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MAGSAT SCIENTIFIC INVESTIGATIONS

The nature of the geomagnetic field and of presatellite and early satellite measurements is described. The objectives of each investigation in the areas of geomagnetic modeling, crustal magnetic anomaly studies, investigations of the inner earth, and studies of external current systems are presented, along with some early results from Magsat.

INTRODUCTION

The near-earth magnetic field, as measured by the magnetometers on Magsat, contains contributions from three sources: the earth's core, the earth's crust, and external current systems in the earth's ionosphere and beyond. By far the largest in magnitude is the field from the core, or the "main" field. The main field is nearly dipolar in nature. Its strength is more than 50,000 nT (nanoteslas) at the poles and near 30,000 nT at the equator. Its variation with time ("secular" variation) is slow, with a maximum of about 1% per year. External current systems are time varying on a scale of seconds to days and can vary in magnitude from a fraction to thousands of nanoteslas. The current systems are located in a cavity-like region surrounding the earth, known as the "magnetosphere." Although these currents are always present, their strength and location vary considerably between periods of magnetic quiet and periods of magnetic disturbance.

Magnetic fields from the earth's crust are by far the smallest in amplitude of the three sources at satellite altitudes. Their strength at Magsat altitudes is between 0 and 50 nT. Also called "anomaly fields," the sources are associated with variations in the geologic or geophysical properties in the earth's crust; accordingly, their temporal variations are on a geologic time scale.

Prior to the satellite era the earth's magnetic field was (and still is) monitored by means of permanent magnetic observatories that measure the ambient field continuously and by periodically repeating measurements at selected sites. Field surveys are necessary to fill in the spatial gaps between observatories and repeat sites. Such surveys were first conducted by early mariners and land surveyers. Edmund Halley made a sea voyage during 1689-1700 expressly to survey the magnetic field over the oceans. In 1701 he published the first chart of the magnetic declination in the region of the Atlantic Ocean; in the following year he extended his chart to the Indian Ocean and to the sea near China.

In addition to land and sea surveys, some aircraft have been especially adapted for the measurement of magnetic fields. Such surveys usually, although not always, measured only the scalar magnitude of the field. Many countries have been surveyed in their entirety, some more than once. Unfortunately, the United States has not yet been totally surveyed. In addition to their obvious value for modeling the earth's main field, such surveys are particularly useful for mapping the anomaly field at low altitude and, as a result, have been conducted by the oil and mineral exploration industries on a local scale.

Satellite measurements of the geomagnetic field began with the launch of Sputnik 3 in May 1958 and have continued sporadically in the intervening years. Table 1 is a list of spacecraft that have made significant contributions to our understanding of the near-earth geomagnetic field. Each had its own limitations, ranging from a lack of global coverage caused by the absence of on-board tape recorders to limited accuracy due either to instrumental shortcomings or to ambient spacecraft fields. Prior to Magsat, only the Polar Orbiting Geophysical Observatory (Pogo) satellites (OGO -2, -4, and -6) had provided an accurate, global geomagnetic survey. Their alkali vapor magnetometers provided measurements of the field magnitude about every half second over an altitude range of about 400 to 1500 km.[1,2]

A new era in near-earth magnetic field measurements began with NASA's launch of Magsat in October 1979. Magsat has provided the first truly global geomagnetic survey since the Pogo satellites and the very first global survey of vector components of the geomagnetic field. Designed with two major measurement tasks in view, Magsat provided a global vector survey of the main geopotential field and a lower altitude measurement of crustal anomalies. These tasks stemmed directly from the Magsat mission objectives outlined by Ousley in this issue. Data from Magsat are being analyzed by many investigators, some of whom are working cooperatively.

OVERVIEW OF INVESTIGATIONS

Investigations are being carried out by scientists at the Goddard Space Flight Center (GSFC) and

Table 1

SATELLITES THAT HAVE MEASURED THE NEAR-EARTH GEOMAGNETIC FIELD

Satellite	*Inclination* (*degs*)	*Altitude Range* (*km*)	*Dates*	*Instrument*	*Approximate Accuracy* (*nT*)	*Coverage*
Sputnik 3	65	440 – 600	5/58 – 6/58	Fluxgates	100	USSR
Vanguard 3	33	510 – 3750	9/59 – 12/59	Proton	10	Near ground station*
1963-38C	Polar	1100	9/63 – 1/74	Fluxgate (1-axis)	30 – 35	Near ground station
Cosmos 26	49	270 – 403	3/64	Proton	Unknown	Whole orbit
Cosmos 49	50	261 – 488	10/64 – 11/64	Proton	22	Whole orbit
1964-83C	90	1040 – 1089	12/64 – 6/65	Rubidium	22	Near ground station
OGO-2	87	413 – 1510	10/65 – 9/67	Rubidium	6	Whole orbit
OGO-4	86	412 – 908	7/67 – 1/69	Rubidium	6	Whole orbit
OGO-6	82	397 – 1098	6/69 – 7/71	Rubidium	6	Whole orbit
Cosmos 321	72	270 – 403	1/70 – 3/70	Cesium	Unknown	Whole orbit
Azur	103	384 – 3145	11/69 – 6/70	Fluxgate (2-axis)	Unknown	Near ground station
Triad	Polar	750 – 832	9/72 – present	Fluxgate	Unknown	Near ground station

*"Near ground station" indicates no on-board recorder. Data were acquired only when the spacecraft was in sight of a station equipped to receive telemetry.

the U.S. Geological Survey (USGS), and by scientists selected in response to a NASA Announcement of Opportunity (AO). The work at GSFC includes derivation of the first geomagnetic field models from Magsat, derivation of the global anomaly map from Pogo, and some interpretations of that map in terms of geologic/geophysical models of the earth's crust. The USGS effort, under the direction of Frank Frischknecht, includes both field modeling and magnetic charting as carried out by Joseph Cain and Eugene Fabiano, and crustal modeling by Jeff Phillips and others. A total of 19 domestic and 13 foreign investigators were selected from responses to the AO. Table 2 lists these investigators, their institutions, and a brief description of their proposed investigations. More detailed information regarding the investigations will be given in the remainder of this paper, which is divided into four sections corresponding to four relatively distinct areas of scientific investigation, namely:

1. Geomagnetic field modeling;
2. Crustal magnetic anomaly studies, i.e., postulating the crustal structure and composition that cause the magnetic anomalies;
3. Investigations of the inner earth (the core, mantle, and core/mantle interface area); and
4. Studies of external current systems.

GEOMAGNETIC FIELD MODELING

Geomagnetic field modeling derives the spherical harmonic potential function that best represents the main field of the earth in a least-squares sense. Theoretically, such a potential function could be made to represent both the core and crustal fields exactly. Practically, a restricted model must be chosen because of the finite limitation on computer size and speed. Most researchers attempt only to represent the core field with a potential function and use alternate methods of describing the crustal fields.

