The 1995 Revision of the Joint US/UK Geomagnetic Field Models. II: Main Field

John M. Quinn\textsuperscript{1}, Rachel J. Coleman\textsuperscript{1}, Susan MacMillan\textsuperscript{2}, and David R. Barracough\textsuperscript{2}

\textsuperscript{1}Naval Oceanographic Office, Stennis Space Center, MS 39522-5001, U.S.A.
\textsuperscript{2}British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland

(Received November 13, 1995; Revised May 29, 1996; Accepted July 7, 1996)

This paper presents the 1995 main-field revision of the World Magnetic Model (WMM-95). It is based on Project MAGNET high-level ($\geq$15,000 ft.) vector aeromagnetic survey data collected between 1988 and 1994 and on scalar total intensity data collected by the Polar Orbiting Geomagnetic Survey (POGS) satellite during the period 1991 through 1993. The spherical harmonic model produced from these data describes that portion of the Earth's magnetic field generated internal to the Earth's surface at the 1995.0 Epoch. When combined with the spherical harmonic model of the Earth's secular variation described in paper I, the Earth's main magnetic field is fully characterized between the years 1995 and 2000. Regional magnetic field models for the conterminous United States, Alaska and, Hawaii were generated as by-products of the global modeling process.

1. Introduction

The World Magnetic Model (WMM) spherical harmonic coefficients are produced jointly by the British Geological Survey (BGS) in Edinburgh, Scotland and the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Mississippi, on behalf of the British Hydrographic Office (BHO) in Taunton, England, and the Defense Mapping Agency (DMA), Washington, D.C. These models are produced at 5-year intervals, as are DMA's Declination/Grid-Variation charts, while charts of several other geomagnetic components are published by DMA at 10-year intervals. The 1995.0 Epoch corresponds to a 10-year interval when all of the geomagnetic components will be published in chart form (DMA, 1993).

The WMM has a wide range of applications in commercial and military navigational and attitude/heading reference systems, geophysical prospecting, and basic geomagnetic research. The WMM may be found, either as a piece of hardware in the form of a computer chip or as a piece of software in most Global Positioning System (GPS) receivers, in commercial and military aircraft, and even in the Space Shuttle. Among many other applications, the model is used for directional oil drilling, for airport radar and satellite communications antennae alignment, and as a core-mantle boundary condition for geomagnetic dynamo theories.

The 1995.0 Epoch World Magnetic Model (WMM-95) consists of a degree and order 12 spherical-harmonic main-field (MF) geomagnetic model, the derivation of which is described in this paper, and a degree and order 8 spherical-harmonic geomagnetic secular-variation (SV) model, the derivation which is described in paper I (Macmillan et al., 1997). The SV model describes the annual rate-of-change of the Earth's main magnetic field. WMM-95 is considered to be a valid description of the Earth's internally generated magnetic field between the years 1995.0 and 2000.0. Subsequently, it will be replaced in the year 2000 by WMM-2000.

The main sources of data for the 1995 Epoch MF modeling were NAVOCEANO's Project MAGNET vector aeromagnetic data collected between 1988 and 1994, and NAVOCEANO's Polar Orbiting...
2. The Mathematical Model

The internal portion of the Earth's magnetic field has associated with it a geomagnetic potential \( V_{\text{int}}(r, \theta, \phi, t) \), which can be expressed in terms of a spherical-harmonic expansion as follows:

\[
V_{\text{int}}(r, \theta, \phi, t) = R_E \sum_{n=1}^{12} \left( \frac{R_E}{r} \right)^{n+1} \sum_{m=0}^{n} \left( g_{nm}(t) \cos(m\phi) + h_{nm}(t) \sin(m\phi) \right) P_n^m(\cos \theta) \tag{1}
\]

where the spherical coordinates \((r, \theta, \phi)\) correspond to the radius from the center of the Earth, the colatitude (i.e., \(90^\circ-\text{latitude}\)), and the longitude. The \(P_n^m(\cos \theta)\) represent the Schmidt-normalized associated Legendre functions of degree \(n\) and order \(m\). \(R_E\) is the mean radius of the Earth (6371.2 km), while \(g_{nm}(t)\) and \(h_{nm}(t)\) are referred to as the Gauss coefficients at time \(t\), where \(t\) is the time in years (e.g., 1997.312). The Gauss coefficients are slowly varying functions of time and are expressed in the form of a Taylor series expansion where only terms up to first order in time are retained so that:

\[
g_{nm}(t) = g_{nm}(T_{\text{Epoch}}) + \dot{g}_{nm}(t - T_{\text{Epoch}}) \quad T_{\text{Epoch}} \leq t \leq T_{\text{Epoch}} + 5 \tag{2a}
\]

\[
h_{nm}(t) = h_{nm}(T_{\text{Epoch}}) + \dot{h}_{nm}(t - T_{\text{Epoch}}) \quad T_{\text{Epoch}} \leq t \leq T_{\text{Epoch}} + 5 \tag{2b}
\]

where \(T_{\text{Epoch}}\) is the model's base epoch, which for WMM-95 is 1995.0. Thus, \(g_{nm}(T_{\text{Epoch}})\) and \(h_{nm}(T_{\text{Epoch}})\) are the Schmidt-normalized Gauss coefficients for the MF portion of the WMM at the model's base epoch, while \(\dot{g}_{nm}\) and \(\dot{h}_{nm}\) are the Schmidt-normalized Gauss coefficients for the SV portion of the WMM. The core-generated field is the dominant contributor to the observed field at the Earth's surface through spherical harmonic degree and order 12, where the model is truncated. The magnetic field vector \(B_{\text{int}}(r, \theta, \phi, t)\) is the negative gradient of Eq. (1) and has components \(B_r\text{int}(r, \theta, \phi, t)\), \(B_\theta\text{int}(r, \theta, \phi, t)\), and \(B_\phi\text{int}(r, \theta, \phi, t)\).

