Practical Magnetotellurics

The magnetotelluric (MT) method is a technique for probing the electrical conductivity structure of the Earth to depths of up to 600 km. Although less well known than seismology, MT is increasingly used both in applied geophysics and in basic research. This is the first book on the subject to go into detail on practical aspects of applying the MT technique.

Beginning with the basic principles of electromagnetic induction in the Earth, this introduction to magnetotellurics aims to guide students and researchers in geophysics and other areas of Earth science through the practical aspects of the MT method: from planning a field campaign, through data processing and modelling, to tectonic and geodynamic interpretation. The book contains an extensive, up-to-date reference list, which will be of use to both newcomers to MT and more experienced practitioners of the method. MT is presented as a young and vibrant area of geophysical research with an exciting potential that is yet to be fully realised.

The book will be of use to graduate-level students and researchers who are embarking on a research project involving MT, to lecturers preparing courses on MT and to geoscientists involved in multidisciplinary research projects who wish to incorporate MT results into their interpretations.

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There are two possible outcomes: If the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery.

Enrico Fermi

Contents

Preface

This book was written for students and researchers in geophysics, geology, and other Earth sciences, who wish to apply or understand the magnetotelluric (MT) method. It is intended to be an introduction to the subject, rather than an exhaustive treatise. At the same time, we do not shirk raising controversial issues, or questions for which there are no easy answers, as we do not wish to give the impression that all of the interesting problems have been solved. MT is very much a dynamic, evolving science.

We acknowledge a bias towards long-period MT studies of the deep crust and mantle. Just as one cannot drink the water from the bottom of a glass until one has drunk the water from the top (unless one has a drinking straw), electromagnetic waves cannot penetrate the deep crust or mantle without being influenced by overlying crustal structures. Hence, longer-period electromagnetic waves, which penetrate deeper into the Earth than shorter-period waves, will necessarily image a higher level of complexity than shorter-period waves. The student who has understood long-period MT sounding should, therefore, have no problem applying their knowledge to audiomagnetotellurics (AMT) and shallow crustal studies.

We have organised the chapters according to the sequence of steps most likely to be encountered by a student embarking on an MT project: from theory to field campaign, to data processing and modelling, through to tectonic and geodynamic interpretation. Some mathematical tools and derivatives are included in the Appendices.

All subjects of a scientific or technical nature have a tendency to spawn jargon, and MT is no exception. Words or phrases that may be deemed jargon are highlighted in italics, and are explained in a Glossary.

No man (or woman) is an island. We extend special thanks to Rainer Hennings who helped with illustrations.

Symbols

Symbols for which no units are given refer to dimensionless parameters. Note that this list does not include symbols used in the Appendices. We have endeavoured to use the symbols most commonly assigned to common parameters. Occasionally, this results in a symbol having more than one meaning. Where ambiguity occurs, the chapter in which a symbol has a different meaning than the meaning that occurs more frequently in the book is noted in parentheses.

$\underline{\underline{A}}$	local anisotropy operator
A, B, C, E	impedance commutators $[\mathrm{V}^2\,\mathrm{A}^{-2}]$
$\mathbf{B}$	magnetic field, magnetic induction $[\text{Tesla (T)} = \mathrm{V\,s\,m^{-2}}]$
B_x, B_y, B_z	components of $\mathbf{B}$ in Cartesian co-ordinates [T]
B_r, B_ϑ, B_λ	components of $\mathbf{B}$ in spherical co-ordinates [T]
C	Schmucker–Weidelt transfer function [km]
$\underline{\underline{C}}$	local scatterer distortion tensor (Chapter 5)
$c_{11}, c_{12}, c_{21}, c_{22}$	elements of $\underline{\underline{C}}$
d	distance [km]
$\mathbf{D}$	electric displacement $[\mathrm{C\,m^{-2}} = \mathrm{A\,s\,m^{-2}}]$
D_1, D_2, S_1, S_2	modified impedances $[\mathrm{V\,A^{-1}}]$
dt	sampling interval [s]
$\mathbf{E}$	electric field $[\mathrm{Vm^{-1}}]$
E_x, E_y	components of $\mathbf{E}$ in Cartesian components $[\mathrm{Vm^{-1}}]$
$\tilde{E}$	electric east–west component in the frequency domain $[\mathrm{Vm^{-1}}]$
f	frequency [Hz]
g	scalar galvanic factor (Chapter 5)
g^{i}, g^{e}	spherical harmonic expansion coefficients (internal and external parts) [T]
g_{ik}	spectral window weight (Chapter 4)
h	surface-layer thickness [km]

