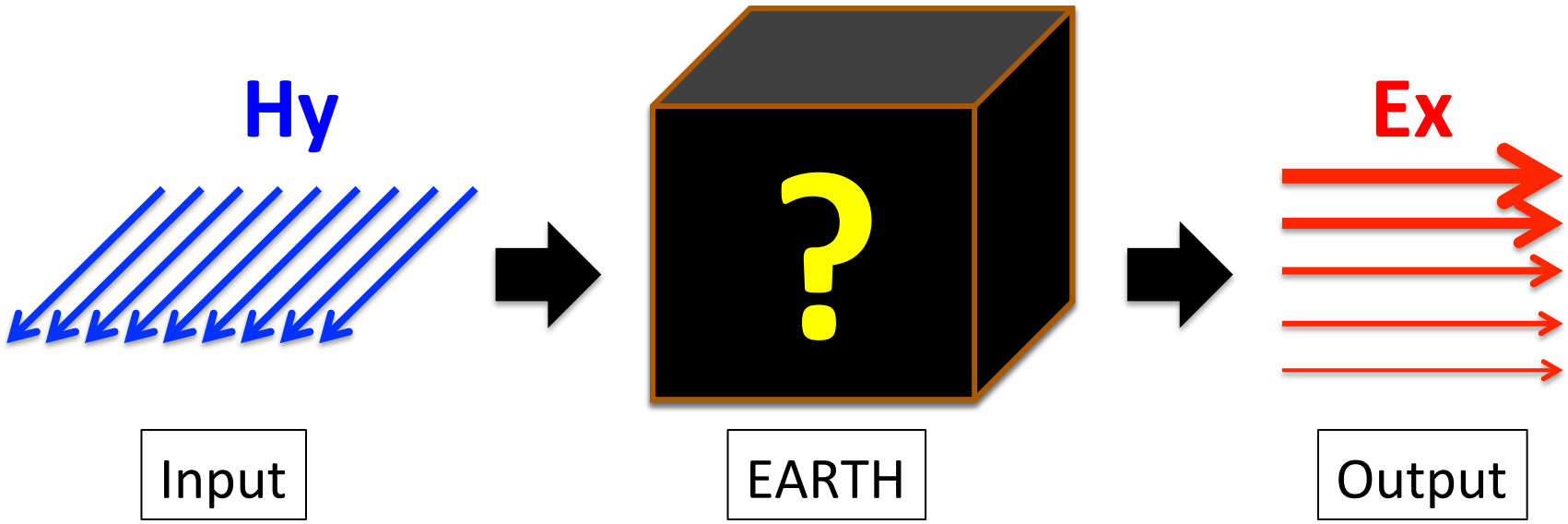
orthogonal electric field induced within the Earth by the time-varying magnetic field

Note that the amplitude of the electric field decreases with depth

The decay rate of the E field depends on Zxy, the impedance of the Earth

This is what we want to find!

How do we figure out Z?



If we know Hy and Ex we can determine the properties of the Earth.

Magnetotelluric Impedance

We need to solve Maxwell's equations for some relationship between a time-varying magnetic field and the corresponding induced electrical field…

But first we make two assumptions:

1. Plane wave source
   - The only source of telluric currents is very long wavelength
   - Earth is much more conductive than the atmosphere

2. Quasi static approximation
   - Displacements currents don't matter!

These assumptions make Maxwell's equations much easier to solve.

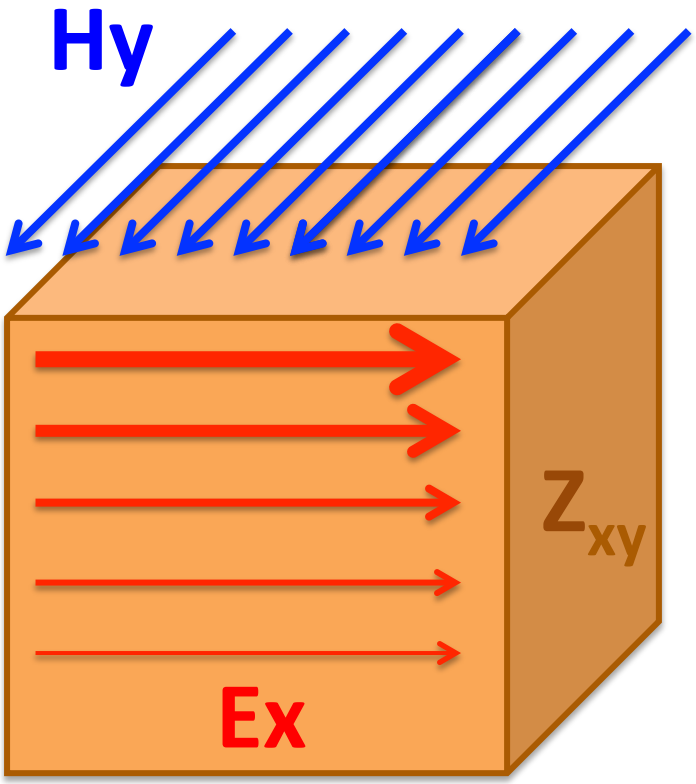
Magnetotelluric Impedance

Solve Maxwell's equations to find:

