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FINAL PROJECT REPORT

Data Use Investigation for the Magnetic Field Satellite (MAGSAT) Mission: Geomagnetic Field Forecasting and Fluid Dynamics of the Core

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Abstract

MAGSAT data have been used to construct a variety of spherical harmonic models of the main geomagnetic field emanating from Earth's liquid core at epoch 1980. This project emphasized the use of these models to evaluate a number of important theoretical and practical geophysical questions. The main accomplishments are:

(1) the accurate determination of the radius of Earth's core by a novel magnetic method, utilizing models of MAGSAT data in comparison with earlier geomagnetic models (Voorhies and Benton, 1982)

(2) the calculation of estimates, based on MAGSAT data, of the long-term range of variation of geomagnetic Gauss coefficients (Benton and Coulter, 1982)

(3) the establishment of a preferred truncation level (at order and degree N=8,) from MAGSAT data for current spherical harmonic models of the main geomagnetic field from the core (Benton, Estes, Langel, and Muth, 1982)

(4) the evaluation, in terms of a model based partly on MAGSAT data (GSFC 9/80), of a new method for taking account of electrical conduction in the mantle when the magnetic field is downward continued to the core-mantle boundary (Benton and Whaler, 1982).

(5) the establishment, from GSFC 9/80, that upwelling and downwelling of fluid motion at the top of the core is probably detectable, observationally.

One important original objective, to produce a new fluid dynamic geomagnetic forecast method and to test it against MAGSAT observations, was not accomplished for reasons given below.

1. Introduction

The thrust of this project has been the utilization of a variety of spherical harmonic models of MAGSAT data (most of which were especially constructed by R. A. Langel (GSFC) and R. H. Estes (BTS) for this project) to implement, evaluate and test a number of recent theoretical efforts to advance our understanding of the fluid dynamics of Earth's liquid core. Since that is where this planet's magnetic field is principally generated, knowledge of core dynamics is essential to the long-range goal of forecasting the magnetic field forward in time. Most of the theoretical highlights and their applications are covered in the 10 progress reports prepared under this contract, and several papers have been published in the open literature (refer to the last section of this report for a list). In this final report, we re-capitulate some major highlights of this project and then turn to the four specific research tasks of this contract.

2. Selected Highlights

(1) The complete electromagnetism appropriate to a model of Earth's mantle in which the electrical conductivity, σ , is radially symmetric but otherwise arbitrary, was developed entirely in terms of a unique poloidal and toroidal decomposition of a magnetic vector potential. For the relatively weak conductivities thought to occur throughout Earth's mantle, a suitable regular, second order perturbation solution for the poloidal problem was developed. This has now been implemented in terms of the magnetic model GSFC 9/80, which incorporates MAGSAT data. The theory and results are described in Benton and Whaler (1982) which is paper #6 in the final listing

of this report. The general conclusions are (i) that, surprisingly, uncertainty in the Gauss coefficients (i. e. model errors) dominates the uncertainty in the mantle conductivity profile; (ii) correction of the radial main field, Br, and its secular variation, $\partial B_r/\partial t$, for the effects of mantle conduction are, respectively, likely to be unimportant and vital; (iii) mantle conduction does not selectively amplify the magnitudes of effective Gauss coefficients, indeed many are found to be damped by conduction.

(2) Two theoretical methods of extracting horizontal fluid motions just below the core-mantle boundary from magnetic observations taken at or above Earth's surface were developed. Both methods require initial knowledge of upwelling and downwelling at selected points on the core-mantle boundary (the critical points where the vertical magnetic field is, locally, either extreme or of saddlepoint structure). Interpolation on the core boundary is then used either in the horizontal induction equation or in Ohm's law to complete the problem. The two methods are derived in Benton (1982), paper #1 below; implementation has not yet been accomplished, but the intention is to use GSFC 9/80 for that purpose.

(3) In 1978, Hide proposed a novel technique for locating the top of Earth's core solely on the basis of magnetic data taken at Earth's surface. The idea rests on treating the core as a perfect conductor ($\sigma\to\infty$) and the mantle as an insulator ($\sigma\to 0$). Then magnetic flux is frozen into the core fluid so the number of field lines crossing Earth's surface, r=a, varies in time, but the number crossing the core-mantle boundary (CMB), r=b, is constant in time. The "number of field lines" is quantified by the unsigned

or absolute magnetic flux crossing a spherical surface of radius r:

$$P(r,t) \equiv \int_0^{2\pi}\int_0^{\pi} | B_r(r,\theta,\phi,t) | r^2 \sin\theta \, d\theta \, d\phi .$$

Spherical harmonic analysis of the vertical magnetic field, B_r, is used for downward continuation from r=a. The CMB is that radius at which P becomes stationary in time.

The technique is not only of great theoretical beauty, it can also be put to a stringent practical test since the radius of Earth's core is very accurately known from seismology (b=3485 km). A first effort to use data on this problem, by Hide and Malin, was only partially successful but Voorhies and Benton (1982), paper #3 below, obtained excellent agreement with seismology by utilizing a different technique together with specially prepared models of MAGSAT data (described in Benton, Estes, Langel, and Muth, 1982, paper #2). MAGSAT data from the two early quiet days, Nov. 5, 6, 1979 were re-fit to the same order and degree as the pre-MAGSAT models GSFC 12/66 and IGS65. Then two values of P at epochs separated by at least 15 years were compared at various depths within the Earth. Constancy of P was found (for models back to 50 years ago) at a tightly clustered group of radii near 3485 km. In the worst case, the core radius, determined magnetically, was 62 km or 1.8% above the seismically determined CMB. (The technique has recently been extended to GSFC 9/80 with even better results.) This is probably the most significant piece of work to come out of this project. It confirms Hide's idea, proves that the core is indeed a highly conducting region while the mantle is nearly insulating (on the time and length scales of interest), and also establishes some reliability of both MAGSAT data and earlier main field models.

(4) The main physical idea underlying much of our current work is that, in the short run, say for periods up to a few thousand years, and for resolvable length scales of 500 km or so, the core can be treated as a perfect conductor with magnetic flux frozen into the fluid because there is not then enough time for ohmic diffusion to separate fluid parcels from magnetic field lines. In the course of this project, we discovered a novel way to use this frozen-flux hypothesis to say something about how large, in magnitude, the geomagnetic Gauss coefficients might have been in the past, and therefore, how close in time Earth might be to the next polarity reversal. This was not anticipated at the time this project was originally planned, so it doesn't fall directly within any of the contract tasks.

Having established that the absolute flux crossing the CMB is constant in at least the short term, we next ask how large a given Gauss coefficient could possibly have been in the distant past by considering the value it becomes when all presently existing field lines are kinematically rearranged into a pattern of pure form corresponding to that harmonic alone. Formulae for these ideal Gauss coefficients were derived and then evaluated using the absolute magnetic flux crossing the CMB as determined from MAGSAT data (Benton and Coulter, 1982, paper #4 below). Ratios of actual to idealized values of the Gauss coefficients were also determined and interpreted to imply that Earth is probably <u>not</u> close to its next reversal.

However, it has recently been pointed out by Gubbins that the process just defined does not truly give frozen-flux limits to the Gauss coefficients (a simple counterexample shows that the dipole coefficient can exceed the value determined by Benton and Coulter, when more than one harmonic is present). We agree with this criticism. Fortunately, this does not vitiate the existence of a frozen-flux upper bound to each Gauss coefficient, but rather points to the need for more work to actually evaluate those bounds.

(5) Another unanticipated result was the determination of a way to both bound and estimate the bound on an overturning time of Earth's core using magnetic data at Earth's surface. The idea was sketched in Progress Report #7 and has now been implemented using the model GSFC 9/80, with very interesting results. A paper is planned but not yet available (paper #2 on page 16).

(6) Much of the present and future work on core geophysics requires reliable models of the main field and/or secular variation at the CMB. The normal mathematical representation of magnetic field data is in terms of a truncated expansion in spherical harmonics of the magnetic scalar potential. Usually the data for such models are selected from a nonuniformly spaced grid on which the retained spherical harmonics are not orthogonal. Therefore, the Gauss coefficients depend upon truncation level of the fit, in contrast to the usual situation where orthogonal basis functions are used. This sort of model dependence was explored in terms of the MAGSAT data by Benton, Estes, Langel, and Muth (1982), paper #2. The same irregularly spaced MAGSAT data set (essentially the calibration data for the two early magnetically quiet days, 5 - 6 November 1980) were fit to successively increasing truncation levels N_F=2, 3, ..., 14. The resulting models, refits to MAGSAT data, are designated MGSTRF below. Interestingly, they showed surprisingly small dependence of Gauss coefficient on truncation level. In examining other magnetic properties of interest (magnetic energy

spectrum, magnetic contours on the CMB, numbers of critical points of B_r) we concluded that N=8 is a logical place to truncate such expansions if the magnetic field is to be extrapolated down to the core surface.

3. Contract Tasks

a. "Construct at least two conventional kinematic forecast models for epoch 1980, using pre-MAGSAT data."

