

THE MAGNETIC FIELD OF THE EARTH'S LITHOSPHERE

THE SATELLITE PERSPECTIVE

R. A. Langel

W. J. Hinze



CAMBRIDGE
UNIVERSITY PRESS

CONTENTS

<i>Preface</i>	<i>page</i> xiii
1 LITHOSPHERIC MAGNETIC FIELDS AT SATELLITE ALTITUDE	1
1.0 Introduction	1
1.0.1 Looking into the Earth's Interior	1
1.0.2 Historical Development of Satellite Magnetic Anomaly Studies	4
1.1 The Magnetic Field from the Lithosphere of the Earth	5
1.1.1 Definitions and Relationships	5
1.1.2 Magnetism of Rocks	7
1.2 Introduction to Anomaly Maps	9
1.3 General Characteristics of Satellite Data	13
2 EARTH'S MAGNETIC FIELD	18
2.0 Introduction	18
2.1 The Field from the Earth's Core	20
2.1.1 Spherical Harmonic Models	20
2.1.2 Magnetic Coordinates	24
2.1.3 Time Scales	25
2.2 The Field from Sources External to the Earth	26
2.2.1 The Magnetosphere	26
2.2.2 Fields from the Ionosphere During Magnetic Quiet Conditions	26
2.2.3 Temporal Magnetic Disturbances	28
2.2.4 Magnetic Activity Indices	33
2.3 The Measured Field at Satellite Altitude	37

3 MEASUREMENT OF THE NEAR-EARTH MAGNETIC FIELD FROM SPACE	40
3.0 Introduction to Satellite Data	40
3.1 Magnetometers	41
3.2 Error Sources	42
3.3 Satellites Measuring the Near-Earth Magnetic Field	46
3.4 Satellites Contributing to Lithospheric Magnetic Field Studies	48
3.5 Data-Processing Issues	51
3.5.1 Calibration of a Vector Magnetometer by a Scalar Magnetometer	51
3.5.2 Determination of Spacecraft Field and Attitude Bias	52
3.5.3 Dealing with Discontinuities in the Attitude Solution	53
4 ISOLATION OF ANOMALY FIELDS	56
4.0 Long-Wavelength Magnetic Anomalies	56
4.1 Notation and Procedure	58
4.2 Selection of Quiet Data	59
4.3 Isolation from the Main Field	61
4.3.1 Model Degree	62
4.3.2 Main-Field Secular Variation	64
4.3.3 Coordinate Systems	65
4.3.4 Model Contamination by Ionospheric Fields	65
4.3.5 Spherical Harmonic Degree and Wavelength	66
4.4 Analysis of Long-Wavelength Trends	70
4.4.1 Correction Function for Magnetospheric Fields	70
4.4.2 Ad Hoc Trend Corrections	71
4.4.3 High-Pass Filtering	72
4.4.4 Crossover Analysis	75
4.4.5 Polynomial Fit Along Orbital Tracks	76
4.5 Wavelength Domain Estimation for the Common Signal in Multiple Sources	77
4.5.1 Fourier Harmonic Correlation Analysis	78
4.5.2 Spherical Harmonic Correlation Analysis	81
4.5.3 Trade-Offs in the Correlation Analysis	82
4.5.4 Spherical Harmonic Relationships	83