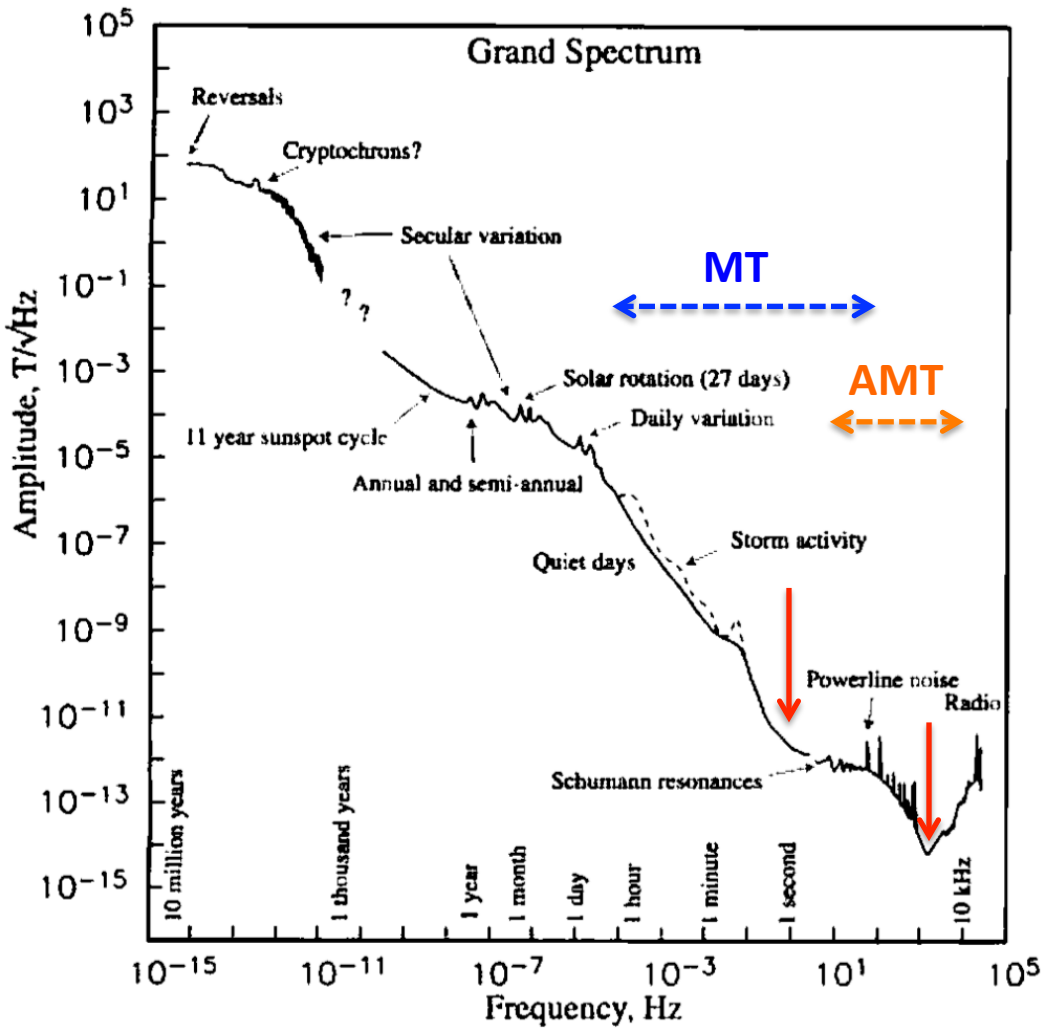
$$H_Y(\omega)Z(\omega) = E_X(\omega)$$

$$\boxed{Z_{XY}(\omega) = \frac{E_X(\omega)}{H_Y(\omega)}}$$

In a 3D earth, impedance is a 2x2 tensor with complex components

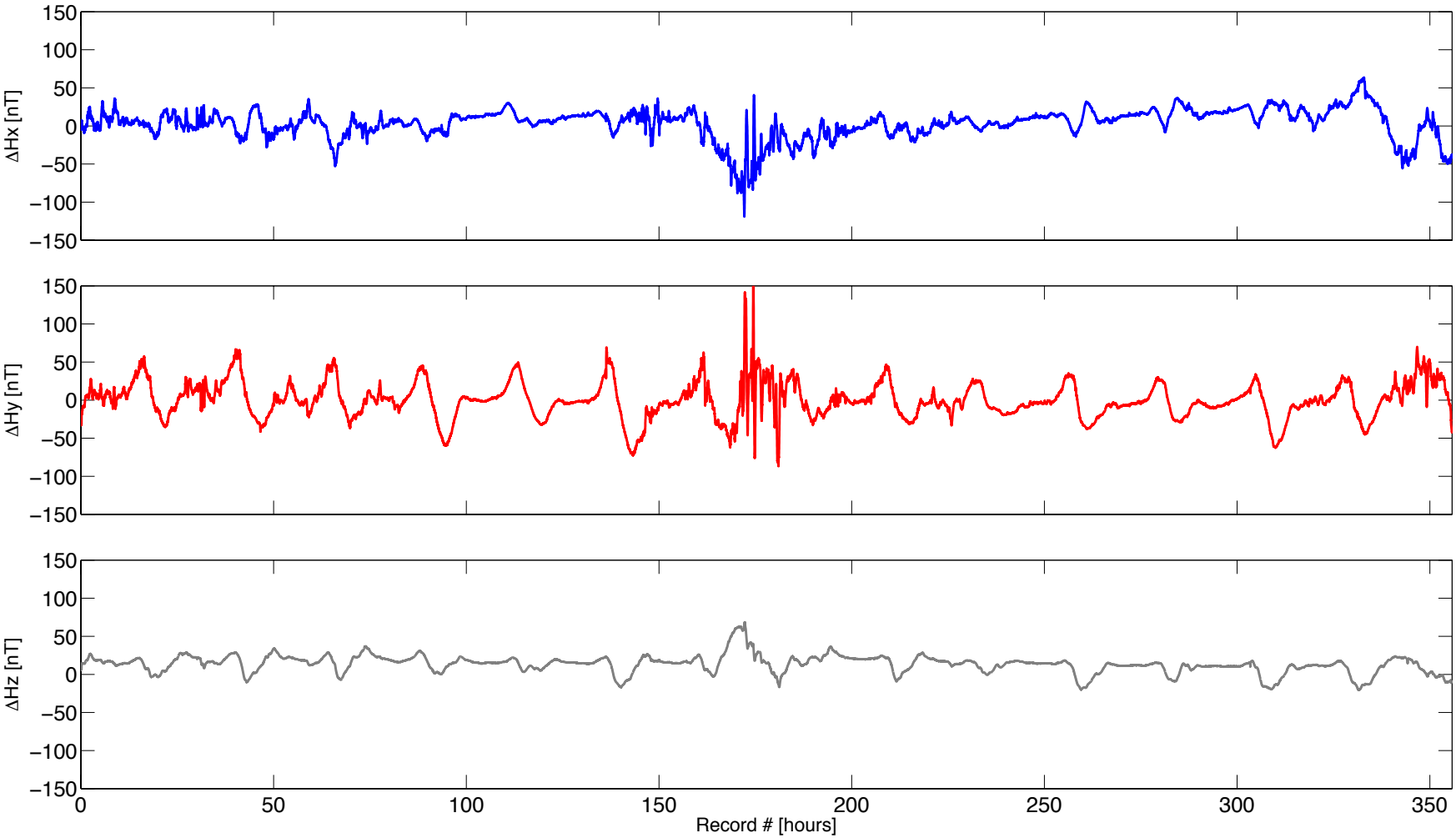


Magnetotelluric Source Fields



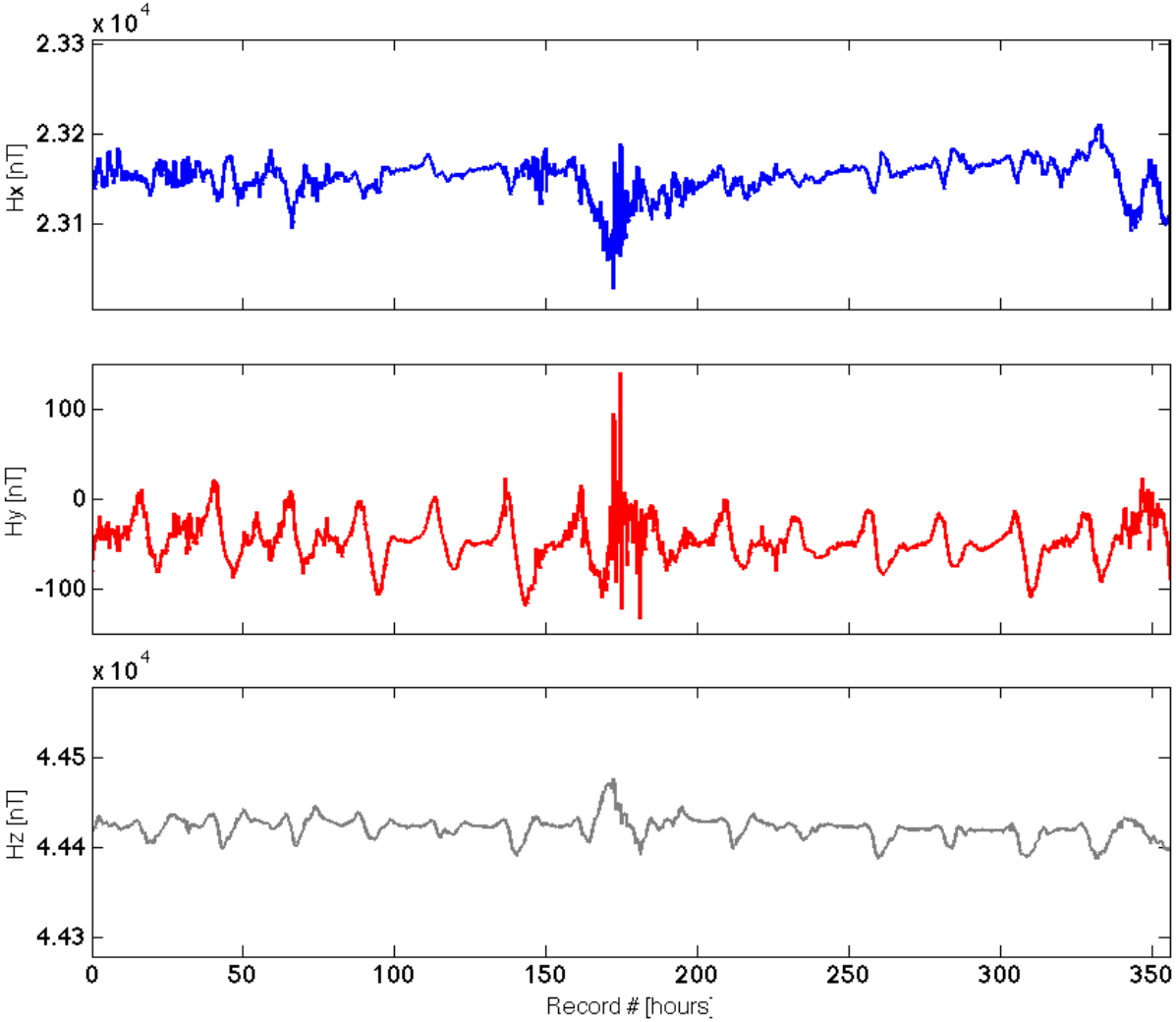
