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MAGSAT SCIENTIFIC INVESTIGATIONS

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MAGSAT

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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. Nearly dipolar in nature, the strength of the main field is near 60,000 nT (nanotesla) at the poles and near 30,000 nT at the equator. Its temporal variation, called 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 fractions of a nT to thousands of nT. These current systems are located in a cavity-like region surrounding the earth and known as the magnetosphere. Although always present, the strength and location of these currents vary considerably between periods of magnetic quiet and periods of magnetic disturbance. 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 zero and 50 nT. Also called "anomaly fields," the sources are associated with variations in the geologic and/or geophysical properties in the earth's crust and, 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 both by means of permanent magnetic observatories, which 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 in the years 1698-1700 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 and 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 have 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 U.S. 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 industry on a local scale.

Satellite measurements of the geomagnetic field began with the launch of Sputnik 3 in May of 1958 and have continued sporadically in the intervening years. Table 1 is a list of spacecraft which have made significant contributions to our understanding of the near-earth geomagnetic field. Each has its own limitations, from a lack of global coverage due to 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 OGO 2, 4 and 6 (POGO) satellites have provided a truly accurate, global geomagnetic survey. These satellites operated between 1965 and 1971 and their alkali vapor magnetometers provided global measurements of the field magnitude approximately every ½ second over an altitude range of about 400 to 1500 km (Cain and Langel, 1971; Langel, 1974a).

A new era in near-earth magnetic field measurements began with NASA's launch of Magsat in October of 1979. Magsat is providing the first truly global geomagnetic survey since the Pogo satellites, and the very first global survey of vector components of the geomagnetic field. Magsat is designed with two major measurement tasks in view: to provide a global vector survey of the main geopotential field and to provide a lower-altitude measurement of crustal anomalies. These tasks stem directly from the Magsat mission objectives outlined by <u>Ousley</u> (this issue). Analysis of the data from Magsat will be carried out by a large number of investigators, some of whom are working cooperatively. The next section indicates who these investigators are and the following sections describe in more detail the type of investigations they will be conducting.

OVERVIEW OF INVESTIGATIONS

Investigations are being carried out by scientists at Goddard Space Flight Center (GSFC), the U.S. Geological Survey (USGS) and by scientists selected in response to a NASA Announcement of Opportunity (AO). Much of this report reflects the work at GSFC, which includes derivation of the first geomagnetic field models from Magsat, derivation of the global anomaly map from POGO, and some interpretation 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 institution, and a brief description of their proposed investigation. More detailed information regarding most of these investigations will be given in the remainder of this paper which, not counting the Conclusion, 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 which causes the magnetic anomalies;
3. Investigations of the inner earth: the core, mantle and core-mantle interface area;
4. Studies of external current systems.

GEOMAGNETIC FIELD MODELING

By geomagnetic field modeling is meant derivation of the spherical harmonic potential function which 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. In practice a restricted model must be chosen on practical grounds: the finite limitation on computer size and speed. Most researchers attempt only to represent the core field with a potential function and utilize 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 long term, or secular, variation in the main geomagnetic field which 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 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 will furnish another. These, together with existing surface data, will permit accurate global representation of secular variation for the period beginning with OGO 2 until the demise of Magsat: roughly October 1965 through July 1980. Future 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 (Backus, 1970; Hurwitz and Knapp, 1974; Stern and Bredekamp, 1975; Lowes, 1975). This ambiguity will be 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 will be finalized in early 1980, the total intensity charts by the end of 1980, and the world charts by August 1981. Magsat data will contribute to all of these sets of charts.

To provide timely input for all applications, a series of field models will be derived from data during quiet magnetically times over the period of data accumulation. One has already been generated from two full days of data (Langel et al., 1980c). At appropriate intervals this model 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 have the lowest Kp indices. The highest three hourly Kp value is 1+, which occurred only once. Plots of Dst and of the data itself also indicated that these days were indeed very quiet. Accordinly, a selection of 7468 data points from these days was used to derive the first geomagnetic field model from Magsat (Langel et al., 1980c). The spherical harmonic coefficients are given in Table 3. Vector data above 50^{o} latitude were not included because of curl-free fields from field aligned currents. Such fields are transverse to the main field and, as shown by Langel (1974a), have little or no effect on the field magnitude. However, 1679 values of B_r, 1681 of B_θ, and 1694 values of B_ϕ were included for latitudes below 50^{o}.

This model fits the selected data with the mean and standard deviations shown in the following Table:

COMPONENT	MEAN DEVIATION (nT)	STANDARD DEVIATION (nT)
Scalar Magnitude	0	8
B_r	22	52
B_θ	10	55
B_ϕ	84	97

The source of the non-zero means for the vector data appears to be a bias of 4-7 arc-minutes in the initial attitude solution. The standard deviation of the scalar data is mainly due to a combination of fields from external and crustal sources, neither of which is modeled. The standard deviation of the vector data is due to current lack of precision in spacecraft attitude.

As part of our preparation for Magsat, Pogo data was combined with surface data from observatories between 1960 and 1977, selected repeat data, and selected shipborne data to derive what we consider to be the best possible pre-Magsat model (Langel et al., 1980b). Both constant and first derivative time terms were included to degree and order 13. This model, designated PMAG(10/79), utilized a new technique for dealing with the observatory data.

As at the satellite, surface fields contain contributions from the three sources. For field modeling the annual mean value for each observatory are usually utilized so that the external contribution is some (hopefully small) averaged value. Crustal anomaly fields are, however, typically quite large. For past models the rms residual of surface data to the model has typically been between one and two hundred nT (see, e.g., Cain et al., 1967). 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(10/79) model. After solving for the coefficients of the potential function and the observatory "biases," the rms residual of the observatory data was reduced to 16 nT. For repeat data this procedure was not feasible due to lack of extensive temporal change. These data were incorporated by including only locations where three or more measurements, at different times, were available. Each component at each location was then represented by a linear fit and only the rate of change was utilized in deriving PMAG(10/79). The residual to the fit was 6 nT per year. 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 27 nT.

Utilizing 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 also 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 adequately mathematically representing each. The French and British will attempt a very accurate model of secular variation both for the purpose of predicting the field in the future and also for use in 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 better isolate the crustal anomaly fields in those areas.

Magsat will provide an accurate model of the main geomagnetic field, but its expected lifetime is 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 using scalar data, 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 period 1965-1980.