The objective, then, is to first remove or at least minimize external fields from the observed POGS and Project MAGNET data through judicious selection of these data and by making external field corrections through modeling and other ad-hoc procedures, thereby isolating the internal portion of the observed field from these data. The second objective is to evaluate the Gauss coefficients via a least-squares fitting of the model coefficients to the internal portion of the observed magnetic vector component and/or scalar intensity data.

3. Data Sources and Analyses

3.1 Preliminary models

Observatory and Repeat Station data available through May 1994 were used by the BGS to generate revised SV models covering the periods 1985–1990 and 1990–1995. These models were derived in accordance with the procedures described by Macmillan (1994) and in paper I. The 1985–1990 SV model
was then used to revise the WMM-90 MF model as described by Quinn et al. (1995). Combining this revised MF model with the revised 1990–1995 SV model yields a model designated as WMM-90m, which was used as the initial best-guess model in subsequent analyses. The subscript “m” indicates that this model is a “modified” and updated version of WMM-90.

The WMM-90m model served five functions. First it was used to temporally adjust the Project MAGNET vector aeromagnetic data to 14 selected epochs coinciding with 14 subsets of POGS data. Second, it was used to calibrate, or ground-truth, the POGS data using Europe as the calibration range. Third, it was used to compute statistics intended to weight the POGS and Project MAGNET data. Fourth, it was used as the initial guess in the nonlinear least-square modeling algorithm. Finally, it was used, in lieu of Project MAGNET vector data, to generate model vector data at 5° grid intervals in a ±20° band about the geomagnetic equator to counter the Backus effect while computing the external field intrinsic to the POGS data. Regarding this last use, the intention was to isolate the POGS-only external field which, at each of the 14 POGS data subsets, was considered coherent. It was felt that Project MAGNET data crustal influences could possibly have contaminated these POGS-only results. So, they were not used.

3.2 Project MAGNET data

The Project MAGNET vector aeromagnetic data consists of two data subsets. The first subset consists of 78 high-altitude (>15,000 ft.) survey flights which were flown from October 1988 through September 1990. These data correspond to projects with the C32 designation and were collected prior to the structural remodeling of the Project MAGNET aircraft which took place during 1991 and 1992. These data covered substantial portions of ocean areas around the world and included flights to both the north and south magnetic poles and a survey of Australia. The second subset consists of 56 high-altitude surveys flown from January through December 1993. These data correspond to projects with the D32 designation. Flights from this project were mainly confined to an equatorial band ±20° about the geomagnetic equator.

Processed data from both data subsets consist of one vector magnetic data sample every 2 seconds (i.e., 0.5 Hz sample rate) yielding 1,216,686 vector records for the C32 project flights and 1,050,462 vector records for the D32 project flights, yielding a total of 20,018 vector aeromagnetic records. All 2,267,148 vector records were employed to determine the statistics for weighting the data selected from each flight. These statistics and other flight distribution information are given by Quinn et al. (1995). The Project MAGNET data calibration procedures, compensation methods for aircraft generated magnetic fields, and other data reduction procedures, as well as measurement accuracies of various elements of the Project MAGNET instrument suite are described by Coleman (1992).

The Project MAGNET aircraft is a Lockheed RP3D Orion. Prior to 1990 its instrument suite consisted of a Honeywell, fluxgate vector-magnetometer; a Texas Instruments ASQ-81 absolute-scalar, metastable-helium magnetometer; a GPS receiver, a precision barometric altimeter; and an electrostatic gyro for attitude determination. Post 1990, a radar altimeter was added to the instrument suite while the Electrostatic gyro was replaced with a ring-laser gyro. For post 1990 modeling only, the radar altimeter data was used for height determinations since the barometric data yielded slightly larger RMS magnetic field statistics with respect to a given field model than did the edited radar altimeter data.

Data from the various instruments aboard the aircraft were time-synced to within 10-milliseconds. Surveys were flown at night (local time) to minimize Solar-driven external field effects that contribute to the magnetic Daily-Variation (DV). Otherwise, no DV corrections were made. The flights are generally of long-range over remote ocean areas, which precludes the monitoring of DV. These aircraft data were collected at all times of the year, over the course of many years. So, the overall aeromagnetic data set is presumed to be nearly incoherent with respect to DV. However, there may be longer term Solar-cycle influences in these data which are still likely to be coherent and which were not addressed. Each flight typically lasts 10 to 12 hours and is flown at an average speed of about 440 km/hr. A short-wavelength filter with a 7 km cutoff is routinely applied to Project MAGNET survey data collected at altitudes greater
than 15,000 feet. The Honeywell vector magnetometer is calibrated at least once each year at the National Aeronautics and Space Administration's (NASA's) Coil Room Facility in Greenbelt, Maryland, or at the U.S. Geological Survey's Magnetic Calibration Facility in Fredericksburg, Virginia.