4.6	Analytics of Lithospheric and Ionospheric Fields	87
4.6.1	Introduction	87
4.6.2	Estimation of the Coefficients	89
4.6.3	Data from a Single Local Time	90
4.6.4	Time Variations	94
4.6.5	Summary and Discussion	96
4.7	Models of the Equatorial Electrojet from <i>Magsat</i> Data	97
4.8	A High-Latitude Disturbance Model	104
4.9	Spherical Harmonic Models	108
4.10	A Recommended Procedure	108
5	REDUCTION AND INVERSION	111
5.0	Overview	111
5.1	The Fundamental Inversion Problem	113
5.1.1	The Magnetic Field of a Dipole	113
5.1.1.1	Basic Principles, the Dipole Potential	113
5.1.1.2	Geometric Relationships and Transformations	115
5.1.1.3	Dipole Field Expressions	117
5.1.2	Magnetization and Susceptibility	117
5.1.3	The Equivalent Source Method, a Finite-Parameter Solution	119
5.1.4	Reduction to Common Inclination (to the Pole) and Magnitude	122
5.1.5	Uniqueness Considerations	123
5.2	Basics of Estimation	124
5.2.1	Overview	124
5.2.2	Minimum-Variance Estimation with A Priori Information	126
5.3	Local Models	129
5.3.1	Spherical Cap Harmonic Analysis	129
5.3.2	Rectangular Harmonic Analysis	132
5.3.3	Gridding by Collocation	135
5.3.3.1	The Basic Formalism	135
5.3.3.2	Local Covariance Functions	136
5.3.3.3	Use of Collocation in Magnetic Anomaly Studies	138
5.3.4	Summary of Local Models	139

5.4	Global Models	139
5.4.1	Spherical Harmonic Potential	139
5.4.2	Non-Potential Spherical Harmonic Representation	140
5.4.3	Efficient Computation Techniques with Spherical Harmonics	142
5.4.3.1	Formulation of Solution by Integration	142
5.4.3.2	Data Gridded Along Circles of Equal Latitude	142
5.4.3.3	Data Gridded According to Equal Area	143
5.4.3.4	Interpolation for Missing Data	143
5.4.4	Equivalent Source Models	143
5.4.5	Summary of Global Models	144
5.5	Dealing with Instability: Principal-Component Analysis	144
5.5.1	Causes and Examples of Instability	144
5.5.2	Principal-Component Analysis	146
5.5.3	Example from Equivalent Source Modeling	148
5.6	Dealing with Instability: Minimum-Norm Solutions	150
5.6.1	Minimum-Norm Concepts	150
5.6.2	Ridge Regression	152
5.6.3	Geomagnetic Norms	153
5.6.3.1	Magnetic Field Norms	153
5.6.3.2	A Magnetization Norm	155
5.6.4	Generalized Inverse Methods	155
5.6.4.1	Introduction	155
5.6.4.2	Formalism for Forming the Gram Matrix with Perfect Data	156
5.6.4.3	Imperfect Data	160
5.6.4.4	Dealing with Large Numbers of Data	161
5.6.4.5	Scalar Data	162
5.6.4.6	Applications to Satellite Anomaly Data	163
5.6.5	Minimum-Norm Magnetization	164
5.6.5.1	Basic Formalism	164
5.6.5.2	Elements of the Three-Dimensional Gram Matrix	165
5.7	An Estimate of the Potential Function and Susceptibility	166
5.7.1	The Potential	167
5.7.2	Susceptibility	169
5.8	The Usefulness of Vector Data	171
5.9	Summary	174

Appendix 5.1: Calculation of Derivatives of the Trace of Matrix Products	175
Appendix 5.2: Vector and Hilbert Spaces	176
A5.2.1 Vector Spaces	176
A5.2.2 Hilbert Spaces	179
Appendix 5.3: Calculation of Elements of the Gram Matrix Λ	179
A5.3.1 Matrix Elements for the ψ Norm	180
A5.3.2 Matrix Elements for the B_r Norm	180
6 ANOMALY MAPS	184
6.0 Introduction	184
6.1 Tabulation of Published Maps	185
6.2 Scalar Maps at Low and Middle Latitudes	199
6.2.1 Maps Based on Data from the POGO Satellites	199
6.2.2 Maps Based on Data from <i>Magsat</i>	202
6.2.3 Maps Based on Combined <i>Magsat</i> and POGO Data	205
6.3 Vector Maps at Low and Middle Latitudes	208
6.4 Maps of the Polar Regions	215
6.4.1 Factors in High-Latitude Data	215
6.4.2 North Polar Scalar Maps	217
6.4.3 South Polar Scalar Maps	221
6.4.4 Vector Maps	223
6.5 Comparisons Between Maps	223
6.5.1 A Correlation Procedure	223
6.5.2 Correlative Intercomparison of Final Maps	227
6.5.2.1 Low- and Middle-Latitude Scalar Maps	227
6.5.2.2 Low- and Middle-Latitude ΔZ Maps	229
6.5.2.3 Polar Scalar Maps	230
6.6 Comparisons of Satellite and Surface Surveys	233
6.6.1 Problems with Intercomparing Surface and Satellite Surveys	233
6.6.1.1 Differences in Main-Field and Regional-Field Removal	234
6.6.1.2 Missing and Spurious Long Wavelengths	236
6.6.2 Published Comparisons	239
6.6.2.1 Canada	239