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

CRUSTAL MAGNETIC ANOMALY STUDIES

By crustal magnetic anomaly is meant the residual field when 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 utilized 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 apppear in regional compilations of aeromagnetic and shipborne data (see, e.g., Pakiser and Zeitz, 1965; Zietz et al., 1966; Shuey et al., 1973; Hall, 1974; Kruitkhovskaya and Paskevich, 1977). 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 their extremely large scale, both of these assumptions are invalid for satellite-derived anomalies, 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. (1975) discovered that the lower altitude data contained separable fields due to crustal anomalies, thus opening the door to a new class of investigations. None of the satellites shown in Table 1 were 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. (1980a) 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 selection of 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 these crustal fields. Figure 2, for example, shows the Bangui or Central African anomaly first discovered by Regan et al. (1975).

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 were 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 $\pm 50^{\circ}$ latitude. The resulting map is shown in Figure 3.

For geologic studies, such anomaly maps must be inverted to a description of the magnetic properties of the crustal rocks. Such inversions are not unique and 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 (Mayhew, 1979) and Australia (Mayhew et al., 1980). This technique assumed a constant 40 km thickness of the magnetic crust and derives the magnetization in such a crust which 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 Figure 4. In many regions known geologic features are clearly outlined (e.g., the Basin and Range, 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.

Anomaly maps, or even magnetization maps, are not an end in themselves. The object of these efforts is the derivation of models of the crust and upper mantle for large scale regions of the globe. There are many kinds of models. They have as common purposes generalization of 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 one 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 this depth. These models can be combined with velocity 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 up 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 types, some of which are also listed in Figure 5. There are no hard-and-fast rules about the combination sequence; this 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 these studies; the altitude range was high, most data being above 500 km, and the data were of field magnitude only. Magsat addresses both of these shortcomings. Its lower altitude increases the resolution by roughly a factor of two and the field strength of the anomalies by a factor of between two and five, depending on the geometry of the source region. With field magnitude data, only indirect estimates of remanent magnetization are possible (Bhattacharyya, 1977). The vector data from Magsat measures anomaly directions other than along the earth's main field.

We at GSFC will derive a basic global magnetic anomaly map from the Magsat data. Many investigators will use the map, and/or the associated magnetization map, directly in their investigations. Other investigators will re-examine 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, Hall	Canada
Hinze and Keller	South and Central America
Mayhew	United States
Johnson, Dooley	Australia, Antarctica
LeMoel	Europe and Central Africa

This type of modeling will be carried out by the investigators listed above for the continental size regions indicated. When the larger region has been modeled, features of particular interest will become the subject of more intensive investigation. 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 which will utilize maps made at GSFC include Pacca (Brazil), Bently (Antarctica) and Hastings (Africa and South America).

Mayhew, Hinze, Coles and Pacca will pay particular attention to mapping of 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 utilizing 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 (1979) in the region around the Central African Empire where Orstom has a large amount of correlative data. Gasparini (Osservatorio Vesuviano) will investigate the Curie depth and volcanism in the Mediterranean area. Won (N.C. State University) will study a combination of Magsat, aeromagnetic and regional gravity data in the eastern Piedmont of the U.S. Carmichael and associates (U. of Iowa) will study the central mid-continent of the U.S. with particular attention paid to the known mid-continent geophysical anomaly.

In contrast to the large number of investigations cited as studying continental type regions, there are only three investigators 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 (U. 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 utilize 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 upon careful laboratory measurements, some at the higher temperatures and pressures of the lower crust. Preliminary studies by Wasilewski et al. (1979) 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 (U. 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 6378 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 gravity 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 (U. of Colorado) to study properties of the fluid motions in that core and, in turn, appropriate magnetohydrodynamic constraints will be investigated to determine if they can aid in better modeling the secular variation.

When magnetospheric fields are time-varying, they 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 utilize Magsat vector measurement together with surface data for a more accurate analysis than 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 occurring with daily regularity and of 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, and periods where the magnetic disturbances become irregular are called magnetically disturbed. When the irregular fields are large but mainly confined to high latitudes it is called a magnetic substorm, and 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 6 is an artists conception (based on Figure 1 of Heikkila, 1972 wherein find a more detailed explanation) of the magnetic environment of the earth, the magnetosphere. 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 out in a "tail" to the anti-sunward 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. The ring current, however, intensifies considerably during periods of magnetic disturbance and causes substantial fields at Magsat.

In addition to the currents shown in Figure 6, 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 phenomena. At high latitudes very intense currents flow, often associated with auroral phenomena. These currents, illustrated schematically in Figure 7 (Langel, 1974b) are coupled to the ring current and to currents in the tail of the magnetosphere.

Because Magsat is near sun-synchronous it will sample mainly twilight local times, a distinct disadvantage for synoptic studies of the magnetospheric fields, which are relatively fixed in local time. However, because Magsat is the first near-earth satellite to obtain global vector measurements and because its measurement accuracy far exceeds that of those spacecraft which did obtain some near-earth vector measurements, it is expected to be very useful in extending previous research regarding these 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 but Regan (Phoenix Corp.) will particularly work toward removing external field effects from anomaly data.

Klumper (U. 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 (NRL, Canada) and Potemra (Johns Hopkins, Applied Physics Lab) will particularly 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).

Figure 8 shows the effects of field-aligned currents in Magsat data. Delta-X, -Y, -Z 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 will be available for any interested user through the National Space Sciences Data Center at Goddard Space Flight Center.

If Magsat proves successful, 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, concepts for which are still in the stage of discussions as to their feasibility.

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TABLE 1: SATELLITES WHICH HAVE MEASURED THE NEAR-EARTH GEOMAGNETIC FIELD

SATELLITE	INCLINATION	ALTITUDE RANGE (km)	DATES	INSTRUMENT	APPROXIMATE ACCURACY (γ)	COVERAGE
Sputnik 3	65^0	440-600	5/58 - 6/58	Fluxgates	100	USSR
Vanguard 3	33^0	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	49^0	270-403	3/64	Proton	unknown	whole orbit
Cosmos 49	50^0	261-488	10/64-11/64	Proton	22	whole orbit
1964-83C	90^0	1040-1089	12/64-6/65	Rubidium	22	near ground station
OGO-2	87^0	413-1510	10/65-9/67	Rubidium	6	whole orbit
OGO-4	86^0	412-908	7/67-1/69	Rubidium	6	whole orbit
OGO-6	82^0	397-1098	6/69-7/71	Rubidium	6	whole orbit
Cosmos 321	72^0	270-403	1/70-3/70	Cesium	unknown	whole orbit
Azur	103^0	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 was acquired only when the spacecraft was in sight of a station equipped to receive telemetry.

