BTS07-84-05/rb
1049

February 1984

NASA CR- 175230

POTENTIAL UTILITY OF FUTURE SATELLITE MAGNETIC FIELD DATA

Contract Nas 5-27597

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center
Greenbelt, Maryland 20771

(NASA-CR-175230) POTENTIAL UTILITY OF FUTURE SATELLITE MAGNETIC FIELD DATA Final Report (Business and Technological Systems, Inc.) 32 p HC A03/MF A01 CSCL 05B
N84-24691
Unclas
G3/15 13436

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REPORT OF THE MAGNETIC FIELD WORKSHOP

Foreword

Magnetic field measurements by satellite have for many years provided data essential to the accurate global charting of the geomagnetic field. More recently, an exciting new field of scientific inquiry involving the use of such data for studies of regional geology has emerged, and is now rapidly approaching maturity. NASA is in the process of evaluating the future of its program in this area. To provide information required for such an evaluation, this report was compiled by BTS personnel with inputs from a number of Magsat Principal Investigators and other contributors. Michael Mayhew, formerly with BTS and currently with the National Science Foundation, was especially helpful in providing and coordinating information. This document is intended to (1) outline the requirements for a program of geomagnetic field studies which will satisfy a wide range of user needs in the interim period between now and the time at which data from the Geopotential Research Mission (GRM) becomes available, and (2) consider the long-term needs for NASA's program in this area. Section 1 of this report is an overview of the subject. Sections 2 and 3 present a justification for the recommended activities in the near-term and long-term, respectively. Section 4 contains a summary of the recommendations reached by the contributors to this report. The contributors, whose valued inputs are gratefully acknowledged, are listed on the following page.

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1.0 OBJECTIVES OF THIS REPORT

The geomagnetic field is highly complex with significant spatial and temporal variation. Recent scientific and engineering developments have led to important advances in our understanding of this global geophysical phenomenon and its applications in geology, tectonophysics, navigation, communications, and many other fields. Because understanding geomagnetism requires global observations at a range of altitudes, satellite programs have been critical in this recent progress. As a result, NASA has taken a leadership role in the study of geomagnetism. As NASA plans its scientific programs for the next decade, it is essential that continued study of the geomagnetic field and its relationships to other scientific and engineering endeavors be an integral part of the Earth and space physics programs.

This report presents results compiled with inputs from a number of Magsat Principal Investigators and other contributors in an effort to develop recommendations for NASA's activities in geomagnetism during the next decade. The report presents both near-term activities which focus on the applications of existing data sets to a number of scientific problems of critical importance and on longer term activities involving new spacecraft missions. These missions are designed to extend the accuracy, coverage, and resolution of existing data and will significantly extend the range of achievable scientific objectives and resulting applications which are essential to our evolving understanding in the Earth sciences.

1.1 Background

The geomagnetic field is composed of three major components:

- The core field is the major part of the geomagnetic field and is believed to be caused by fluid motion of conducting material in the Earth's outer core. The field variations have large amplitudes, broad spatial features (i.e., wavelengths of 3000 km and longer), and significant low-frequency temporal variations (i.e., measured in years, decades, centuries, etc.).

- The crustal field forms a relatively small part of the geomagnetic field, but it is significant since it is caused by geologic structure and the state of crustal minerals. The spatial variations of the crustal field occur with characteristic wavelengths ranging up to a few thousand km. Though of small amplitude compared to the core field, the crustal field is of major scientific importance. For example, the pattern of magnetic anomalies in the sea floor is a critical part of the scientific evidence for the theory of plate tectonics which has led to a revolution in solid Earth geophysics over the past twenty years.

- The external field is caused by electrical currents in the ionosphere and magnetosphere. Magnetic field variations due to the external field occur on all spatial and temporal scales. The external field accounts for the most complex and dynamic part of the geomagnetic field.

Since magnetic field measurements are the sum of contributions from the above three parts of the field plus measurement errors arising from instrumental, positional, and other error sources, there is a major challenge to successful data interpretation. Measurements of the magnetic field are routinely made by land-based observatories, ships, aircraft, and satellites. These observations have been made globally (but with poor spatial distribution except for those made by satellite) over many years and are the basis for scientific theories of the geodynamo, geomagnetic field models, reconnaissance activities in geophysical exploration, small craft navigation, and other applications.

Recognizing the scientific and engineering importance of the geomagnetic field, NASA has developed a number of geomagnetic satellite projects. These began in 1959 with the Vanguard satellite and have continued through the recent Magsat mission (1979-1980). NASA's satellite programs have made accurate global geomagnetic reference models feasible (e.g., The International Geomagnetic Reference Field), have led directly to new scientific discoveries of long wavelength anomalies having sources in the deep crust, to the first global magnetic anomaly maps, to new discoveries concerning the magnetohydrodynamics in the core, and to new discoveries of the electrical current structures in the external field. Space technology has made possible a greatly increased understanding of the geomagnetic field, and, consequently, our understanding of the Earth.