In our view, the best pre-MAGSAT models of the main magnetic field are the ones designated GSFC 12/66 (Cain, Hendricks, Langel, and Hudson, 1967) and IGS65 (Barraclough, Harwood, Leaton, and Malin, 1978). They were the ones used by Voorhies and Benton (1982) to successfully determine the core radius magnetically. The former model was a fit, at order and degree N=10, to all available data from 1900 to 1966; main field, secular variation, and secular acceleration were all included to that same order and degree. The epoch of the coefficients in the publication is 1960. The model IGS65 was designed to be interpolative in the sense that its epoch of determination, 1965, was centered with respect to the span of data selected (which fell within the interval from 1955 to 1973). Gauss coefficients of the main field and secular variation were determined to order and degree N=8.

These two pre-MAGSAT models have been kinematically foredated to epoch 1980 by way of straight-forward truncated Taylor series expansion in time using all of the available coefficients in each model; so the extrapolation for GSFC 12/66 is parabolic in time and over an interval of 14 years beyond the period constrained by data, whereas for IGS65, the extrapolation was linear but only for 7 years beyond the data span.

The resulting foredated Schmidt-normalized Gauss coefficients (in nanotesla) are displayed in the second through fifth columns of Table 1.

b. "Produce a fluid dynamic forecast model at 1980 from models of pre-MAGSAT data. This effort should also result in velocity vector or streamline maps of the surface motion of the core, and contour maps of the magnetic elements at Earth's surface and the core for 1980."

It has not proven possible to complete this task in a satisfactory fashion. However, contour maps of B_r, B_θ, B_ϕ (measured positive in the upward, southward, and eastward directions, respectively) for the model GSFC 9/80 (at epoch 1980) are included as Figures 1, 2, 3. In these figures, the top and bottom panels are the field at Earth's surface and the core surface, respectively. Comparison of the two shows (a) the effect of geometric amplification in the enhanced field values at the core and (b) the dominance of smaller scale fields at the core because the higher harmonics amplify more than the lower ones.

The major work that was accomplished on this task was the development of two theoretical methods, based on interpolation, for determining surface fluid motions of the core given adequate measurements of B_r and $\partial B_r/\partial t$ at Earth's surface (Benton, 1981, paper #1). However, the implementation of those methods, needed to complete the task, has not been carried out, basically for two reasons. Firstly, the methods are far more subtle and intricate than was imagined at the time the proposal for this contract was written in early 1979. Sets of contours of certain magnetic components and their space derivatives need to be found first; then the intersections of different contours must be located; other magnetic quantities have to be evaluated at those intersections; and finally (and most difficultly) a one-dimensional interpolation scheme along contours between intersection points has to be developed to evaluate needed functions on which the fluid motions depend. This is clearly a more involved problem than anticipated; its solution will have to be the focus of future work.

A second obstacle to completing this task was the gradual realization that our present global knowledge of the secular variation at Earth's surface is simply not good enough to warrant extrapolation to the core. In particular, the higher harmonics, which amplify the most, are precisely those least well constrained by available observations. Hence, the extrapolation process is most apt to result in an overly noisy version of secular variation at the core. (We now believe that the new "harmonic spline" technique of Loren Shure and her collaborators at Scripps may provide a potential way out of at least part of this difficulty). On the other hand, as Benton and Whaler (1982) show, conduction in the mantle also probably needs to be taken into account for downward continuation of secular variation. Moreover, the errors in Gauss coefficients presents a severe obstacle to obtaining a reliable extrapolation. The discouraging conclusion we have reached is that, at present, it is probably premature to attempt implementing the fluid dynamic method of magnetic forecasting, because the results would not be sufficiently trustworthy to justify the enormous effort involved.

c. "Conduct a feasibility study of methods by which magnetohydrodynamic constraints arising from the frozen-flux hypothesis can be incorporated into geomagnetic data fitting procedures. Also, attempt to estimate uncertainties in Gauss coefficients and/or contour maps associated with downward extrapolation through the mantle."

The feasibility study called for here has been essentially completed, but not in a form for publication. It was found that quite a large number of constraints can be imposed on secular variation modelling if additional physical assumptions are made. The basic ideas have been incorporated into a proposal recently submitted to NASA by the present PI, under the title: "Constraints on geomagnetic secular variation modeling from electromagnetism and fluid dynamics of Earth's core". For example, the assumption of perfect core conductivity implies that magnetic flux through each null flux contour on the CMB must remain constant. At the present epoch this probably provides five or six constraints.

Another example is that, to the extent Earth's core is a nearly steady, self-excited dynamo, then the total magnetic energy stored outside the core is constant in time and this provides a bilinear constraint on the sum of products of Gauss coefficients and their first time derivatives. If the spectrum of magnetic energy is imagined to be constant, then the number of separate scalar constraints is the same as the truncation level of the spherical harmonic expansion. It is very much hoped that the incorporation of such constraints into secular variation modeling will be accomplished under the NASA grant currently being reviewed.

There are at least two independent ways to estimate uncertainties in Gauss coefficients or resulting magnetic properties determined from them at the core-mantle boundary. As was done in constructing model GSFC 12/66, the data can be divided into two nearly (or hopefully) independent subsets and Gauss coefficients are then determined separately. The differences are a measure of error. Alternatively, the covariance matrix which arises in the least squares fitting procedure determines standard errors of the Gauss coefficients associated with the fitting process itself. These latter numbers are only a lower bound on the true errors, but they are still indicative of relative error between coefficients. This last procedure was that used in building the recent model GSFC 9/80 by Langel and his collaborators.

To determine how the errors in Gauss coefficients are propagated into errors of derived magnetic properties at the core surface, we have used GSFC 9/80 to evaluate $(\partial B_r/\partial t)/B_r$ $(=\partial u/\partial r)$ and its standard deviation at the 41 critical points (where $\partial B_r/\partial \theta$, $\partial B_r/\partial \phi$ simultaneously vanish) on the CMB which occur for a truncation level of N=8 (the importance of this quantity is discussed by Whaler, 1980, 1982, Benton, 1981, 1982). The results of this computation are summarized in Table 2, which gives the number of a critical point, its location in co-latitude and longitude, the resulting value of $(\partial B_r/\partial t)/B_r$, its standard deviation, and the ratio of the standard deviation to the value. The final column of that table is 5 times the penultimate column; it indicates the result of a somewhat arbitrary lengthening of the error bars by a factor of 5 over the values indicated in the report by Langel, Estes, and Mead (1981). A conclusion from this tabulation is that upwelling at the core boundary does seem to be observationally detectable in the model GSFC 9/80; this contrasts with Whaler's conclusion based on the IGRF model at 1965.

Another example of error bar calculation is given in Voorhies and Benton (1982), where Gauss coefficient errors are folded into the problem of calculating the absolute magnetic flux crossing the CMB.

d. "Conduct preliminary intercomparisons of various geomagnetic field models truncated at different degrees and compare the forecast models with the conventional MAGSAT-based model".

The first part of this task was the primary subject taken up in the paper by Benton, Estes, Langel, and Muth (1982). The models referred to above as MGSTRF (re-fits to MAGSAT) were constructed at variable truncation level (N=2, 3, 4, ..., 14) and the dependence on N of both the resulting Gauss coefficients and several geomagnetic properties derivable from them was examined. Generally, the effects of aliasing from omitted coefficients was found to be surprisingly small for this particular selection of data.

The final part of this task is accomplished by comparing the two kinematic forecast models GSFC 12/66 and IGS65 at epoch 1980 with the MGST 6/80 model of MAGSAT data, whose epoch is 1979.85 (Langel et. al., 1980). The Gauss coefficients of this model are included as the 9th and 10th columns of Table 1, while those of GSFC 9/80 are, for comparison, given in the 7th and 8th columns.

In Figures 4, 5, 6 we display contours of the difference fields ΔB_r, ΔB_θ, ΔB_ϕ where the difference is the value seen by MAGSAT minus the value predicted by the forecast model. For the upper and lower panel of each figure we have used GSFC 12/66 and IGS65, respectively. The fitting level for the MGSTRF models was chosen to be identical to that of these pre-MAGSAT models, for consistency.

Generally, these figures quantify just how poor is our ability to kinematically forecast the magnetic field forward by 14 or 7 years beyound the end of the data span. The top panel of Figure 4 shows a maximum discrepancy in B_r of magnitude almost 2400 nT (in the Indian Ocean). Halving the interval of extrapolation (from 14 years to 7 years) reduces the maximum discrepancy between model and MAGSAT to 661 nT (i. e. by nearly a factor of four, refer to lower panel of Figure 4). Somewhat surprisingly, the pattern of the discrepancies is quite similar for the two cases.

Figures 5, 6 give similar contour plots for the horizontal field components. The large 1510 nT discrepancy in Figure 5 for B_θ, near India, drops to 368 nT when the extrapolation interval is halved, while an 1119 nT descrepancy in B_ϕ (Figure 6) south-east of Africa also fades dramatically to a few hundred nT upon halving the extrapolation interval.

Generally, the Indian Ocean appears to be a region of great error for all three components. Also, the radial component is typically more poorly forecast than either of the horizontal components. This is unfortunate, in view of the fact that most information about core fluid dynamics requires information on B_r rather than B_θ, B_ϕ. On the other hand, these results do provide substantial incentive for continuing to pursue the fluid dynamic forecast technique, for there is obviously plenty of room to improve on in the conventional kinematic technique.

