E82-10388
CR-169177

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QUARTERLY STATUS AND TECHNICAL

PROGRESS REPORT #7

INVESTIGATION OF THE EFFECTS OF EXTERNAL CURRENT SYSTEMS ON THE MAGSAT DATA UTILIZING GRID CELL MODELING TECHNIQUES

NASA CONTRACT NO. NAS5-26309
UTD #E0533-01

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Period Reported: 1 April 1982 - 30 June 1982

Date of Submission: 1 July, 1982

(E82-10388) INVESTIGATION OF THE EFFECTS OF EXTERNAL CURRENT SYSTEMS ON THE MAGSAT DATA UTILIZING GRID CELL MODELING TECHNIQUES Quarterly Status Technical Progress Report, 1 Apr. - 30 Jun. (Texas Univ. at Dallas, N82-32810
HCA02
Unclas
G3/43 00388

Submitted to

NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

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OF POOR QUALITY

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. 7	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Investigation of the Effects of External Current Systems on the MAGSAT Data Utilizing Grid Cell Modeling Techniques		5. Report Date 1 July, 1982
		6. Performing Organization Code
7. Author(s) David M. Klumpar		8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Space Sciences, The University of Texas at Dallas, P.O. Box 688, Richardson, TX 75080		10. Work Unit No.
		11. Contract or Grant No. NAS5-26309
		13. Type of Report and Period Covered Quarterly Status 4/1/82-6/30/82
12. Sponsoring Agency Name and Address Harold Oseroff, Code 902, NASA/Goddard Space Flight Center, Greenbelt, MD 20771		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The overall objective of this effort in support of the Magsat project is to study the feasibility of modeling magnetic fields due to certain electrical currents flowing in the earth's ionosphere and magnetosphere. This seventh quarterly status and technical progress report contains a reprint of a technical article published in the April 1982 issue of the Geophysical Research Letters. This article is a direct result of support under this contract. The report also discusses initial testing of the modeling procedure that has been developed to compute the magnetic fields at satellite orbit due to current distributions in the ionosphere and magnetosphere. The modeling technique utilizes a linear current element representation of the large-scale space-current system.

17. Key Words (Selected by Author(s)) Magsat; Magnetic Fields; Birkeland currents	18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages 7	22. Price*

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

I. INTRODUCTION

The overall goal of this investigation is to study the feasibility of modeling the magnetic fields produced by certain electrical currents flowing in the earth's ionosphere-magnetosphere system. Vector magnetic field measurements from the near-polar orbiting Magsat satellite contain, in addition to the main geomagnetic field and crustal anomaly fields, contributions that arise from these external currents. In fulfilling the ultimate goals of the Magsat project, it is desirable that the external current effects be identified in the observations and subsequently separated from the internal field. The objective of this investigative effort will be to determine the capability of a modeling procedure to facilitate the separation of these external and internal components.

The approach of this feasibility study shall be to develop forward modeling procedures through which the magnetic effects of model currents may be derived. It is intended to include, separately, the equatorial electrojet, S_q currents, and the effects due to auroral zone and polar cap currents including the high latitude ionosphere-magnetosphere coupling currents. In each case candidate current systems will be devised and resulting 'typical' magnetic field signatures calculated for comparison with Magsat observations.

II. ACCOMPLISHMENTS DURING REPORTING PERIOD

1. Publications

The technical article on the following pages was published during this reporting period in the April, 1982 issue of Geophysical Research Letters. The findings of this article are a direct result of support under this contract.

GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 4, PAGES 361-364, APRIL 1982

A TECHNIQUE FOR MODELING THE MAGNETIC PERTURBATIONS PRODUCED BY FIELD-ALIGNED CURRENT SYSTEMS

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Abstract. A computational procedure is introduced for calculating the magnetic fields produced by virtually any distributed system of electrical currents. This procedure is being applied to the modeling of magnetic fields produced near the earth and on its surface by horizontal currents flowing in the ionosphere and by the so-called Birkeland currents flowing along the geomagnetic field at high magnetic latitudes. This report describes briefly the principles that underlie the technique and illustrates the results obtained when the model is applied to the interpretation of perturbation fields being measured by the polar-orbiting magnetic fields satellite (MAGSAT). Even for a very simple assumed current distribution we calculate magnetic field residuals whose large-scale features are similar to those deduced from MAGSAT measurements. A predominately sunward magnetic perturbation is obtained over the region poleward of the Region 1 current system as a natural consequence of balanced Region 1 and Region 2 currents. The model predicts the existence of low-latitude magnetic effects of auroral currents that represent potential sources of error for spherical harmonic representations of the geomagnetic field.