Table 2
List of 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	To adjust the Gauss coefficients of the main field model of the Magsat data set to satisfy dynamic constraints; to use Magsat data to test the ability to forecast the structure of the internal geomagnetic field
B. N. Bhargava	Indian Institute for Geomagnetism/INDIA	Magsat for Geomagnetic Studies in the Indian Region	Prepare a regional geomagnetic reference field and magnetic anomaly maps over the Indian and neighboring regions; to gain a clearer understanding of secondary effect features and the variability of the dawn/dusk field; to study in detail the equatorial electrojet and transient variations
Robert F. Brammer	The Analytic Sciences Corporation	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/CANADA	Studies of High Latitude Current Systems Using Magsat Vector Data	Understand the physical processes which 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	To analyze Magsat anomaly data to synthesize a total geologic model and interpret crustal geology in the midcontinent region; to contribute to the interpretation and calculation of the depth of the Curie Isotherm

Table 2 (continued)

INVESTIGATOR	INSTITUTION/COUNTRY	TITLE	OBJECTIVES
Richard L. Coles	Energy, Mines and Resources Canada/ 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 air-craft 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, 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	Analysis of 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	To produce a state vector to predict field values for several years beyond the Magsat model; to obtain optimal estimates of field values throughout the 1900-1980 period
M. R. Godivier	Office de la Recherche Scientifique et Technique Outremer/FRANCE	Magnetic Anomaly of Bangui	Improve the explanation of the cause of the Bangui anomaly, using Magsat data, other magnetic data, gravity, seismic, and heat flow data
Stephen E. Haggerty	University of Massachusetts	The Mineralogy of Global Magnetic Anomalies	To interpret Magsat data to locate mafic and ultramafic source rocks and lineament expressions of anomalies that can be corre-lated with crustal of upper mantle depths; to determine mineral stabilities pertinent to magnetic anomalies to determine the magnetic properties of metamorphic rocks

Table 2 (continued)

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 the crust mantle magnetization
Christopher G. A. Harrison	University of Miami	Investigations of Medium Wavelength Magnetic Anomalies in the Eastern Pacific Using Magsat Data	To determine the relationship of magnetic anomalies with surface geological features
David A. Hastings	Michigan Technological University	An Investigation of Magsat and Complementary Data Emphasizing Precambrian Shields and Adjacent Areas of West Africa and South America	To determine the Magsat magnetic signatures of various tectonic provinces; to determine the geological associations of these signatures; to synthesize Magsat and other data with mineral resources data globally
John F. Hermance	Brown University	Electromagnetic Deep-Probing (100-1000 kms) of the Earth's Interior from Artificial Satellites: Constraints on the Regional Emplacement of Crustal Resources	To 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	Magnetic anomalies will be used to develop lithospheric models to determine the properties of principal tectonic features; magnetic anomalies of South America will be correlated with those of adjacent continental areas to attempt to reconstruct Gondwanaland (see 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	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	To provide models of the seismic velocity structure of the lithosphere (see above)

Table 2 (continued)

INVESTIGATOR	INSTITUTION/COUNTRY	TITLE	OBJECTIVES
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	To determine the distribution of intermediate wavelength magnetic anomalies of lithospheric origin in the oceans; the extent to which Magsat describes the distribution, and to determine the cause of these anomalies
Jean-Louis Le Mouel	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.	To 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	To model the core field; compute equivalent spherical harmonic coefficients for comparison with other field models; to 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
Thomas A. Potemra	Johns Hopkins University	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 which can be used to improve geomagnetic field models

Table 2 (continued)

INVESTIGATOR	INSTITUTION/COUNTRY	TITLE	OBJECTIVES
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 better defining 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	To 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	Examination of 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

Table 3. The MGST(3/80) field model. The mean radius of the Earth was assumed to be 6371.2 km. Mean epoch is 1979.85.

n	m	g_n^m, nT	h_n^m, nT
1	0	-29990.1	0.0
1	1	-1958.1	5609.5
2	0	-1993.2	0.0
2	1	3027.7	-2129.5
2	2	1662.4	-192.3
3	0	1269.6	0.0
3	1	-2180.1	-331.4
3	2	1251.7	270.6
3	3	833.3	-250.6
4	0	937.2	0.0
4	1	782.7	211.9
4	2	399.2	-257.6
4	3	-419.8	51.3
4	4	198.7	-297.6
5	0	-213.7	0.0
5	1	357.1	42.9
5	2	261.0	148.8
5	3	-73.3	-150.5
5	4	-162.8	-78.8
5	5	-46.5	90.6
6	0	48.9	0.0
6	1	65.3	-14.4
6	2	41.1	93.8
6	3	-192.2	70.9
6	4	3.9	-43.2
6	5	14.1	-2.7
6	6	-107.8	17.2
7	0	70.6	0.0
7	1	-58.6	-81.2
7	2	1.9	-27.2
7	3	20.5	-5.1
7	4	-12.3	16.4
7	5	-0.2	18.6
7	6	10.9	-22.9
7	7	-2.1	-9.2
8	0	18.1	0.0
8	1	6.7	6.7
8	2	-0.2	-17.8
8	3	-10.8	4.2
8	4	-7.1	-22.1
8	5	4.4	9.3
8	6	2.4	16.0
8	7	6.0	-13.1
8	8	-1.8	-15.8
9	0	5.7	0.0
9	1	10.1	-21.3
9	2	1.0	15.0
9	3	-12.8	9.0
9	4	9.3	-4.9
9	5	-3.1	-6.7
9	6	-1.3	8.7
9	7	6.6	9.5
9	8	1.5	-6.7
9	9	-4.5	3.5
10	0	-3.1	0.0
10	1	-3.6	1.3
10	2	2.4	0.6
10	3	-5.2	2.5
10	4	-2.0	5.5
10	5	4.6	-4.3
10	6	3.2	-0.1
10	7	0.6	-1.4
10	8	2.1	3.5
10	9	3.5	-0.4
10	10	-1.0	-6.5
11	0	2.2	0.0
11	1	-1.3	0.7
11	2	-1.8	1.9
11	3	2.2	-1.1
11	4	0.2	-2.7
11	5	-0.5	0.7
11	6	-0.3	-0.1
11	7	1.9	-2.3
11	8	1.9	0.0
11	9	-0.3	-1.6
11	10	2.1	-0.8
11	11	2.4	0.8
12	0	-1.7	0.0
12	1	0.6	0.9
12	2	-0.1	0.3
12	3	-0.1	2.2
12	4	0.3	-1.5
12	5	0.6	0.6
12	6	-0.6	0.3
12	7	-0.4	-0.3
12	8	-0.0	0.3
12	9	-0.7	-0.3
12	10	0.0	-1.5
12	11	0.1	-0.5
12	12	1.4	-0.3
13	0	0.1	0.0
13	1	-0.4	-0.2
13	2	0.3	0.4
13	3	-0.5	1.7
13	4	-0.1	0.1
13	5	1.2	-0.6
13	6	-0.5	-0.1
13	7	0.1	1.0
13	8	-0.4	0.1
13	9	-0.0	0.9
13	10	0.0	0.4
13	11	-0.1	-0.4
13	12	0.7	-1.1
13	13	0.4	0.5

