INTRODUCTION TO CONTROLLED-SOURCE ELECTROMAGNETIC METHODS

This volume describes how controlled-source electromagnetic methods are used to determine the electrical conductivity and hydrocarbon content of the upper few kilometres of the earth, on land and at sea. The authors show how the signal-to-noise ratio of the measured data may be maximised via suitable choice of acquisition and processing parameters and selection of subsequent data analysis procedures. Complete impulse responses for every electric and magnetic source and receiver configuration are derived, providing a guide to the expected response for real data. One-, two- and three-dimensional modelling and inversion procedures for recovery of earth conductivity are presented, emphasising the importance of updating model parameters using complementary geophysical data and rock physics relations. Requiring no specialist prior knowledge of electromagnetic theory, and providing a step-by-step guide through the necessary mathematics, this book provides an accessible introduction for advanced students, researchers and industry practitioners in exploration geoscience and petroleum engineering.

ANTON ZIOLKOWSKI is Professor of Petroleum Geoscience at the University of Edinburgh. He co-invented the multichannel transient electromagnetic (MTEM) surveying method for hydrocarbon reservoir detection and co-led the technology spin-out. He is a member of the Institute of Electrical and Electronics Engineers and the American Geophysical Union, an honorary member of the Society of Exploration Geophysicists, a Fellow of the Royal Academy of Engineering and a fellow of the Royal Society of Edinburgh. He has received the Conrad Schlumberger and Desiderius Erasmus awards of the European Association of Geoscientists and Engineers.

EVERT SLOB is Professor of Geophysical Electromagnetic Methods at the Delft University of Technology, where he teaches undergraduate and graduate classes. He was Editor-in-Chief of the journal *Geophysics* and on the board of directors of the Society of Exploration Geophysicists from 2013 to 2015, of which he remains a member. He is also a member of the European Association of Geoscientists and Engineers and the American Geophysical Union.

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Detecting Subsurface Fluids

ANTON ZIOLKOWSKI
The University of Edinburgh

EVERT SLOB
Delft University of Technology

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Preface

The aim of this book is to make the benefits of controlled-source electromagnetic (CSEM) methods more widely appreciated by geoscientists and engineers, and to provide an approach that has sound theoretical foundations and a clear description of the practical aspects of CSEM data acquisition, processing and interpretation.

CSEM methods are used to explore for contrasts in subsurface electrical conductivity and are especially useful to search for subsurface fluids, including resistive hydrocarbons and conductive saline water. For example, CSEM methods have the potential to detect hydrocarbons before drilling. Since three out of four exploration wells contain no hydrocarbons, it may pay to carry out CSEM exploration before drilling to increase the likelihood of finding oil or gas. Saline water at depths of 2–4 km is usually hot enough to provide heat for buildings. In many countries, heating consumes more energy than transport and electricity generation combined. CSEM has the potential to find the geothermal resources that can reduce our dependence on fossil fuels.

Theoretical work on the concept of CSEM methods and the use of loops and antennas for exploration dates back to the 1950s. Onshore techniques were developed commercially and by the academic community. Offshore techniques were developed initially by academics. By 1991, Misac N. Nabighian was able to bring all this work together in the two-volume book *Electromagnetic Methods in Applied Geophysics*, published by the Society of Exploration Geophysics. In the first decade of the twenty-first century, CSEM became a tool for de-risking exploration drilling for deep-water prospects. Compared with seismic exploration, however, CSEM is still in its infancy and is still expensive per data point. There is clearly room for development.

It is now well understood in seismic exploration that broad bandwidth data are essential for good imaging of subsurface structures, whether the data are processed in the time domain or the frequency domain. A key concept is the idea of an impulsive source and the resulting impulse response of the earth. This concept is equally applicable to CSEM and is at the heart of our description of the method. For the source time function, CSEM has a big advantage over seismic exploration methods: it is very easy to reverse the polarity of current flow and create source time functions that have desirable properties. Furthermore, the source time function is easily measured and recovery of the resulting impulse responses from the measured data by deconvolution is straightforward. The impulse responses may be processed in the time domain or the frequency domain to determine subsurface resistivities.