6.6.2.2	United States	241
6.6.2.3	Marine Regions	243
6.7	Global Interpretive Maps	243
6.8	Regional Maps	244
6.8.1	General Comments	244
6.8.2	Maps of Higher Resolution	246
6.9	Summary and Recommendations	248
7	MAGNETIC ANOMALIES AND THEIR SOURCES	250
7.0	Introduction	250
7.1	Sources of Magnetization Contrasts	251
7.1.1	Fundamental Types of Magnetism	251
7.1.2	Magnetic Minerals	256
7.1.3	Magnetic Petrology	258
7.2	Lithospheric Magnetization	263
7.2.1	Continental Lithosphere	263
7.2.2	Oceanic Lithosphere	268
7.3	Summary	272
8	METHODS IN INTERPRETATION	274
8.0	Introduction	274
8.1	Qualitative/Semi-Quantitative Methods	275
8.1.1	Map Comparisons	275
8.1.2	Application of Poisson's Theorem	278
8.2	Quantitative Methods, Forward Modeling	279
8.2.1	Introduction	279
8.2.2	Flat-Earth Models	281
8.2.3	A Spherical-Earth Model	282
8.2.4	A Method for Specification of Magnetization Contrasts	286
8.3	Typical Magnetic Anomalies	293
8.4	Horizontal Resolution	299
8.4.1	Resolution of Pairs of Magnetic Blocks in Satellite Scalar Magnetic Field Data	299
8.4.2	Resolution of <i>Magsat</i> Data	302
8.5	Global Magnetization with A Priori Information	302
8.6	Discussion	311

9 GLOBAL SATELLITE MAGNETIC ANOMALY INTERPRETATION	312
9.1 Implications of the SEMM for Interpretation	312
9.2 North America	315
9.2.1 Overview	315
9.2.2 Anomaly Studies	321
9.2.2.1 Ungava Anomaly	321
9.2.2.2 Crustal Thickness/Free-Air Gravity and Magnetization in the United States	323
9.2.2.3 Correlation of Magnetization with Heat Flow	327
9.2.2.4 Models of the Southeastern United States	330
9.2.2.5 The Mississippi Embayment	332
9.2.2.6 Florida and the Bahamas Platform	335
9.2.3 Discussion	337
9.3 Africa	338
9.3.1 Overview	338
9.3.2 Anomaly Studies	341
9.3.2.1 Central Africa	341
9.3.2.2 Northwest Africa	346
9.3.2.3 Evidence of Large-Scale Remanent Magnetization	349
9.4 Australia	350
9.5 Europe	355
9.5.1 Overview	355
9.5.2 Anomaly Studies	362
9.6 Oceans	369
9.6.1 General	369
9.6.2 Plateaus and Rises	371
9.7 Summary	376
Appendix 9.1: References to Regional Studies	379
<i>Glossary of Symbols</i>	383
<i>Common Abbreviations</i>	393
<i>References</i>	395
<i>Index</i>	417