One of the principal contributions of satellite magnetic field measurements to geomagnetism has been to make available a truly global distribution of data. Surface measurements are notably sparse, particularly in oceanic and remote regions. The problem is compounded by the secular variation in the main geomagnetic field that, as was stated earlier, can amount to as much as 1% per year in some localities. This means that to represent the global geomagnetic field accurately at any given time (epoch), worldwide measurements must be made at times near that epoch, a feat only achieved by satellite observations and even then only by the Pogo and Magsat satellites with their on-board tape recorders and near-polar orbits. Accurate global representation of the secular variation itself would require periodic worldwide surveys, something often spoken of but yet to become a reality. The Pogo satellites accomplished one such survey and Magsat provided another. These, together with existing surface data, permit accurate global representation of secular variation for the period beginning with OGO-2 until the demise of Magsat. Future

Table 2

LIST OF MAGSAT INVESTIGATORS

Investigator	*Institution/Country*	*Title*	*Objectives*
David R. Barraclough	Institute of Geological Sciences, United Kingdom	Spherical Harmonic Representation of the Main Geomagnetic Field for World Charting and Investigation of Some Fundamental Problems of Physics and Geophysics	Produce an accurate model of the main geomagnetic field, together with reliable estimates of the accuracy of coefficients
Charles R. Bentley	University of Wisconsin	Investigation of Antarctic Crust and Upper Mantle Using Magsat and Other Geophysical Data	Using Magsat data, devise a general framework for the structure of Antarctica into which more specific and local measurements can be integrated
Edward R. Benton	University of Colorado	Geomagnetic Field Forecasting and Fluid Dynamics of the Core	Adjust the gauss coefficients of the main field model of the Magsat data set to satisfy dynamic constraints; use Magsat data to test the ability to forecast the structure of the internal geomagnetic field
B. N. Bhargava	Indian Institute for Geomagnetism	Magsat for Geomagnetic Studies in the Indian Region	Prepare a regional geomagnetic reference field and magnetic anomaly maps over Indian and neighboring regions: (a) to gain a clearer understanding of secondary effect features and the variability of the dawn/dusk field, and (b) to study in detail the equatorial electrojet and transient variations
Robert F. Brammer	The Analytic Sciences Corporation (TASC)	Satellite Magnetic and Gravity Investigation of the Eastern Indian Ocean	Produce magnetic anomaly maps of the Indian Ocean; quantify the comparison between Magsat data and Geos-3 gravity data; interpret the magnetic data using ancillary data
J. Ronald Burrows	National Research Council of Canada	Studies of High-Latitude Current Systems Using Magsat Vector Data	Understand the physical processes that control high-latitude current systems; improve the confidence level in studies of internal field sources
Robert S. Carmichael	University of Iowa	Use of Magsat Anomaly Data for Crustal Structure and Mineral Resources in the U.S. Midcontinent	Analyze Magsat anomaly data to synthesize a total geologic model and interpret crustal geology in the midcontinent region; contribute to the interpretation and calculation of the depth of the Curie isotherm
Richard L. Coles	Energy, Mines and Resources, Canada	The Reduction, Verification and Interpretation of Magsat Magnetic Data over Canada	Select quiet-time data; correct Magsat data for disturbance fields and apply the routines; compare Magsat and vector airborne data; combine Magsat and aircraft data of magnetic anomalies; produce regional interpretations relating to earth structure
James C. Dooley	Bureau of Mineral Resources, Australia	Magsat Data, the Regional Magnetic Field, and the Crustal Structure of Australia and Antarctica	Incorporate Magsat data into regional magnetic field charts to improve their accuracy; determine if differences exist in temperature-depth curves for different tectonic areas; study the boundaries between major tectonic blocks and between continental and oceanic crust; determine Curie point depth and crustal magnetization for Antarctica
Naoshi Fukushima	Geophysics Research Laboratory, Japan	Proposal from Japanese National Team for Magsat Project	Analyze the regional geomagnetic field around Japan and Japanese Antarctica; study the contributions to magnetic variations by electric currents and hydromagnetic waves in and above the ionosphere
Paolo Gasparini	Osservatorio Vesuviano, Italy	Crustal Structures under the Active Volcanic Areas of Central and Eastern Mediterranean	Calculate the depth of the Curie temperature for the Mediterranean area and relate to areas of volcanic activity; investigate the Italian and Tyrrhenian anomaly
Bruce P. Gibbs	Business and Technological Systems, Incorporated	Geomagnetic Field Modeling by Optimal Recursive Filtering	Produce a state vector to predict field values for several years beyond the Magsat model; obtain optimal estimates of field values throughout the 1900-1980 period
M. R. Godivier	Office de la Recherche Scientifique et Technique, Outremer (ORSTOM), France	Magnetic Anomaly of Bangui	Improve the explanation of the cause of the Bangui anomaly, using Magsat data, other magnetic data, and gravity, seismic, and heat flow data
Stephen E. Haggerty	University of Massachusetts	The Mineralogy of Global Magnetic Anomalies	Interpret Magsat data to locate mafic and ultramafic source rocks and lineament expressions of anomalies that can be correlated with crustal of upper mantle depths; determine mineral stabilities pertinent to magnetic anomalies to ascertain the magnetic properties of metamorphic rocks

Table 2 (continued)

LIST OF MAGSAT INVESTIGATORS

Investigator	*Institution/Country*	*Title*	*Objectives*
D. H. Hall	University of Manitoba, Canada	Identification of the Magnetic Signatures of Lithostratographic and Structural Elements in the Canadian Shield Using Magnetic Anomalies and Data from Individual Tracks from Magsat	Confirm and extend the model for crust mantle magnetization
Christopher G. A. Harrison	University of Miami	Investigations of Medium Wavelength Magnetic Anomalies in the Eastern Pacific Using Magsat Data	Determine the relationship of magnetic anomalies with surface geological features
David A. Hastings	U.S. Geological Survey, EROS Data Center	An Investigation of Magsat and Complementary Data Emphasizing Precambrian Shields and Adjacent Areas of West Africa and South America	Determine the Magsat magnetic signatures of various tectonic provinces; determine the geological associations of these signatures; synthesize Magsat and other data with mineral resources data globally
John F. Hermance	Brown University	Electromagnetic Deep-Probing (100-1000 km) of the Earth's Interior from Artificial Satellites; Constraints on the Regional Emplacement of Crustal Resources	Evaluate the applicability of electromagnetic deep-sounding experiments using natural sources in the magnetosphere
William J. Hinze	Purdue University	Application of Magsat to Lithospheric Modeling in South America: Part I—Processing and Interpretation of Magnetic and Gravity Anomaly Data	Use magnetic anomalies to develop lithospheric models to determine the properties of principal tectonic features; correlate magnetic anomalies of South America with those of adjacent continental areas to attempt to reconstruct Gondwanaland (see Keller below)
B. David Johnson	Macquarie University, Australia	An Investigation of the Crustal Properties of Australia and Surrounding Regions Derived from Interpretation of Magsat Anomaly Field Data	Produce a map of surface magnetization to understand the evolution of the crust and to aid in mineral exploration
G. R. Keller	The University of Texas at El Paso	Application of Magsat to Lithospheric Modeling in South America: Part II— Synthesis of Geologic and Seismic Data for Development of Integrated Crustal Models	Provide models of the seismic velocity structure of the lithosphere (see Hinze above)
David M. Klumpar	The University of Texas at Dallas	Investigation of the Effects of External Current Systems on the Magsat Data Utilizing Grid Cell Modeling Techniques	Apply a modeling procedure to the vector Magsat data in order to separate the terrestrial component from that due to extraterrestrial sources
John L. LaBrecque	Lamont-Doherty Geological Observatory	Analysis of Intermediate-Wavelength Magnetic Anomalies over the Oceans in Magsat and Sea Surface Data	Determine the distribution of intermediate wavelength magnetic anomalies of lithospheric origin in the oceans, the extent to which Magsat describes the distribution, and the cause of these anomalies
Jean-Louis LeMouel	Institut de Physique du Globe de Paris, France	Magsat Investigations Consortium	Reduce Magsat vector data for a global analytic field model and constant altitude field maps; compare Magsat data to regional studies; study features of the core field; correlate globally and regionally Magsat and gravimetric data
Michael A. Mayhew	Business and Technological Systems, Incorporated	Magsat Anomaly Field Inversion and Interpretation for the U.S.	Construct a regional crustal temperature/heat flow model based on a developed magnetization model, heat flow/production data, and spectral estimates of the Curie depth
Michael A. Mayhew	Business and Technological Systems, Incorporated	Equivalent Source Modeling of the Main Field Using Magsat Data	Model the core field; compute equivalent spherical harmonic coefficients for comparison with other field models; examine the spectral content of the core field
Igor I. Gil Pacca	Instituto Astronomico e Geofisico—UPS, Brazil	Structure, Composition, and Thermal State of the Crust in Brazil	Construct preliminary crustal models in the Brazilian territory; point out possible variations in crustal structure among different geological provinces

