

INTRODUCTION TO GEOMAGNETIC FIELDS

Introduction to Geomagnetic Fields is a textbook for advanced undergraduate and graduate students of geophysics. It explains the natural magnetic fields in and surrounding the Earth that arise from a variety of electric currents. Such electric currents exist within atomic structures, in the Earth's liquid outer core, in the ionized upper atmosphere, and in the Earth's space environment during solar–terrestrial disturbances (magnetic storms).

The author clearly presents these different components of the Earth's magnetic field with a minimum of mathematical complexity. Variations in the geomagnetic field over a range of time-scales are discussed, including reversals of the Earth's main dipolar field, disturbances of the magnetosphere caused by particles and fields radiating from the Sun, and daily changes caused by the tidal and wind motion of the ionosphere. Readers are also introduced to the techniques and instrumentation for measuring geomagnetic fields, and to the range of applications for which these measurements are used.

This second edition has been fully revised to include many of the most recent advances in this subject area. It has been designed as a textbook for use with semester courses in geomagnetism and includes student exercises at the end of each chapter. Special appendices review relevant mathematical techniques and direct the reader to various journals, books, organizations, and websites where the latest computer programs for geomagnetism may be downloaded. Solutions to the exercises can be found at <http://www.cambridge.org/9780521822060>.

WALLACE CAMPBELL graduated with a Ph.D. in Physics from the University of California, Los Angeles, in 1959. Following a year with the Geophysical Institute in the University of Alaska, he accepted a position for geomagnetic field studies with the National Bureau of Standards Laboratory in Boulder, Colorado, that subsequently became the Environmental Research Laboratory of NOAA. He remained there until 1973 when a federal reorganization transferred his group to the United States Geological Survey in Golden, Colorado, for studies in geomagnetic applications. He retired from the USGS in 1996 and since then has worked as a Guest Scientist with the Solar–Terrestrial Physics Division, National Geophysical Data Center of NOAA. Dr Campbell is the author of 128 geomagnetism publications. His research subjects include ionospheric currents, deep-Earth electrical conductivity, geomagnetic storms, geomagnetic pulsations, quiet-time field variations, and geomagnetic field applications. He is also the coeditor (and contributing author) of the textbook *Physics of Geomagnetic Phenomena* (1967) and the author of *Earth Magnetism: a Guided Tour Through Magnetic Fields* (2001).

Cambridge University Press

978-0-521-82206-0 - Introduction to Geomagnetic Fields: Second Edition

Wallace H. Campbell

Frontmatter

[More information](#)

Cambridge University Press
978-0-521-82206-0 - Introduction to Geomagnetic Fields: Second Edition
Wallace H. Campbell
Frontmatter
[More information](#)

INTRODUCTION TO GEOMAGNETIC FIELDS

Second Edition

WALLACE H. CAMPBELL



Cambridge University Press
978-0-521-82206-0 - Introduction to Geomagnetic Fields: Second Edition
Wallace H. Campbell
Frontmatter
[More information](#)

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9780521822060

© Wallace H. Campbell 1997, 2003

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 1997

Second edition 2003

A catalogue record for this publication is available from the British Library

ISBN 978-0-521-82206-0 Hardback

ISBN 978-0-521-52953-2 Paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page</i> ix
<i>Acknowledgements</i>	xii
1 The Earth's main field	1
1.1 Introduction	1
1.2 Magnetic Components	4
1.3 Simple Dipole Field	8
1.4 Full Representation of the Main Field	15
1.5 Features of the Main Field	34
1.6 Charting the Field	41
1.7 Field Values for Modeling	47
1.8 Earth's Interior as a Source	51
1.9 Paleomagnetism	58
1.10 Planetary Fields	62
1.11 Main Field Summary	63
1.12 Exercises	65
2 Quiet-time field variations and dynamo currents	67
2.1 Introduction	67
2.2 Quiet Geomagnetic Day	68
2.3 Ionosphere	74
2.4 Atmospheric Motions	81
2.5 Evidence for Ionospheric Current	86
2.6 Spherical Harmonic Analysis of the Quiet Field	92
2.7 Lunar, Flare, Eclipse, and Special Effects	102
2.8 Quiet-Field Summary	108
2.9 Exercises	109
3 Solar–terrestrial activity	111
3.1 Introduction	111
3.2 Quiet Sun	113
3.3 Active Sun, Sunspots, Fields, and Coronal Holes	116
3.4 Plages, Prominences, Filaments, and Flares	122
3.5 Mass Ejections and Energetic Particle Events	127
3.6 Interplanetary Field and Solar Wind Shocks	128
3.7 Solar Wind–Magnetosphere Interaction	135
3.8 Geomagnetic Storms	139