Introduction

The magnetic field measured from near-earth orbit, although dominated by the earth's main magnetic field, contains significant components that arise from electrical currents flowing in the ionosphere-magnetosphere system. In particular, at high latitudes near the auroral oval, currents flowing parallel to the geomagnetic field may cause perturbations in the locally measured magnetic field in excess of 1500 nT directed primarily transverse to the main geomagnetic field. Such field-aligned current signatures were first measured from satellite 1963-38C and reported by Zmuda et al. [1966, 1967]. Since that time magnetometers on a number of low-altitude satellites (TRIAD, ISIS, AE-C, S3-2) have been used to infer the nature of the magnetic perturbations arising from field-aligned currents [e.g., Iijima and Potemra, 1976a,b; Klumpar et al., 1976; McDiarmid et al., 1978a,b; Klumpar, 1979; Bythrow et al., 1980, 1981; Doyle et al., 1981; and others]. In 1979 a dedicated magnetic fields satellite was launched to make the first global vector survey of the geomagnetic field.

The magnetic fields satellite, MAGSAT, was placed in a near-earth sun-synchronous orbit with the objectives of making precise magnetic field measurements to accurately describe the earth's main magnetic field and to map, on a global basis, the fields caused by sources in the earth's crust [Langel, 1979]. It was recognized early in the program that the sensitive magnetometers would also measure the magnetic field produced by currents flowing in the ionosphere-magnetosphere system external to earth and that at some locations and times these external effects would even mask the crustal anomaly fields.

Analyses of these externally caused magnetic perturbations in terms of the responsible currents have generally assumed a highly idealized, local system of paired, infinitely long, planar, parallel current sheets oriented perpendicular to the satellite trajectory. Kisabeth [1979] took a major step towards eliminating these restrictive geometrical assumptions by devising a computational technique to determine the magnetic perturbations that would arise from more general distributions of currents. The present work represents a new effort to model the magnetic perturbations resulting from distributed electrical currents flowing in space around the earth. To that end a method has been developed for calculating the magnetic field at any point in space due to an assumed spatial distribution of electric currents. This paper briefly describes the computation technique and discusses several important aspects of the magnetic perturbations that result from a simple large-scale Birkeland and ionospheric current system resembling that previously deduced from the large body of near-earth magnetic field measurements. We conclude by comparing signatures derived from MAGSAT measurements with those predicted by the computational technique.

Several aspects of the field perturbations derived from the modeled large-scale current system raise questions about commonly accepted interpretations of satellite-borne magnetic observations. They are:

1. For a balanced Birkeland current system in which all of the field-aligned current closes in the N-S direction between the Region 1 and Region 2 field-aligned current sheets, there still exists a sunward-directed magnetic perturbation in the region poleward of the Region 1 currents. Thus, contrary to some suggestions, a polar "top-hat" field distribution does not necessarily imply a net field-aligned current in the Region 1 current system.
2. Significant magnetic field perturbations due to high latitude currents extend to latitudes well below those normally associated with the auroral zone.
3. The existence of a positive perturbation in the sunward component of the magnetic field over the polar cap does not require a cross polar cap current, but rather arises as a natural consequence of a balanced classical Region 1 and Region 2 Birkeland current system.

The Field Modeling Technique

The magnetic field computation technique is based upon the additive properties of vector fields. In general, the field vector at a point in space is the vector sum of the vector components arising from all of the elemental field sources in the universe. In the present case, the magnetic field at a point is computed by summing the contributions of all of the assumed currents that exist everywhere in space. The assumed current distribution is modeled by decomposing the actual current distribution into an arbitrary number of finite length current elements. The technique itself relies upon the use of an analytical expression for the magnetic field of a straight current carrying filament having an extended and smoothly varying cross-sectional current density. The cross-sectional current density profile looks somewhat like a square wave pulse with rounded corners. The use of such a platykurtic distribution has been found to eliminate discontinuities that exist in a square wave representation and allows for easy calculation of the vector magnetic field at any point in the world space.