Table 2 (continued)

LIST OF MAGSAT INVESTIGATORS

Investigator	*Institution/Country*	*Title*	*Objectives*
Thomas A. Potemra	The Johns Hopkins University Applied Physics Laboratory	A Proposal for the Investigation of Magsat and Triad Magnetometer Data to Provide Corrective Information on High-Latitude External Fields	Identify and evaluate high-latitude external fields from the comparison of data acquired by the Magsat and Triad spacecraft that can be used to improve geomagnetic field models
Robert D. Regan	Phoenix Corporation	Improved Definition of Crustal Magnetic Anomalies in Magsat Data	Develop an improved method for the identification of magnetic anomalies of crustal origin in satellite data by defining better and removing the most persistent external field effects
David P. Stern	NASA/Goddard Space Flight Center	Study of Enhanced Errors and of the Secular Magnetic Variation Using Magsat Models and Those Derived in Pogo Surveys	Estimate the secular variation over the period 1965-80 by removing mathematical instability based upon scalar field intensity alone
David W. Strangway	University of Toronto, Canada	Proposal to Analyze the Magnetic Anomaly Maps from Magsat over Portions of the Canadian and Other Shields	Examine the expected difference between the Grenville and Superior provinces
Ihn Jae Won	North Carolina State University	Compatibility Study of the Magsat Data and Aeromagnetic Data in the Eastern Piedmont of the U.S.	Evaluate the compatibility between the Magsat and aeromagnetic data in the eastern North Carolina Piedmont

satellite surveys will be needed for accurate global representations beyond the lifetime of Magsat.

Although Pogo data were global and taken over a short time span, the limitation of measuring only the field magnitude resulted in some ambiguity in the field direction in spherical harmonic analyses based on Pogo data alone.[3-6] This ambiguity is being removed by the acquisition of global vector data with Magsat.

The USGS is currently in the process of updating world and national magnetic charts and field models. Three sets of charts are being prepared: a U.S. chart of declination, a U.S. chart of total field intensity, and a set of world charts for all components. The declination chart was finalized in early 1980, the total intensity charts will be by the end of 1980, and the world charts by August 1981. Magsat data will contribute to all of these charts.

To provide timely input for all applications, a series of field models will be derived from data during magnetically quiet times over the period of data accumulation. One model has already been generated from two full days of data.[7] At appropriate intervals it will be updated with additional data, culminating in a final model incorporating all data with fine attitude coordinate accuracy, to be available about October 1981. Magsat data will also be combined with data from the Pogo satellites and other sources to derive predictive models with temporal terms.

Of the Magsat data currently available for analysis, November 5 and 6, 1979, showed the lowest value of magnetic activity indices. Plots of the data indicated that those days were indeed very quiet magnetically. Accordingly, a selection of 15,206 data points from those days was used to derive the first geomagnetic field model from Magsat, designated MGST (6/80).[7] The spherical harmonic coefficients are given in Table 3. Vector data above 50° latitude were not included because of non-curl-free fields from field-aligned currents. Such fields are transverse to the main field and, as shown by Langel,[2] have little or no effect on the field magnitude. However, 3354 values of B_r, 3345 of B_θ, and 3361 of B_ϕ were included for latitudes below 50°. (B_r, B_θ, and B_ϕ are the radial, north-south, and east-west components — in a spherical coordinate system — of the geomagnetic field.)

This model fits the selected data with the mean and standard deviations as follows:

Component	*Mean Deviation (nT)*	*Standard Deviation (nT)*
Scalar magnitude	0.1	8.2
B_r	2.5	6.5
B_θ	−0.1	7.6
B_ϕ	0.5	7.4

The deviations are mainly due to a combination of fields from unmodeled external and crustal sources.

As part of our preparation for Magsat, Pogo data were combined with surface data from observatories between 1960 and 1977, with selected repeat data, and with selected shipborne data to derive what we consider to be the best possible pre-Magsat model.[8] Constant and first-, second-, and third-derivative time terms were included to degree and order 13, 13, 6, and 4, respectively. This model, designated PMAG (7/80), used a new technique for dealing with the observatory data. As at

Table 3

SPHERICAL HARMONIC COEFFICIENTS FOR MAGSAT GEOMAGNETIC FIELD MODEL MGST (6/80)

Internal Coefficients (nT)

n	m	g_n^m	h_n^m
1	0	-29989.6	
1	1	-1958.6	5608.1
2	0	-1994.8	
2	1	3027.2	-2127.3
2	2	1661.6	-196.1
3	0	1279.9	
3	1	-2179.8	-334.4
3	2	1251.4	270.7
3	3	833.0	-251.1
4	0	939.3	
4	1	782.5	211.6
4	2	398.4	-256.7
4	3	-419.2	52.0
4	4	199.3	-297.6
5	0	-217.4	
5	1	357.6	45.2
5	2	261.0	149.4
5	3	-73.9	-150.3
5	4	-162.0	-78.1
5	5	-48.3	91.8
6	0	48.3	
6	1	65.2	-14.5
6	2	41.4	93.4
6	3	-192.2	70.6
6	4	3.5	-42.9
6	5	13.7	-2.4
6	6	-107.6	16.9
7	0	71.7	
7	1	-59.0	-82.4
7	2	1.6	-27.5
7	3	20.5	-4.9
7	4	-12.6	16.1
7	5	0.6	18.1
7	6	10.6	-22.9
7	7	-2.0	-9.9
8	0	18.4	
8	1	6.8	6.9
8	2	-0.1	-17.9
8	3	-10.8	4.0
8	4	-7.0	-22.3
8	5	4.3	9.2
8	6	2.7	16.1
8	7	6.3	-13.1
8	8	-1.2	-14.8
9	0	5.6	
9	1	10.4	-21.1
9	2	1.1	15.2
9	3	-12.6	8.9
9	4	9.5	-4.8
9	5	-3.3	-6.5
9	6	-1.3	9.0
9	7	6.8	9.5
9	8	1.4	-5.9
9	9	-5.1	2.1
10	0	-3.3	
10	1	-3.5	1.4
10	2	2.5	0.4
10	3	-5.3	2.6
10	4	-2.1	5.6
10	5	4.6	-4.2
10	6	3.1	-0.4
10	7	0.6	-1.3
10	8	1.8	3.5
10	9	2.8	-0.5
10	10	-0.5	-6.2
11	0	2.4	
11	1	-1.3	0.7
11	2	-1.9	1.7
11	3	2.2	-1.1
11	4	0.1	-2.7
11	5	-0.4	0.6
11	6	-0.3	-0.1
11	7	1.7	-2.4
11	8	1.8	-0.3
11	9	-0.6	-1.4
11	10	2.1	-1.6
11	11	3.5	0.6
12	0	-1.6	
12	1	0.4	0.6
12	2	-0.1	0.6
12	3	-0.1	2.3
12	4	0.6	-1.5
12	5	0.5	0.5
12	6	-0.6	0.2
12	7	-0.4	-0.4
12	8	0.1	0.0
12	9	-0.4	0.0
12	10	-0.2	-1.5
12	11	0.7	0.3
12	12	0.0	0.7
13	0	0.0	
13	1	-0.5	-0.4
13	2	0.3	0.4
13	3	-0.7	1.6
13	4	0.0	0.0
13	5	1.2	-0.6
13	6	-0.4	-0.1
13	7	0.4	0.8
13	8	-0.6	0.2
13	9	0.2	0.8
13	10	0.1	0.5
13	11	0.4	-0.1
13	12	-0.4	0.0
13	13	0.0	-0.1