Constable and Constable, 2004

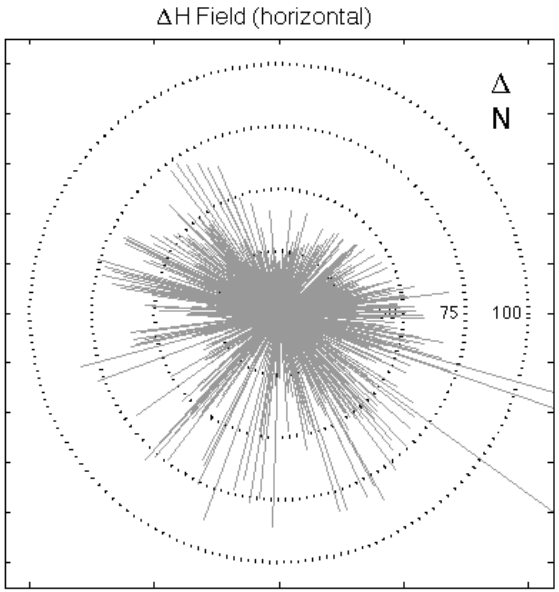
Magnetotelluric Source Fields

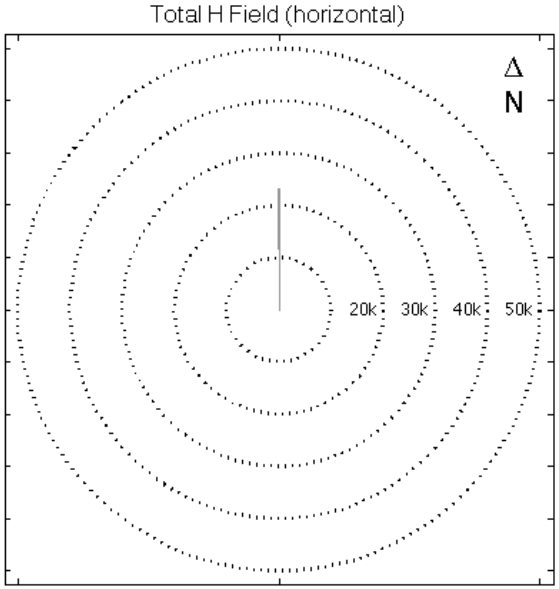


Two weeks of 4 Hz data

MT Source Field

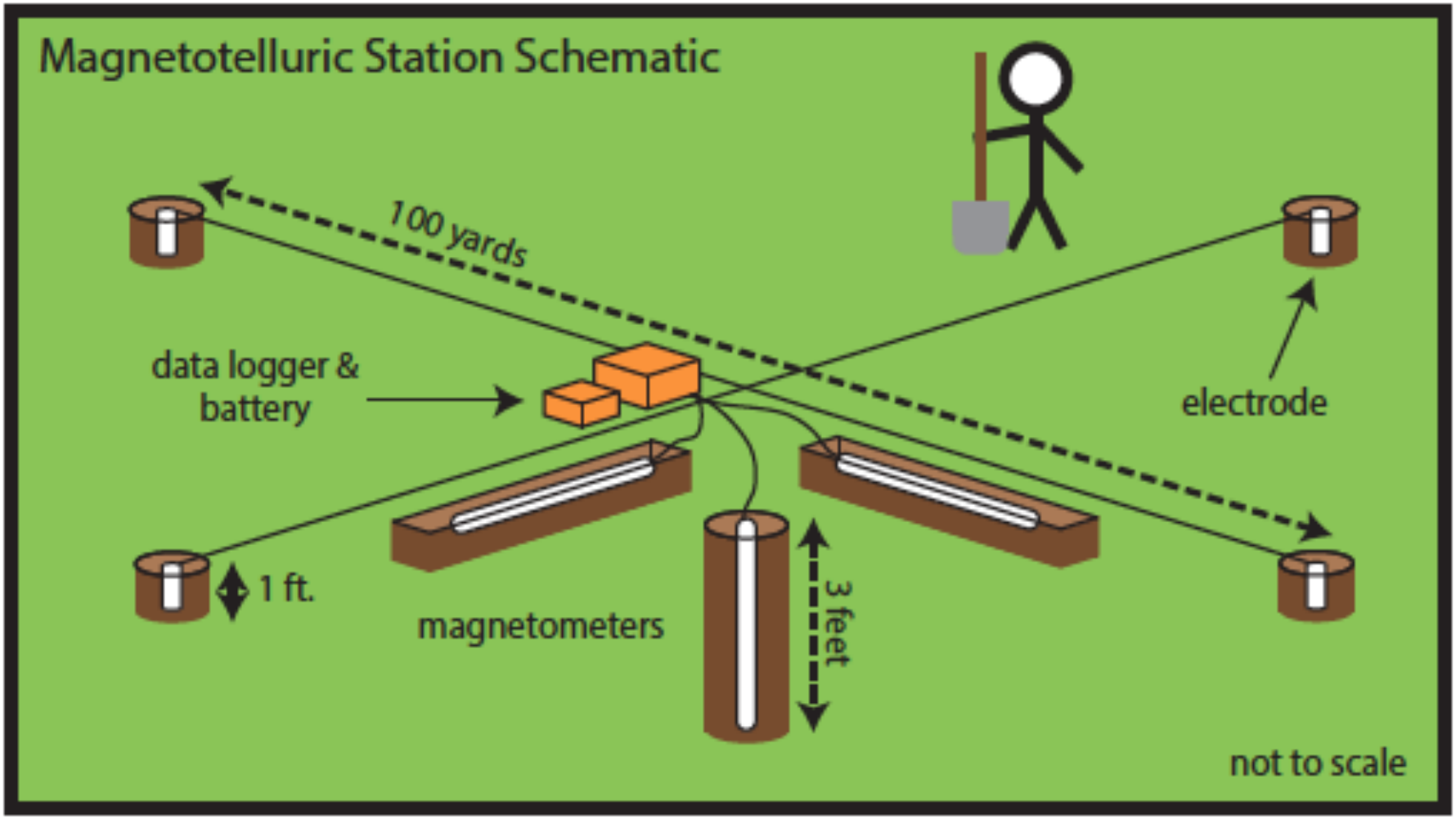




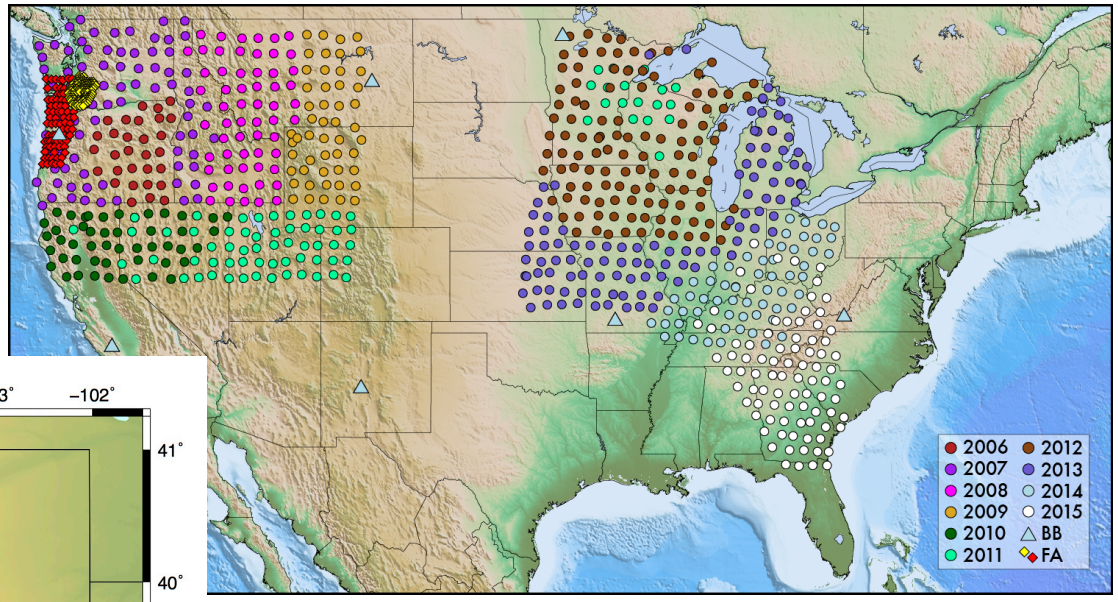


Collected in geomagnetic coordinates in northern New Mexico