3.9	Substorms	142
3.10	Tail, Ring, and Field-Aligned Currents	144
3.11	Auroras and Ionospheric Currents	152
3.12	Radiation Belts	165
3.13	Geomagnetic Spectra and Pulsations	168
3.14	High Frequency Natural Fields	173
3.15	Geomagnetic Indices	175
3.16	Solar–Terrestrial Activity Summary	184
3.17	Exercises	186
4	Measurement methods	189
4.1	Introduction	189
4.2	Bar Magnet Compass	190
4.3	Classical Variometer	194
4.4	Astatic Magnetometer	195
4.5	Earth-Current Probe	196
4.6	Induction-Loop Magnetometer	198
4.7	Spinner Magnetometer	200
4.8	Fluxgate (Saturable-Core) Magnetometer	201
4.9	Proton-Precession Magnetometer	203
4.10	Optically Pumped Magnetometer	205
4.11	Zeeman-Effect Magnetometer	210
4.12	Cryogenic Superconductor Magnetometer	212
4.13	Gradient Magnetometer	213
4.14	Comparison of Magnetometers	215
4.15	Observatories	215
4.16	Location and Direction	219
4.17	Field Sampling and Data Collection	219
4.18	Tropospheric and Ionospheric Observations	221
4.19	Magnetospheric Measurements	222
4.20	Instrument Summary	225
4.21	Exercises	226
5	Applications	228
5.1	Introduction	228
5.2	Physics of the Earth's Space Environment	229
5.3	Satellite Damage and Tracking	230
5.4	Induction in Long Pipelines	233
5.5	Induction in Electric Power Grids	235
5.6	Communication Systems	237
5.7	Disruption of GPS	239
5.8	Structure of the Earth's Crust and Mantle	239
	5.8.1 Surface Area Traverses for Magnetization Fields	241
	5.8.2 Aeromagnetic Surveys	241

5.8.3	Conductivity Sounding of the Earth's Crust	246
5.8.4	Conductivity of the Earth's Upper Mantle	251
5.9	Ocean Bottom Studies	253
5.10	Continental Drift	255
5.11	Archeomagnetism	257
5.12	Magnetic Charts	257
5.13	Navigation	258
5.14	Geomagnetism and Weather	259
5.15	Geomagnetism and Life Forms	262
5.16	Solar–Terrestrial Disturbance Predictions	269
5.17	Magnetic Frauds	271
5.17.1	Body Magnets	277
5.17.2	Prediction of Earthquakes	277
5.18	Summary of Applications	278
5.19	Exercises	279
Appendix A	Mathematical topics	280
A.1	Variables and Functions	280
A.2	Summations, Products, and Factorials	282
A.3	Scientific Notations and Names for Numbers	282
A.4	Logarithms	283
A.5	Trigonometry	284
A.6	Complex Numbers	285
A.7	Limits, Differentials, and Integrals	287
A.8	Vector Notations	289
A.9	Value Distributions	291
A.10	Correlation of Paired Values	294
Appendix B	Geomagnetic organizations, services, and bibliography	296
B.1	International Unions and Programs	296
B.2	World Data Centers for Geomagnetism	298
B.3	Special USGS Geomagnetism Website	303
B.4	Special Geomagnetic Data Sets	304
B.5	Special Organization Services	306
B.6	Solar–Terrestrial Activity Forecasting Centers	309
B.7	Bibliography for Geomagnetism	312
B.8	Principal Scientific Journals for Geomagnetism	313
Appendix C	Utility programs for geomagnetic fields	315
C.1	Geomagnetic Coordinates 1940–2005	315
C.2	Fields from the IGRF Model	316
C.3	Quiet-Day Field Variation, Sq	316
C.4	The Geomagnetic Disturbance Index, Dst	317
C.5	Location of the Sun and Moon	318

C.6	Day Number	318
C.7	Polynomial Fitting	319
C.8	Quiet-Day Spectral Analysis	319
C.9	Median of Sorted Values	319
C.10	Mean, Standard Deviation, and Correlation	320
C.11	Demonstration of Spherical Harmonics	320
C.12	Table of All Field Models	321
	<i>References</i>	322
	<i>Index</i>	332

Preface

This second edition of *Introduction to Geomagnetic Fields* has been redesigned as a classroom textbook for a semester course in geomagnetism. Student exercises have been added at the end of each chapter. Outdated figures and tables are replaced with more modern equivalents. Recent discoveries, field information, and references have been added along with special websites and computer programs. The basic structure of the original edition remains, providing a condensed and more readable coverage of geomagnetic topics than is afforded by existing textbooks.

My intention has been to focus upon the basic concepts and physical processes necessary for understanding the Earth's natural magnetic fields. When mathematical presentation is required, I have tried to remove the mystery of the scientists' special jargon and to emphasize the meanings of important equations, rather than obscure the relationships with complex formulas. Because some formulas are needed to appreciate geomagnetism, I have included, in an appendix, a succinct review of the required mathematical definitions and facts. For those readers who are approaching the subject of Earth magnetic fields for the very first time it may be helpful to start with the small layman's presentation, devoid of all mathematical equations, that I provided as *Earth Magnetism: A Guided Tour Through Magnetic Fields*, Academic Press, San Diego, 151 pp, 2001.