External Coefficients (nT)

n	m	$\bar{g}_n^m$	$\bar{h}_n^m$
1	0	20.4	
1	1	-0.6	-0.4

The mean radius of the earth is 6371.2 km
The mean epoch is 1979.85

the satellite, surface fields contain contributions from the three sources. For field modeling the annual mean value for each observatory is usually used so that the external contribution is some averaged value (we hope, small). However, crustal anomaly fields are typically quite large. For past models the rms residual of surface data to the model has been typically between 100 and 200 nT.[9] We have incorporated a procedure for solving independently for the "bias" or anomaly field in each component at each observatory. This procedure was used for the first time in the derivation of the PMAG (7/80) model. After solving for the coefficients of the potential function and the observatory biases, the rms residual of the observatory data was reduced to below 28 nT for all components. For repeat data this procedure was not feasible because of a lack of extensive temporal coverage. These data were incorporated by including only locations where three or more measurements, made at different times, were available. Each component at each location was then represented by a linear fit; only the rate of change was used in deriving PMAG (7/80). The residual to the fit was 10 nT per year for all components. For shipborne data, 39 long tracks in regions devoid of other surface measurements were selected. These were low-pass filtered with a cutoff of 500 km to eliminate the crustal anomaly field. The rms residual to the fit was 38 nT. Extension of this model by the addition of Magsat data does not change the above quoted residuals a great deal, and the resulting model, GSFC (9/80), is in good agreement with MGST (6/80) at the Magsat epoch.

Using quick-look data from the first few days of Magsat operation, various pre-Magsat models were evaluated. These results are summarized in Table 4.

Global geomagnetic models will be undertaken by the USGS (Cain, Fabiano) and by the French investigators under the direction of LeMouel and the British investigators under the direction of Barraclough. The USGS investigators, in addition to publishing charts of the field, will pay particular attention to the problem of separating the core, crustal, and external contributions to the field, and of developing an adequate mathematical representation of each. The French and British will attempt a very accurate model of secular variation for predicting the field in the future and for studying properties of core fluid motions and interactions at the core/mantle boundaries. In addition to the global models, several investigators will attempt more accurate regional models for particular areas in order to isolate better the crustal anomaly fields in those areas.

Magsat will provide an accurate model of the main geomagnetic field, but its lifetime was too short for determining the secular variation of the field. The secular variation can be determined through comparison with earlier global surveys of the geomagnetic field from space, but such surveys are known to suffer from enhanced errors in certain sequences of harmonic terms. Stern (GSFC) will use the Magsat model to evaluate the extent of such enhanced errors, correct them, and then use the corrected models for deriving the mean secular variation over the 1965-1980 period.

Gibbs (Business and Technological Systems) will attack the secular variation problems from a statistical point of view by using recursive estimation theory to combine conventional models into optimal estimates of the field parameters for any given time. The statistical information so derived should enable a more accurate prediction capability as well as more accurate *a posteriori* models.

An alternative to the classical spherical harmonic representation will be attempted by Mayhew (Business and Technological Systems). He will

Table 4

RESIDUALS OF SELECTED MAGSAT DATA TO SOME PUBLISHED FIELD MODELS (nT)

		POGO (2/72)[10]	*IGRF 1975*[11]	*AWC/75*[12]	*IGS/75*[13]	*WC80*[14]	*PMAG (7/80)*[8]
Scalar:	mean deviation	9	−91	60	21	−21	−2
	standard deviation	105	124	125	119	117	79
	rms deviation	105	154	139	121	119	82
B_r:	mean deviation	6	12	25	20	31	13
	standard deviation	208	192	152	134	121	93
	rms deviation	208	192	154	135	125	94
B_θ:	mean deviation	18	51	−4	15	22	33
	standard deviation	114	108	93	84	89	59
	rms deviation	115	120	94	86	92	67
B_ϕ:	mean deviation	0	1	2	0	1	1
	standard deviation	165	125	89	89	61	61
	rms deviation	165	125	89	89	61	61

adopt methods of anomaly modeling by equivalent sources, representing the main field with an array of dipoles at a fixed radius within the core. If such a method proves feasible, it will potentially use less computer time than the usual methods.

CRUSTAL MAGNETIC ANOMALY INVESTIGATIONS

A crustal magnetic anomaly is the residual field after estimates of the core and external fields have been subtracted from the measured field. An anomaly map is a contour map of the measured average anomaly field at the altitude of the data. Anomaly maps have been derived from aeromagnetic and shipborne data for many years and used in the construction of geologic/geophysical models of the crust. Investigations with aeromagnetic and shipborne magnetic data have mainly concentrated on the very localized anomalies associated with small-scale geologic features and localized mineralization. However, in the past few years there has been an increased interest in studies of the broad-scale anomalies that appear in regional compilations of aeromagnetic and shipborne data.[15-19] Satellite anomaly maps are of recent origin and describe only the very broadest scale anomalies. Aeromagnetic and shipborne anomaly maps have usually been interpreted assuming a flat earth and a constant ambient field over the region of interest. Because of the extremely large scale of satellite-derived anomalies, both of these assumptions become invalid, thus necessitating development of new analysis techniques.

Originally, it was thought impossible to detect fields of crustal origin in satellite data. However, while analyzing data from the Pogo satellites, Regan *et al.*[20] discovered that the lower altitude data contained separable fields caused by crustal anomalies, thus opening the door to a new class of investigations. None of the satellites shown in Table 1 was designed for solid earth studies, yet results from the Pogo satellites have demonstrated the capability of mapping broad-scale anomalies. Although the map of Regan *et al.* was partially contaminated by "noise" from magnetospheric and ionospheric fields, the reality and crustal origin of several of the anomalies defined by the map were clearly demonstrated. More recently Langel *et al.*[10] have compared a Pogo-derived anomaly map with upward-continued aeromagnetic data from western Canada. Figure 1 shows the results of that comparison. The two maps are in substantial agreement, demonstrating further both the reality and crustal origin of the anomalies.