Field Measurements

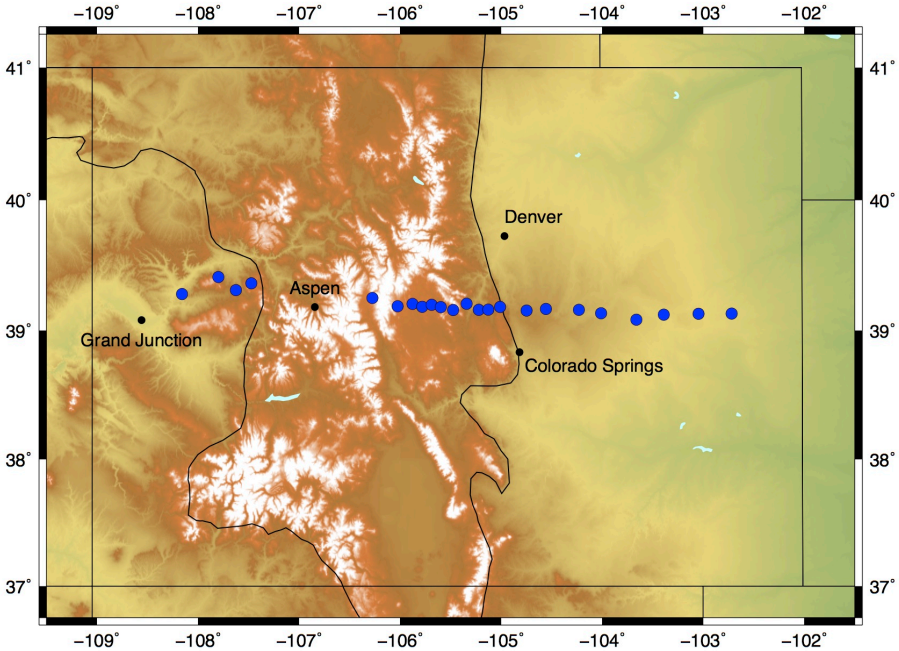


Field Measurements

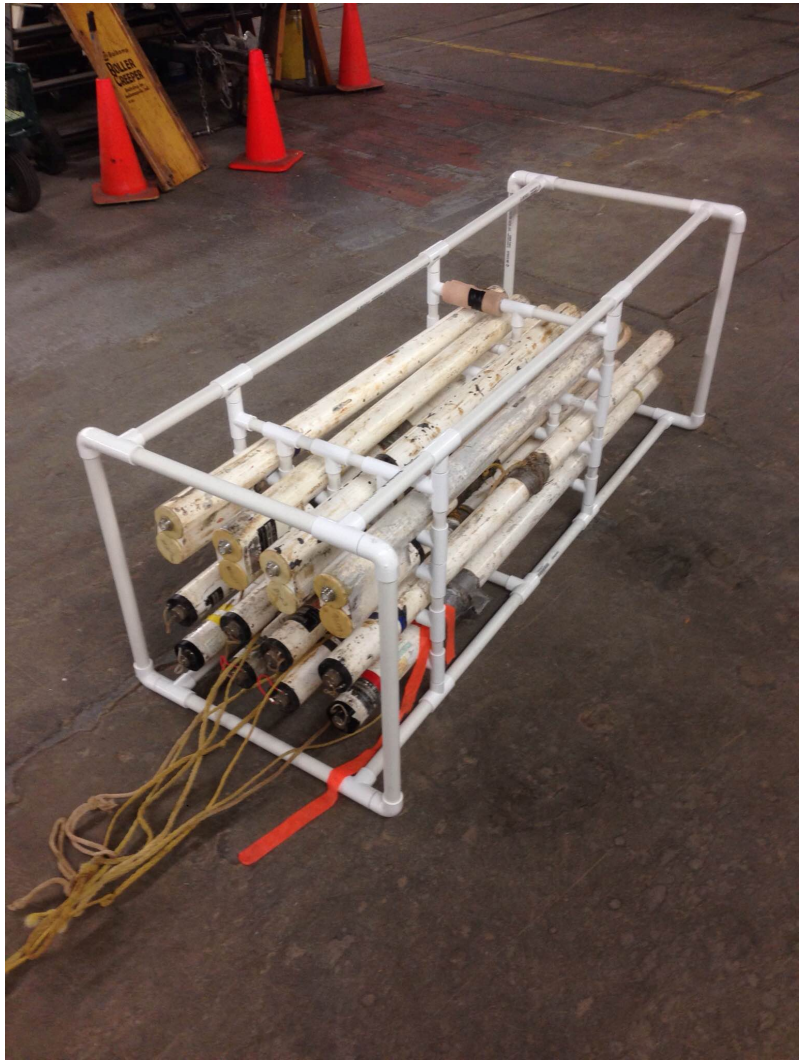


EarthScope MT Array

DRIFTER Profile

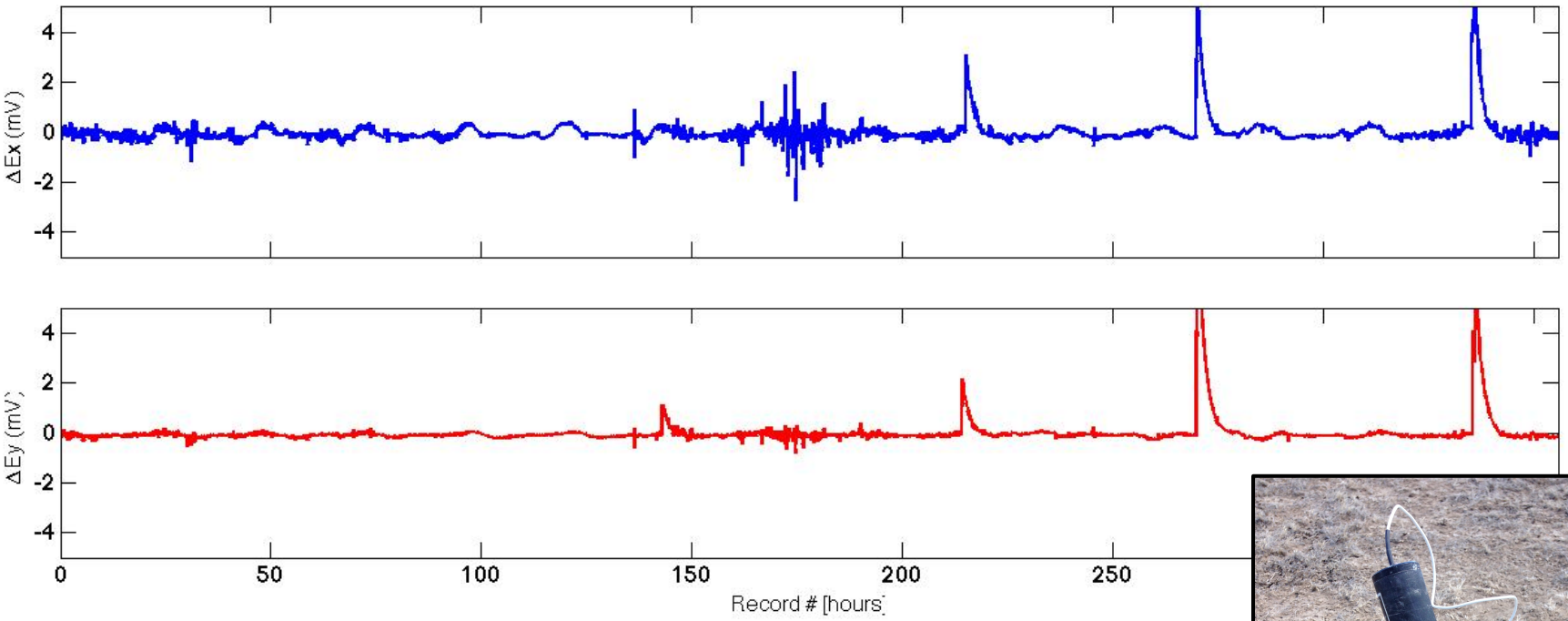


Field Measurements

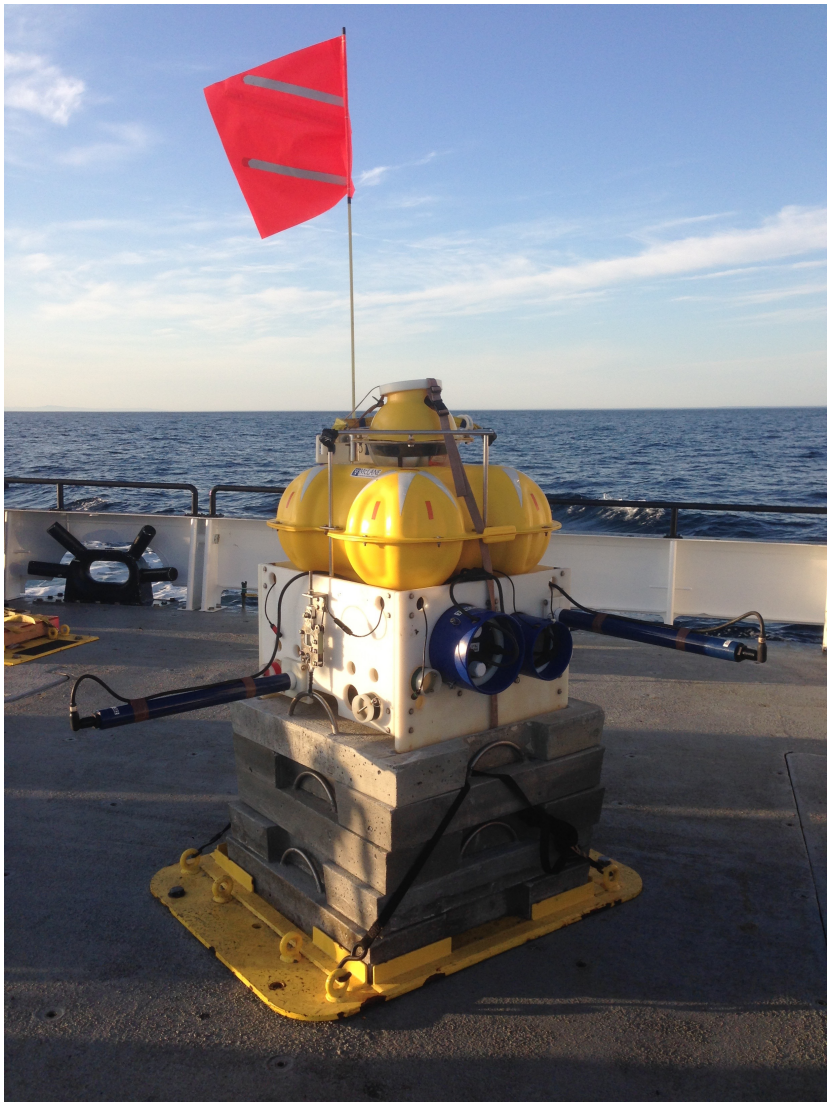


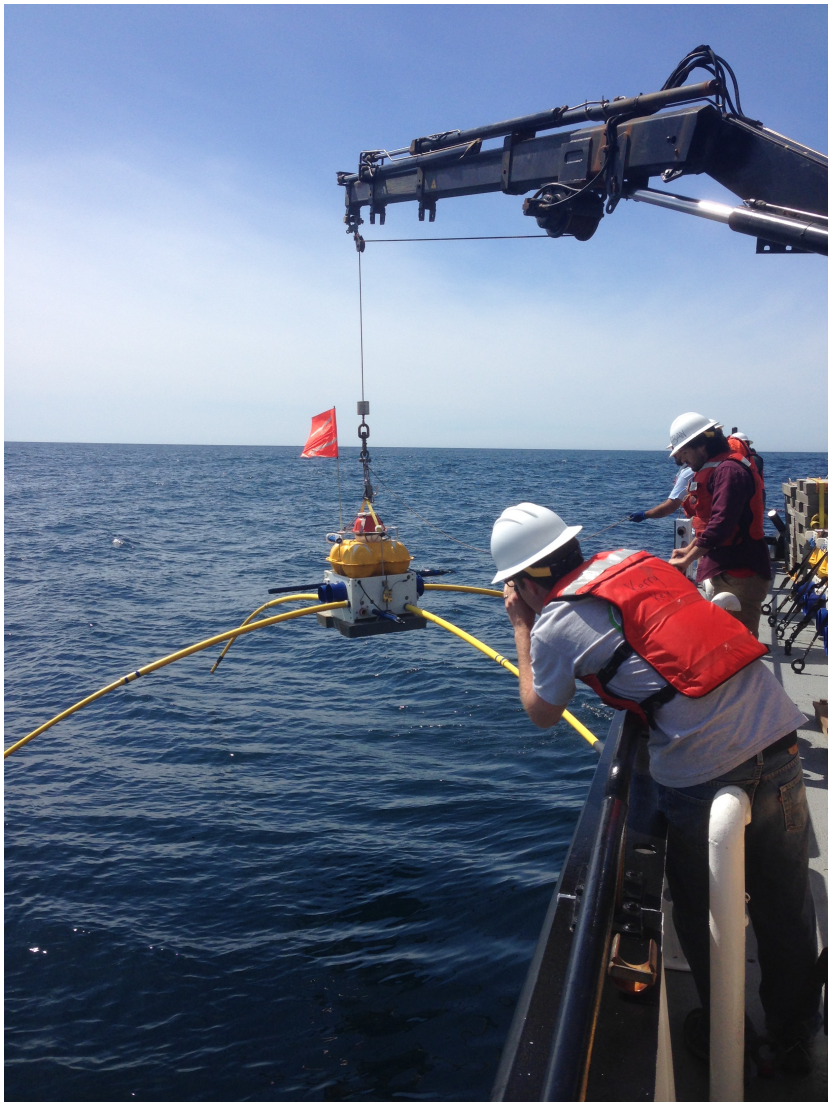