The preponderance of Project MAGNET survey data were collected in ocean areas straddling the geomagnetic equator. The intent was to provide absolute vector-magnetic measurements in the equatorial region to counter the Backus effect which is also known as the Perpendicular Error effect (Stern et al., 1980). This effect is a spherical-harmonic modeling error of mathematical origin that generates spurious magnetic anomalies along the geomagnetic equator if only scalar Total-Magnetic-Intensity measurements are available for modeling.

3.3 POGS data

The Polar Orbiting Geomagnetic Survey (POGS) satellite was launched April 11, 1990. The salient design characteristics, processing procedures, and calibrations applied to POGS data are given by Quinn et al. (1993). The satellite was inserted into a near circular, polar orbit ranging in altitude between 700 km to 750 km. The satellite inclination was 89.9°. Its orbit was not sun-synchronous and so, covered all local times. The fluxgate vector magnetometer was located at the tip of an 8-ft. non-magnetic, Copper-Beryllium boom and had a resolution of 2 nT per vector axis. Although the satellite carried a vector magnetometer, there was essentially no attitude determination system on the satellite with which to orient the magnetometer. We say essentially no attitude determination system because a coarse attitude device was constructed from 9 of the 52 solar panels which provided some attitude with respect to the sun-line for the satellite but not for the boom-mounted magnetometer relative to the satellite. However, the accuracy of this system was at best only ±3° with degrading accuracy as the satellite approached the dawn-dusk meridian. So, the solar panels were used as a coarse sun-sensor which provided no data on the night-side of the Earth. Consequently, the POGS mission was essentially a scalar magnetic survey of the Earth. The attitude data were nevertheless made available with the rest of the POGS data since applications other than the WMM may find it useful.

The POGS fluxgate magnetometer was constructed at NASA and was similar to those used on the Defense Meteorological Satellite Program (DMSP) satellite series. These magnetometers are not absolute instruments and so, have a tendency to drift. Extra thermal insulation was added to the magnetometer to minimize this drift which originates within the magnetic sensors and their associated electronics. The maximum possible magnetometer drift at the time of launch was estimated to be less than 50 nT/yr. The actual drift was one third of this estimate. Additionally, the satellite's quartz clock, to which the magnetic data were time tagged prior to telemetry to a ground station, also had a tendency to drift. If not properly taken into account, both of these drifts can be misinterpreted as secular variation.

The POGS quartz-clock bias and drift were determined by periodically monitoring the POGS clock via scheduled timing pulses sent form the satellite to the Master Ground Station, located at NAVOCEANO, which was equipped with a cesium standard clock calibrated at the Naval Observatory. Each pulse was of known duration (20 seconds). The difference between the scheduled end of the pulse, which was known a-priori, and the actual end of the pulse, accounting for the time taken to travel the distance between the satellite and the ground station, yields the POGS quartz-clock timing error. This error could be measured to within 10 milliseconds. Repeating this procedure at roughly 10-day intervals during the 1991.0 to 1993.7 time-frame yields the POGS quartz clock bias and drift rates reported by Quinn et al. (1993). The time corrected magnetics data could then be temporally merged with the ephemeris data supplied by DMA. The ephemeris timing accuracy was better than one millisecond. Data collected prior to 1991.0 were considered unusable. During this period the ground station antennae pattern was being reconfigured for better satellite communications.

After the POGS data reduction was complete, it was determined that for a short section of data between 1991.0 and 1991.4, the quartz-clock bias and drift corrections were in error. Due to circumstances related to the dismantling of the magnetics program at NAVOCEANO, which was ongoing at the time, it was not possible to recompute and reapply the clock bias and drift corrections to this data segment as we would
normally have done. Rather than throwing this small data segment away, the error was accounted for, we believe to a good approximation, by assuming that the magnetometer drift in this short data segment was the same as that in the remainder of the POGS data set. Any additional field drift, computed for the short data segment during ground-truthing in the European calibration area discussed below, was attributed to the clock-calibration error and was subsequently used to compensate for this error.

The ephemeris was derived from Doppler tracking data obtained from DMA’s Tracking Network (TRANET), which monitored the signals from two POGS-mounted beacons with different frequencies. The satellite ephemeris was reconstructed using the GEM-10B gravity model. The resulting satellite positioning Spherical Error Probable (SEP) was estimated by DMA to be less than 75 meters. The TRANET stations were dismantled in October 1993. This event effectively ended the POGS data gathering mission. Shortly thereafter, communications with the satellite degraded substantially. The satellite remains in orbit as a piece of space debris.

The POGS magnetometer bias and drift were determined by selecting the Solar quiet-time POGS total intensity data over the European area bounded by 40°N and 60°N and by 5°W and 35°E; correcting for external field effects; subsequently removing the WMM-90m from the total intensity data; and then minimizing the residual with respect to the bias and drift coefficients of a linear drift model via least-squares. Within the European calibration range the total intensity is a monotonically increasing function of latitude. Due to the north-south orientation of the satellite’s orbit, the magnetic field observed by the satellite is also a monotonic function of both latitude and time. Consequently, with respect to the clock-calibration-error in the short 1991.0 to 1991.4 data segment, one expects the linear clock-drift to translate, at least approximately, into an apparent linear drift in the magnetic field residuals versus time. Due to the heavy clustering of magnetic observatories in this calibration range, the WMM-90m model, which is based on data supplied by these observatories, should be extremely accurate in this region and so is a good, but not necessarily ideal, reference to assess instrument drift and thereby to provide ground-truthing. The results of these drift computations are given by Quinn et al. (1995). There were 816 observations in the 1991.0 to 1991.4 time segment containing the clock-error problem. The RMS error for this segment of the drift calculation was 9.9 nT. The time segment from 1991.4 to 1993.7 contained 2716 observations and yielded an RMS drift error of 10.8 nT.