The techniques for preparing such a map include selecting suitable quiet-time data, removing the best estimate of the fields not originating in the earth's crust, and averaging data at the appropriate resolution. It is believed that these techniques can be readily adapted to Magsat data, both scalar and vector. It will be some months before an anomaly map is available from Magsat data. Individual pass residuals, however, clearly show the presence of

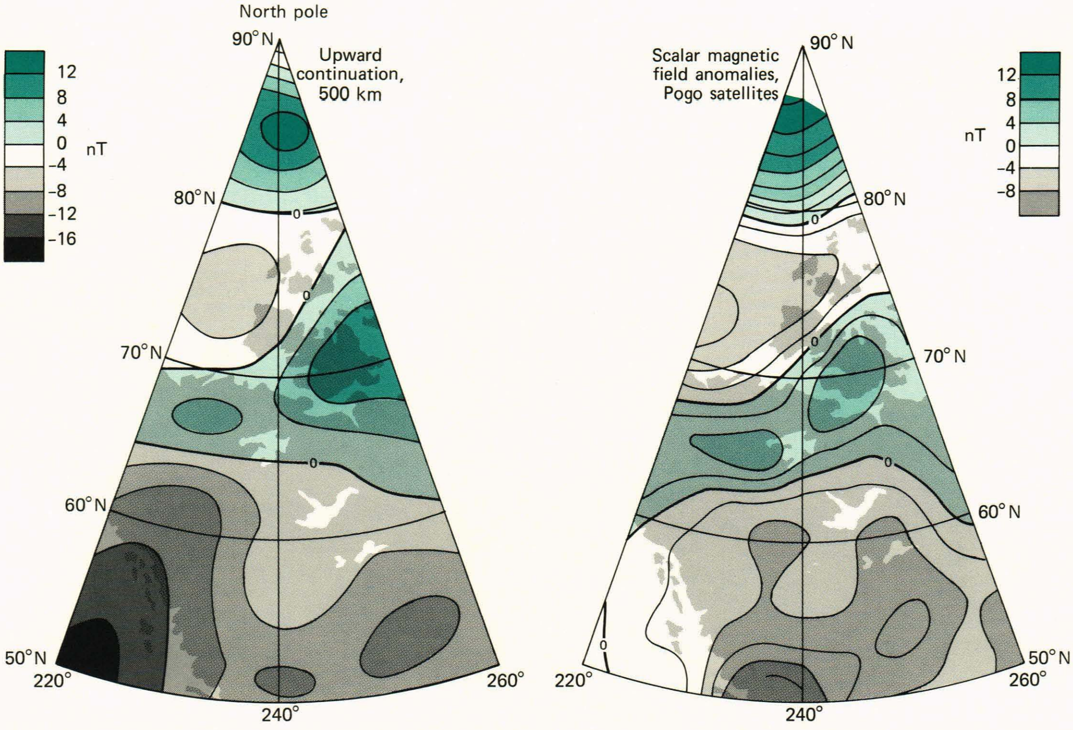

Fig. 1—Comparison of anomaly maps from upward continued aeromagnetic data and from Pogo data. Units are nanoteslas (nT).

these crustal fields. Figure 2, for example, shows the Bangui or Central African anomaly first discovered by Regan *et al.*[20]

The basic anomaly maps are only a starting point for interpretation. To maximize their usefulness they must be transformed to a common altitude and to the anomalies that would be present if the earth's field had the same inclination everywhere (reduction to a common inclination). Preliminary techniques for reduction to common altitude now exist and have been applied to Pogo data between ±50° latitude. The resulting map is shown in Fig. 3.

For geologic studies such anomaly maps must be inverted to a description of the magnetic properties of the crustal rocks. The inversions are not unique; constraints from other data sources will be required in their interpretation. As a first step in such modeling, traditional equivalent source methods, adapted for the case of a spherical earth with changing field inclination, have been applied to the United States[21] and Australia.[22] This technique assumes a constant 40 km thickness of the magnetic crust and derives the magnetization in such a crust that would cause the anomalies seen at the spacecraft. All of the anomalous field is assumed to be induced; i.e., remanent magnetization is assumed to be zero. The results for the United States are shown in Fig. 4. In many regions, known geologic features are clearly outlined (e.g., the Basin and Range Province, Colorado Plateau, Rio Grande Rift, Michigan Basin, and Mississippi Embayment) whereas some features are notable by the absence of magnetic features (e.g., the mid-continent gravity high). It will be some years before these maps are fully understood and interpreted, but they promise to shed new light on the geology of the deep crust.

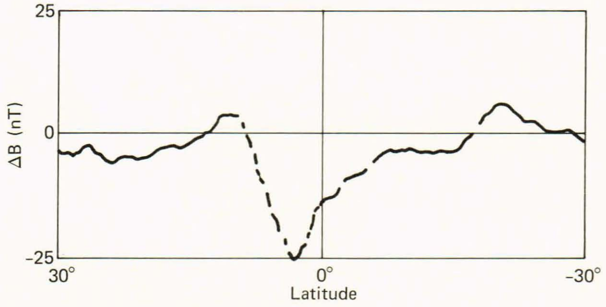

Fig. 2—The Bangui or Central African anomaly as seen in Magsat data. The equatorial longitude is 14.6°; the altitude is 425 km. ΔB is the residual anomalous field after subtracting a model of the core field from the measured field.

Anomaly maps, or even magnetization maps, are not an end in themselves. The object of these efforts is to derive models of the crust and upper mantle for large-scale regions of the globe. There are many kinds of models; their common purpose is to generalize observations and prediction. Through synthesis of particular models, complex models of crustal geologic systems are built up in terms of structural and compositional variations and the movements of material and energy. Conclusions can then be drawn about the evolution of regions that lead to inferences about the distribution of natural resources.

Figure 5 is an outline of an example of how one might think of the process of synthesizing models, beginning with satellite magnetic field data and including correlation with other data types. Models of gross variations in mean magnetization to the Curie isotherm can be developed from satellite data. This serves to quantify the anomaly map and can be of great utility in more detailed analysis of the data. Correlatively, from gravity measurements, variations in mean density to some fixed depth can be inferred, assuming homogeneity below that depth. These models can be combined with velocity

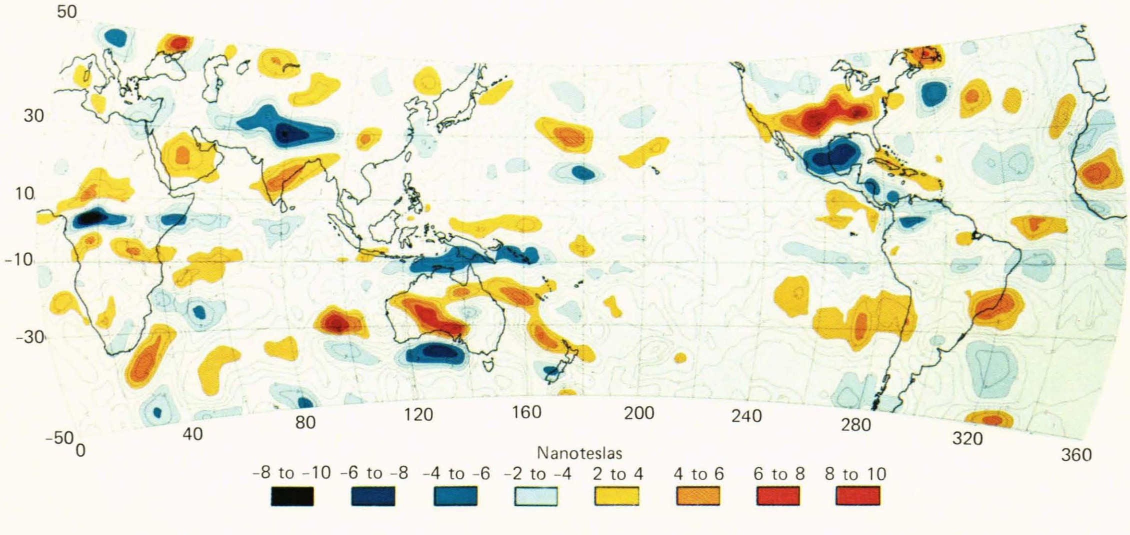

Fig. 3—Scalar magnetic anomaly map from the Pogo satellites reduced to 500 km altitude.