1.2 Scientific Importance

Measurements of the geomagnetic field are used by scientists at government agencies (e.g., NASA, USGS, Navy, NOAA, Air Force, Foreign Agencies), universities and private corporations for many applications. These include the following:

- solid Earth geophysics
- non-renewable resource assessment and exploration
- ionospheric and magnetospheric modeling
- navigation
- archeology

In the field of solid Earth geophysics, geomagnetic field measurements provide one way of "seeing" into the earth. Unlike many satellite remote sensing measurements, geomagnetic measurements are directly affected by subsurface features. Because the internal magnetic field is caused by dynamic processes in the core and magnetization variations in the crust, geomagnetic field data provide a basis for physical inferences about such phenomena as the structure and composition of the crust and variations in the fluid flow in the core. For example, when used in combination with other geophysical data, geomagnetic field measurements provide information about the thermal state and configuration of the deep crust. Additionally, effects of continental drift are visible in the magnetic anomaly patterns that have been mapped by the POGO and Magsat satellite missions. These and other scientific inferences would be impossible without this remote sensing aspect of the geomagnetic field.

The satellite missions are also critical to understanding the core field because they alone provide global coverage at a relatively uniform data structure and quality. The complex magnetohydrodynamic phenomena in the core are not well understood at present, and both theoretical and observational advances are required to explain such phenomena as geomagnetic field reversals, westward drift of the non-dipole field, and other secular variations. Because of the temporal variation in the geomagnetic field (i.e., secular variation), continual global monitoring of the geomagnetic field is needed.

In the area of non-renewable resource assessment and exploration, satellite magnetic observations provide information on the regional tectonic framework in which hydrocarbons and mineral resources are generated. A detailed study of magnetic anomaly patterns is a key reconnaissance tool for resource assessment exploration geophysics in the search for oil, gas and minerals of strategic and economic importance. For example, current research is directed at determining the extent to which continental rifts are related to the distribution of metallic ores and geothermal energy. Ancient, buried rifts are seen in the magnetic anomaly field which has been mapped by Magsat. Greater knowledge of the correlation between continental geology and this long wavelength anomaly field will aid our understanding of the tectonics and associated resources in less accessible regions.

As the satellite programs continue to improve measurement accuracy and resolution, the regional geomagnetic reference models that are used to aid the exploration process will improve. These improvements are needed in order to avoid errors in data reduction and resulting data interpretations and will become increasingly important in both conventional magnetometer surveys and in newer survey approaches using vector magnetometers and magnetic gradiometers.

The area of ionospheric and magnetospheric modeling is important in itself for understanding ionospheric effects on spacecraft and communications systems, and indirectly, because of the difficulties in measuring and determining the core and crustal magnetic field in the presence of ionospheric disturbances. Geomagnetic field data can greatly increase our understanding of the generating mechanism and variability in the ionospheric electrical current systems in the surrounding solar terrestrial environment and our ability to interpret measurements of the core and crustal fields.

Magnetic charts are used for navigation by government agencies like the Federal Aviation Administration and by private operators. These charts are produced by the U. S. Geological Survey and the Naval Oceanographic Office, and require regular revision because of the temporal variations in the magnetic field. For example, in some parts of the world the magnetic field may change several percent in a few years. A systematic global observing program is needed to provide continuing data to maintain accurate charts. Satellite systems are unique in providing the necessary global coverage for these charts.

1.3 Present Opportunities

At present, NASA has several excellent opportunities to build on past successes in observing and understanding the geomagnetic field in order to meet future scientific and engineering needs. The factors that create these opportunities are the following:

- a large global data base
- an existing community of experienced scientific investigators
- new advances in computational capabilities
- experience in advanced geophysical mission planning

As a result of a substantial effort over the past twenty years, a significant global geomagnetic field data base exists. This data base includes measurements from several spacecraft (e.g., POGO series, Magsat), aeromagnetic data (e.g., project MAGNET), marine data (e.g., oceanographic ships from many institutions) and geomagnetic observatories (e.g., U.S. and foreign). NASA's satellite programs have been instrumental in stimulating international cooperation and data exchanges which have been of considerable benefit in contributing to advances in solid Earth geophysics. Much of this data base has not yet been analyzed in light of new developments in geomagnetic field modeling techniques and theoretical geophysical advances. This global data base can be integrated and processed to provide improved estimates of secular variation, regional magnetic anomalies and understanding of external field effects. Thus, there exists a considerable opportunity to exploit the existing data base for further advances in the scientific areas described in Section 1.2.

As a result of NASA's satellite magnetometer programs and support to various related scientific activities, we now have a large community of scientists familiar with the scientific potential and practical aspects of modeling and analyzing the geomagnetic data base. Consequently, there exists an important opportunity to apply the expertise of this established community (e.g., Magsat investigators) to integrate and exploit the existing data base by extending current research areas and initiating new research.