Anomalous low- and mid-latitude magnetic fields, not previously observed in either the POGO or MAGSAT missions, were observed in the POGS data. Given the 700 km to 750 km altitude of the POGS satellite, which is in the F-layer of the ionosphere, these fields were tentatively attributed to the Equatorial Anomaly effect as well as equatorial and mid-latitude Spread-F effects which are believed to be generated by currents that are closely associated with thermal winds upwelling from the lower ionosphere (Kelley, 1989). In extremely quiet times, these effects, as seen by POGS, are limited to the equatorial regions. As magnetic activity increases in response to changes in the Solar Wind speed and intensity, these apparent ionospheric disturbances move to higher latitudes and exhibit a latitudinal banding characteristic of resonant modes of excitation. Although we feel it unlikely, the possibility that these anomalous fields are due to some miscalibration of the magnetometer could not be ruled out. Regardless of the interpretation, these fields were clearly not of internal origin and required isolation and removal.

The isolation of these fields was accomplished by generating preliminary MF models at each of 14 epochs centered on 14 select-groups of quiet-time, 10-day POGS data files. Vector data from the WMM-90m model were used in the ±20° band straddling the geomagnetic equator in order to control the Backus effect, while POGS data were used exclusively outside of this band. Hindsight suggests that it would have been better to use some POGS data inside the equatorial band as well. Except for equal area weighting, no weights were applied. Internal Gauss coefficients to degree and order 12 and external Gauss coefficients to degree and order 5 were computed at each of the 14 epochs. That is, 14 models were computed at 14 distinct epochs. Scalar total intensity values generated from the internal and external parts of these models were removed from each 10-day file. The residuals were averaged over all geomagnetic longitudes for each 1° geomagnetic latitude band, yielding 10-day averaged ionospheric-field correction profiles of which Fig. 1 is typical. Field-Aligned current effects are clearly evident in the polar regions.
Profiles similar to that of Fig. 1 were removed from each POGS 10-day file prior to making the final models.

The quiet-time POGS data selection criteria for both the preliminary and final modeling were: the planetary $K (Kp)$ index be less than 2+, the absolute value of the Disturbance storm-time ($Dst$) index be less than 50 nanoTeslas, and the data fall locally in time between 7 PM and 5 AM. The data distribution resulting from these selection criteria are given by Quinn et al. (1995). The 14 POGS data subsets spanned the interval between 1991.0 and 1993.7, with each subset resulting from these selection criteria containing approximately 18,000 records with good spatial distribution and localized in time from 20 to 60 days depending on Solar activity which governs the quiet-time data selection.

4. Modeling

As was the case for the preliminary models, the final models were generated using the least-squares method of Cain et al. (1967). Again, the internal model was to degree and order 12, while the external model was to degree and order 5. Three additional parameters, corresponding to an external Ring Current model of the type used by Langel and Estes (1985), were introduced as unknown parameters to be determined. Thus, a total of 168 internal Gauss coefficients, 35 external Gauss coefficients, and 3 $Dst$ related Ring Current coefficients were determined at each of 14 separate epochs spanning the time interval between 1991.0 and 1993.7.
The Project MAGNET observatory airswing-calibration-flights typically yield RMS errors on the order of 35 nT, while POGS RMS errors for each 10-day file with respect to WMM-90m averaged approximately 45 nT. Since these two numbers were nearly the same, the relative weighting of the two data sets was taken to be one along with the model data. All data were equal-area weighted using a factor of $\sin \theta$, where $\theta$ is the co-latitude.

To minimize the effects on the modeling of attitude determination errors that are intrinsic to vector data, Project MAGNET data and model data were used exclusively in the ±20° band straddling the geomagnetic equator where such data were necessary to control the Backus effect in accordance with the recommendations of Lowes and Martin (1987). Outside of this band, POGS data were used exclusively. This amounts to a geomagnetic latitude band weight factor $w(\Theta)$ of 0 or 1 according to data type, where $\Theta$ is the geomagnetic latitude.

RMS statistics were computed for the $r$, $\theta$, $\varphi$ and $F$ magnetic components of Project MAGNET data on a flight-by-flight basis. Statistics were also computed for the $F$ magnetic component of the POGS data. These statistics were computed relative to WMM-90m. Relative weights were assigned for each magnetic component using the squared ratio of the average RMS error for a given magnetic component for all flights (10-day files) used in a model to that of a particular flight (10-day file) for the same magnetic component.

Editing the quiet-time POGS data was not a straightforward matter due to Field-Aligned current effects and to the anomalous field tentatively attributed to Spread-$F$ effects that was broadly present at all latitudes. So, even though the average of these effects for a given 10-day file were removed using ionospheric correction profiles like that of Fig. 1, individual data records, particularly in the auroral zones, are expected to be widely scattered about the average and are considered as outliers. These were down-weighted by the factor:

$$w_0 = e^{-\left(\frac{AB}{3\sigma}\right)^2}$$

where $AB$ is the residual value computed with respect to WMM-90m, while $\sigma$ is the RMS error of the 10-day file computed with respect to WMM-90m prior to the removal of the ionospheric correction field rather than after. Thus $\sigma$ is somewhat larger than would otherwise have been if computed with ionospherically corrected data. So, the POGS down-weighting is not as strong as it might first appear. A similar weighting factor was used on the Project MAGNET vector-component data, which contain anomalous crustal influences, as well as magnetic effects from Solar quiet (Sq) currents and the Equatorial Electrojet current.