The student reader is expected to have a familiarity with the elementary scientific concepts identified by words of specific meaning, such as "force, velocity, energy, temperature, heat, charge, light waves, and fields of electric, magnetic, and gravitational nature". Excellent help is available if you are among those readers who have somehow missed receiving an explanation of these terms in your schooling. Albert Einstein and Leopold Infeld realized this need back in 1938 and wrote for you a small book, *The Evolution of Physics* (republished by Simon and Schuster, New York, 1961), which is as applicable today as it was over sixty years ago. That book uses remarkable simplicity of logic and language to reveal the fundamental concepts and terms now in use by physical scientists. In particular, with no mathematical formulas, their

first two chapters not only provide the necessary basics for the science novice but also can reawaken an appreciation of the physical world made dormant by a schooling overdose of isolated facts and mathematical gymnastics.

To be called a proper “Introduction to Geomagnetic Fields” my book must contain the particular subjects that I have grouped into five chapters as follows. In Chapter 1 we explore the Earth’s main field, consider its dipole representation, examine the vast extension of the fields into space, decipher the modeling methods of compact field representation, locate the many magnetic poles, and discuss paleomagnetic field reversals due to the source currents in the deep liquid core of the Earth. In Chapter 2 we find the reasons for quiet-time regular daily and seasonal field variations arising as electric currents in our Earth’s upper atmosphere. We separate out the secondary currents that are induced to flow in the Earth itself – but find application in determining Earth conductivity profiles. In Chapter 3 we consider the major disturbances to the ordered particle and field configuration about the Earth. These geomagnetic storms have their origin in solar outbursts and act as monitors of changes in our space environment. In Chapter 4 we discover how magnetic field sensors (magnetometers) function, discuss some observation techniques, and look at measurement methods on the ground and in space. Finally, in Chapter 5 we consider the many useful applications of our knowledge of the main geomagnetic field and its temporal changes.

The book also contains three appendices. Appendix A is a review of mathematical concepts that the reader will encounter. Appendix B provides a guide to the major international organizations, a geomagnetism bibliography, and the useful source and website addresses for geomagnetic information. Appendix C gives the description of free special computer programs that are designed to help the beginning student in geomagnetism.

I have included more than the typical amount of text illustrations. They have been carefully selected to clarify concepts for the reader, rather than to burden him with a tedious overabundance of data reproductions. A great number of significant website addresses have been included. Although I have tried to guide the reader to known non-volatile websites, neither I nor the publisher can be held responsible if a site listed in this book is modified or disappears. The book index has been limited to those special words that I have considered to be of particular importance for an introduction to geomagnetic fields; don’t expect to find place names, etc. This is a beginning textbook about geomagnetism; for full details on each of the chapter topics please borrow, from your library, the excellent reference books listed in Appendix B.

For the interpretation of phenomena, I have tried to stay with the current scientific consensus. However, in the future, many aspects of geomagnetism that are still being explored will undoubtedly change some of my viewpoints. Perhaps you can be the one to make such a contribution.

WHC

Acknowledgments

This small book had its origin, organization, and testing in my tutorial lectures at US Geological Survey; the Space Environment Laboratory of the National Oceanic and Atmospheric Administration; the World Data Center of the National Geophysical Data Center; the Australian Geological Survey Organisation (now Geoscience Australia); the Australian IPS Radio and Space Services; the Colorado School of Mines; the University of Colorado; the Academy of Sciences, Beijing; and the University of Cairo, Egypt.

I give special thanks for the guidance provided by researchers whose works are listed in the Bibliography and Reference sections, all of whom have made important contributions to the study of geomagnetic fields. In addition I have relied heavily on my personal scientific publications; the unreferenced figures are my own.

I appreciate the help of many scientists, teachers, special friends, and excellent technical reviewers who provided suggestions and material for improving various sections of the book. In particular, for assistance in preparing this second revision, I give special thanks to J. Quinn and D. Herzog (both at the US Geological Survey, Golden, USA), S. McLean, H. Coffey, E. Kihn, and B. Poppe (all at the National Oceanic and Atmospheric Administration, Boulder, USA), C. Barton, P. McFadden, and P. Milligan (all at Geophysics Australia, Canberra, Australia), D. Cole (at IPS Radio and Space Services, Sydney, Australia), D. Boteler (at the Geological Survey of Canada), G. Rostoker (at the University of Alberta, Canada), M. Barreto (at Observatorio Nacional, Rio de Janeiro, Brazil) and A. Adam (at the Geodetic and Geophysical Research Institute, Sopron, Hungary). I also thank my wife Beth, who assisted in editing the manuscript and endured my many hours spent at the computer.

WHC