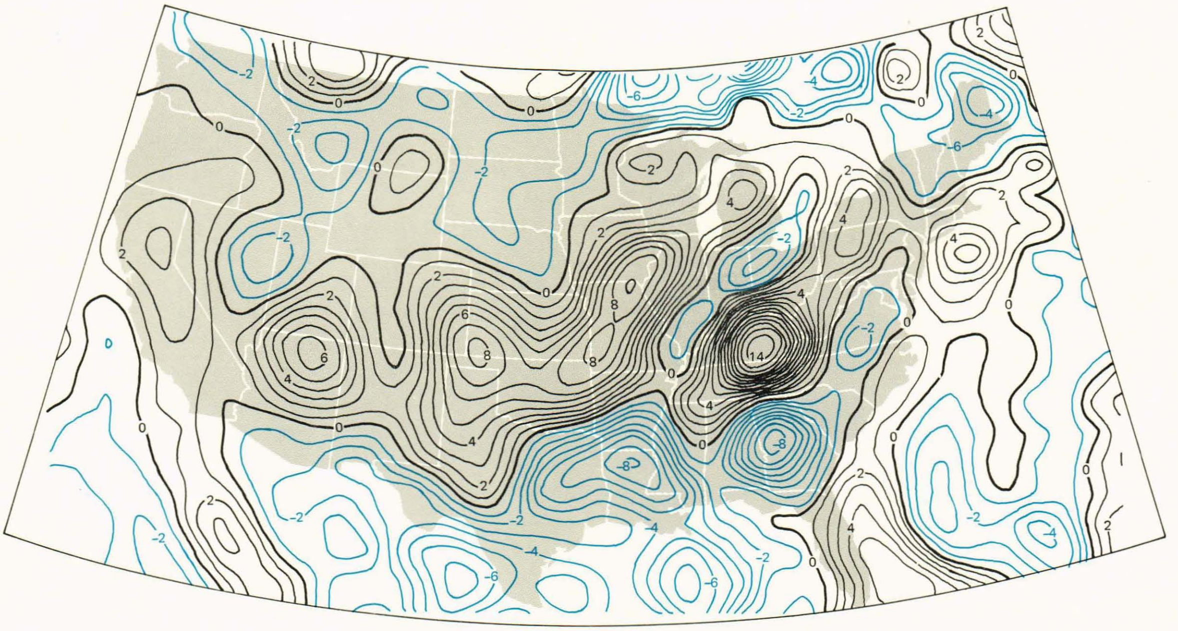

Fig. 4—Equivalent bulk magnetization derived from Pogo satellite data assuming a constant-thickness magnetic crust of 40 km. Units are EMU/cm^3 × 10^4.

models based on seismic data and with compositional models based on laboratory measurements of rock properties to give large-scale models of crustal structure and composition. Similarly, models of relative movements and of temperature distribution can be built for very large regions. These large-scale models can then be used to make more detailed models for smaller regions using a variety of data, some of which are also listed in Fig. 5. There are no hard and fast rules about the combination sequence, which depends on the region and the data available. Further, the process is an iterative one in which new data are sought based on predictions from interim models.

The Pogo satellites from which these maps were derived had two severe limitations for the studies: the altitude range was high (most data were from above 500 km), and the data were of field magnitude only. Magsat addresses both shortcomings. Its lower altitude increases the resolution by roughly a factor of 2 and the field strength of the anomalies by a factor of between 2 and 5, depending on the geometry of the source region. This is dramatically illustrated in Fig. 6, which shows a comparison between the lowest altitude Magsat data and low-altitude Pogo data. The Magsat data are at 187-191 km, while the Pogo data are at 414-420 km. The tracks are nearly coincident geographically.

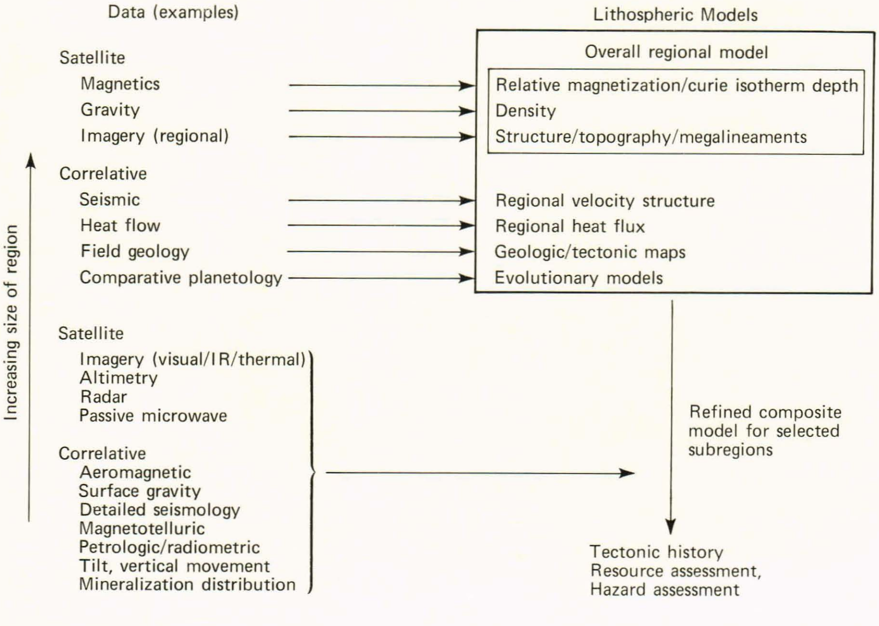

Fig. 5—Synthesis of geologic/geophysical models (idealized outline).