Since the Project MAGNET data and the POGS data were largely collected concurrently in time, no age-dependent weight factor was applied to these data in contrast to the 1990 Epoch modeling sequence. The total weight applied to a specific data point is a product of the foregoing weight factors:

$$w_{i'k'l'mn} = w_{mn}(\Theta)\left(\frac{\sigma_{lm}}{\sigma_{klm}}\right)^2 e^{-\left(\frac{AB}{3\sigma_{klm}}\right)^2} \sin \theta_i$$

where the indices correspond to the following:
- $i'$th - data point,
- $k'$th - aircraft flight or satellite 10-day file,
- $l'$th - magnetic component ($r$, $\theta$, $\varphi$, $F$),
- $m'$th - data type (Project MAGNET, POGS),
- $n'$th - geomagnetic latitude band (inside/outside the ±20° band).

Using the above weighting, 14 magnetic field models were computed at distinct epochs between 1991.0 and 1993.7. These were designated WMD-01 through WMD-14. The internal and external coefficients of all 14 models are tabulated in Quinn et al. (1995). A few of the low order internal Gauss coefficients are plotted as functions of time in Figs. 2(a) and 2(b). These coefficients exhibit clear secular
Fig. 2(a). Low order Gauss coefficients $g_{10}$ to $g_{22}$ versus time; computed at 14 epochs designated by the "+" symbol.
Fig. 2(b). Low order Gauss coefficients $h_{11}$ to $h_{32}$ versus time; computed at 14 epochs designated by the "+" symbol.
behavior with little noise. This was the case for all internal coefficients through degree and order 12. Subsequently, a linear least-square fit through each of the 14 equally weighted values of each coefficient was performed using 1992.5 as the reference point, which was roughly at the center of the POGS data set. This yields a set of MF Gauss coefficients at the 1992.5 Epoch plus a set of SV coefficients spanning the interval 1990.0 to 1995.0. The SV model was truncated to degree and order 8 and averaged with the SV portion of WMM-90m to create the SV portion of WMM-90r, where the subscript “r” means “revised”. This SV model in turn was used to temporally adjust the 1992.5 MF coefficients backward to 1990.0.

Table 1. WMM-90 (revised) Schmidt normalized Gauss coefficients, units: MF nT; SV nT/yr.

| n | m | $g_n^m$ | $h_n^m$ | $\dot{g}_n^m$ | $\dot{h}_n^m$ |
|---|---|---------|---------|-------------|-------------|
| 1 | 0 | -29,775.1 | 0.0 | 18.6 | 0.0 |
| 1 | 1 | -1,845.7 | 5,405.1 | 12.7 | -17.9 |
| 2 | 0 | -2,127.2 | 0.0 | -13.5 | 0.0 |
| 2 | 1 | 3,061.1 | -2,282.6 | 3.5 | -15.3 |
| 2 | 2 | 1,687.7 | -372.6 | -0.4 | -9.2 |
| 3 | 0 | 1,308.8 | 0.0 | 2.0 | 0.0 |
| 3 | 1 | -2,240.1 | -280.1 | -6.7 | 3.8 |
| 3 | 2 | 1,249.9 | 291.0 | -0.6 | 2.0 |
| 3 | 3 | 805.3 | -355.5 | -7.8 | -12.2 |
| 4 | 0 | 937.0 | 0.0 | 0.6 | 0.0 |
| 4 | 1 | 780.4 | 248.9 | 0.5 | 2.1 |
| 4 | 2 | 324.9 | -237.4 | -6.8 | -1.3 |
| 4 | 3 | 421.4 | 85.3 | 0.5 | 2.9 |
| 4 | 4 | 140.3 | -299.1 | -5.3 | -1.4 |
| 5 | 0 | -214.0 | 0.0 | 0.9 | 0.0 |
| 5 | 1 | 353.5 | 42.7 | 0.1 | 0.2 |
| 5 | 2 | 244.7 | 152.6 | -1.3 | 1.0 |
| 5 | 3 | -110.1 | -152.6 | -2.4 | 0.5 |
| 5 | 4 | -162.8 | -68.2 | 0.0 | 1.8 |
| 5 | 5 | -34.8 | 99.9 | 2.3 | 0.9 |
| 6 | 0 | 64.0 | 0.0 | 0.9 | 0.0 |
| 6 | 1 | 65.6 | -17.7 | 0.0 | 0.5 |
| 6 | 2 | 60.1 | 81.8 | 0.8 | -1.5 |
| 6 | 3 | -179.1 | 70.9 | 2.0 | -0.3 |
| 6 | 4 | 1.0 | -51.3 | -0.3 | -0.8 |
| 6 | 5 | 18.0 | -1.0 | -0.3 | 0.8 |
| 6 | 6 | -92.5 | 23.8 | 0.3 | 1.9 |
| 7 | 0 | 78.5 | 0.0 | -0.1 | 0.0 |
| 7 | 1 | -63.6 | -78.6 | -0.9 | 0.5 |
| 7 | 2 | 3.1 | -26.0 | -0.6 | 0.3 |
| 7 | 3 | 26.6 | -1.4 | 0.6 | 0.6 |
| 7 | 4 | 1.0 | 21.5 | 1.0 | -0.3 |
| 7 | 5 | 6.2 | 17.0 | 0.5 | -0.1 |
| 7 | 6 | 8.7 | -22.6 | 0.1 | -0.2 |
| 7 | 7 | 1.1 | -3.8 | -0.7 | -0.6 |
| 8 | 0 | 24.2 | 0.0 | 0.1 | 0.0 |
| 8 | 1 | 4.9 | 12.4 | -0.3 | 0.5 |
| 8 | 2 | -1.0 | -18.0 | -0.1 | -0.3 |
| 8 | 3 | -10.6 | 5.8 | 0.2 | 0.1 |
| 8 | 4 | -12.5 | -22.9 | -0.8 | 0.5 |
| 8 | 5 | 2.1 | 12.7 | 0.1 | -0.1 |
| 8 | 6 | 3.1 | 12.5 | 0.1 | -1.1 |
| 8 | 7 | -0.9 | -17.0 | -0.8 | -0.4 |
| 8 | 8 | -7.0 | -5.8 | -0.3 | -0.6 |
| 9 | 0 | 2.9 | 0.0 | 0.0 | 0.0 |
obtain the MF portion of WMM-90, and forward to 1995.0 to obtain the MF portion of WMM-95. The BGS SV model covering the period 1995.0 to 2000.0 is the SV portion of WMM-95. The coefficients for WMM-90 are listed in Table 1. The coefficients for WMM-95 are listed in Table 2. The WMM-90 MF model, truncated to degree and order 10, is the US/UK candidate for the 1990.0 Epoch Definitive Geomagnetic Reference Field (DGRF-90). The WMM-95 model, truncated to degree and order 10, is the US/UK candidate for the 1995.0 Epoch International Geomagnetic Reference Field (IGRF-95).