4. Acknowledgement

As this project reaches its conclusion, the Principal Investigator takes this opportunity to record his indebtedness especially to the MAGSAT Project Scientist, Dr. Robert A. Langel, who has been an unusually supportive colleague and now, collaborator. Thanks are also due to Dr. Ronald H. Estes of BTS for invaluable assistance to this project and to Locke Stuart and Harold Oseroff of NASA/GSFC for constructive administrative cooperation.

5. Publications Supported by this Contract

1. Benton, E. R., "Inviscid, frozen-flux velocity components at the top of Earth's core from magnetic observations at Earth's surface. Part 1. A new methodology," Geophysical and Astrophysical Fluid Dynamics 18, 157-174 (1981).

2. Benton, E. R., Estes, R. H., Langel, R. A., and Muth, L. A., "Sensitivity of selected geomagnetic properties to truncation level of spherical harmonic expansions," Geophysical Research Letters 9, 254-257 (1982).

3. Voorhies, C. V., and Benton, E. R., "Pole-strength of the Earth from MAGSAT and magnetic determination of the core radius," Geophysical Research Letters 9, 258-261 (1982).

4. Benton, E. R., and Coulter, M. C., "Frozen-flux upper limits to the magnitudes of geomagnetic Gauss coefficients based on MAGSAT observations," Geophysical Research Letters 9, 262-264 (1982).

5. Benton, E. R., "The geomagnetic dynamo in Earth's core," submitted to Reviews of Geophysics and Space Physics (1982).

6. Benton, E. R., and Whaler, K. A., "Rapid diffusion of the poloidal geomagnetic field through the weakly-conducting mantle: a perturbation solution," submitted to Geophysical Journal of the Royal Astronomical Society (1982).

6. Papers in Preparation

1. Benton, E. R., and Voorhies, C. V., "On the frozen-flux approximation for Earth's core" (to be submitted to Geophysical Journal of the Royal Astronomical Society).

2. Benton, E. R., "Some bounds and estimates on the intensity of upwelling in Earth's liquid core" (to be submitted to Geophysical and Astrophysical Fluid Dynamics).

7. Additional Papers Referred to in the Text

Barraclough, D. R., Harwood, J. M., Leaton, B. R. and Malin, S. R. C., "A definitive model of the geomagnetic field and its secular variation for 1965-I. Derivation of model and comparison with IGRF," Geophys. J. R. astr. Soc. 55, 111-121 (1978).

Cain, J. C., Hendricks, S. J., Langel, R. A., and Hudson, W. V., "A proposed model for the International Geomagnetic Reference Field-1965," J. Geomag. Geoelec. 19, 335-355 (1967).

Langel, R. A., Estes, R. H., and Mead, G. D., "Some new methods in geomagnetic field modeling applied to the 1960-1980 epoch," NASA Tech. Meme. 93868, 40 pages, Dec. 1981 (also to appear in J. Geomag. Geoelec.)

Langel, R. A., Estes, R. H., Mead, G. D., Fabiano, E. B., and Lancaster, E. R., "Initial geomagnetic field model from MAGSAT vector data," Geophys. Res. Lett. 7, 793-796 (1980).

Whaler, K. A., "Does the whole of the Earth's core convect?" Nature 287, 528-530 (1980).

Whaler, K. A., "Geomagnetic secular variation and fluid motion at the core surface," in press, Phil. Trans. R. Soc. Lond. A, 1982.

TABLE 1. SCHMIDT-NORMALIZED GAUSS COEFFICIENTS (IN nT) FOR SEVERAL GEOMAGNETIC MODELS KINEMATICALLY FOREDATED TO EPOCH 1980.0 FOR COMPARISON WITH MAGSAT MODEL MGST 6/80

		IGS65		GSFC 12/66		GSFC 9/80		MGST 6/80	
n	m	g	h	g	h	g	h	g	h
1	0	-30025.1		-30145.4		-29987.9		-29989.6	
	1	-1978.4	5711.2	-1943.0	5686.8	-1957.4	5606.7	-1958.6	5608.1
2	0	-1996.9		-2067.5		-1996.7		-1994.8	
	1	3003.9	-2154.4	2988.9	-2196.6	3027.7	-2128.8	3027.2	-2127.3
	2	1652.8	-154.3	1397.9	-135.9	1662.9	-198.6	1661.3	-196.1
3	0	1282.4		1239.3		1280.2		1279.9	
	1	-2188.2	-313.5	-2212.1	-283.4	-2180.8	-335.5	-2179.8	-334.4
	2	1265.5	279.6	1334.2	275.6	1251.3	270.9	1251.4	270.7
	3	775.9	-267.1	690.2	-241.8	832.9	-251.5	833.0	-251.1
4	0	938.2		978.7		937.1		938.3	
	1	799.8	189.2	803.9	118.1	782.3	211.8	782.5	211.6
	2	415.0	-257.3	474.7	-254.7	397.2	-256.8	398.4	-256.7
	3	-400.6	53.8	381.7	25.9	-419.6	52.4	-419.2	52.0
	4	201.3	-299.4	167.5	-395.8	198.3	-298.0	199.3	-297.6
5	0	-199.2		-183.3		-217.1		-217.4	
	1	360.4	49.1	368.1	31.5	357.0	45.2	357.6	45.2
	2	293.4	157.2	325.2	152.4	261.5	149.9	261.0	149.4
	3	-40.4	-168.8	-26.4	-169.8	-74.3	-150.7	-73.9	-150.3
	4	-167.0	-73.4	-163.9	-98.5	-161.5	-77.7	-162.0	-78.1
	5	-41.0	83.1	-4.6	70.4	-47.7	91.8	-48.3	91.8
6	0	40.7		38.4		49.1		48.3	
	1	66.4	-17.0	79.9	-3.1	65.0	-14.6	65.2	-14.5
	2	27.0	101.1	19.6	101.8	42.0	93.4	41.4	93.4
	3	-186.3	87.4	-171.3	113.6	-191.4	70.9	-192.2	70.6
	4	5.1	-55.0	10.7	-58.8	3.9	-42.9	3.5	-42.9
	5	4.0	-4.5	8.6	3.4	14.1	-1.9	13.7	-2.4
	6	-122.0	26.8	-95.1	-0.5	-107.1	17.5	-107.6	16.9

		IGS65		GSFC 12/66		GSFC 9/80		MGST 6/80	
n	m	g	h	g	h	g	h	g	h
7	0	73.9		55.2		71.0		71.7	
	1	-64.4	-79.8	-62.9	-78.5	-58.1	-83.2	-59.0	-82.4
	2	-4.3	-26.7	-34.5	-20.8	1.3	-27.1	1.6	-27.5
	3	14.3	2.3	-4.0	6.1	20.1	-5.5	20.5	-4.9
	4	-13.0	6.9	-26.1	24.0	-13.0	15.9	-12.6	16.1
	5	0.4	17.7	-26.4	14.5	0.8	17.8	0.6	18.1
	6	20.0	-25.2	11.7	-6.3	10.8	-23.6	10.6	-22.9
	7	-7.9	7.2	-10.8	1.0	-2.7	-9.9	-2.0	-9.9
8	0	20.4		17.9		18.9		18.4	
	1	8.3	2.3	19.7	-10.6	7.2	7.5	6.8	6.9
	2	-2.1	-17.5	40.3	-20.7	0.9	-17.7	-0.1	-17.9
	3	-15.0	6.4	-15.0	6.8	-10.4	3.2	-10.8	4.0
	4	-4.7	-18.4	6.7	-35.5	-7.1	-22.4	-7.0	-22.3
	5	-2.6	14.3	3.3	5.6	4.0	9.4	4.3	9.2
	6	11.3	15.3	2.5	22.7	3.7	16.3	2.7	16.1
	7	5.2	-12.2	6.8	-11.5	7.1	-13.4	6.3	-13.1
	8	3.4	-12.9	-3.8	-26.9	-1.3	-15.2	-1.2	-14.8
9	0			6.4		5.2			
	1			2.8	-0.4	10.7	-21.8		
	2			-27.3	27.4	1.0	16.0		
	3			-11.5	6.1	-12.0	8.9		
	4			7.7	7.6	9.2	-4.9		
	5			-5.5	-0.1	-3.9	-7.5		
	6			-10.6	8.4	-1.1	9.5		
	7			13.4	24.1	7.1	10.8		
	8			10.3	-2.5	1.5	-5.3		
	9			-12.6	21.1	-5.0	2.1		
10	0			-4.3		-3.3			
	1			-4.7	-17.1	-4.1	1.0		
	2			23.4	-13.9	2.7	-0.1		
	3			-6.0	-0.2	-5.5	2.6		
	4			3.4	4.0	-1.6	5.5		
	5			6.4	-21.4	5.2	-4.3		
	6			6.1	-3.1	2.6	-1.3		
	7			3.6	-1.8	1.3	-1.1		
	8			7.0	3.0	2.4	4.4		
	9			9.8	1.0	3.2	-0.6		
	10			-4.3	-13.4	-0.3	-6.2		