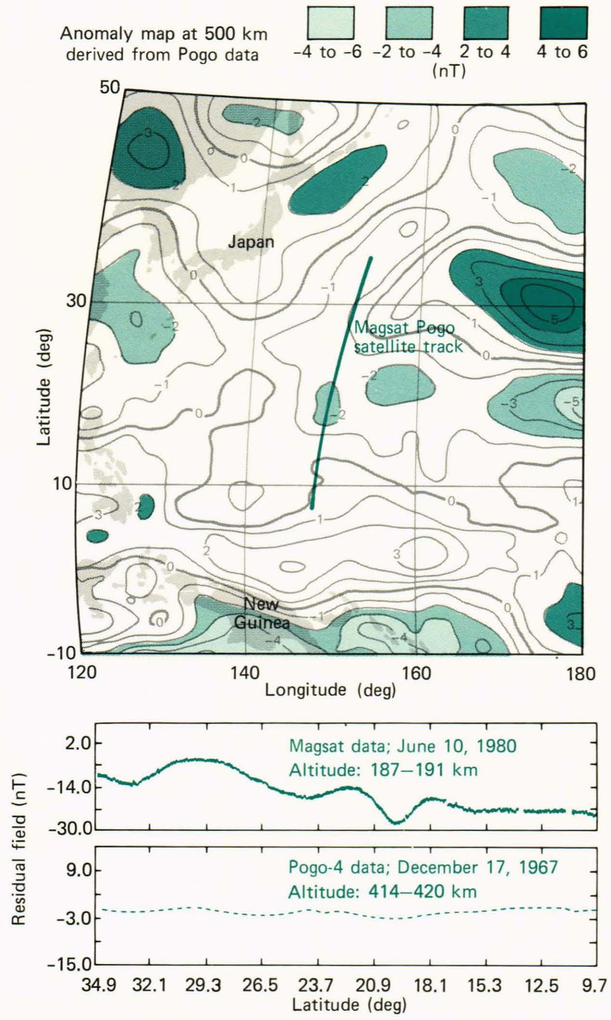

Fig. 6—Comparison between Pogo (OGO-4) data and the lowest altitude data from Magsat.

Magsat's lower altitude greatly enhances the resolution and signal strength of the anomalies. With field magnitude data, only indirect estimates of remanent magnetization are possible.[23] The vector data from Magsat measure anomaly directions other than along the earth's main field.

GSFC will derive a basic global magnetic anomaly map from the Magsat data. Many investigators will use that map or the associated magnetization map directly in their investigations. Other investigators will reexamine the basic derivation of the anomaly map and seek to extend or modify these techniques. Among the latter are:

Investigator	*Region Investigated*
Bhargava	India
Fukushima	Japan and vicinity
Coles and Hall	Canada
Hinze and Keller	South and Central America
Mayhew	United States
Johnson and Dooley	Australia and Antarctica
LeMouel	Europe and Central Africa

This type of modeling will be used by the investigators just listed for the continent-size regions indicated. When the larger region has been modeled, features of particular interest will become the subject of more intensive investigations. In some cases existing tectonic features have already been singled out for more localized modeling, such as the Narmada-son lineament in central India (Bhargava), the Superior province of Canada (Strangway), or the Japan Trench (Fukushima).

Continental-scale studies will utilize maps made at GSFC, including those of Pacca (Brazil), Bentley (Antarctica), and Hastings (Africa and South America).

Mayhew, Hinze, Coles, and Pacca will pay particular attention to mapping the Curie isotherm. Hinze, Keller, and Hastings are interested in the implications of the Magsat data for the plate-tectonic reconstruction of Africa and South America, a topic now under study by Langel, Frey, and Mead at GSFC using the Pogo data.

In addition to the continental-scale studies, several investigators will study more limited areas or particular tectonic features. Godivier (ORSTOM) will extend the work of Regan and Marsh[24] in the region around the Central African Republic where ORSTOM has a large amount of correlative data. Gasparini (Osservatorio Vesuviano) will investigate the Curie depth and volcanism in the Mediterranean area. Won (North Carolina State University) will study a combination of Magsat, aeromagnetic, and regional gravity data in the eastern Piedmont of the United States. Carmichael and associates (University of Iowa) will study the central midcontinent of the United States with particular attention to the known midcontinent geophysical anomaly.

In contrast to the large number of investigators studying continental-type regions, only three investigators are giving concentrated attention to oceanic regions. There are several reasons for this. First, the satellite anomaly maps derived from Pogo data show very few anomalies in oceanic regions compared to continental regions. Second, theoretically, the thinner oceanic crust should not contain anomalous features of comparable size to continental crust. Harrison (University of Miami) notes that a minimum in the power spectrum should occur between the contributions from core and crustal sources but that such a minimum is not present in spectra from shipborne data over oceanic basins. He will use Magsat data to study the intermediate wavelength anomalies. Brammer (TASC) will concentrate his efforts on a study of Magsat and Geos-3 altimeter gravity data in the eastern Indian Ocean.

LaBreque (Lamont-Doherty) will organize the existing shipborne data in an effort to help describe the secular variation over oceanic areas and to provide surface anomaly maps suitable for upward continuation and comparison with Magsat data.

Underlying all crustal models derived from Magsat and correlative data is a need for understanding the basic magnetic properties of crustal rocks. Such understanding depends on careful laboratory measurements, some at the higher temperatures and pressures of the lower crust. Preliminary studies[25] have already claimed to show the extremely significant result that the Moho is a magnetic boundary even when the Curie isotherm lies in the mantle. Wasilewski and the other GSFC investigators are continuing these efforts. Particular attention to petrologic constraints, the effects of oxygen fugacity, and other properties will be given by Haggerty (University of Massachusetts). A substantial refinement of the petrology of source rocks responsible for deep crustal anomalies is expected.

INVESTIGATIONS OF THE INNER EARTH

Man has directly penetrated only a few kilometers of the 6371 km distance to the earth's center. Information about the inner earth must be obtained by indirect methods such as seismology and measurements of the gravitational and magnetic fields.

Combining Magsat data with Pogo and near-surface surveys will permit more accurate determination of the secular variation of the core field. This variation will be used by Benton (University of Colorado) to study properties of the fluid motions in that core; in turn, appropriate magnetohydrodynamic constraints will be investigated to determine if they can aid in better modeling the secular variation.

When they are time-varying, magnetospheric fields result in induced fields within the earth because of the finite conductivity of the earth. The characteristics of these induced fields are determined by the properties of the materials in the earth's mantle (i.e., composition, temperature). At present the limiting factor in determining a precise conductivity profile within the earth, with adequate spatial resolution, is the accuracy possible in determining the external and induced fields. Hermance (Brown University) will use Magsat vector measurements together with surface data for a more accurate analysis than was previously possible.

STUDIES OF EXTERNAL CURRENT SYSTEMS

Early observers of the earth's magnetic field discovered that it continually undergoes transient changes. These changes include systematic variations that occur with daily regularity and irregular variations, both of amplitude and of a totally different kind, superimposed on the regular variations. Periods of time when the changes are mostly regular are called magnetically quiet; periods when the magnetic disturbances become irregular are called magnetically disturbed. When the irregular fields are large but mainly confined to high latitude, the condition is called a magnetic substorm; when the irregular fields are large and worldwide, it is called a magnetic storm. To understand such changes in field, one must realize that the space surrounding the earth contains several ''species'' of electric current. The energy for these currents comes ultimately from the sun. Figure 7 is an artist's conception (based on Fig. 1 of Heikkila,[26] wherein there is a more detailed explanation) of the magnetic environment of the earth. A stream of charged particles from the sun, called the solar wind, confines the earth's magnetic field to a cavity known as the magnetosphere. This cavity is compressed on the front, or sunward, side and drawn