### Table 2. WMM-95 schmidt normalized model coefficients, units: MF nT; SV nT/yr.

| n | m | g^m_n | h^m_n | g^m_n | h^m_n |
|---|---|-------|-------|-------|-------|
| 1 | 0 | -29,682.1 | 0.0 | 17.6 | 0.0 |
| 1 | 1 | -1,782.2 | 5,315.6 | 13.2 | -18.0 |
| 2 | 0 | -2,194.7 | 0.0 | -13.7 | 0.0 |
| 2 | 1 | 3,078.6 | -2,359.1 | 4.0 | -14.6 |
| 2 | 2 | 1,685.7 | -418.6 | -0.3 | -7.2 |
| 3 | 0 | 1,318.8 | 0.0 | 0.8 | 0.0 |
| 3 | 1 | -2,273.6 | -261.1 | -6.6 | 4.0 |
| 3 | 2 | 1,246.9 | 301.0 | -0.5 | 2.2 |
| 3 | 3 | 766.3 | -416.5 | -8.5 | -12.6 |
| 4 | 0 | 940.0 | 0.0 | 1.2 | 0.0 |
| 4 | 1 | 782.9 | 259.4 | 1.1 | 1.3 |
| 4 | 2 | 290.9 | -230.9 | -6.8 | 1.0 |
| 4 | 3 | -418.9 | 99.8 | 0.3 | 2.5 |
| 4 | 4 | 113.8 | -306.1 | -4.5 | -1.2 |
| 5 | 0 | -209.5 | 0.0 | 0.9 | 0.0 |
| 5 | 1 | 354.0 | 43.7 | 0.5 | 0.5 |
| 5 | 2 | 238.2 | 157.6 | -1.4 | 1.5 |
| 5 | 3 | -122.1 | -150.1 | -1.7 | 0.6 |
| 5 | 4 | -162.8 | -59.2 | 0.0 | 1.7 |
| 5 | 5 | -23.3 | 104.4 | 2.1 | 0.6 |
| 6 | 0 | 685.0 | 0.0 | 0.4 | 0.0 |
| 6 | 1 | 65.6 | -15.2 | -0.3 | 0.7 |
| 6 | 2 | 64.1 | 74.3 | 0.3 | -1.5 |
| 6 | 3 | -169.1 | 69.4 | 2.1 | -0.5 |
| 6 | 4 | -0.5 | -55.3 | 0.0 | -0.7 |
| 6 | 5 | 16.5 | 3.0 | -0.4 | 1.1 |
| 6 | 6 | -91.0 | 33.3 | -0.4 | 2.6 |
| 7 | 0 | 78.0 | 0.0 | -0.3 | 0.0 |
| 7 | 1 | -68.1 | -76.1 | -1.1 | 0.3 |
| 7 | 2 | 0.1 | -24.5 | -0.5 | 0.0 |
| 7 | 3 | 29.6 | 1.6 | 0.5 | 0.7 |
| 7 | 4 | 6.0 | 20.0 | 1.3 | -0.6 |
| 7 | 5 | 8.7 | 16.5 | 0.1 | 0.1 |
| 7 | 6 | 9.2 | -23.6 | 0.0 | -0.6 |
| 7 | 7 | -2.4 | -6.8 | -0.9 | -0.4 |
| 8 | 0 | 24.7 | 0.0 | 0.1 | 0.0 |
| 8 | 1 | 3.4 | 14.9 | 0.0 | 0.4 |
| 8 | 2 | -1.5 | -19.5 | 0.4 | -0.3 |
| 8 | 3 | -9.6 | 6.3 | 0.3 | 0.1 |
| 8 | 4 | -16.5 | -20.4 | -1.3 | 0.8 |
| 8 | 5 | 2.6 | 12.2 | 0.5 | -0.1 |
| 8 | 6 | 3.6 | 7.0 | 0.4 | -1.3 |
| 8 | 7 | -4.9 | -19.0 | -0.9 | -0.9 |
| 8 | 8 | -8.5 | -8.8 | 0.1 | -1.1 |
| 9 | 0 | 2.9 | 0.0 | 0.0 | 0.0 |
NORTH MAGNETIC POLE MOVEMENT

Fig. 3(a). North magnetic pole movement: 1945–2000; stereographic projection.