$\mathbf{H}$	magnetic intensity $[\mathrm{A\,m^{-1}}]$
I	current [A]
$\underline{j}$	current density $[\mathrm{A\,m^{-2}}]$
$\boldsymbol{k}$	wavenumber $[\mathrm{m^{-1}}]$
K	capacitance $[\mathrm{F = A\,s\,V^{-1}}]$
l	layer thickness [km]
M_{R}	model roughness
$\tilde{N}$	electric north–south component in the frequency domain $[\mathrm{V\,m^{-1}}]$
p	skin depth, penetration depth [km]
$P_n^m(\vartheta)$	associated Legendre polynomials
q	inverse homogenous half-space model transfer function $[\mathrm{km^{-1}}]$
$\underline{\underline{Q}}$	magnetic field distortion tensor $[\mathrm{A\,V^{-1}}]$
R	resistance $[\Omega = \mathrm{V\,A^{-1}}]$
r, ϑ, λ	spherical co-ordinates
S	sensitivity $[\mathrm{mVnT^{-1}}]$
S_1, S_2, D_1, D_2	modified impedances $[\mathrm{V\,A^{-1}}]$
$\underline{\underline{S}}$	local shear operator (Chapter 5)
t	time [s]
T	period [s]
$\underline{\underline{T}}$	local twist operator (Chapter 5)
T_x, T_y	induction arrow components
U	scalar potential of $\mathbf{B}$ (Chapter 1) $[\mathrm{Vs\,m^{-1}}]$
$\mathbf{U}$	general field vector (Chapter 6)
U	voltage (Chapters 3 and 8) [V]
$\mathbf{v}$	velocity $[\mathrm{m\,s^{-1}}]$
$w(f)$	frequency-dependent convolution function describing sensor sensitivity (Chapter 4)
w_i	weight of the ith frequency in a robust processing scheme
$\underline{\underline{W}}$	perturbation matrix (Chapter 10)
x, y, z	Cartesian co-ordinates (z positive downwards)
$\tilde{X}, \tilde{Y}, \tilde{Z}$	magnetic north, east and vertical components in the frequency domain $[\mathrm{A\,m^{-1}}]$
z	depth [km]
$\mathbf{Z}$	impedance $[\mathrm{V\,A^{-1}}]$
Z_n	impedance of the nth layer of a layered-Earth model $[\mathrm{V\,A^{-1}}]$
$\underline{\underline{Z}}$	impedance tensor $[\mathrm{V\,A^{-1}}]$
$Z_{xx}, Z_{xy}, Z_{yx}, Z_{yy}$	elements of $\underline{\underline{Z}}$ $[\mathrm{V\,A^{-1}}]$
$Z^{\mathrm{V}}, Z^{\mathrm{D}}$	upwards, downwards biased estimate of the impedance $[\mathrm{V\,A^{-1}}]$

α	rotation angle [°]
α	smoothing constant in the non-dimensional weight function (Equation 7.7) used to parameterise model roughness in 2-D *RRI inversion* (Chapter 7)
β	probability
$\underline{\underline{\beta}}_{\alpha}$	rotation matrix
χ^2	Groom–Bailey misfit measure of the 2-D model with local scatterer
γ	electrical connectivity
δ	phase difference between the elements in one column of $\underline{\underline{Z}}$[°]
δE	electric noise (Chapter 4) $[\mathrm{V\,m^{-1}}]$
$\delta\phi$	phase difference between the principal polarisations of $\underline{\underline{Z}}$[°] (Chapter 5)
$\varepsilon, \varepsilon_0$	electrical permittivity, electrical permittivity of free space $[\mathrm{A\,s\,V^{-1}\,m^{-1} = F\,m^{-1}}]$
ε^2	model misfit measure
ε^2	residuum (Chapters 3, 4)
η_{f}	electric charge density (Chapter 2) $[\mathrm{C\,m^{-3} = A\,s\,m^{-3}}]$
η	misfit measure for the 2-D model with local scatterer (phase-sensitive skew)
η	constant in the non-dimensional weight function (Equation 7.7) used to parameterise model roughness in 2-D *RRI inversion* (Chapter 7)
η	porosity (Chapter 8)
ϑ, λ, r	spherical co-ordinates
κ	2-D model misfit measure (Swift skew)
λ	wavelength [m]
μ, μ_0	magnetic permeability, magnetic permeability of free space $[\mathrm{Vs\,A^{-1}\,m^{-1} = H\,m^{-1}}]$
μ	misfit measure of the layered-Earth model with local scatterer (Chapter 5)
ν	number of degrees of freedom
ρ	resistivity $[\Omega\,\mathrm{m = V\,mA^{-1}}]$
ρ_{a}	apparent resistivity $[\Omega\,\mathrm{m = V\,m\,A^{-1}}]$
σ	conductivity $[\mathrm{Sm^{-1} = A\,V^{-1}\,m^{-1}}]$
σ	variance (Chapters 4 and 5)
Σ	layered-Earth misfit measure
τ	conductance $[\mathrm{S = A\,V^{-1}}]$

τ	relaxation time (Chapter 8, Section 8.1)
ϕ	magnetotelluric phase [°]
ϕ	volume fraction of the conductive phase in two-phase media (Chapter 8)
ω	angular frequency $[\mathrm{s}^{-1}]$
ψ	coherence