Field Measurements

Electric Field Measurement



Marine Magnetotellurics



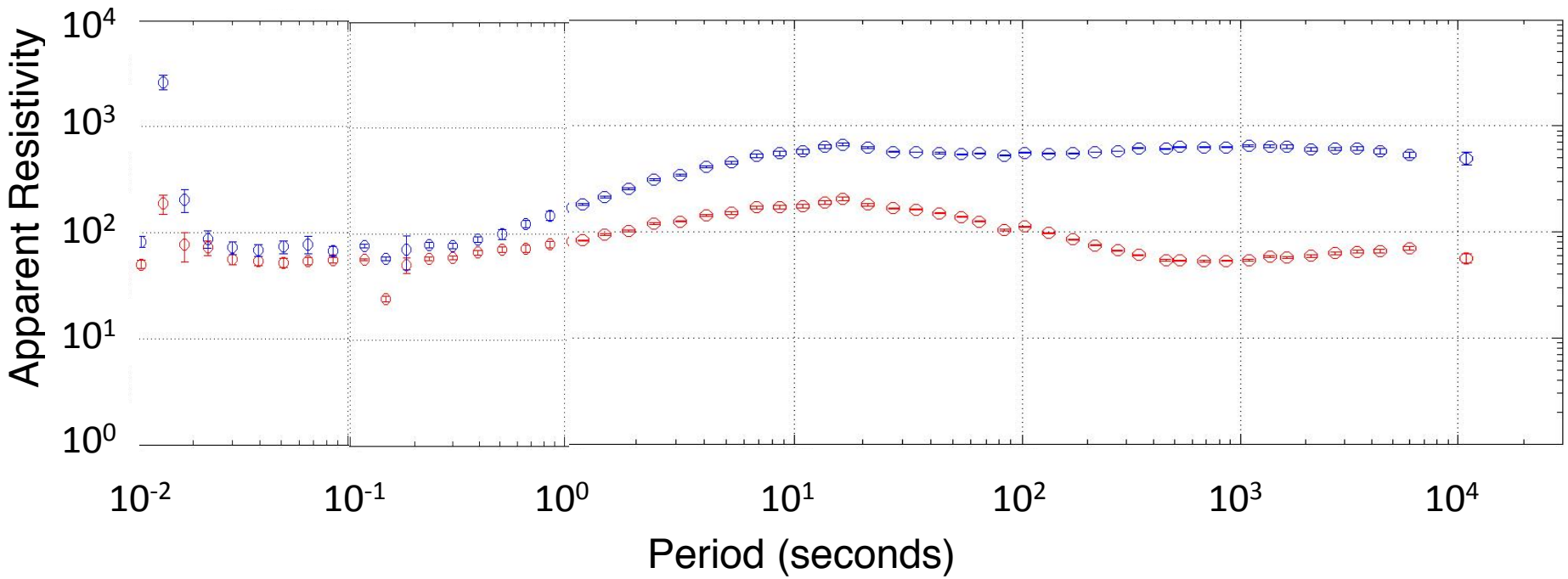


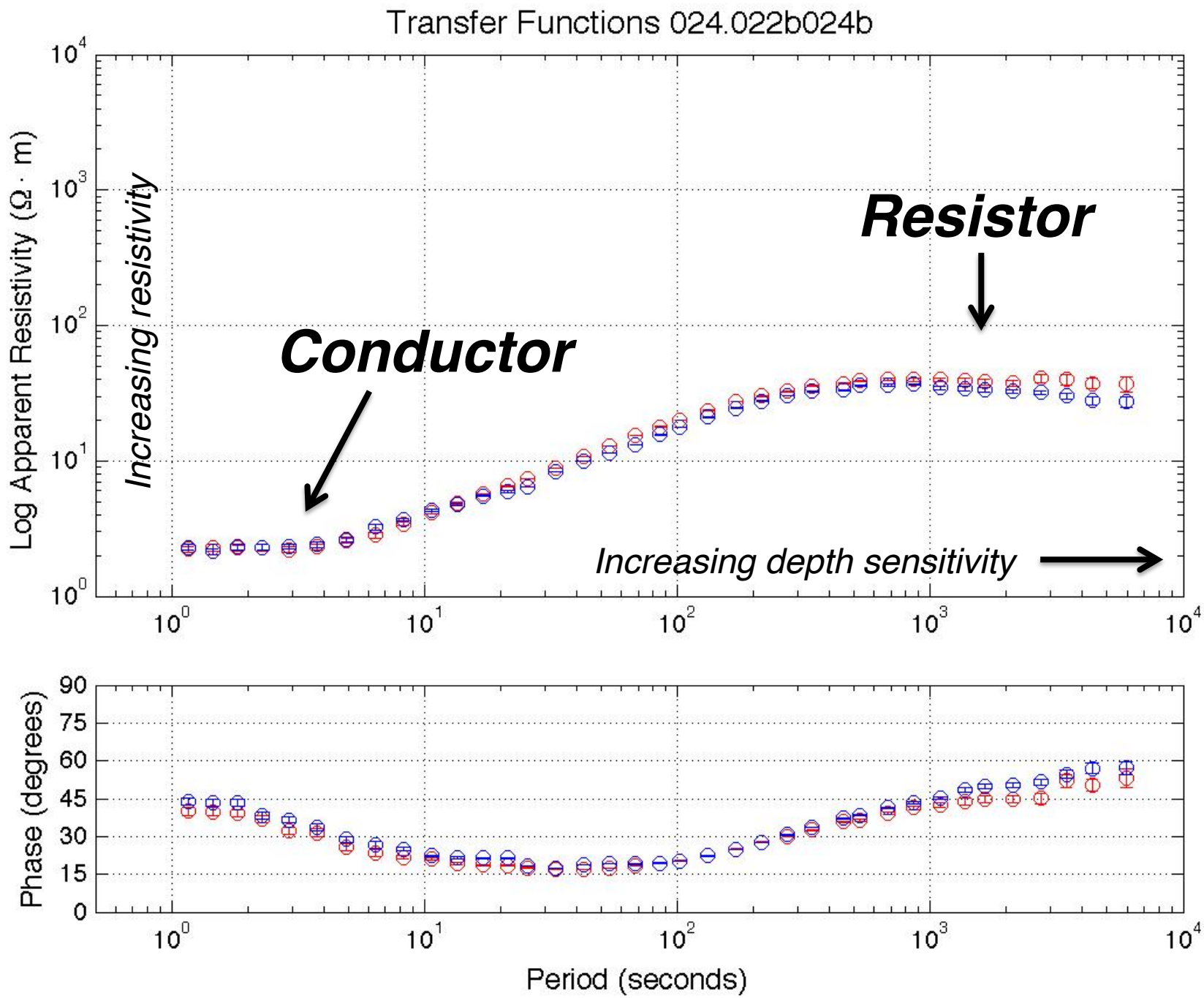
Apparent Resistivity

Impedance (Z) is a complex value and non-intuitive to interpret.

But if we calculate the magnitude of impedance we get apparent resistivity:

$$\rho_{XY} = \frac{\left|Z_{XY}\right|^2}{\mu_0 \omega}$$

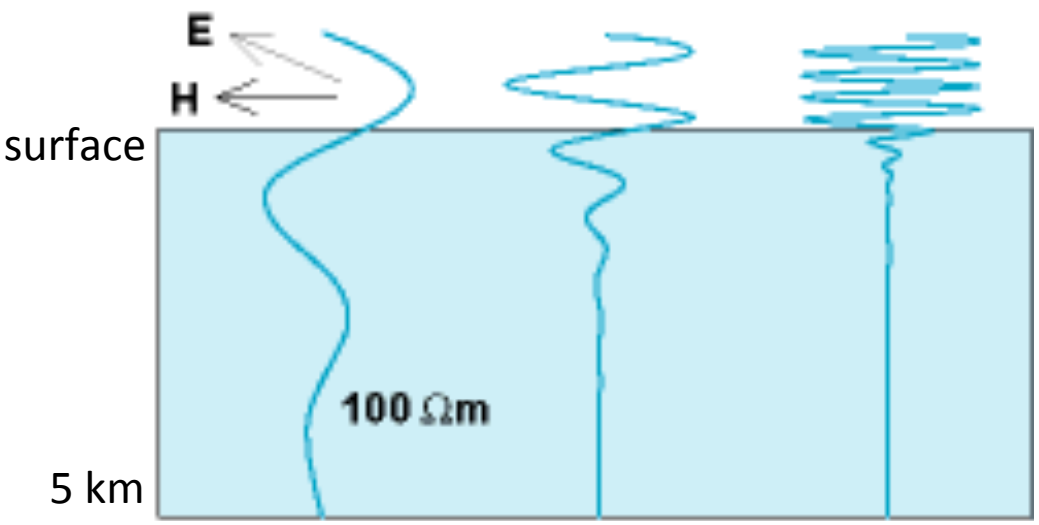



Transfer Functions 024.022b024b
Log Apparent Resistivity (Ω · m)
Increasing resistivity
Conductor
Resistor
Increasing depth sensitivity
Phase (degrees)
Period (seconds)

How deep are we looking?