TABLE 2. THE INTENSITY AND SIGNIFICANCE RATIO OF CORE UPWELLING AND DOWNWELLING AT CRITICAL POINTS OF THE VERTICAL MAGNETIC FIELD ON THE CORE-MANTLE BOUNDARY, AS DETERMINED FROM GEOMAGNETIC FIELD MODEL GSFC 9/80 TRUNCATED AT ORDER AND DEGREE N=8

CRITICAL POINT NUMBER	CO-LATITUDE (DEGREES)	EAST LONGITUDE (DEGREES)	$\dot{B}_r/B_r$ (10^{-2}/YR)	$\sigma(\dot{B}_r/B_r)$ (10^{-2}/YR)	$\frac{\sigma(\dot{B}_r/B_r)}{\dot{B}_r/B_r}$ (%)	$\frac{\sigma(\dot{B}_r/B_r)}{\dot{B}_r/B_r}$ (%)
1	7.9	328.9	3.45	0.098	2.9	14.3
2	22.1	175.8	-0.44	0.021	4.7	23.7
3	27.8	27.1	1.22	0.031	2.6	12.9
4	32.7	110.6	-0.16	0.008	4.8	23.8
5	37.4	268.6	0.23	0.009	4.0	20.0
6	39.8	47.4	-0.17	0.051	29.2	146.2
7	41.4	322.9	0.53	0.026	4.9	24.5
8	50.8	167.9	-0.55	0.144	26.3	131.5
9	57.3	84.1	-0.29	0.026	8.9	44.6
10	61.9	234.0	-1.35	0.055	4.1	20.3
11	62.7	27.8	0.47	0.021	4.4	22.1
12	62.9	22.5	0.53	0.021	3.9	19.3
13	64.5	309.4	-2.44	0.068	2.8	13.9
14	65.3	57.4	0.12	0.017	14.2	71.1
15	68.7	315.0	-0.66	0.060	9.2	46.1
16	71.6	225.9	0.42	0.051	12.1	60.4
17	74.2	215.3	0.82	0.058	7.1	35.3
18	74.6	148.1	-4.25	0.157	3.7	18.4
19	81.3	187.4	0.12	0.035	28.8	144.2
20	92.4	348.1	0.19	0.032	17.1	85.3
21	95.3	357.7	0.76	0.028	3.8	18.8
22	96.4	58.7	-0.08	0.039	46.3	231.5
23	97.5	28.2	0.21	0.018	8.3	41.3
24	100.2	82.3	-0.24	0.023	9.9	49.5
25	111.7	293.4	-1.82	0.108	6.0	29.8
26	112.9	263.9	0.56	0.036	6.5	32.3
27	117.1	172.9	0.12	0.022	18.4	92.2

(TABLE 2 CONTINUED)

CRITICAL POINT NUMBER	CO-LATITUDE (DEGREES)	EAST LONGITUDE (DEGREES)	$\dot{B}_r/B_r$ (10^{-2}/YR)	$\sigma(\dot{B}_r/B_r)$ (10^{-2}/YR)	$\frac{\sigma(\dot{B}_r/B_r)}{\dot{B}_r/B_r}$ (%)	5 $\frac{\sigma(\dot{B}_r/B_r)}{\dot{B}_r/\dot{B}_r}$ (%)
28	119.1	89.3	-0.39	0.021	5.5	27.4
29	121.8	154.1	-0.75	0.024	3.2	15.8
30	122.0	351.1	-6.12	0.174	28.5	142.3
31	124.9	255.3	0.53	0.037	7.0	35.0
32	126.6	43.6	-0.54	0.032	6.0	29.9
33	127.0	2.6	-8.64	0.596	6.9	34.5
34	128.2	330.4	0.87	0.087	10.1	50.5
35	135.8	200.9	-0.70	0.036	5.0	25.2
36	138.7	293.8	-0.07	0.022	33.9	169.4
37	144.0	344.3	0.13	0.039	30.5	152.5
38	145.0	119.3	-0.27	0.010	3.8	19.2
39	155.9	338.5	0.23	0.045	20.0	99.9
40	157.8	138.5	0.07	0.010	15.3	76.5
41	165.3	220.5	-0.01	0.001	107.9	539.4

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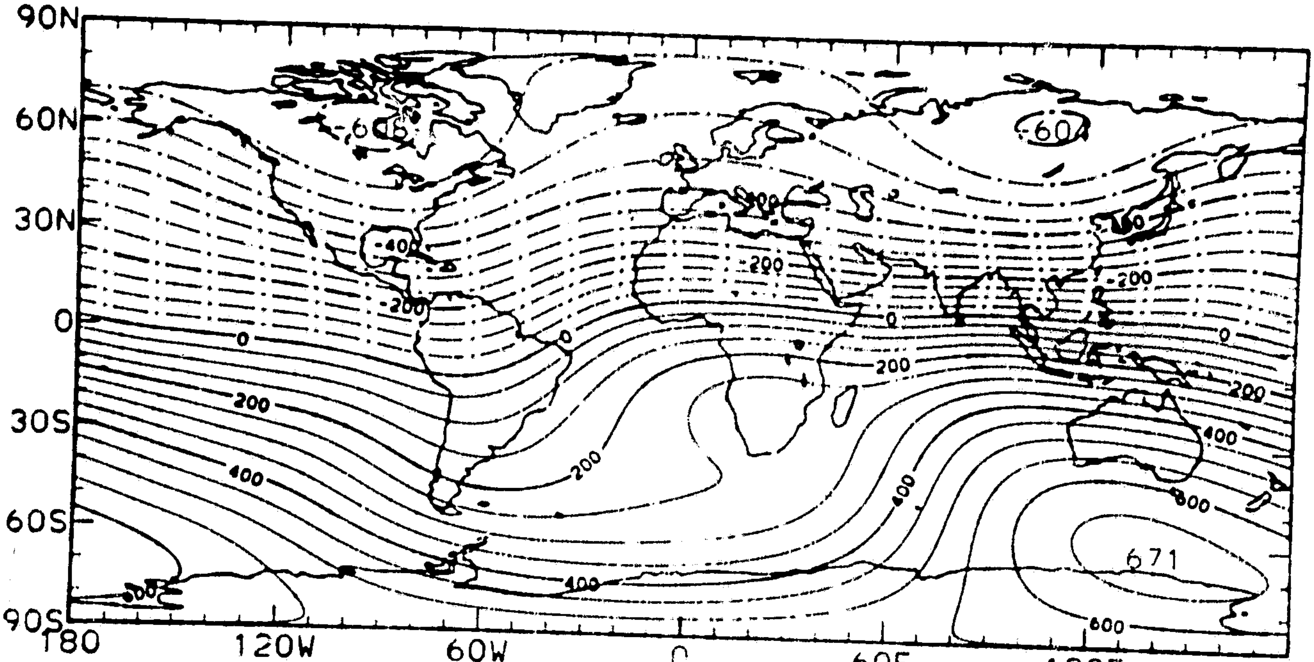
RADIAL MAGNETIC FIELD FOR GSFC 9/80 AT R=6371.2 KM



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RADIAL MAGNETIC FIELD FOR GSFC 9/80 AT R=3485.0 KM