The total current distribution to be calculated is represented by an arbitrary number of these finite length current elements. Typically several hundred such current elements are used to represent the horizontal and field-aligned current distribution over the high latitude ionosphere. By a suitable summation of the field at each point due to the contributions from all current elements, the magnetic field may be calculated anywhere, such on the earth's surface or along a satellite orbit.

As an illustration of the technique, we show in Figure 1 a simple, hypothetical, ionospheric current distribution that is characterized by dominant north-south currents. A large-scale eastward electrojet current flows from noon across the dusk hemisphere toward midnight while a westward electrojet current is directed through the dawn hemisphere from noon to midnight. All currents are confined to a shell running between 60° and 76° latitude. This horizontal current system requires, for continuity, that there be accompanying field-aligned currents, which are shown in Figure 2. The circles represent the locations of possible field-aligned current elements and the cross hatching represents the direction and relative magnitude of the field-aligned

Paper number 2L0114.
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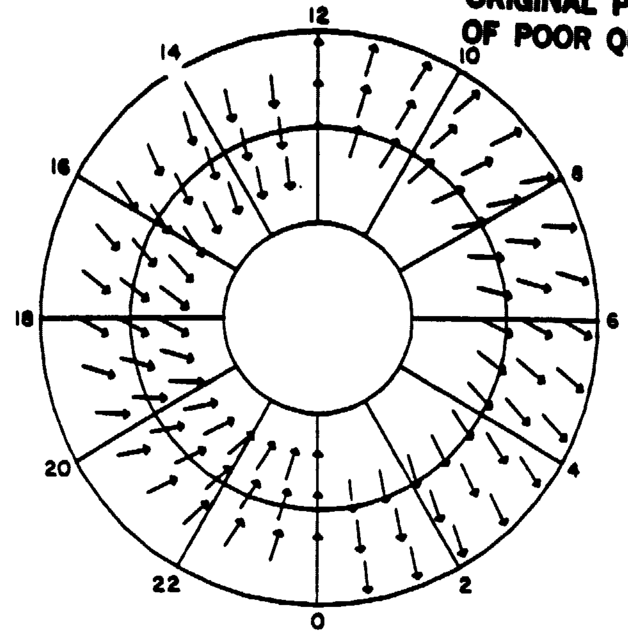
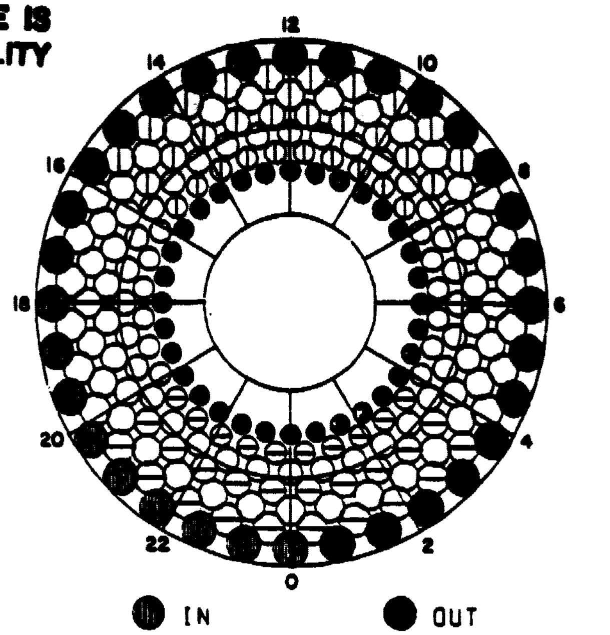


DISTRIBUTION OF IONOSPHERIC CURRENTS

Figure 1. High latitude distribution of horizontal ionospheric currents plotted on a latitude versus local time coordinate grid. All horizontal currents are constrained to flow inside a channel between 60° and 76° latitude.



DISTRIBUTION OF FIELD ALIGNED CURRENTS

Figure 2. The distribution of field-aligned currents required to maintain current continuity with the horizontal currents shown in Figure 1.

currents. Vertical hatching depicts the presence of an inward current, which is seen to exist at low latitudes in the post-noon to midnight sector and at high latitudes in the morning hemisphere. Horizontal hatching indicates the outward current at high latitudes on the evening hemisphere and at low latitudes in the morning hemisphere. These high and low latitude field-aligned currents represent the Region 1 and Region 2 currents deduced by Iijima and Potemra [1976a,b] from a study of the TRIAD data.