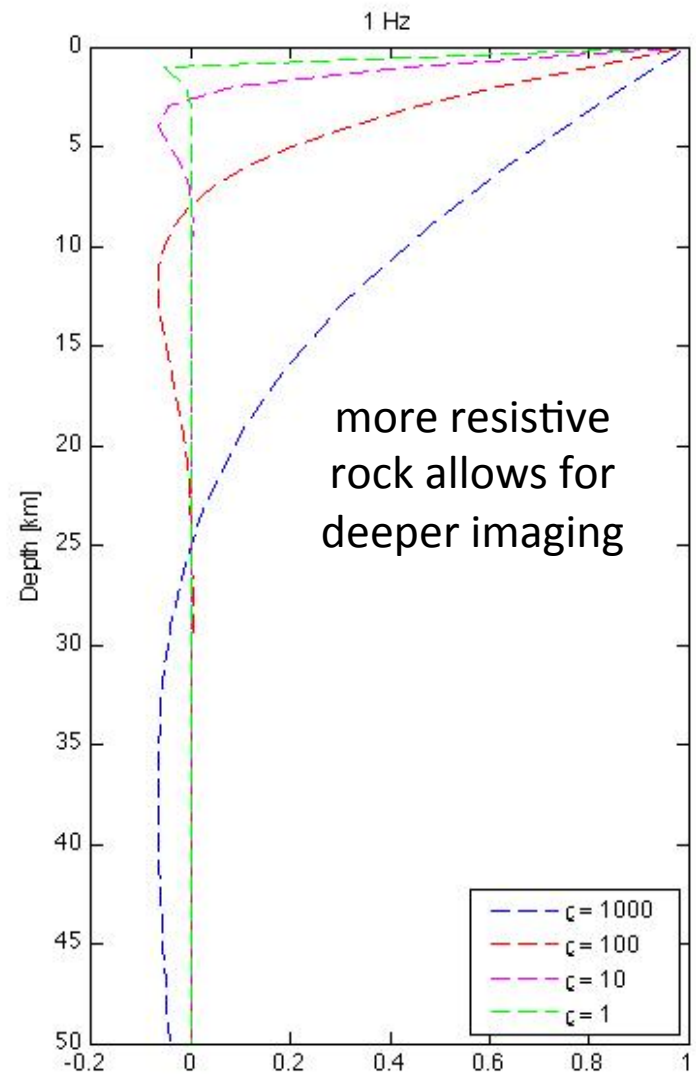
Inductive skin depth (in km):

$$\delta \approx 0.5\sqrt{\frac{\rho}{f}}$$



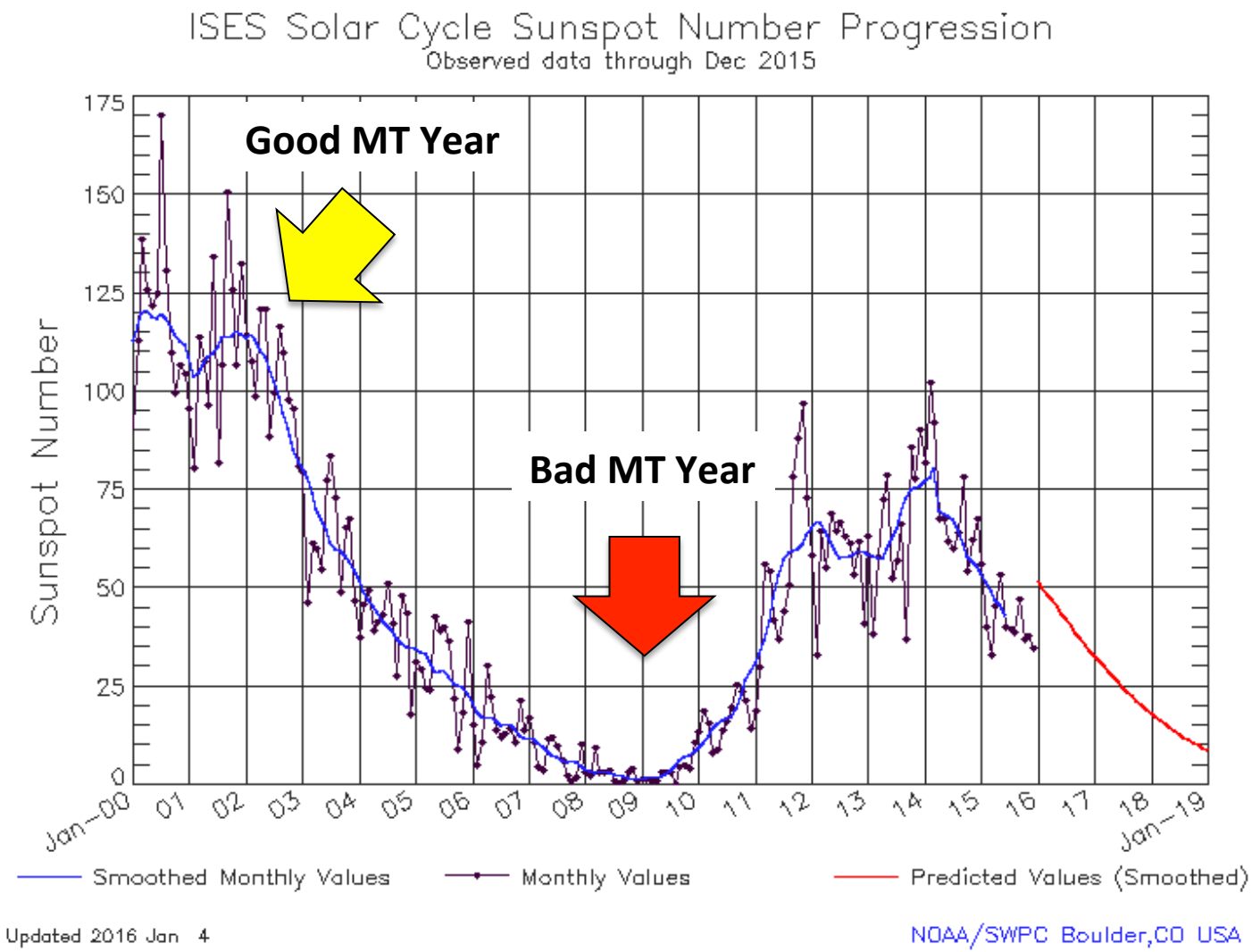
frequency:	0.01 Hz	0.25 Hz	25 Hz
skin depth:	5 km	1 km	0.1 km

