Response of a layered Earth to a plane wave, insight into the magnetotelluric method

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The magnetotelluric (MT) method is a widely used geophysical technique, in particular for imaging geothermal systems, that is sensitive to Earth structures as shallow as tens of meters to depths of hundreds of kilometers. The source energy is electromagnetic waves, generated in the atmosphere by lightning strikes and interactions with solar wind and Earth's magnetic field. These waves travel as plane waves through the atmosphere and ground. The animation is built to visually explore the physics of wave propagation and relate them to observed data. This enhances intuition and comprehension of the equations and highlights the dynamic nature of the wave propagation, unlike the static nature of data.

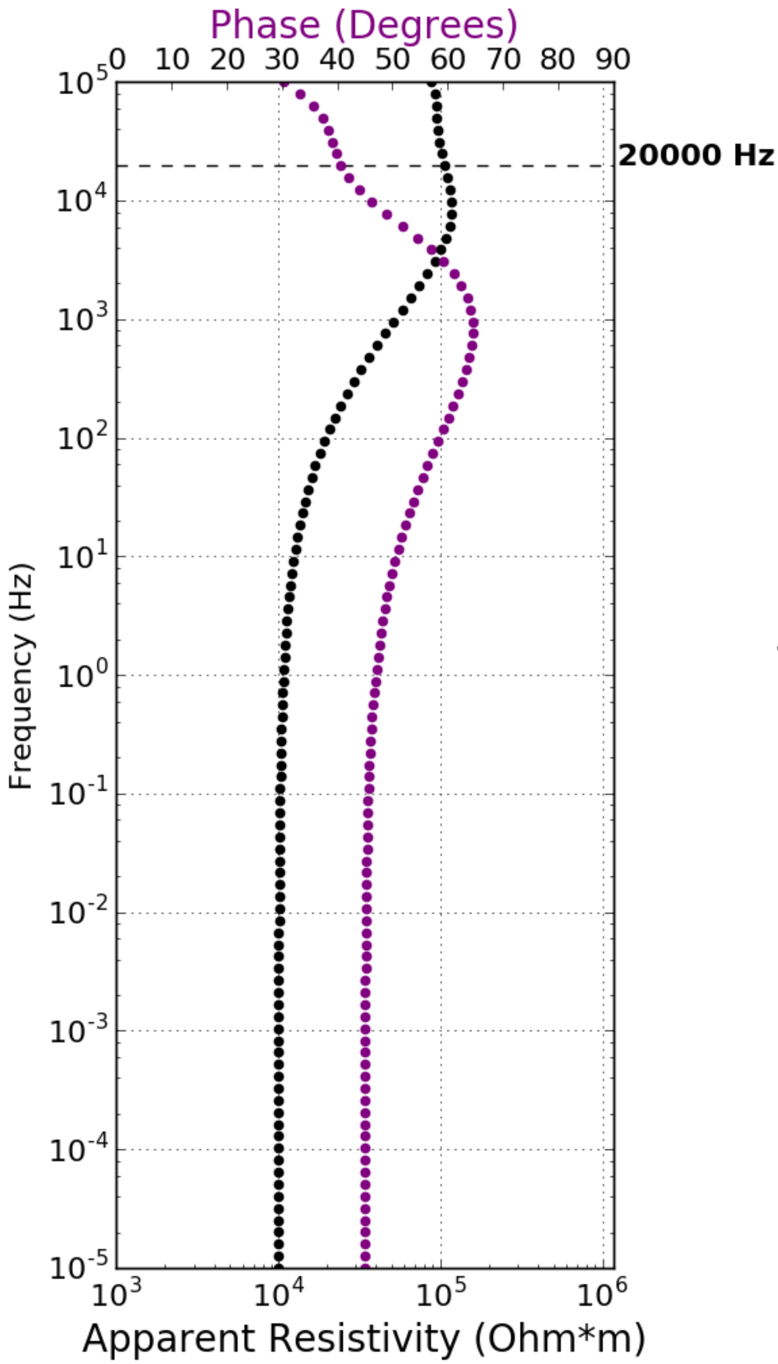
Electromagnetic waves are governed by Maxwell's equations and hence are sensitive to contrasts in physical properties that can be interpreted in terms of geologic structure and fluid content. The diagnostic physical property for MT is electrical conductivity σ (or its inverse resistivity ρ). The impact of contrasts in dielectric permittivity ε and magnetic permittivity μ is expected to be negligible.