TABLE 4

DEVIATIONS OF MAGSAT DATA FROM MODEL (nT)

MODEL	REFERENCE	SCALAR MEAN DEVIATION	SCALAR STANDARD DEVIATION	B_r MEAN DEVIATION	B_r STANDARD DEVIATION	B_θ MEAN DEVIATION	B_θ STANDARD DEVIATION	B_ϕ MEAN DEVIATION	B_ϕ STANDARD DEVIATION
IGRF	IAGA, 1976	-90	125	29	204	44	146	62	181
AWC/75	Barraclough et al., 1975	61	127	46	153	+10	115	62	157
IGS/75	Peddie and Fabiano, 1976	23	120	40	137	8	114	61	155
POGO(02/72)	Langel et al., 1980a	9	107	25	211	12	145	61	208
PMAG(10/79)	Langel et al., 1980b	5	95	29	151	12	123	60	174

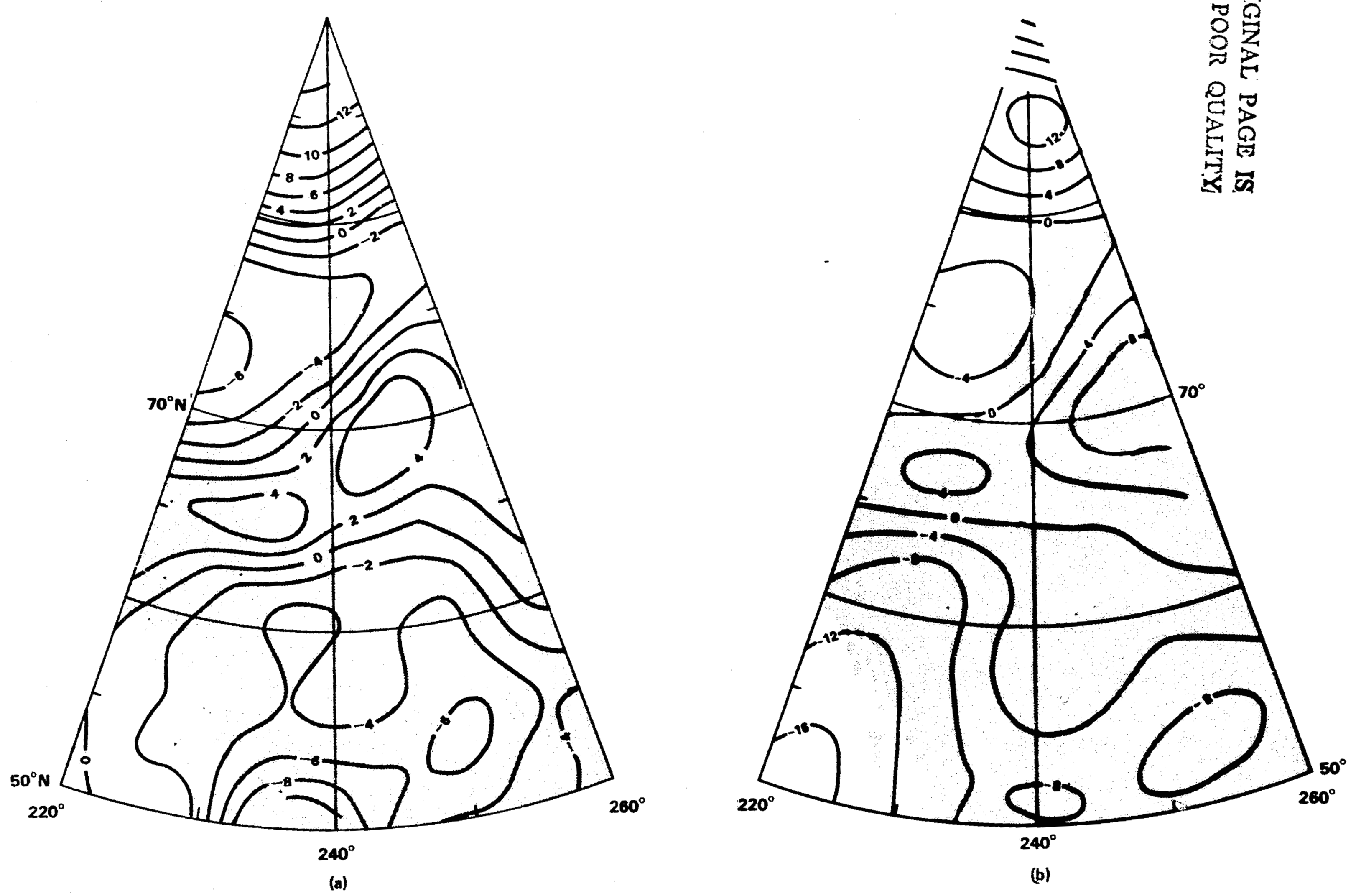
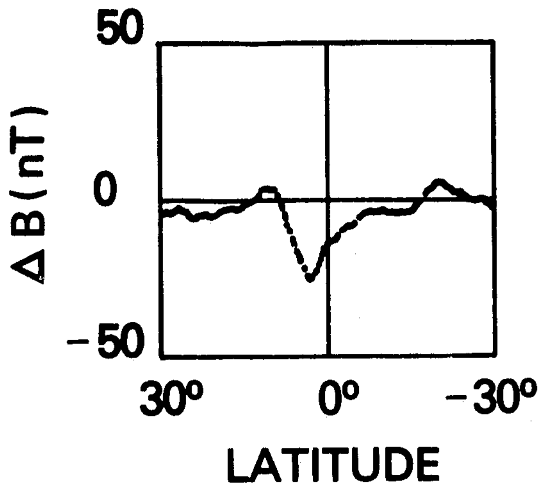


Figure 1: Comparison of anomaly maps from upward continued aeromagnetic data and from POGO data. Units are nT.