There are some similarities with seismic exploration, but there are major differences. The most important difference is, of course, the physics. Seismic data obey the wave equation; electromagnetic (EM) data in conducting media such as fluid-filled rocks obey the diffusion equation. Seismologists often use ray theory to describe what happens to the waves – how they reflect, refract and diffract. Unfortunately, ray theory does not apply to diffusive data. Seismologists are accustomed to lining up seismic arrivals that have the same shape and estimating seismic velocities as a result – the velocities are determined from the data themselves. Such techniques cannot be used to estimate resistivities from EM data, because the shape of the wave changes as it propagates. Instead, the resistivities are normally estimated from the data by inversion, which is a kind of modelling. For a seismologist this can be frustrating. This book is written partially for seismologists who would like an easy way ‘in’ to understanding electromagnetics.

The book is written for students, researchers and practitioners. Much of the material has been presented as courses for undergraduate and graduate geophysics students at the University of Edinburgh and at Delft University of Technology. The mathematical background required is partial differential equations, vector algebra, Fourier transforms and Laplace transforms.

We have had discussions with many friends and colleagues, and thank in particular, Bruce Hobbs, Paul Stoffa, David Wright, David Taylor, Dieter Werthmüller and our students for all their help and comments. We thank Cambridge University Press for agreeing to publish the book. Susan Francis has been especially kind, helpful, encouraging and patient.

Anton thanks his lovely wife Kate for constant support.

Notation and Conventions

Symbols

Symbol	Description	SI units
a	tortuosity factor in Archie's law	–
A	area	m^2
$\mathbf{B}$	vector magnetic induction	$V\ s\ m^{-2}$
c	propagation velocity	$m{\cdot}s^{-1}$
c_w	speed of sound in water	$m{\cdot}s^{-1}$
$c_0 = 299,792,458$	electromagnetic wave propagation velocity	$m{\cdot}s^{-1}$
$\mathbf{D}$	electric flux density	$C\ m^{-2}$
∇	del, or nabla, vector operator	m^{-1}
$\mathbf{E}$	vector electric field intensity	$V{\cdot}m^{-1}$
ε	electrical permittivity	$C^2{\cdot}N^{-1}{\cdot}m^{-2}$
$\varepsilon_0 \approx 8.85 \times 10^{-12}$	electrical permittivity of free space	$C^2{\cdot}N^{-1}{\cdot}m^{-2}$
δ	skin depth	m
$\delta(t)$	impulse function	s^{-1}
Δx_s	distance between source electrodes	m
Δx_r	distance between receiver electrodes	m
f	frequency	Hz
F	formation factor	–
G	Green's function (units depend on problem)	–
$\gamma = \sqrt{\zeta\sigma}$	horizontal wavenumber	m^{-1}
$\gamma_v = \sqrt{\zeta\sigma_v}$	vertical wavenumber	m^{-1}
$\Gamma = \sqrt{\kappa^2 + \gamma^2}$	vertical wavenumber	m^{-1}
$\Gamma_v = \sqrt{\lambda^2\kappa^2 + \gamma^2}$	vertical wavenumber	m^{-1}
h_j	thickness of jth layer (Chapter 1)	m
$\mathbf{H}$	vector magnetic field intensity	$A\ m^{-1}$