The availability of significantly increased computer capabilities both within NASA and at other investigator organizations must also be considered. Past and current research efforts that were limited by available computational resources may be significantly extended at low incremental cost by the availability of parallel vector computer architectures and low-cost, yet powerful, dedicated mini-computers. The availability of increased computer resources will permit the integration of data bases of diverse data types (e.g., satellite, aircraft, surface). Design of computer algorithms, data base management software systems, and multi-source interpretation techniques are also in progress in a number of related geophysical disciplines. Furthermore, the increased computational power will permit the implementation of new signal processing algorithms for detection and high resolution estimation of magnetic anomalies, estimation of secular variation, and upward/downward continuation of magnetic fields. These algorithms thus will permit efficient comparison of differing measurements and validation of derived models. Consequently, the opportunity exists to increase our understanding of the relationships among these data types and to develop effective algorithms for geophysical modeling and interpretation.

The experience obtained from past satellite geomagnetic missions and from the consequent analysis and interpretation of the data provides a considerable resource for planning successful future missions. Given the length of time required to plan, launch, and analyze data from spacecraft, NASA should begin now to plan these next missions, knowing that the scientific community will have sufficient time to assess existing data and to develop algorithms for processing and interpretation. A considerable opportunity exists to use the emerging scientific results, the experience of the mission planners and investigator teams, the computational resources and the global data base to plan new missions which will advance many scientific objectives in the Earth sciences.

2.0 NEAR-TERM ACTIVITIES

As noted, the magnetic field measured at satellite altitudes is the sum of three fields having fundamentally different sources. For the dual purposes of satisfying pressing near-term needs in the geomagnetic field area and preparing for analysis of data from future missions, work is needed on methodologies for separating the various fields, on applying them to newly collected and reprocessed satellite and surface data, and on modeling the various sources in order to study the Earth.

2.1 Main Field

Accurate, up-to-date models of the main field are required for a number of applications, including the production of declination charts for navigation, removal of background fields from aeromagnetic and ship-borne magnetic surveys, satellite attitude control and determination, the probing of various fluid motions in the Earth's core, and calculations of field lines and conjugate points for ionospheric and magnetospheric studies. However, because of the secular variation of the field, field models become unreliable and out of date within a few years. At present, field models must be recomputed every few years with newly-collected data, and it has become quite clear that only satellite surveys supplemented by ground-based observations provide an adequate global data base. On the other hand, a more accurate model of secular change would greatly extend the period of usefulness of field models. Knowledge of the secular variation is crucial in tying together regional aeromagnetic and marine surveys taken at different epochs and it is one of the few sources of information regarding the Earth's core, where the internal field originates. It is estimated that a factor of 2 to 5 improvement in SV can be realized by further analysis of existing data, using some of the new methods outlined below, and using heretofore unused data.

2.1.1 Physical Models of the Core Field

One objective of devising a better description of the Earth's magnetic field is to enable us to arrive at better physical models of fluid dynamic motions within the outer core of the Earth. It is these motions which cause the secular variation of the field. One impediment to modeling fluid motions is that the magnetic field observations on which models are based need to be extrapolated down to the core-mantle boundary (CMB). In this downward extrapolation, the higher degree terms of the spherical harmonic representation of the field, although less well known, become ever increasing in importance, such that at the CMB the degree 12 terms, for instance, are almost as important as the degree 2 terms. Due to the high-order field caused by crustal magnetization, almost nothing is presently known about core field coefficients beyond degree 13. Also, the current models of secular variation rarely allow changes in coefficients beyond degree 8, because the higher degree terms are only poorly observed by the data.

Since SV can be determined from a series of main field models closely spaced in time, our knowledge of SV is largely dependent upon our knowledge of the geomagnetic field at past epochs in comparison to current models. Therefore, knowledge of fluid dynamic processes within the core can be significantly advanced by continuing to study past epochs of the field, with the objective of obtaining a more accurate SV model. Such a model must attempt not only to define more accurately the lower degree SV components but also higher degree components to see if there are observable coherent changes through time.

It has been estimated that for the 1965 International Geomagnetic Reference Field (IGRF), the main field at the CMB is known to about 60%, but that the SV is so badly known that only its root-mean square (RMS) magnitude can be estimated at the CMB. The 1965 IGRF used poorly distributed data prior to 1964. Since we now have 17 more years of better distributed data of generally higher quality, including many satellite data and far greater coverage of oceanic areas, often repeated, we have been able to derive a much better mathematical description of the main field and SV at the CMB. These models have shown that in actuality the field at the CMB from the IGRF of 1965 was not known to 60%, but more like 40%. With the newer models we may now be actually achieving 60%. This accuracy is now on the verge of supplying substantial constraints on core magnetohydrodynamics. Improvements in SV by a factor of 2-5 will thus be very significant.

It may ultimately be possible to use fluid dynamic models themselves to constrain mathematical descriptions of the Earth's field. It has been suggested that the unsigned magnetic flux crossing from the conducting core into the insulating mantle should remain constant over times which are long compared with the few decades of world-wide magnetic field coverage presently available. Therefore, accurate knowledge of the field at the CMB could be used to constrain mathematical models of the field and its secular variation.