In addition to the sheet-like currents discussed above, the chosen horizontal current distribution requires that there be an additional downward current near noon and an upward current near midnight. These currents partially feed into the eastward and westward electrojets that flow across the dawn and dusk hemispheres in Figure 1.

The primary question we seek to answer is, what are the magnetic fields produced by such a current system? Figure 3 displays the results of the computation in the upper three panels as latitude profiles of three components of the magnetic field that would be measured at a satellite at 450 km altitude moving along the dusk to dawn meridian. The cartwheel plot at the upper right depicts the path along which the field is computed. The bottom panel displays the field-aligned current density profile as a function of latitude along the satellite orbit, which, as anticipated from the previous figure, passes through only the classical Region 2 and Region 1 Birkeland currents. As expected, the major perturbation appears in the East-West component with the steepest gradients occurring at the location of the local field-aligned currents.

Smaller, but still significant, magnetic field contributions are found in the region equatorward of the low latitude termination of current flow. The magnetic field strength at 50° latitude, a full 10° of latitude equatorward of the auroral currents, are of the order of 10 to 20 nT and decay only slowly with decreasing latitude. The presence of such mid-latitude magnetic effects in satellite measurements may, if not properly attributed to the external current system, contribute to errors in a proper spherical harmonic representation of the main magnetic field. Concentrating now on latitudes poleward of the high latitude currents, it is apparent that there is again a significant magnetic perturbation due to the modeled currents. This so-called "polar top-hat" field perturbation is directed primarily sunward. This model shows that it arises as a natural consequence of a balanced current system in which the upward and downward currents along a meridian are equal.

Such level shifts observed in satellite data have in the past been interpreted as evidence for a net field-aligned current in the Region 1 system [Sugiura and Potemra, 1976], or as a result of cross polar cap currents [Fujii et al., 1981]. Finally, we note that the modeled currents also produce a notable perturbation in the vertical component of B. Such an effect has been detected in the MAGSAT data.

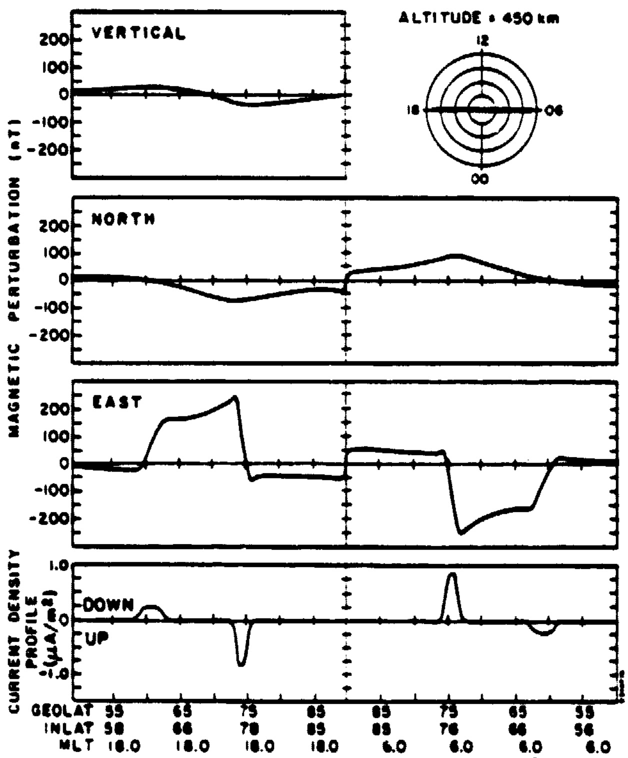


Figure 3. Computed latitude profiles of the vector magnetic field perturbations that would be observed by a magnetometer on a satellite moving along the dusk-dawn meridian at 450 km altitude as a result of the currents shown in Figures 1 and 2.