THE BANGUI OR CENTRAL AFRICAN ANOMALY AS SEEN IN MAGSAT DATA. THE EQUATORIAL LONGITUDE IS 14.6°, THE ALTITUDE IS 425KM.

Figure 2

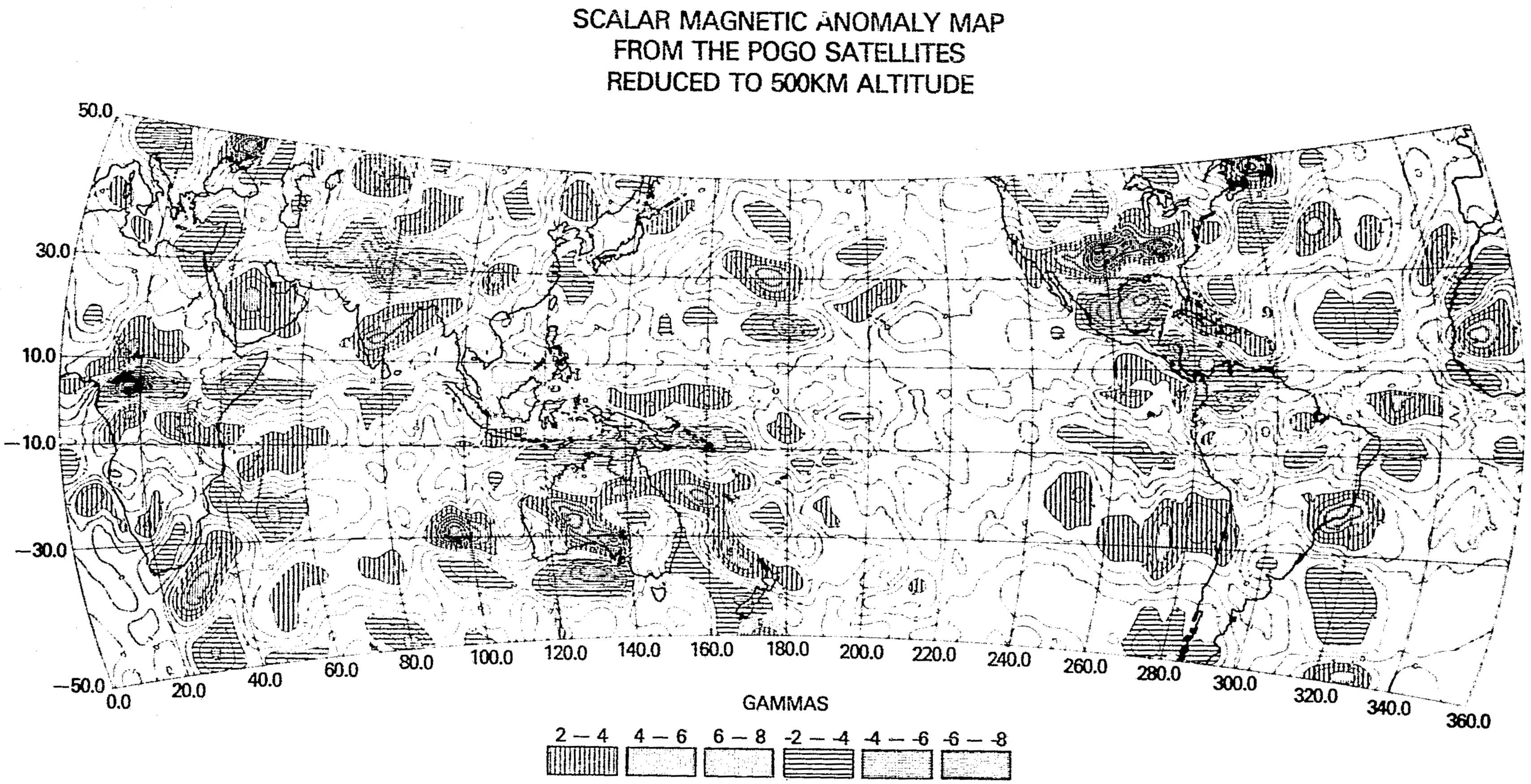

SCALAR MAGNETIC ANOMALY MAP
FROM THE POGO SATELLITES
REDUCED TO 500KM ALTITUDE
50.0
30.0
10.0
−10.0
−30.0
−50.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
220.0
240.0
260.0
280.0
300.0
320.0
340.0
360.0
GAMMAS
2 — 4
4 — 6
6 — 8
-2 — -4
-4 — -6
-6 — -8

Figure 3

EQUIVALENT BULK MAGNETIZATION DERIVED FROM POGO SATELLITE DATA ASSUMING A CONSTANT THICKNESS MAGNETIC CRUST OF 40 KM. UNITS ARE EMU/CC x 10^4.