SOUTH MAGNETIC POLE MOVEMENT

Fig. 3(b). South magnetic pole movement: 1945–2000; stereographic projection.
Table 3. Continental U.S. 1995 epoch schmidt normalized Gauss coefficients, units: MF nT; SV nT/yr. Latitude limits: 20°N to 54°N, longitude limits: 229°E to 299°E.

| n  | m  | $g_n^m$  | $h_n^m$  | $g_n^m$  | $h_n^m$  |
|----|----|---------|---------|---------|---------|
| 1  | 0  | -32,736.2 | 0.0     | -38.5   | 0.0     |
| 1  | 1  | 591.1    | -2,524.4 | 60.6    | -7.2    |
| 2  | 0  | 20,001.1 | 0.0     | -80.5   | 0.0     |
| 2  | 1  | -6,682.8 | 10,787.4 | -208.8  | -327.0  |
| 2  | 2  | 13,128.1 | 1,175.1  | 211.0   | -38.6   |
| 3  | 0  | -30,429.6 | 0.0     | 498.7   | 0.0     |
| 3  | 1  | 7,499.5  | 16,431.7 | 313.4   | 357.2   |
| 3  | 2  | -28,363.4 | -13,361.8 | 25.3    | -118.1  |
| 3  | 3  | 3,147.4  | 1,047.1  | 96.1    | 326.1   |
| 4  | 0  | 8,010.8  | 0.0     | -479.2  | 0.0     |
| 4  | 1  | 1,345.5  | -34,584.7 | -117.5  | 134.4   |
| 4  | 2  | 10,654.5 | 14,816.8 | -253.3  | 308.7   |
| 4  | 3  | 4,732.1  | -18,145.9 | -128.5  | -230.6  |
| 4  | 4  | 5,637.5  | 1,798.7  | -211.7  | 20.0    |
| 5  | 0  | 6,476.9  | 0.0     | 101.1   | 0.0     |
| 5  | 1  | -3,467.7 | 12,415.8 | -29.2   | -224.4  |
| 5  | 2  | 8,295.1  | -3,598.8 | 85.4    | -136.1  |
| 5  | 3  | -6,377.0 | 10,431.0 | -51.5   | 20.7    |
| 5  | 4  | 2,712.5  | 290.1   | 115.3   | -115.5  |
| 5  | 5  | -393.9   | 2,903.7  | 36.9    | -78.0   |
| 6  | 0  | -1,445.5 | 0.0     | 12.6    | 0.0     |
| 6  | 1  | 911.6    | 190.3   | 13.2    | 47.2    |
| 6  | 2  | -2,976.5 | -470.3  | -1.4    | 9.4     |
| 6  | 3  | 1,227.6  | -489.4  | 24.9    | 3.7     |
| 6  | 4  | -1,888.7 | -798.7  | -14.2   | 7.6     |
| 6  | 5  | 66.2    | -164.6  | 35.3    | 21.1    |
| 6  | 6  | -378.1  | 61.9    | 18.4    | 22.8    |

Table 4. Alaska 1995 epoch schmidt normalized Gauss coefficients, units: MF nT; SV nT/yr. Latitude limits: 42°N to 74°N, longitude limits: 160°E to 236°E.

| n  | m  | $g_n^m$  | $h_n^m$  | $g_n^m$  | $h_n^m$  |
|----|----|---------|---------|---------|---------|
| 1  | 0  | -23,917.9 | 0.0     | 77.2    | 0.0     |
| 1  | 1  | -483.7   | 2,497.8 | 5.3     | 140.5   |
| 2  | 0  | -11,788.9 | 0.0     | -168.6  | 0.0     |
| 2  | 1  | 8,221.5  | 6,865.1  | 37.6    | -215.8  |
| 2  | 2  | 7,097.2  | 2,603.6  | -158.6  | 168.8   |
| 3  | 0  | 4,985.2  | 0.0     | 120.3   | 0.0     |
| 3  | 1  | -11,819.6 | -8,699.1 | -73.1   | 46.6    |
| 3  | 2  | -5,815.9 | 928.4   | 148.0   | -222.1  |
| 3  | 3  | -1,417.9 | 1,166.9  | -93.3   | -43.4   |
| 4  | 0  | 1,459.8  | 0.0     | -21.7   | 0.0     |
| 4  | 1  | 5,219.1  | 2,407.8  | 29.0    | 28.7    |
| 4  | 2  | 3,403.0  | -1,385.1 | -64.1   | 66.7    |
| 4  | 3  | -340.8   | -278.0  | 37.6    | -19.9   |
| 4  | 4  | -965.8   | -487.9  | -17.9   | -40.3   |
Fig. 4(b). Secular variation of declination from WMM-95 at 1997.5; units: minutes/yr, projection: corrected mercator.
5. Pole Positions and Movements

The movements of the North and South Magnetic or Dip poles since 1945 are illustrated in Figs. 3(a) and 3(b). These positions were derived from the DGRF models, WMM-90, and WMM-95. The geomagnetic jerk of 1970 is clearly evident at both poles. Sudden changes in the Earth’s magnetic field such as these have been correlated to irregular changes in the Length-of-Day although no cause and effect relationship has been established.