In Figure 4 are shown, for the same current distribution, the magnetic field profiles along a somewhat different orbit where the satellite passes on the dayside of the pole. The main features of the magnetic profiles observed in the dusk-dawn meridian are preserved with the primary difference being a reduction in amplitude of the N-S component and a widening of the E-W profile, as the satellite makes a more oblique pass through the current system.

Although only profiles at satellite altitude have been shown, the modeling procedure described here also allows the field components to be calculated on the surface of the earth. Such a model will permit further understanding of the external sources of the magnetic fields measured on the ground and in space and, in particular, of the complex magnetospheric-ionosphere electrical circuit.

Comparison with MAGSAT Data

From the vector magnetic measurements made by MAGSAT it is possible to derive a difference field by subtracting a model representation of the earth's main magnetic field from the measured field. This difference field is presumably the resultant perturbation that arises from the combined effects of externally produced fields due to currents in space and induced in the earth, crustal anomalies, and inaccuracies in the spherical harmonic model representation of the core field. If in the first approximation we choose to ignore the latter two contributions to the difference field because they are small, and assume a steady state external current system, the difference field will represent only the effects of external currents. Figure 5 shows such a difference field for a dusk to dawn MAGSAT pass over the northern latitudes on November 13, 1979. In producing this difference field a thirteenth degree and order spherical harmonic representation of the main magnetic field referred to as the MGST (6/80) model [Langel et al., 1980] was used. For this orbit the satellite passes just to the dayside of the dusk to dawn meridian. The largest deviations from the model, up to 950 nT in the East-West component, occur as the satellite passes over the dusk auroral oval between 10:56 and 10:59 UT. A deviation of approximately one-third of the E-W component is also present in the N-S component. Furthermore the N-S component has a 130 nT residual deviation extending down below 41° geographic latitude. The

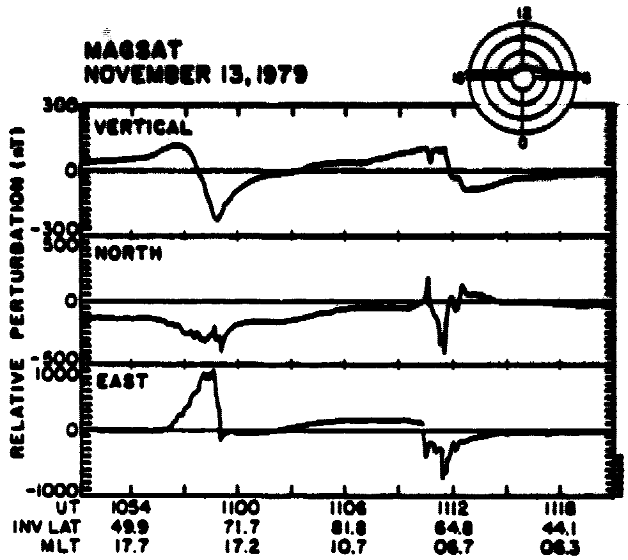


Figure 5. Measured difference fields along a MAGSAT orbit on November 13, 1979. All three components are plotted relative to the MGST (6/80) field model of Langel et al. [1980].

absence of such a low-latitude residual in the E-W component is somewhat at variance with the predictions of the model discussed in the previous section. Two possible explanations may account for this variance. The first is that the auroral current model discussed in the previous section may not accurately portray the real currents during this pass, and that the real current system is producing no E-W field component at low latitude. A second possibility is that the 13th order spherical harmonic expansion has been contaminated by the low latitude fields due to polar currents and as a result has these effects built-in as a part of the main geomagnetic field. The actual resolution of the discrepancy may rest in some combination of these two possibilities and will be one of the objectives of further modeling efforts.

Further comparisons of this MAGSAT difference plot with the perturbations calculated from the simple model and shown in Figure 4 reveal gross similarities in the large-scale features and substantial differences in details. The latter arise from small-scale variations in the actual current sytem that were present during the MAGSAT pass shown in Figure 5 for which no attempt to model has been made in the current distribution discussed here. This comparison serves to illustrate the complexities that exist in the real Birkeland current system.