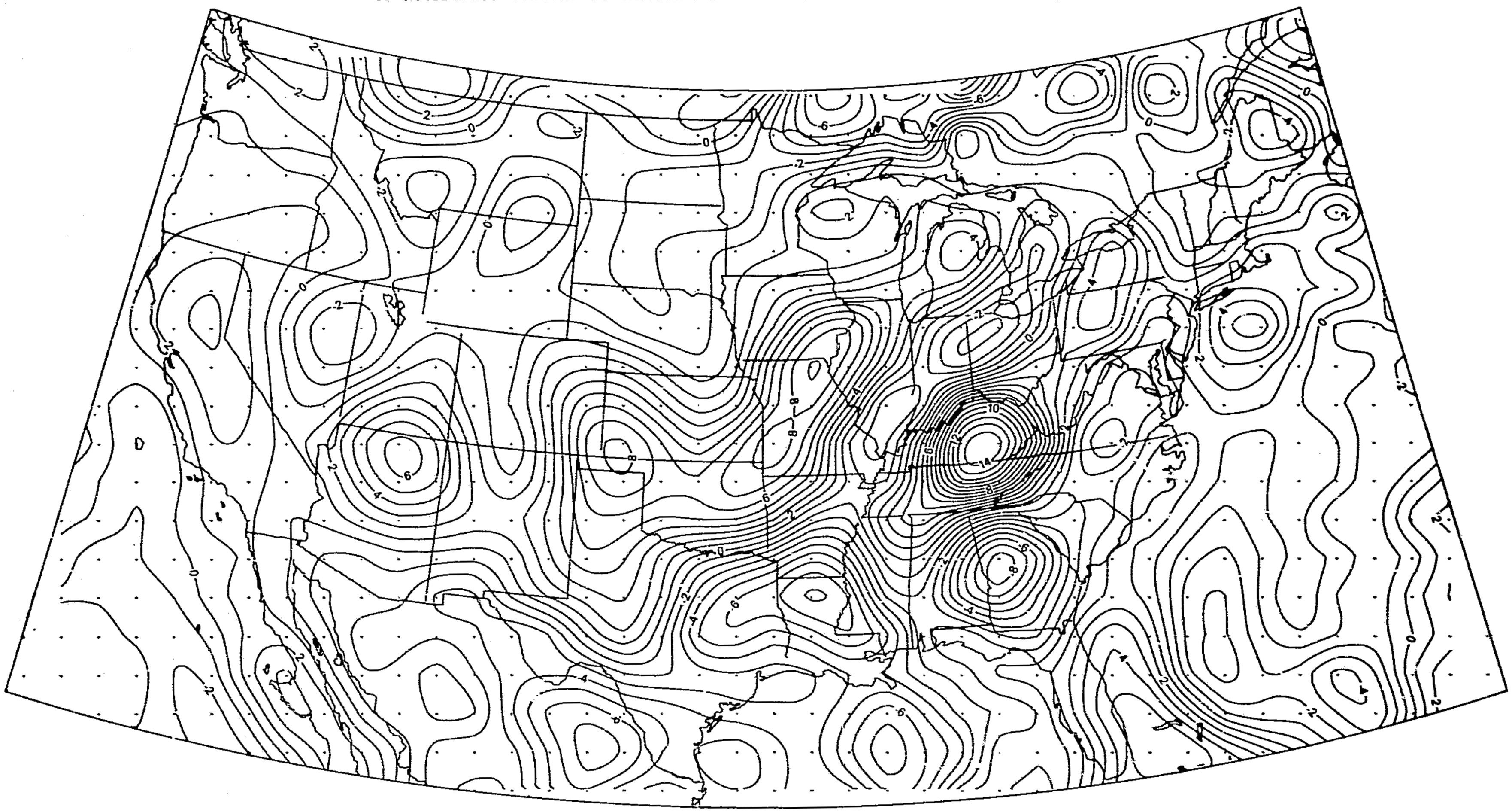


Figure 4

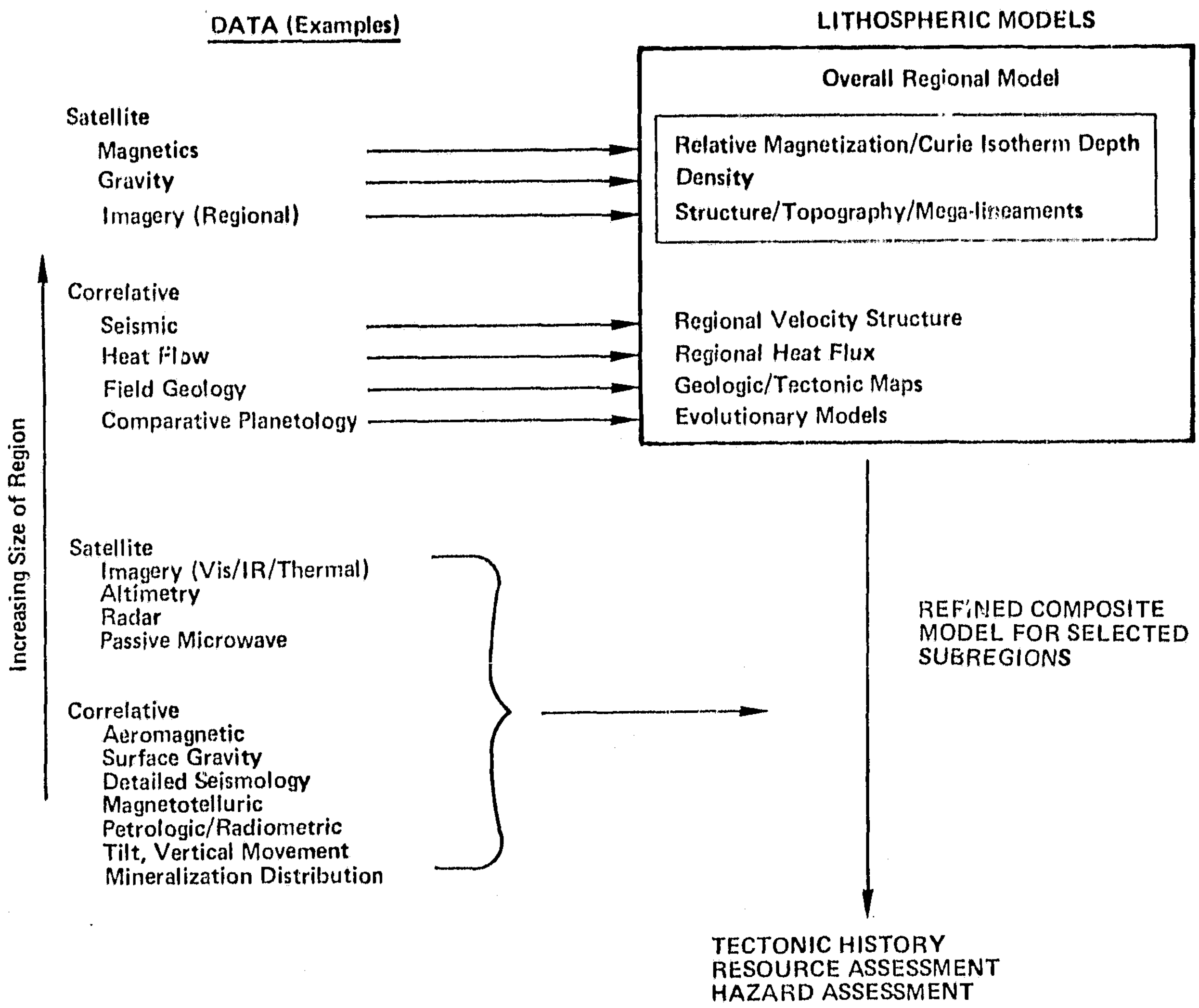


Figure 5. Synthesis of Geological/Geophysical Models—Idealized Outline