I	electric current	A
$\mathbf{I^m}$	magnetic source current dipole moment	V m
$\mathbf{I^e}$	electric source current dipole moment	A m
I_n	modified Bessel function of first kind and order n	–
i, j, k, l	indices	–
$\mathbf{J}$	volume density of induced current vector	A m^{-2}
$\mathbf{J^e}$	volume density of external electric current	A m^{-2}
$\mathbf{J^m}$	volume density of external magnetic current	V m^{-2}
J_n	ordinary Bessel function of first kind and order n	–
$k = \omega/c$	wavenumber	m^{-1}
k_x, k_y, k_z	wavenumber components	m^{-1}
K	bulk modulus	Pa
K_n	modified Bessel function of second kind and order n	–
$\kappa = \sqrt{k_x^2 + k_y^2}$	horizontal wavenumber	m^{-1}
l	length	m
L	length	m
$\lambda = \sqrt{\sigma/\sigma_v}$	coefficient of anisotropy	–
m	cementation factor in Archie's law	–
μ	magnetic permeability	H·m^{-1}
$\mu_0 = 4\pi \times 10^{-7}$	magnetic permeability of free space	H·m^{-1}
n	saturation exponent in Archie's law	–
p	pressure	Pa
$\Pi(t)$	rectangle function	–
ϕ	porosity	–
q	fluid monopole source time function	Pa·m
r	distance	m
R	electrical resistance	Ω
R_h	electrical resistance in horizontal direction	Ω
R_v	electrical resistance in vertical direction	Ω
ρ	electrical resistivity	Ω·m
ρ_0	electrical resistivity of a rock saturated with salt water	Ω·m
ρ_t	resistivity of a rock	Ω·m
ρ_w	electrical resistivity of salt water	Ω·m
ϱ	density	kg·m^{-3}
ϱ_f	volume density of free charge	C m^{-3}

$s = -i\omega$	Laplace variable	Hz
S_{hc}	hydrocarbon saturation	–
S_w	water saturation	–
σ	electrical conductivity, horizontal conductivity	$\text{S}\cdot\text{m}^{-1}$
σ_v	vertical conductivity	$\text{S}\cdot\text{m}^{-1}$
t	time	s
T	period	s
T_g	duration of impulse response	s
T_s	duration of source time function	s
V	voltage	V
$\omega = 2\pi f$	angular frequency	rad s^{-1}
$\mathcal{V}$	volume	m^3
x, y, z	Cartesian coordinates	m
z_s	source depth	m
$\zeta = s\mu_0$	zeta	$\text{H}\cdot\text{m}^{-1}\text{s}^{-1}$

Cartesian Coordinates

We use a right-handed Cartesian coordinate system with the z-axis positive downwards and the air–earth interface at $z = 0$, as shown in Figure 1.

Special Functions

The **ordinary Bessel function of the first kind** and order n is defined as

$$\mathrm{J}_n(\xi) = \frac{\mathrm{i}^{-n}}{\pi} \int_{\psi=0}^{\pi} \exp[-\mathrm{i}\xi \cos(\psi)] \cos(n\psi) d\psi. \tag{1}$$

The **modified Bessel functions of the first and second kinds** and order n are given by

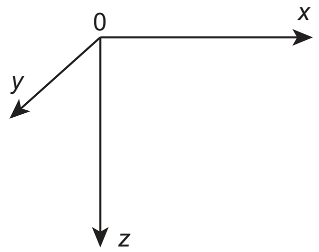

Figure 1 Cartesian coordinates.

$$\mathrm{I}_n(\xi) = \frac{1}{\pi}\int_{\psi=0}^{\pi} \exp[\xi\cos(\psi)]\cos(n\psi)d\psi, \tag{2}$$

$$\mathrm{K}_n(\xi) = \int_{\psi=0}^{\infty} \exp[-\xi\cosh(\psi)]\cosh(n\psi)d\psi. \tag{3}$$

The **error function** is defined as

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_{u=0}^{x} \exp(-u^2)du. \tag{4}$$

The **complementary error function** is defined as

$$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_{x}^{\infty} \exp(-u^2)du. \tag{5}$$

The **gamma function** is defined for all complex numbers except the non-positive integers. For complex numbers with a positive real part, it is defined via a convergent improper integral:

$$\Gamma(z) = \int_0^{\infty} x^{z-1}e^{-x}dx. \tag{6}$$

The **Heaviside function**, also known as the **Step function**, is defined as

$$H(t) = \begin{cases} 0, & t < 0 \\ \frac{1}{2}, & t = 0. \\ 1, & t > 0 \end{cases} \tag{7}$$