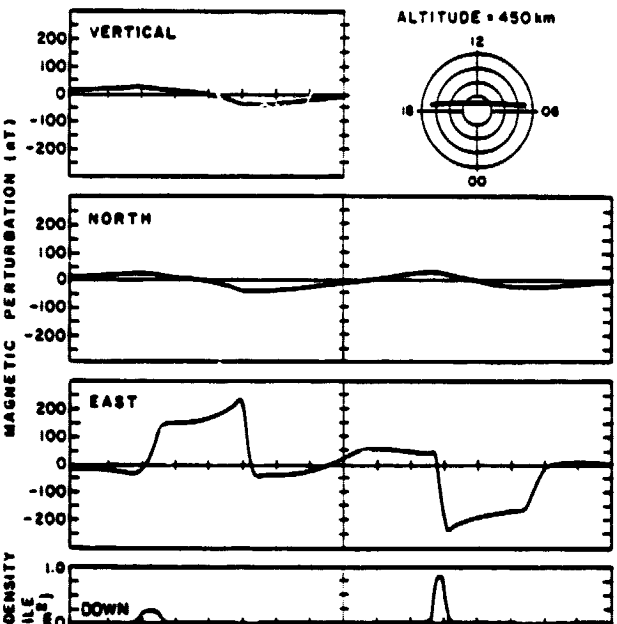


Figure 4. Similar to Figure 3 for a satellite orbit passing on the dayside of the dusk-dawn meridian as shown in the upper right hand corner.

Conclusion

A general calculational procedure has been developed to compute the magnetic field perturbations arising from distributed ionospheric and ionosphere-magnetosphere coupling currents. A simplified current distribution has been chosen to illustrate the technique and the resulting magnetic perturbations have been compared to actual magnetic perturbations measured from MAGSAT. The balanced Birkeland current system produces non-negligible low-latitude magnetic field perturbations. A sunward magnetic perturbation is also produced at latitudes poleward of the high latitude current sheet.

Acknowledgments. This work was supported under National Aeronautics and Space Administration contract number NAS 5-26309.

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(Received November 18, 1981;
accepted January 5, 1982.)

2. Field Modeling

Previous quarterly status reports have chronicled the development of a modeling technique to describe the magnetic perturbations produced at satellite orbit by an assumed ionospheric and Birkeland current system. This modeling routine is currently undergoing verification testing of its component subroutines.

Our modeling capability now allows us to make direct comparisons between model predictions and actual Magsat perturbations by additional software that allows us to calculate along an actual Magsat orbit the magnetic perturbations that would be seen at the satellite for an assumed current distribution. This gives us the capability for direct comparison between measured and predicted perturbations fields. By successive iteration of the input current system the current distribution that yields the best fit between the measured and predicted magnetic perturbations can be determined.

3. Other Activities

During this quarter permission to extend, at no additional cost, the performance period of this contract by 4-months, through November 15, 1982 was granted.

III. PROBLEMS ENCOUNTERED AND RECOMMENDATIONS

The problem discussed in the last two quarterly reports has now been solved with no far-reaching impact to this investigation.

IV. PLANS FOR NEXT REPORTING INTERVAL

The primary goal of this investigative effort is to develop field modeling techniques for the near-earth magnetic field arising from external currents. Such development cannot successfully be carried out without concomitant study and analysis of the actual Magsat data. Hence again during the forthcoming quarter continuing emphasis will be placed on the use of Magsat data to guide our selection of input current systems for direct comparison between predicted magnetic perturbations, and those derived from the Magsat data. To this end we have initiated production processing to determine the magnetic perturbations for a large number of Magsat passes over polar latitudes ($\Lambda > 50^\circ$) for both northern and southern hemisphere. This processing will continue during the next reporting period.

The linear element field modeling procedure will continue to undergo testing during the next reporting period. The emphasis will be placed upon utilizing the flexibility built into the software to choose diverse sets of initial current configurations. One such current configuration is being provided by the Alaska group, which, under the direction of S.-I. Akasofu, has been using the Kisabeth technique to model the current distributions that produce magnetic perturbations in the observations from a meridian chain of magnetometers located in Alaska. Using our modeling procedure we will compute the Birkeland currents required for current continuity and then compute the resulting magnetic perturbations expected both on the ground and at satellite altitude. Direct comparison between our predicted ground level perturbations and their initial input data will permit an assessment of the validity of the modeling technique.

V. FUNDS EXPENDED

The total expenditure of funds under this contract through the end of this reporting period (June 30, 1982) is estimated to be $50,600.00.