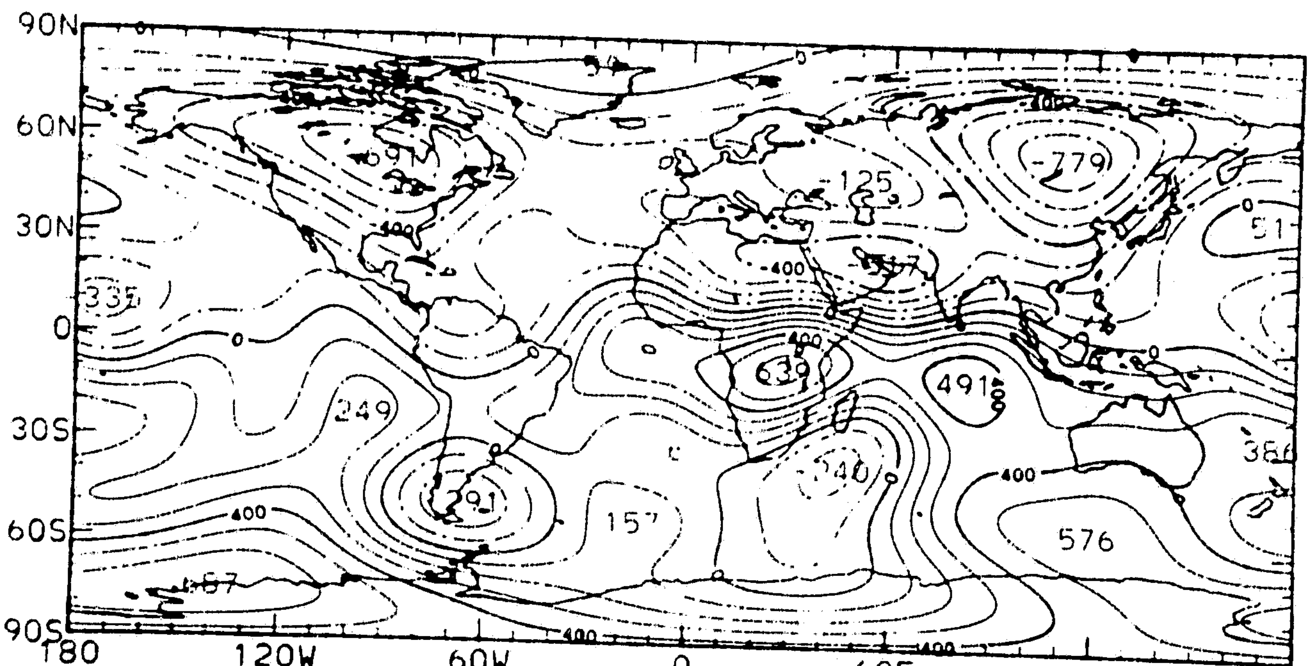

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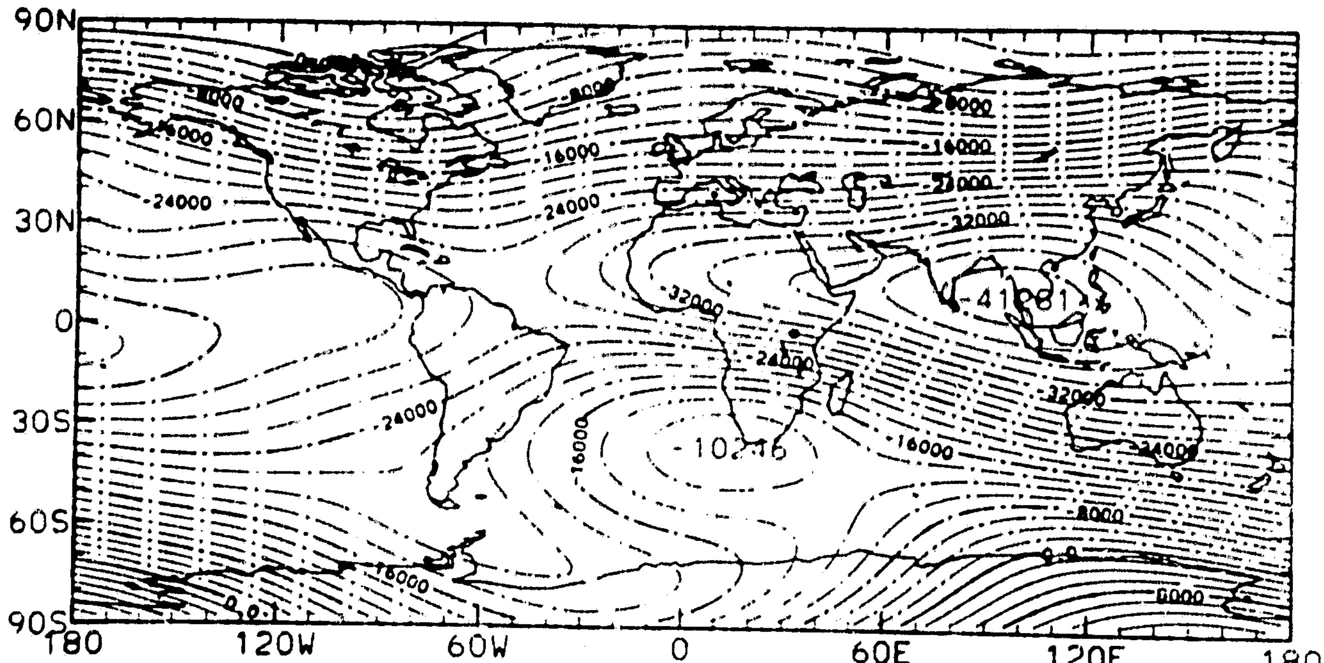
FIGURE 1. CONTOURS OF B_r FOR GEOMAGNETIC MODEL GSFC 9/80 AT EARTH'S SURFACE (TOP) AND THE CORE SURFACE (BOTTOM).

SOUTHWARD MAGNETIC FIELD COMPONENT FOR GSFC 9/80
AT R=6371.2 KM



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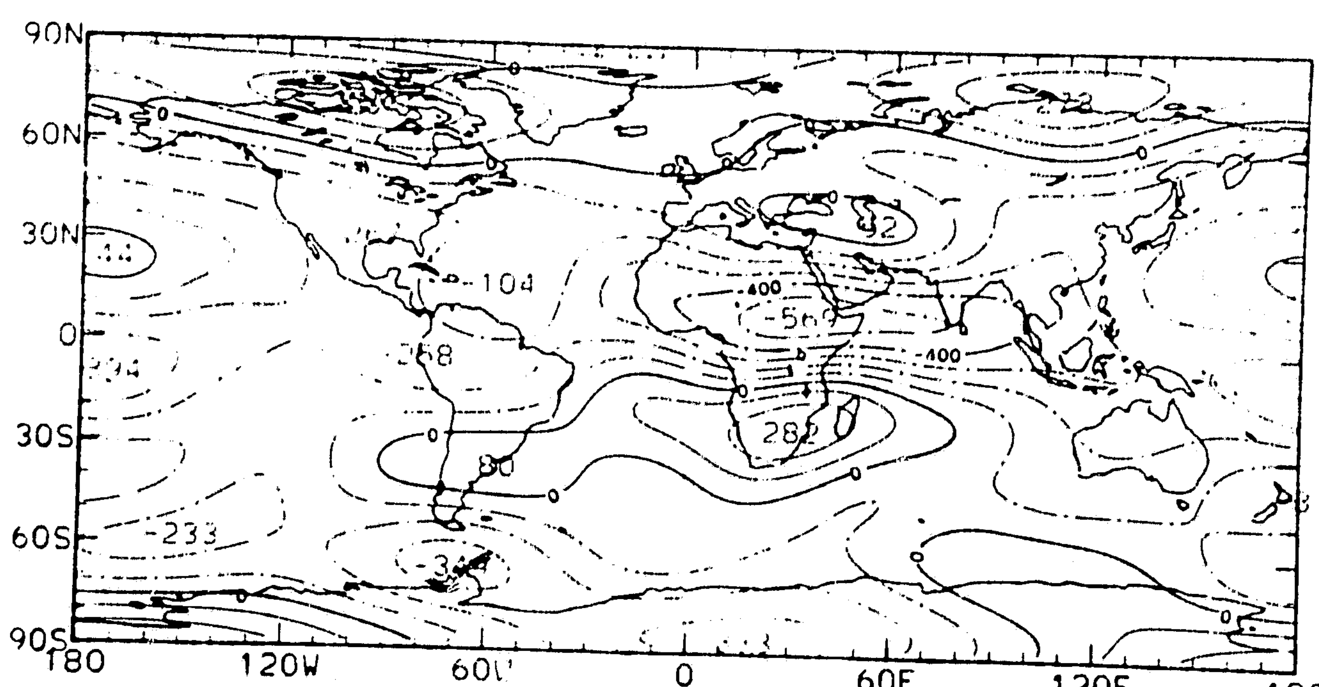
AT R=3485.0 KM



FITTING LEVEL = 13; TRUNCATION LEVEL = 8; CONTOUR INTERVAL = 1000 nT

FIGURE 2. CONTOURS OF B_θ FOR GEOMAGNETIC MODEL GSFC9/80 AT EARTH'S SURFACE (TOP) AND THE CORE SURFACE (BOTTOM).

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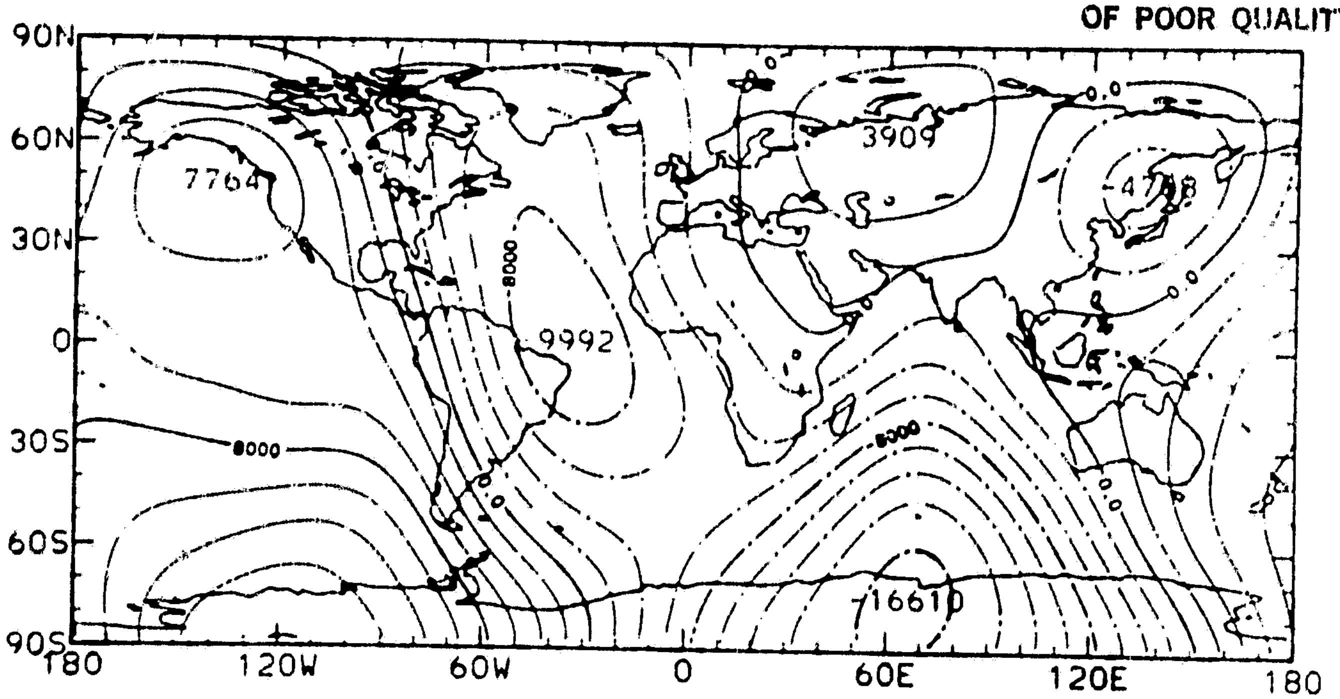
EASTWARD MAGNETIC FIELD COMPONENT FOR GSFC 9/80
AT R=6371.2 KM