2.1.2 Main Field and Secular Variation Modeling Methodology

The main field and its secular variation are closely associated and this is reflected in analysis techniques for their estimation. Current methods use least squares spherical harmonic analysis in which the coefficients are polynomials of time. The predictive capability beyond a few years is negligible, necessitating a new model. Work to improve the time dependent problem should include 1) further development of a filtering-smoothing method which uses several sets of spherical harmonic coefficients as input and shows promise for improving the prediction of the field, and 2) the investigation of alternative expansions in time, such as sinusoids, splines, or rational fractions.

Researchers have recognized that internal estimates of accuracy for spherical harmonic models obtained by least squares estimation are generally much lower than differences between independent models (by factors of 4 to 10) or the RMS of residuals based on different data sets. This indicates that the modeling process has serious shortcomings in representing the physical process driving the field over more than short periods of time. In particular, the conventional approach to estimating the coefficients of a scalar magnetic potential by a spherical harmonic expansion is aliased by incorrect parameterization of the secular variation, by improper truncation level (terminating the expansion at a wavelength greater than that observable in the data) and by inappropriate weighting of data. The techniques of linear error analysis may be used to qualitatively determine which coefficients are observable in the data available for modeling, and what influence ignored coefficients will have on the solution.

Moreover, the weighting used in the least squares parameter adjustment should reflect the data accuracy. Data correlation (such as between vector components) should also be correctly modeled. The ability to model secular variation over more than a few years will be greatly facilitated by including the physics of core dynamical processes into the estimation algorithm. This can be accomplished by including non-linear constraint equations (such as frozen magnetic flux constraints at the core-mantle boundary) into the least squares estimation. This could have a pronounced effect on our ability to reduce correlations in the solution parameters and obtain accurate secular variation models. These problem areas must be addressed to meet modeling accuracy goals of 0.2 nT/year (or about 10 nT/year for the overall SV) for the long wavelength secular coefficients.

For main field modeling, all data except satellite data are highly perturbed by fields originating in the crust of the earth. These anomaly fields can be several thousands of nT in any of the components and represent a large noise source when attempting to model the field originating in the Earth's core. Appropriate techniques must be developed (such as filtering marine survey data and aeromagnetic data and differentiating with respect to time or solving for local anomaly fields with repeat and observatory data) to properly accommodate these data into the core field model without aliasing the solution. The impact of using large quantities of scalar data which can introduce ambiguities in the spherical harmonic solution (the Backus ambiguity) must also be addressed. In utilizing satellite data, methods to account for ionospheric and magnetospheric currents must be developed.

It is widely believed that the geomagnetic field represented by spherical harmonic degrees beyond about 12 is a mixture of the field of crustal origin and that originating from inside the core. At present, there is no definite way to discriminate the crustal field from the core field within this spectral band. Separation may be possible when the short-term variation for this spatial resolution is clarified through the development of good SV models. If magnetization is mainly by induction or viscous build-up, as it is likely to be in the deep crust, individual magnetic anomalies will change character somewhat with time in a predictable manner with changes in the local main field vector, and this may help to make the separation. New approaches such as parameterization using core dipole sources may shed light on the separation problem and should be pursued.

The feasibility of using alternative methods to the standard least square spherical harmonic approach to field modeling are currently being investigated. One approach is to use optimal recursive filtering techniques to predict the main field and its secular variation based on combinations of conventionally obtained spherical harmonic models with stochastic models for the secular variation errors. Another method, of particular relevance to studies of core physics, involves the use of general inverse theory designed to produce "smoothed" models at the core. This eliminates the downward continuation problem for spherical harmonic models in which the uncertain high order terms dominate the solution. These techniques, together with new modeling representations (other than the standard polynomial expansions in time) for the secular variation must be pursued to improve the capability of modeling the main field.

2.1.3 Data

Secular change models depend for their accuracy on the availability of an adequate global distribution of data at intervals of a few years. The principal sources of data for main field modeling have been (1) permanent magnetic observatories, (2) repeat measurements at selected sites with intervals between measurement of one to six years, (3) surveys from aircraft and ship, and (4) satellite measurements. Only the satellite surveys are truly global. Relevant surveys from which data are generally available were conducted by the Vanguard, Cosmos 49, OGO, and, most recently,by the Magsat spacecraft. Satellite data, because of its global coverage, provides the basis for modern magnetic field modeling. However, early missions, such as Vanguard, COSMOS 49 and the early OGO's were limited in accuracy by the uncertainty in the spacecraft position, and only the scalar magnitude was measured. Modern gravity models are sufficiently improved to warrant consideration of computing more precise orbits. Other available satellite scalar data, such as from the DOD spacecraft S3-2 launched in 1976 and the NASA Dynamics Explorer (DE), should be utilized if possible.

In periods when no spacecraft is measuring the field, truly global coverage is not available. This results in field models with large errors in some locations, such as the ocean areas, because of inadequate determination of the secular variation. In periods where global satellite surveys are not available, permanent magnetic observatories must still be regarded as the primary source of information regarding the temporal changes, and properly placed magnetic observatories and repeat stations, with measurements repeated every 3-5 years, are needed to alleviate this temporal and spatial distribution problem. The expected distribution of surface data in the coming decade omits many large areas, particularly in the oceans, which are needed in order to improve secular variation models at key locations throughout the world. Repeat measurements should be made for a sufficient period (from several days to two weeks) to insure that the measurements are representative of quiet day periods. A concerted effort involving NASA and also the principle data collecting agencies (e.g. USGS, NOAA, Air Force) is needed to bring together and properly assess the quality of these data sets.