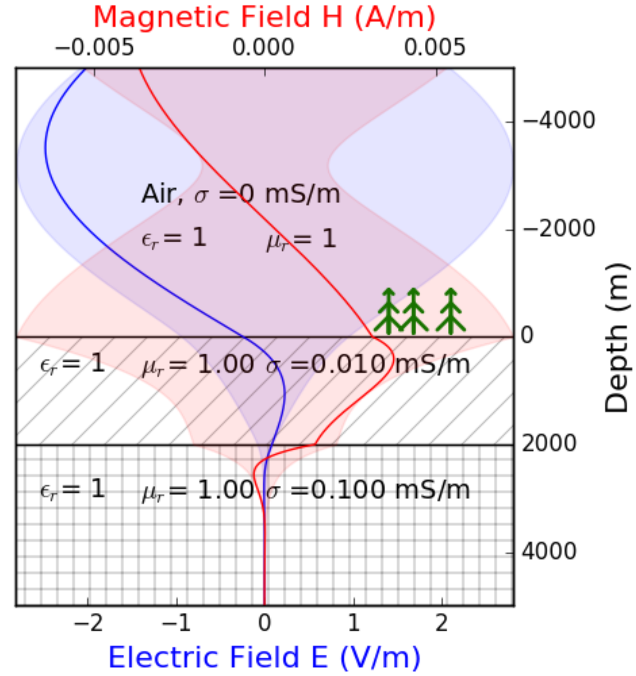
Any wave that hits the Earth gets refracted vertically because of the extreme contrast in conductivity, regardless of the angle of incidence. It is thus sufficient to model a vertically propagating plane wave. For our modelling we assume a 1D layered Earth.

The panels of the figure allow us to break down the physics into simpler pieces. The lower-right panel illustrates the reflection and transmission of the wave at interfaces. At the Earth's surface, most of the downward propagating wave is reflected while the transmitted part diffuses downward. The upper-right panel shows the total (sum of their up and down going) electric and magnetic fields. The depth of investigation is regulated by a damping effect on the transmitted wave’s amplitude due to the increase of conductivity.

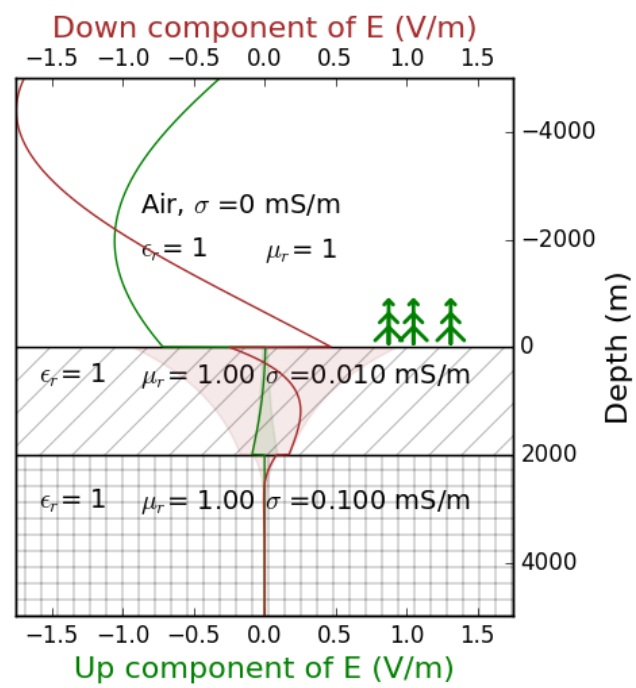
Data in an MT survey are electric and magnetic fields measurements, which are the sum the Earth's responses but also the unknown natural field sources. The unknown source is overcome by using the ratio of the electric and magnetic fields, called the impedance. Impedance is a complex number whose amplitude is used to estimate an apparent resistivity while its phase provides information about changes in resistivity. Impedances are measured at many frequencies, as the depth of investigation increases as the frequency decreases. This is illustrated in the left panel displaying MT data. The measured apparent resistivity is equal to the resistivity of the upper layer when sampling at high frequencies, there is little contribution from the second layer. At intermediate frequencies, we measure an averaged apparent resistivity as well as an increase in the phase. At low frequencies, the apparent resistivity is converging to the lower layer resistivity while the phase stabilizes to its normal value of 45 degrees.

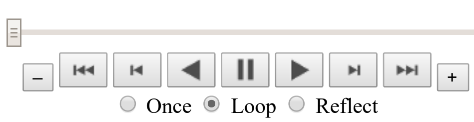
This animated plot has been realized for http://em.geosci.xyz, an educational initiative at the University of British Columbia aiming to provide interactive resources and case histories for electromagnetic geophysics to promote its use for solving exploration, geotechnical and environmental problems.


Phase (Degrees)
0 10 20 30 40 50 60 70 80 90
20000 Hz
Frequency (Hz)
10^5 10^4 10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5}
10^3 10^4 10^5 10^6
Apparent Resistivity (Ohm*m)


Magnetic Field H (A/m)
−0.005 0.000 0.005
Air, σ =0 mS/m
ϵ_r = 1 μ_r = 1
ϵ_r = 1 μ_r = 1.00 σ =0.010 mS/m
ϵ_r = 1 μ_r = 1.00 σ =0.100 mS/m
−4000 −2000 0 2000 4000
Depth (m)
−2 −1 0 1 2
Electric Field E (V/m)

time = **0** μs


Down component of E (V/m)
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5
Air, σ =0 mS/m
ϵ_r = 1 μ_r = 1
ϵ_r = 1 μ_r = 1.00 σ =0.010 mS/m
ϵ_r = 1 μ_r = 1.00 σ =0.100 mS/m
−4000 −2000 0 2000 4000
Depth (m)
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5
Up component of E (V/m)


Once
Loop
Reflect