longer period = deeper imaging

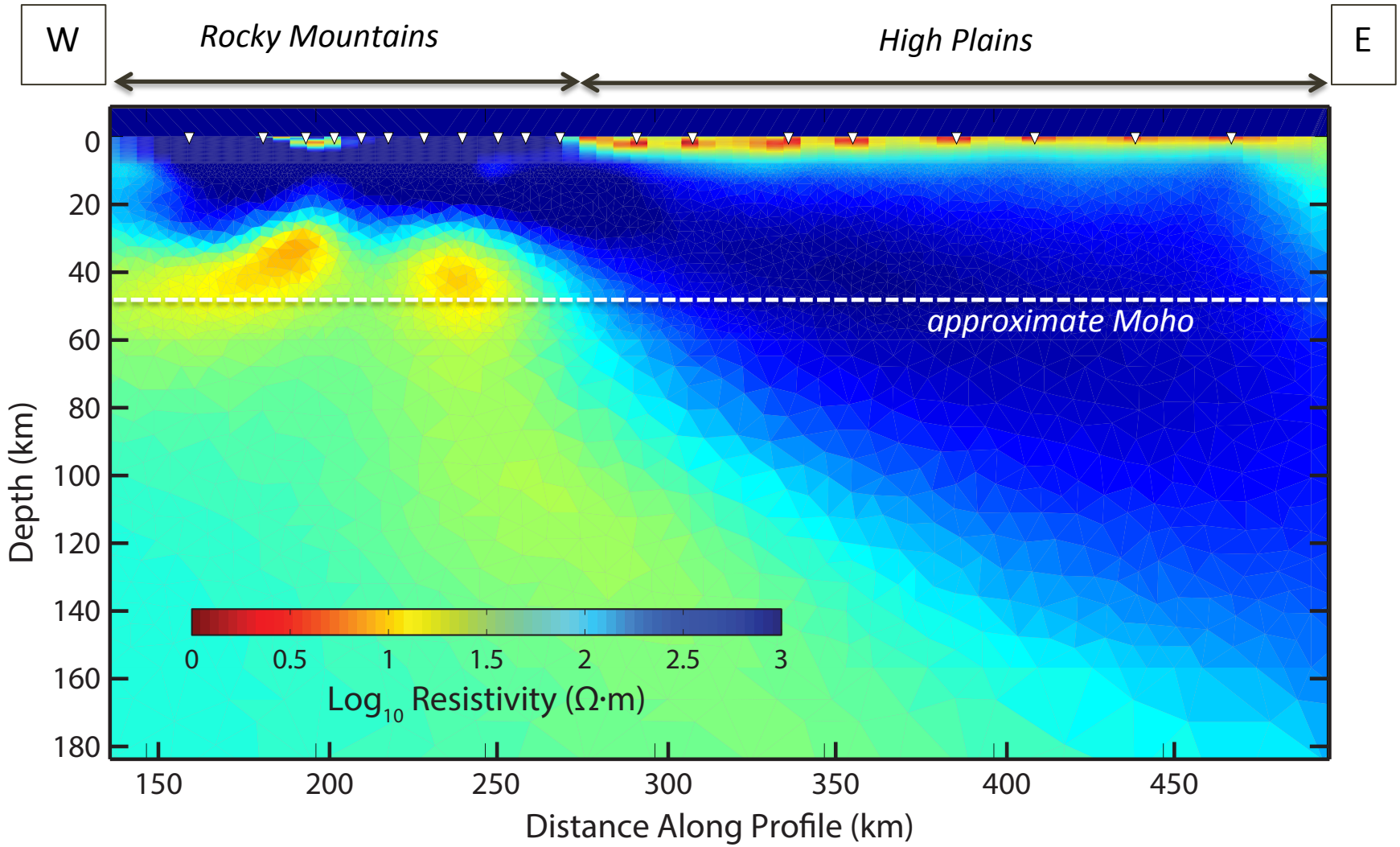


Electric Field Amplitude w/ Depth

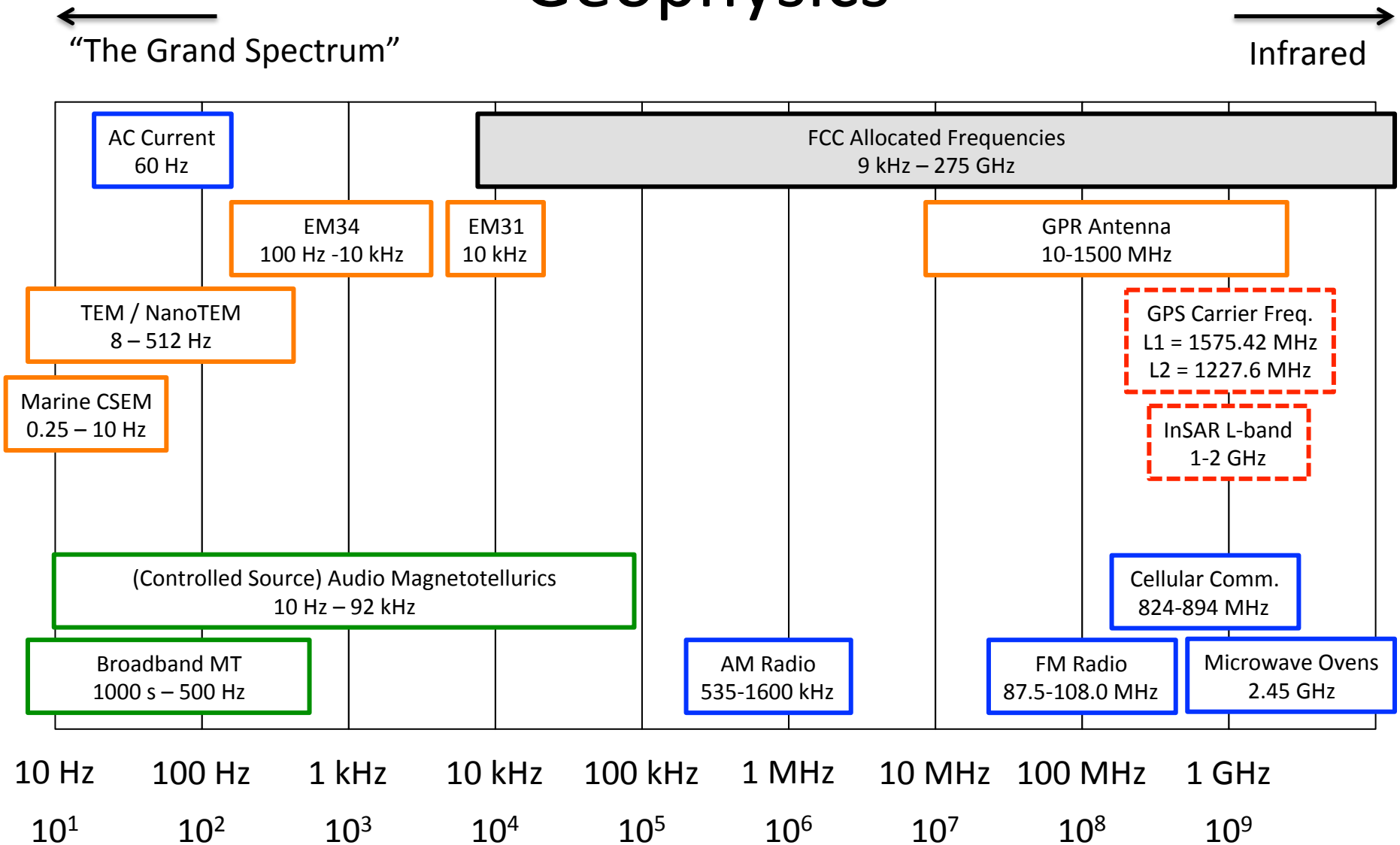
Signal Strength



Resistivity Models



Applications (just a few examples)

- **Resource exploration:** onshore and offshore hydrocarbon exploration, mining, geothermal heat sources
- **Tectonics:** terrane boundaries, water budget in subduction zones, temperature and composition of the lithosphere
- **Structural Geology:** imaging fault offset beneath sediments, estimating depth to brittle/ductile transition
- **Volcanic Hazard:** 4D study of magma chambers
- **Hydrology:** estimating the volume of a sedimentary basins and the depth to water table

Electromagnetic Spectrum of Geophysics