In recent years an enormous quantity of ship-borne scalar magnetic data has become available, but has as yet had only limited use in main field modeling. Because of the volume of data involved and the diversity of collecting institutions, sophisticated techniques are required to effectively utilize the data in core field modeling. Such techniques should be pursued and full advantage made of these data in future modeling efforts. Similarly, large archives of aeromagnetic data have been accumulated by the exploration industry. While such data is highly proprietary in its original form, its availability in a decimated or averaged form should be pursued.

2.2 Anomaly Field

The anomaly portion of the field arises from variably magnetized rocks lying between the Earth's surface and the Curie iostherm (the "magnetic crust"), and is the part of the magnetic field having direct geologic significance. Magnetic anomaly fields have long been used to study near-surface geology and structure. They have had an important role in the initial evidence for sea-floor spreading that led to our present unifying concepts of plate tectonics. They are routinely used in resource exploration. Magsat has recently measured the Earth's magnetic field with both scalar and vector instruments, and an anomaly component data set has been created by subtracting a mathematical model of the main (core) field. External field contamination has been reduced by selecting data from "quiet" times and by making crude corrections for certain known effects. Global 2x2° average anomaly maps have been produced, and geologic interpretations of these have been made. However, at this stage these are of necessity mostly qualitative. Improvements in techniques for extracting and enhancing the pure anomaly signal and in interpretational techniques will lead to quantitative, relatively high-resolution models of magnetization as a petrophysical parameter in the magnetized part of the crust and uppr mantle. These anomalies, interpreted in concert with other geophysical data and with laboratory determinations of the magnetic properties of rocks characteristic of the deep crust and upper mantle, will make a significant contribution to geologic models of the Earth's lithosphere.

The research program has entered a phase of geologic interpretation which has shown a surprising and exciting degree of promise for studies of lower crustal structure and chemistry, crustal thermal structure, geologic province mapping beneath sediment, water, or ice cover, the ocean-continent transition, and the magnetochemistry of the oceanic crust and upper mantle. But to realize the potential of this new tool for studying the Earth, substantial support for continuing research on extracting information from the data, on analytical techniques for quantitative interpretation, and on laboratory physical properties is needed.

2.2.1 Data Treatment

Improvements in analytical techniques for the treatment of data are needed before the full potential of satellite magnetic measurements is achieved. Reduction of observed magnetic data to the anomaly field requires the elimination of the core-derived main field and transient magnetospheric and ionospheric fields. Improvements in representation of the core field and its secular variation will permit more precise definition of the anomaly field. Certain important external field variations are not well-constrained theoretically; for example, while the equatorial electroject is a well-known magnetospheric phenomenon, it is not well defined mathematically. Elimination of the time variant component of the observed field must be based on techniques for incorporating contemporaneous groundbased observations and on improved statistical techniques. Work on these methodologies is needed.

The problem of delimiting the anomaly field inhibits its analysis, particularly the vector elements. At present, the net effect of uncertainties in the theoretical magnetic field is to bandpass filter the crustal component of the observed field because long wavelength crustal magnetic anomalies are removed with the core-derived field approximation and the short wavelength components with the temporal elements. A related problem is uncertainty in the absolute value of the anomaly base level, which is an important parameter in geologic interpretation of magnetic anomalies. Upward continuation of regional aeromagnetic surveys to satellite altitudes has proved useful in "verifying" satellite data, that is, indicating the degree to which a pure anomaly signal has been extracted from the observations. Verification also can be used in an iterative manner to establish optimum techniques for the treatment of data. Satellite anomaly verifications should continue as new regional survey data become available. In addition to conventional spatial domain correlation techniques, verification techniques should be developed in the wavenumber domains utilizing coherency techniques.

In present data treatment schemes, when dissimilar anomaly results are found between proximal orbits, an ad hoc filter is applied to the data to produce more consistent results. Such filters are without geophysical basis, and are a potential source of anomaly distortion. A meaningful analysis of the cause of inconsistencies in the data between proximal orbits should be investigated, and schemes which have a physical basis developed for removal of the inconsistencies.

Downward continuation of satellite magnetic anomalies to common level closer to the Earth can be accomplished in principle. This is an attractive treatment scheme because of the increasing resolution of the data at lower elevations. However, downward continuation enhances not only shorter wavelength anomalies, but also errors of similar spatial characteristics. Thus, the method has had limited use to date because of the lack of information on potential errors. Further research aimed at identifying such errors and on the relative advantages of various continuation techniques is important. Data sets are available at different elevations for testing the validity of techniques when applied to actual data.

2.2.2 Interpretation Techniques

Models of the sources of magnetic anomalies are the basis for geologic interpretation. A useful preliminary stage in the interpretive process involves mathematical inversion using a variety of source functions to establish hypothetical distributions of magnetization. These results in turn can also be used for data continuation, differentiation, and magnetic pole reductions which provide useful input for more explicit modeling constrained by realistic geologic and geophysical parameters.