An **impulse**, also known as the **Dirac delta function**, is an infinitely strong pulse of unit area that can be defined as the two conditions:

$$\delta(t) = 0, t \neq 0;$$

$$\int_{-\infty}^{\infty} \delta(t)dt = 1. \tag{8}$$

The **rectangle function** is defined as

$$\Pi(t) = \begin{cases} 0, & |t| > \frac{1}{2} \\ \frac{1}{2}, & |t| = \frac{1}{2}. \\ 1, & |t| < \frac{1}{2} \end{cases} \tag{9}$$

The **normalised sinc function** is defined as

$$\mathrm{sinc}(f) = \frac{\sin(\pi f)}{\pi f}. \tag{10}$$

Transforms

A wavefield may be described as a function $a(x, y, z, t)$ that varies with both position (x, y, z) and time (t). We define the **temporal Fourier transform** as

$$\hat{a}(x, y, z, \omega) = \int_{-\infty}^{\infty} a(x, y, z, t)e^{i\omega t}dt, \tag{11}$$

with inverse

$$a(x.y, z, t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{a}(x, y, z, \omega)e^{-i\omega t}d\omega. \tag{12}$$

The **double spatial Fourier transform** of the space–frequency domain function $\hat{a}(x, y, z, \omega)$ is defined as

$$\tilde{a}(k_x, k_y, z, \omega) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \hat{a}(x, y, z, \omega)e^{-i(k_x x+k_y y)}dxdy, \tag{13}$$

with inverse

$$\hat{a}(x, y, z, \omega,) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \tilde{a}(k_x, k_y, z, \omega)e^{i(k_x x+k_y y)}dk_x dk_y, \tag{14}$$

where k_x and k_y are the *horizontal wavenumbers* and the tilde ˜ indicates the further change of domain. Here we have chosen the negative sign for the exponential for transformation from space to wavenumber and therefore the positive sign for the inverse transform.

The forward temporal and spatial Fourier transforms can be combined to give the **forward triple Fourier transform**

$$\tilde{a}(k_x, k_y, z, \omega) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} a(x, y, z, t)e^{i(\omega t-k_x x-k_y y)}dxdydt. \tag{15}$$

Similarly, the inverse transforms 12 and 14 can be combined to give the **inverse triple Fourier transform**

$$a(x, y, z, t) = \frac{1}{8\pi^3}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \tilde{a}(k_x, k_y, z, \omega)e^{-i(\omega t-k_x x-k_y y)}dk_x dk_y d\omega. \tag{16}$$

The **two-sided time-Laplace transform** of $a(x, y, z, t)$ is defined as

$$\hat{a}(x, y, z, s) = \int_{-\infty}^{\infty} a(x, y, z, t)e^{-st}dt, \tag{17}$$

and is the same as the temporal Fourier transform for the substitution $s = -i\omega$, where s is complex. When the real part of s is zero, it becomes identical with the Fourier transform. If $a(x, y, z, t) = 0$ for $t < 0$, only half the integral is required.

The **one-sided time-Laplace transform** is defined as

$$\hat{a}(x, y, z, s) = \int_{0^+}^{\infty} a(x, y, z, t)e^{-st}dt. \tag{18}$$

Because s is complex, the inverse transform is a contour integration in the complex plane

$$a(x, y, z, t)H(t) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} \hat{a}(x, y, z, s)e^{st}ds, \tag{19}$$

where c is a positive constant.

The **time-Laplace and three-dimensional spatial Fourier transform** of $a(x, y, z, t)$ is

$$\breve{a}(k_x, k_y, k_z, s) = \int_{0}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} a(x, y, z, t)e^{-st}e^{-i[k_x x+k_y y+k_z z]}dxdydzdt. \tag{20}$$