THE MAGNETOSPHERE

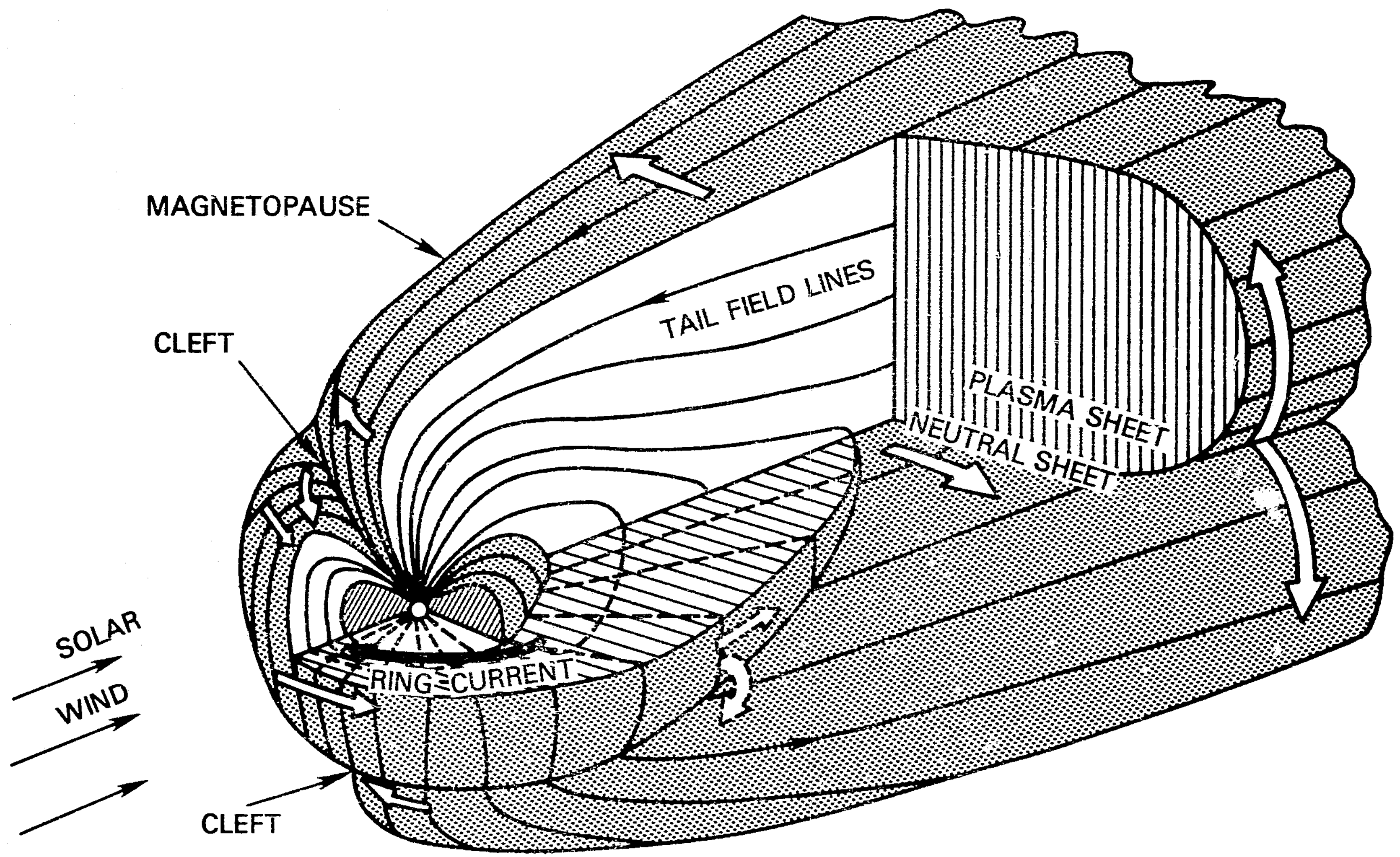


Figure 6: Artists conception of the configuration of the magnetosphere.

Adapted from Heikkila, 1972.