Numerical schemes have only recently become available for modeling geological sources in spherical Earth coordinates by quadrature integration; they are still computationally inefficient, and their potential is far from realized. Alternative modeling schemes should also be investigated. The feasibility of using higher order components of anomalies for investigating details of source geometry can be resolved by further study with existing data. Special consideration should be given to automatic or manual interactive modeling schemes which use two or more geophysical parameters and vector and derivative components of the anomaly field.

Spatial resolution is a critical factor in the design of magnetic mission parameters and in the geologic interpretation of the magnetic anomaly data. While preliminary studies have shown that there is an order of magnitude decrease of resolution with a three-fold increase in observation elevation, the relationship between resolution limit and orbital altitude is poorly defined. Further research, both theoretical and by simulation, is needed to properly answer the resolution question. Use of magnetic gradient measurements will increase anomaly resolution with commensurate benefits to interpretation; a problem worthy of investigation is the use of gradients for downward continuing smaller wavelength anomalies.

An important technique for reducing interpretational ambiguity is to analyze correlations between magnetic anomalies and other classes of geophysical data. Gravity and magnetic data are particularly well suited for correlative analysis because these anomalies often may be related by common source geometry, and the two data types may be used to uniquely define the magnetization-to-density ratio and the minimum ratio of remanent-to-induced magnetization for the geologic body. The acquisition of correlative geophysical and geological data sets as well as research on combined interpretative procedures deserves continued effort.

2.2.3 Laboratory Studies

It is necessary to have laboratory determinations of magnetic properties of actual rock samples to constrain theoretical computer models derived from the satellite anomaly data. Geologic interpretation of Magsat data requires delineation of the configuration of the base of the magnetized rocks and the definition of their petrologic variations which are correlative with changes in magnetic mineralogy associated with conditions of mineral equilibration. Magnetic properties of lithologies represented in the magnetic crust, the effect of elevated temperature and pressure on initial magnetic susceptibility, magnetic viscosity and magnetic stability, are required information. Work on methods for incorporation of this magnetic property data into realistic models compatible with tectonic and chemical evolution of the continents and oceans is also needed.

There are five sources of samples for laboratory analysis. Very old rock of high metamorphic grade, once deep, but now exposed at the surface by erosion, provides evidence of the petrologic, geochemical, and geophysical nature of the lower crust. Country rock fragments within volcanic rocks derived from great depth provide samples of the deep crust and upper mantle. Tectonically exposed sections of the deep continental crust provide an important source of information. Oceanic fracture zones are areas where lower crustal rocks can often be found. Ophiolites, fragments of ancient oceanic crust exposed on land, can give some information about oceanic crustal sections down to and below the oceanic Moho. Together these five sources of materials provide a possible means of understanding the magnetic properties as a function of lithology and metamorphic grade, and thus, when used in conjunction with models derived from magnetic anomalies, geologic history. The laboratory conditions must realistically simulate the temperature and pressure conditions of magnetization of deep crustal rocks. Such laboratory-based studies should be an important element of a program of geopotential research.

2.3 External Fields

The study of external fields is important from three points of view: first, the scientific study of sources of the currents providing the fields; second, the removal of the effects of external sources from models of core and crustal fields; and third, the study of the electrical conductivity of those regions of the Earth, upper mantle and crust, in which the time varying external fields induce secondary currents.

External sources include high altitude magnetospheric currents, field aligned currents and ionospheric currents. Magsat, for the first time, permits the accurate delineation of the near-Earth fields from the fields from the magnetospheric currents. Studies should be pursued to map the behavior of such currents with time and the difference between sources at dawn and dusk. Studies of field aligned and ionospheric currents with Magsat have been minimal, extending mainly to a catalogue of general field morphology. These studies should be extended, probably in conjunction with analysis of data from the Dynamics Explorer spacecraft, toward a more definitive model of the inner magnetosphere. Because of the rapid temporal variations of external fields, adequate analysis is dependent upon availability of contemporaneous surface data. Such data needs to be available digitally with extensive surface coverage. Efforts should be made to acquire and organize these data for time periods of particular interest, e.g., during magnetic storms and substorms and suitable magnetically quiet periods for baseline determination.

Removal of external effects when studying core and crustal fields requires different techniques at different spatial and temporal wavelengths. Magnetospheric fields can, in principle, be accurately modeled along with the core field. In practice, seasonal and local time variations as well as transient variations in the magnetospheric fields make this difficult. Suitable inclusion of, say, hourly values from observatories may mitigate some of the problems. Algorithms for such models should be developed and tested. Shorter wavelength external fields are usually more rapidly varying with time and do not seem to be amenable to modeling with sufficient accuracy to separate them from the core and crustal fields in a meaningful way. In these cases we must rely on filtering techniques, which at present are very rudimentary. More research is needed in this area.