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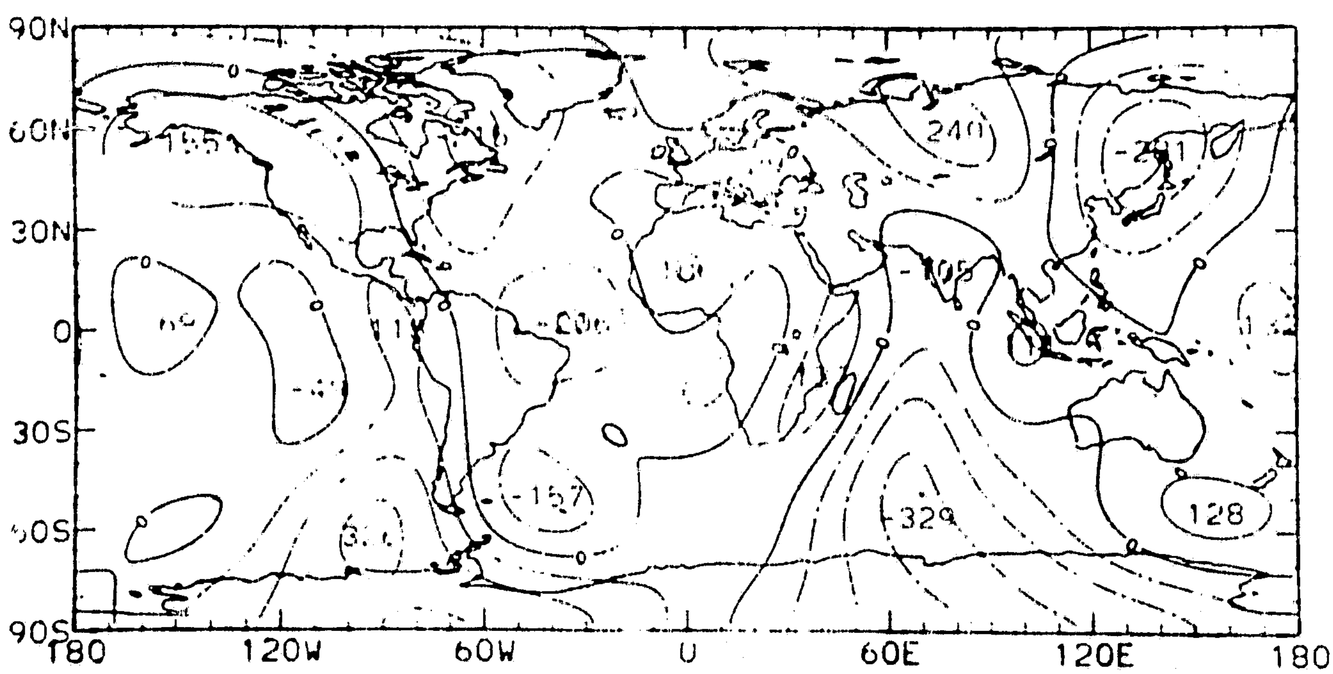
EASTWARD MAGNETIC FIELD COMPONENT FOR GSFC 9/80
AT R=3485.0 KM



FITTING LEVEL = 13; TRUNCATION LEVEL = 8; CONTOUR INTERVAL = 1000 nT

FIGURE 3. CONTOURS OF B_ϕ FOR GEOMAGNETIC MODEL GSFC 9/80 AT EARTH'S SURFACE (TOP) AND THE CORE SURFACE (BOTTOM).

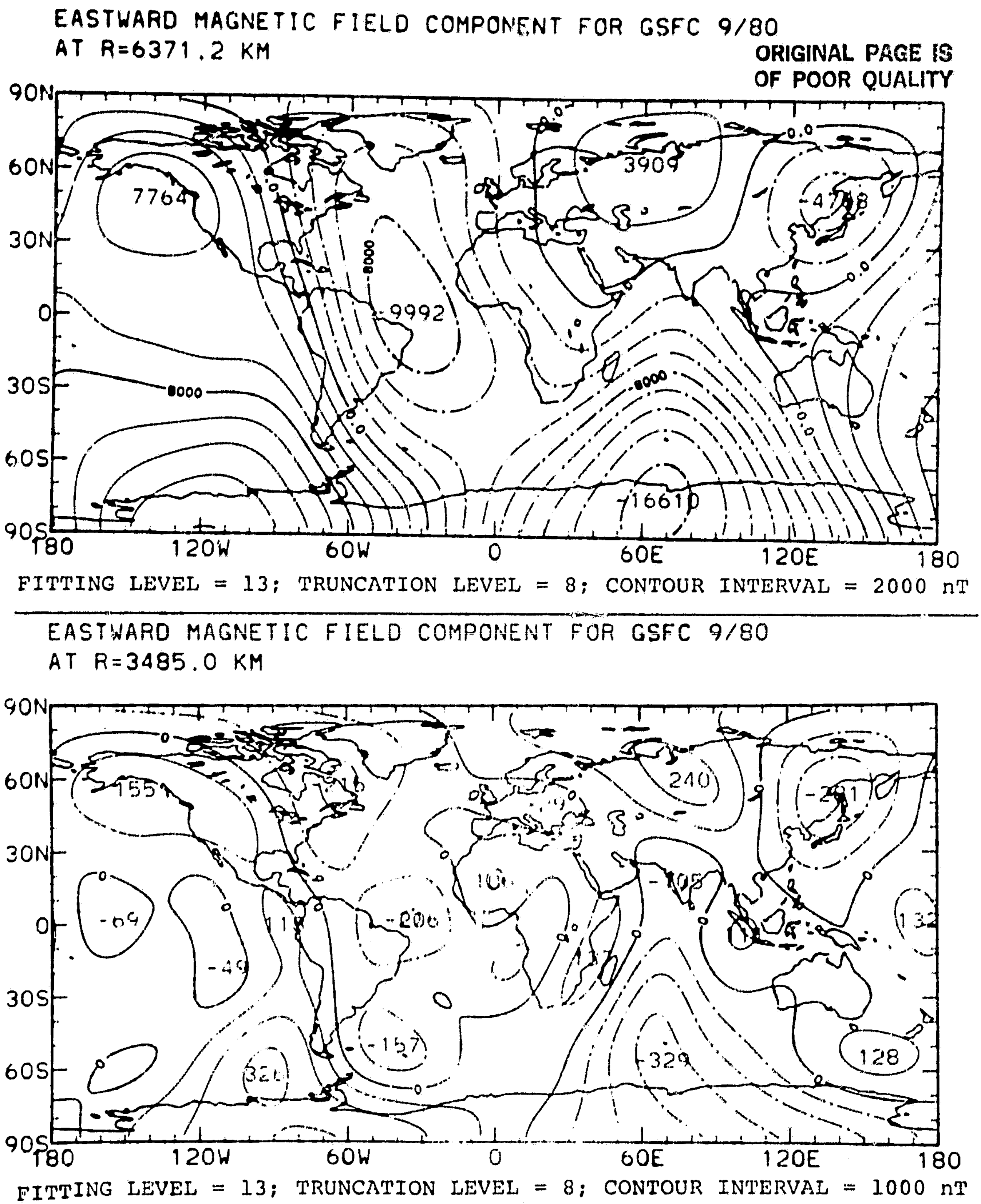
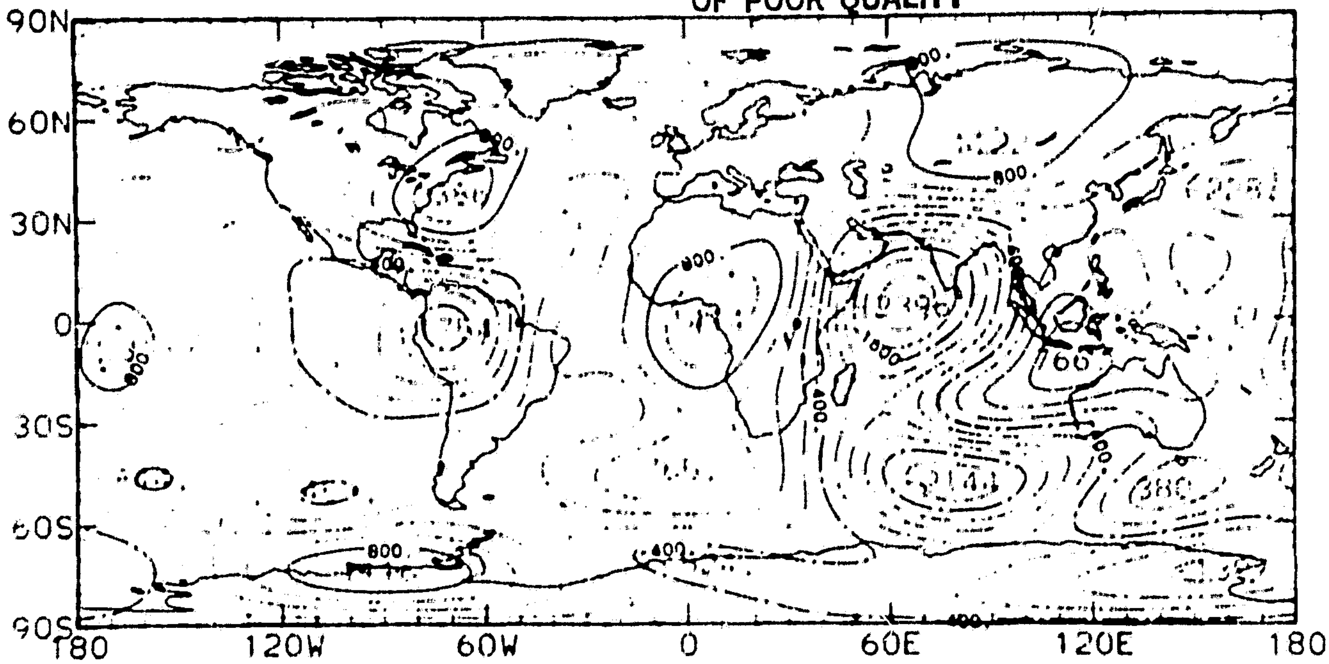