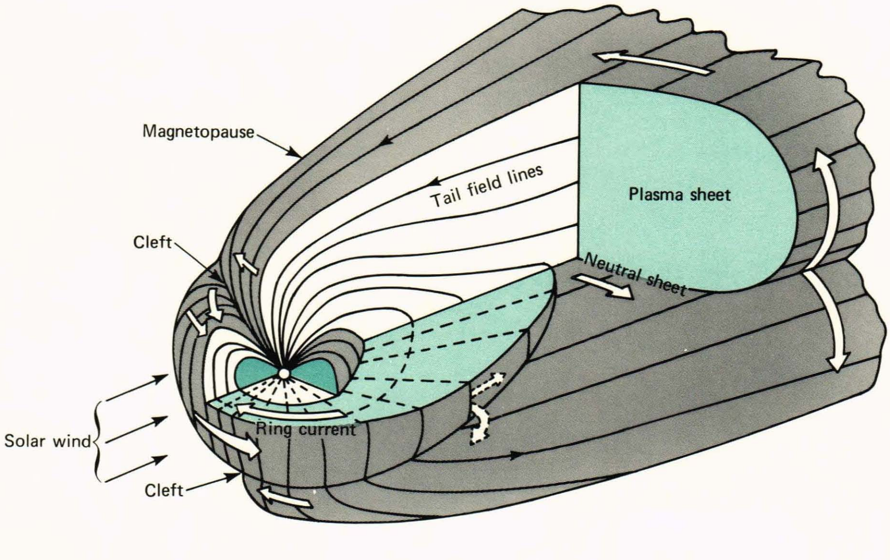

Fig. 7—Artist's conception of the configuration of the magnetosphere, adapted from Heikkila.[26] The magnetosphere is the region into which the earth's magnetic field is confined by the solar wind.

out in a "tail" to the antisunward side. Currents flow, as shown, on the boundaries of this cavity and across the tail. Also, trapped particles within the cavity flow in a "ring current" in a westward direction around the equatorial plane. Most of these currents are relatively distant from the earth and cause only small fields at Magsat locations. However, the ring current intensifies considerably during periods of magnetic disturbance and causes substantial fields at Magsat altitude.

In addition to the currents shown in Fig. 7, a variety of currents flow in the conducting layer of the atmosphere known as the ionosphere. The regular daily variations of the field observed at the surface are from such a current system, known as Sq (S for solar daily variation and q for quiet times). Sq is mainly a low- and mid-latitude phenomenon. At high latitudes very intense currents flow, often associated with auroral phenomena. These currents, illustrated schematically in Fig. 8,[27] are coupled to the ring current and to currents in the tail of the magnetosphere.

Because the Magsat orbit was near sun-synchronous, it sampled mainly twilight local times, a distinct disadvantage for synoptic studies of the magnetospheric fields, which are relatively fixed in local time. However, because it is the first near-earth satellite to obtain global vector measurements and because its measurement accuracy far exceeds that of spacecraft that obtained some near-earth vector measurements, Magsat will be very useful in extending previous research regarding current systems.

One reason for investigating these external current systems with Magsat is to aid in isolating their fields from the core and crustal fields. Several investigators will contribute to this effort. Regan (Phoenix Corp.) in particular will work toward removing external field effects from anomaly data. Klumpar (University of Texas) will concentrate his effort on extending existing models for high-latitude ionospheric currents and the field-aligned currents coupling the ionospheric currents to the magnetosphere. Burrows (NRC, Canada) and Potemra (The Johns Hopkins University Applied Physics Laboratory) will investigate the field-aligned currents, also using correlative data from satellite photographs of auroral phenomena (Burrows) and with simultaneous data from the Triad satellite (Potemra).

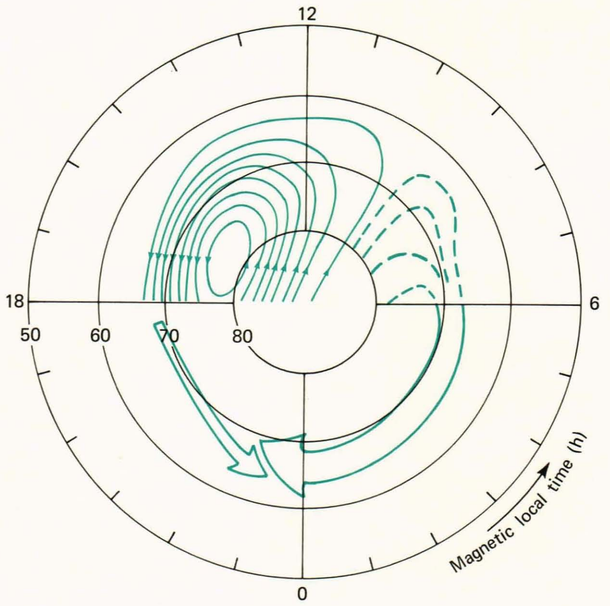

Fig. 8—Conceptual drawing of ionospheric current flow at high altitudes. Arrows indicate direction of current flow. Closure is not shown because some circuits close in the outer magnetosphere via field-aligned current.

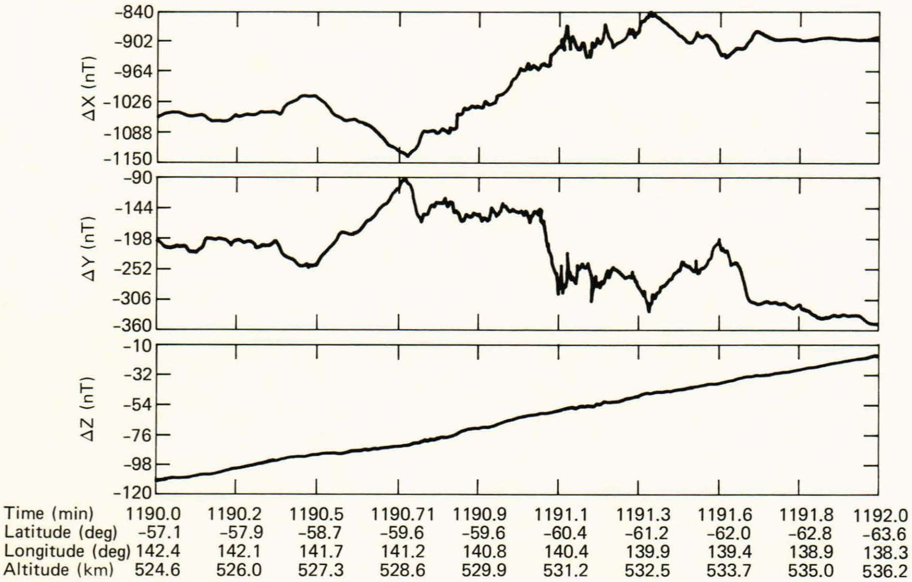

Fig. 9—Magnetic field variation caused by field-aligned current. The scale, in nT, is relative only.

Figure 9 shows the effects of field-aligned currents in Magsat data. ΔX, ΔY, ΔZ are residuals from a field model in a north-, east-, and down-coordinated system. Large-amplitude, highly structured variations occur in the north and east directions but not in the vertical direction, as expected from field-aligned currents.

CONCLUSION

Satellite-based magnetic field measurements make global surveys practical for both field modeling and for the mapping of large-scale crustal anomalies. They are the only practical method of accurately modeling the global secular variation. Magsat is providing a significant contribution, both because of the timeliness of the survey and because its vector measurement capability represents an advance in the technology of such measurements.

Data from Magsat are available for any interested user through the National Space Sciences Data Center at GSFC.

With the success of Magsat, future missions should take two courses. Field modeling requires periodic surveys, but not low-altitude measurements as required for crustal studies. On the other hand, further advances in satellite crustal studies will rest on NASA's ability to orbit magnetometers at still lower altitudes; such concepts are still in the stage of discussions as to their feasibility.

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