Quantitative modeling of the fields of external sources is still not complete; in particular, there remain major unsolved problems concerning the closure of the field aligned currents and of the ionospheric auroral electrojet currents. The studies of these problems require accurate models of the internal fields. Thus, progress in the investigations of the external and internal fields are interactive and mutually dependent. For instance, a full benefit of the OPEN (Origin of Plasmas in Earth's Neighborhood) program planned for late 1980's cannot be obtained without an accurate internal field model for the epoch of the mission. On the other hand, any future improvements on the internal field models would require quantitative modeling of the external fields. The Magsat model of the internal field is now playing a critical role in the interpretations of the magnetic field data from the Dynamics Explorer 1 and 2 spacecraft. In turn, the studies of the external fields with the Magsat and Dynamics Explorer data will assist future improvements in the Magsat internal field model.

Studies of the electrical conductivity of the crust and upper mantle are possible with existing data. Conductivity variations are caused by variations in the temperature and composition of rocks and by changes in geologic structure. Recently, variations in the conductivity of oceanic lithosphere have been correlated with the age of the rocks. Furthermore, local conductivity greatly influences measurements of magnetic observations so that its delination is important to the interpretation of the observatory data. However, studies in this area have failed to distinguish lateral conductivity variations, which surely exist. It has been pointed out that, in principle, combining satellite with appropriate surface data can delineate such variations. Additional effort is required to develop new methods and to fully analyze the available Magsat and POGO data.

3.0 LONG-TERM ACTIVITIES

In working with internal magnetic fields, there are two basic types of surveys that are needed. One type is to define anomalies that occur from the surface to the depth of the Curie isotherm. The other is to define the parameters of the Earth's main field and to monitor its time varying characteristics. There is a strong interdependednce between these two types of measurement programs. Field models, applicable for the time when anomaly measurements are made, are essential for separating the core field from the crustal field. A knowledge of the effects of near surface sources is also essential for separating these effects from the core field. To a certain extent, these two types of measurements, can be accomplished by analysis of data sets from the same missions, but the separation is not complete.

Missions to define anomalies can be considered "one time" data acquisition programs. A successful mission to define anomalies only needs to be repeated when the accuracy of the instrumentation is improved, the orbit parameters such as height and/or inclination are changed, or different types of measurements such as gradients are to be measured. In general, anomaly missions should be planned for a minimum of six months to make it possible to collect adequate quiet data sets. The measurements should be made at as low an orbit height as possible.

Missions to define and monitor the main field of the Earth need continuity. Efforts have been made to revise field models every five years. This revision interval has been found to be inadequate in regions where rapid secular variations are occurring. There is a great need for more frequent monitoring of the global field. Our ability to predict the time variations of the Earth's field based on previous trends or source models for five year intervals is abysmally inadequate. Direct measurement, at least on an annual basis, is the only method available to update these field models. Satellites with orbits high enough (e.g., 500-1000 km) for a long mission duration are appropriate for this function. An added advantage of these higher orbits is that the anomaly fields are greatly reduced relative to the core field. This improves the signal to noise ratio for the core field measurements.

3.1 Planned Missions

The Geopotential Research Mission (GRM) with vector and scalar magnetometers at an orbit height of 160 km will provide a valuable data source for:

- updating global field models
- definition of short wavelength (about 100 km) anomalies
- synergistic use of gravity and magnetic field measurement capabilities and data.

Global data for field models will not have been collected for more than a decade at the earliest date when GRM data can be expected. Two revision cycles of the International Geomagnetic Reference Field (IGRF) will have taken place since Magsat provided the major input. Errors in the IGRF due to secular variation over a decade can be expected to be large, particularly in regions where observatory data are not available.

Significant improvements in measuring the anomaly field can be expected to occur for several reasons. The lower orbit height will make it possible to measure features with shorter wavelengths (a factor of at least 2 improvement over Magsat). The amplitude of the anomalies will be increased by about a factor of 2-3. This improvement in signal level will make it possible to better delineate the shapes of known anomalies and to map weaker anomalies that were hidden in the noise of Magsat data.

The precise positioning required for the gravity measurements of GRM will also be important to the magnetic measurements. Position errors can be a large source for errors in magnetic field measurements. The combined gravity and magnetic data sets, acquired on the same surface, will make it practical to carry out combined interpretations based on these two potential fields. Distributions of two fundamental crustal petrophysical properties, density and magnetization, can then be studied in a consistent way over the same geographic regions.

It is critical that the GRM be started as soon as possible so that the mission can collect data before the solar activity increases to the point where quiet orbits will be difficult to select. At best, the mission cannot be ready until after the solar minimum. Any delays will diminish the amount of quiet magnetic data that can be collected.

Magnetic Monitor Mission(s) with long lifetimes are needed to collect comprehensive global data sets for revising magnetic field models when secular variations are large enough to justify revision. Both vector and total field instruments are needed on this type of satellite. Improvements in attitude determination over Magsat would greatly improve the value of the data.