FIGURE 3. CONTOURS OF B_ϕ FOR GEOMAGNETIC MODEL GSFC 9/80 AT EARTH'S SURFACE (TOP) AND THE CORE SURFACE (BOTTOM).

RADIAL MAGNETIC FIELD FOR MGSTRF-GSFC12/66 AT R=6371.2 KM



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RADIAL MAGNETIC FIELD FOR MGSTRF-IGS65 AT R=6371.2 KM

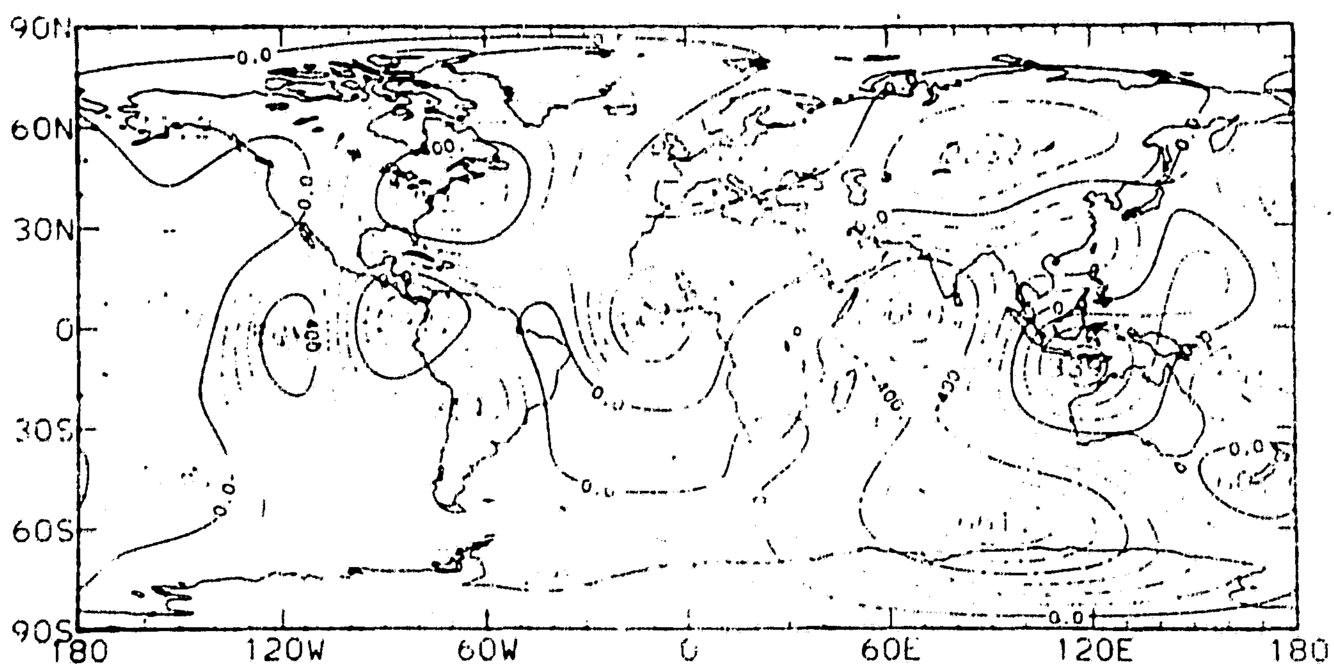

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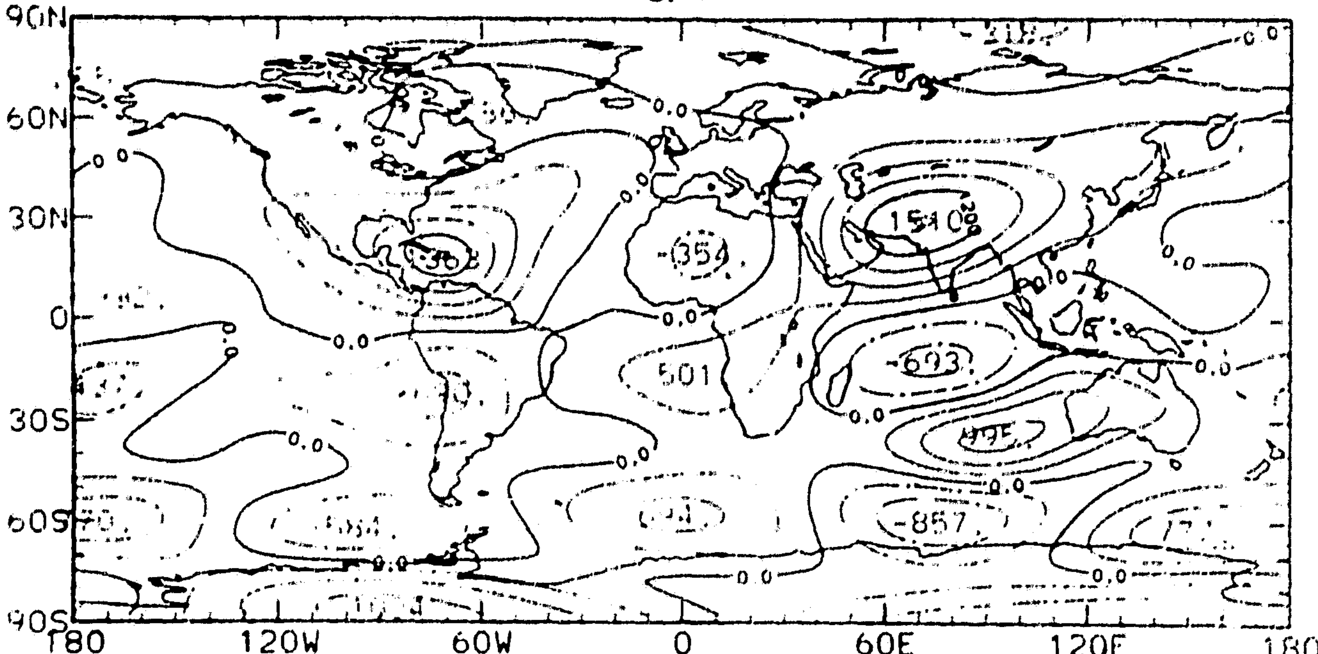
FIGURE 4. CONTOURS OF THE DISCREPANCY BETWEEN B_r AS OBSERVED BY MAGSAT AND B_r AS PREDICTED BY GSFC 12/66 (TOP) OR IGS65 (BOTTOM) AT EPOCH 1980.