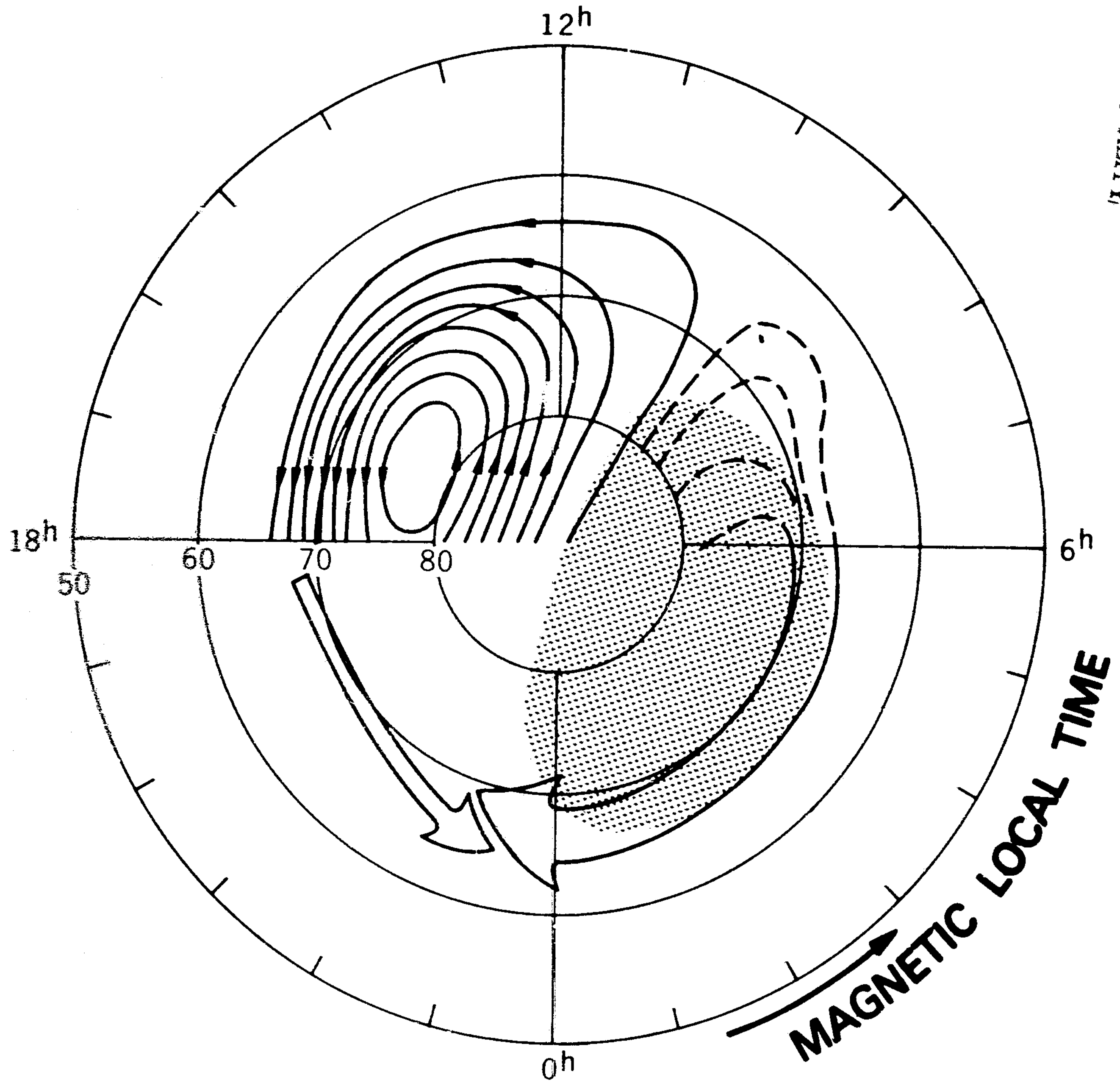


Figure 7: Conceptual drawing of ionospheric currents.

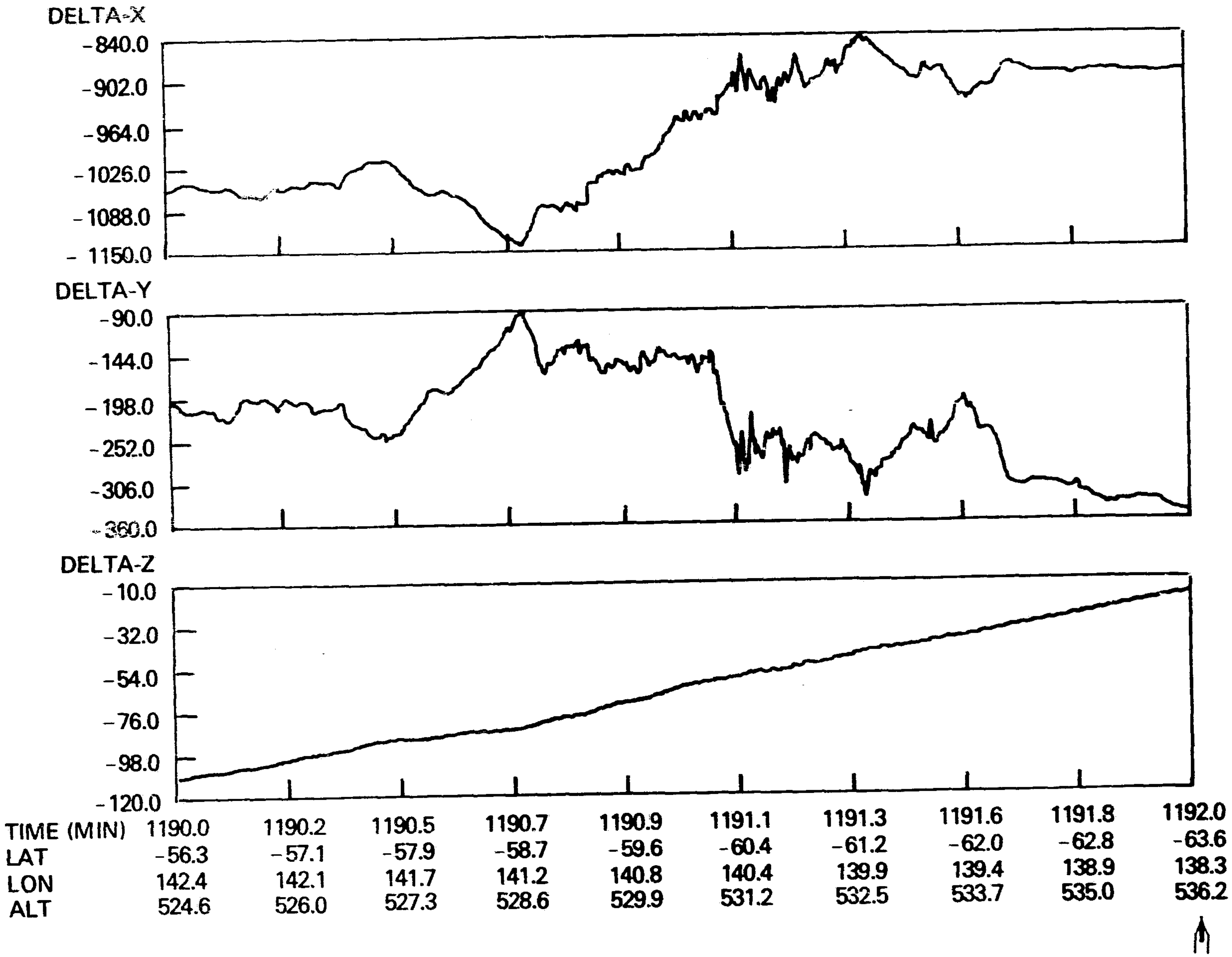


Figure 8: Magnetic field variations due to field-align current.
The scale, in nT, is relative only.

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		11. Contract or Grant No.
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address same as above		
		14. Sponsoring Agency Code

15. Supplementary Notes

The Magsat spacecraft is providing the first global, vector magnetic survey. Investigations using the Magsat data are being carried out by scientists at N

16. Abstract

The Magsat spacecraft is providing the first global, vector magnetic survey. Investigations using the Magsat data are being carried out by scientists at NASA's Goddard Space Flight Center, at the U.S. Geological Survey of the Department of the Interior and by 32 selected investigators. Nineteen of the investigators are from the United States and 13 are from various foreign nations. The investigations described herein fall into four categories: (1) geomagnetic field modeling, (2) crustal magnetic anomaly studies, (3) investigations of the inner earth: the core, mantle and core-mantle interface, and, (4) studies of external current systems.

17. Key Words (Selected by Author(s))	18. Distribution Statement
magnetic field, crustal anomalies, field models, magnetic field investigations	

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