Tether missions are needed to measure anomalies at as low a height as possible. The lower heights are needed to make it possible to obtain shorter wavelength data. Use of a tether may also make it physicially possible to configure instruments for gradient measurements of the magnetic field. The gradients of the magnetic field are attenuated even more rapidly than the field itself. Measurement heights between 125 and 160 km are needed to measure the gradients that can be expected to result from geologic structures. Adequate mission life to obtain coverage from tethered instruments will be a problem if the tether is suspended from the shuttle. A platform with a longer time in orbit (6 months to a year) would be more appropriate. This platform could be serviced by the shuttle periodically. nless improvements can be made in our ability to remove the magnetic fields induced by field aligned currents, through near-term research, an inclination of over 60° may be impractical for a tethered magnetic mission.

For anomaly studies a case can be made for making measurements in a medium-inclination orbit (say 45°) in at least one future mission. It has been found desirable to filter low frequencies along the orbit from the crustal data by subtracting a quadratic fit to the data for portions of an orbit; this is done because the "noise" is larger than the "signal" at the low frequencies. However, as is the usual case when filtering data, some real signal is unavoidably removed along with the noise. This causes errors which are largest in the sectoral harmonics of the field, which can be of high degree and of crustal origin. A medium inclination orbit satellite can be used to help determine these harmonics, which have previously been largely filtered from the crustal data, and thus reduce errors in the crustal maps. This is because the medium inclination orbits will cross the previous polar orbits and can be used as a "tie line". A medium inclination orbit satellite could also be used to improve Magsat crustal maps without an additional polar orbit satellite. Of course, the polar regions will have no coverage, and for main field modeling purposes will have to be surveyed and re-surveyed in some other manner.

3.2 Research Needs:

Much of the research aimed at analytical improvements which was discussed in Near-Term Activities will need to be continued as part of Long-Term Activities. Data reduction and analysis methods need careful consideration as measurement programs are being planned. Simulations, based on realistic source models, can serve as a guide to mission design and identify required measurement accuracies.

One of the most important long-term research activities will be to use the extended time base that can be obtained by the Magnetic Monitor Missions(s) for studying the core magnetic field. Reliable, global, data sets for this purpose were inadequate prior to space acquired magnetic surveys. A long time series represented by these data sets is needed to model the shorter period (a few decades) time variations of the core field. An ability to improve the modeling of these relatively rapid changes in the core field represents an important scientific achievement, and will provide a physical basis for improving predictions of secular variations.

Additional research on the methods of interpretation using vector and gradient measurements needs to be conducted. Models of the gradient field of the core and estimates of the noise produced on the gradients by the external fields are needed. Feasibility studies for constructing magnetic gradiometers for use in space should be conducted.

4.0 RECOMMENDATIONS

It is the view of the contributors to this report that a need exists for a program of geomagnetic field studies spanning the interval between Magsat and future missions, both to satisfy pressing near-term needs and to prepare for full and timely use of future satellite data. The contributors strongly encourage NASA support for such a program, which must be seen as an opportunity for significant scientific advances in a field having very real practical importance to a great many kinds of human endeavor. The following specific recommendations are offered (not necessarily in order of priority).

4.1 Research Needs

1. Develop more accurate main field and secular variation models using reprocessed existing and newly acquired data and new analysis techniques. Investigations should include a) alternate temporal representations to low order polynomial expansions, b) the use of stochastic approaches to modeling, c) the use of physical models of core fluid motions to constrain the parameter estimation, d) techniques to improve the separation of the core-crustal-external fields, and e) the use of general inverse methods. Existing Magsat models for 1980 set the accuracy standard. An accuracy goal for secular variation models of 10nT per year (rms) should give a factor of at least two improvement in main field models for 1950-1980.

2. Study and implement more realistic techniques for estimation of the accuracy of main field models.

3. Develop better physical models of the fluid dynamic motions within the outer core of the Earth using improved knowledge of the field and secular variation at the core-mantle boundary.

4. Develop techniques for more effectively using marine data and aeromagnetic data in main field and secular variation modeling.

5. Carry out "verification" studies involving upward continuation of regional aeromagnetic surveys for comparison with satellite data. This will necessitate creating a data base from existing surveys and verifying their long wavelength integrity. This is important for developing precise procedures for isolating the crustal component of the geomagnetic field.

6. Collect and analyze, in the laboratory, suites of rock samples characteristic of the deep crust and upper mantle. From the measured magnetic and other physical properties of these rocks, develop constraints for source models of anomalies.

7. Extend the quantitative analysis of existing satellite anomaly data (POGO, Magsat, Cosmos-49) by a) development and application of methodologies for detection of shorter wavelength features (e.g. downward continuation), b) development and application of inversions to physically realistic source models, and c) analysis of multiple geophysical data types, with emphasis on combined orbital gravity and magnetic data.

8. Utilize existing spacecraft and surface data to characterize and model the effects of crustal and upper mantle electrical conductivity.

4.2 Data Needs

1. Obtain more accurate selected magnetic data from early satellite missions by improving orbital ephemerides using modern techniques.

2. Continue to expedite the collection of magnetic data from current magnetic observatories and repeat stations. Investigate the feasibility of establishing an interagency (and, ideally, international) program for a temporary magnetometer station network to be operated during the lifetime of future missions.

3. Bring together and assess the quality of observatory, repeat station, marine and aeromagnetic data in an active data file at GSFC.