SOUTHWARD MAGNETIC FIELD COMPONENT FOR MGSTRF-GSFC12/66
AT R=6371.2 KM



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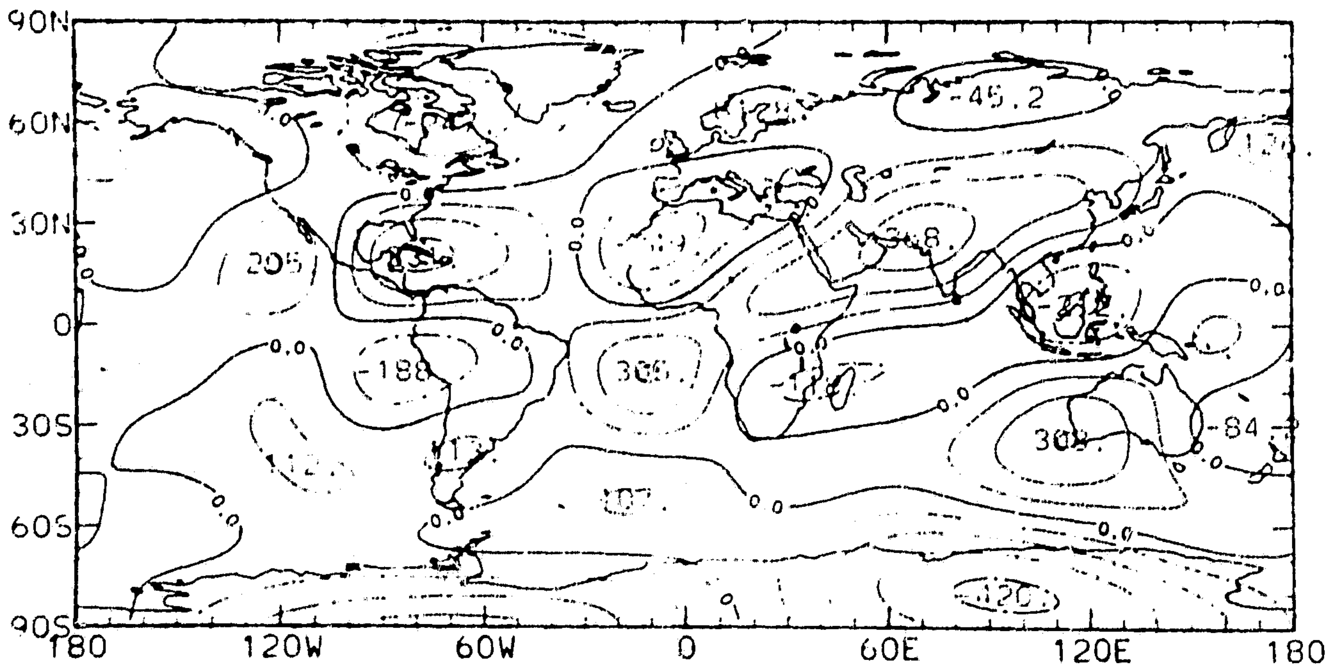
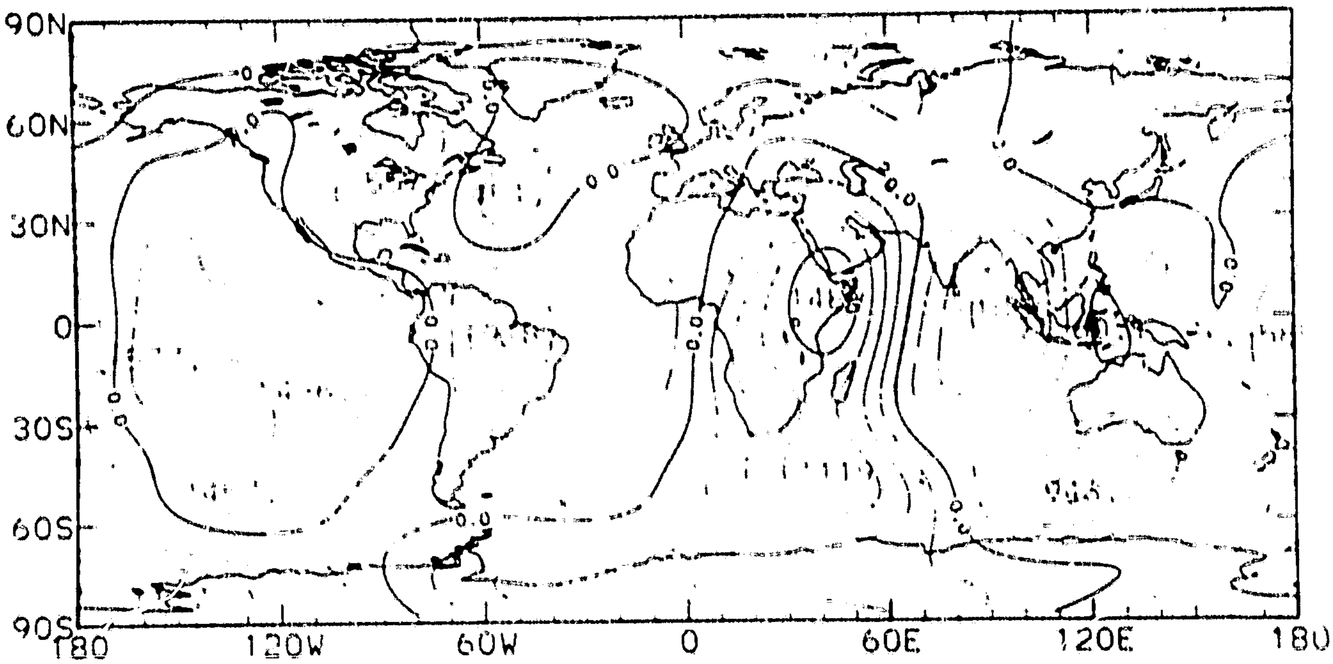
SOUTHWARD MAGNETIC FIELD COMPONENT FOR MGSTRF - IGS 65
AT R=6371.2 KM



FITTING LEVEL = 8; TRUNCATION LEVEL = 8; CONTOUR INTERVAL = 100 nT

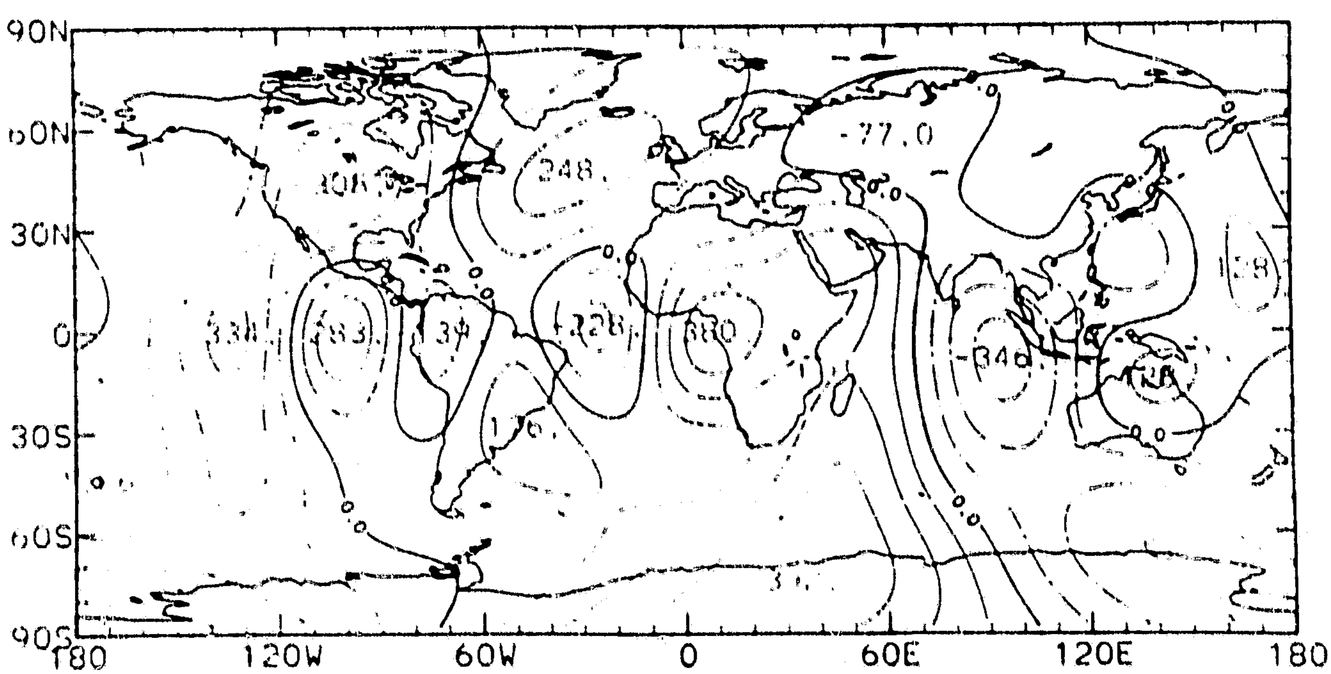
FIGURE 5. CONTOURS OF THE DISCREPANCY BETWEEN B_θ AS OBSERVED BY MAGSAT AND B_θ AS PREDICTED BY GSFC 12/66 (TOP) OR IGS65 (BOTTOM) AT EPOCH 1980.

EASTWARD MAGNETIC FIELD COMPONENT FOR MGSTRF-GSFC12/66
AT R=6371.2 KM



FITTING LEVEL = 10; TRUNCATION LEVEL = 10; CONTOUR INTERVAL = 300 nT

EASTWARD MAGNETIC FIELD COMPONENT FOR MGSTRF - IGS 65
AT R=6371.2 KM



FITTING LEVEL = 8; TRUNCATION LEVEL = 8; CONTOUR INTERVAL = 100 nT

FIGURE 6. CONTOURS OF THE DISCREPANCY BETWEEN B_ϕ AS OBSERVED BY MAGSAT AND B_ϕ AS PREDICTED BY GSFC12/66 (TOP) OR IGS65 (BOTTOM) AT EPOCH 1980.