From WMM-95 at 1995.0, the North-magnetic dipole pole-position is located at +79.30 degrees latitude and -71.46 degrees longitude, while the South-magnetic dipole pole-position is located at -79.30 degrees latitude and +108.54 degrees longitude. The strength of the Earth-centered dipole field is currently decaying at the rate of 7.16 percent per century, which is roughly double the rate at the beginning of this century. If this decay rate were sustained, the dipole field would decay to zero within 1400 years. The dipole field strength has already decayed by 50 percent during the past 2000 years. Since this field screens the Earth from the Solar Wind’s harmful radiation, adverse biological, electronic, and meteorological effects due to this decay are expected to become more pronounced in the decades ahead.

The displacement vector for the eccentric (off-center) dipole for 1995.0 in the usual Earth-fixed spherical coordinate system is 527.2 km radially outward from Earth’s center, with a colatitude of 21.43 degrees and a longitude of +144.77 degrees. This displacement vector is computed from the degree and order 1 and 2 spherical-harmonic Gauss coefficients of WMM-95.

MF and SV contours of the magnetic Declination from WMM-95 are illustrated in Figs. 4(a) and 4(b) respectively. They are plotted with respect to the corrected Mercator Projection and are referenced to the Defense Mapping Agency’s (DMA’s) 1984 World Geodetic System (WGS-84) ellipsoid (DMA, 1991). Additional results derived from the WMM-95 modeling effort are given by Quinn et al. (1995).

6. The U.S. National Regional Models

The U.S. National Regional models for Alaska, Hawaii, and the conterminous United States were derived as by-products of the WMM-95 modeling effort. The degree and order 12 WMM-95 model was combined with the degree 13 through 29 portion of the degree and order 63 M070284 model of Cain et al. (1989). Coefficients above degree and order 12 are essentially time independent and are dominated by regional crustal magnetic influences as seen by MAGSAT. The resulting degree and order 1 through 29 global model was used to generate grids of magnetic field components over the three U.S. regions. These grids, in turn, were used to generate a degree and order 6 spherical harmonic model for the conterminous United States, a degree and order 4 model for Alaska, and a degree and order 2 model for the Hawaiian region. These model coefficients and their regional bounds of validity are listed in Tables 3, 4, and 5.

Key NAVOCEANO Senior Scientists responsible for planning and executing the Project MAGNET survey flights were Virgil Bettencourt, Donald Wilson, Fred Valentine, and Jesus Anglero. The calibration and processing
of aeromagnetic data are complicated affairs. Key geophysicists concerned with these aspects of Project MAGNET data analyses were John Nigro, Larry McDonough, and Dave Irwin. Donald Shiel was the principle geophysicist responsible for deploying and maintaining the Polar Orbiting Geomagnetic Survey (POGS) satellite ground stations and collecting, calibrating, and editing the POGS data from these stations. He also coordinated with the Defense Mapping Agency (DMA) to assure the continuous flow of accurate satellite-tracking data from DMA's TRANET network. Many other NAVOCEANO geophysicists, engineers, and technicians have been involved in the many and varied aspects of Project MAGNET and POGS data collection and data processing.

Of course, this model could not have been produced without the tireless efforts of those many unnamed individuals around the world who collect and process magnetic field data on a day-to-day basis at the geomagnetic observatories. The Dst indices were provided by M. Suglura of the University of Kyoto, Japan. The Kp indices were provided by personnel at Göttingen University and released through Helen Coffey of the National Oceanic and Atmospheric Administration’s National Geophysical Data Center, World Data Center A (NOAA/NGDC/WDCA) in Boulder, Colorado. Both indices are based on observatory data. These indices were key factors in selecting subsets of POGS data for input to this model.

Special recognition must go to the military officers and personnel of the VXN-8 Naval Air Squadron located at the Patuxent River Naval Air Station, Maryland, who safely flew and maintained the Project MAGNET aircraft (a Lockheed RP3D Orion) during the many years of surveying covered by the data used in this and in previous US/UK World Magnetic Models.

A special effort has been made to preserve the several million Project MAGNET and POGS magnetic field measurements collected for use in the 1995 Epoch World Magnetic Model at NOAA/NGDC. This effort has been coordinated by Bob Jones and John Weaver of NAVOCEANO and Ronald Buhmann, Susanne McLean, and Stewart Racey of NGDC. The entire high-level data set from Project MAGNET, going back to its origins in 1953, is now available through NGDC on its own CD-ROM. The entire POGS data set will likewise be available in the future on CD-ROM through NGDC.

Many government agencies were responsible for the POGS satellite. Among these were the Office of Naval Research, the Navy Space Systems Activity, the DoD Space Test Program, and the U.S. Air Force. The experiment fluxgate vector magnetometer was built and calibrated by Mario Acuna and his staff at NASA’s Goddard Space Flight Center, in Greenbelt, Maryland, while the satellite itself was built by Defense Systems, Incorporated, of McLean, Virginia.

This paper is published with the approval of the Director, British Geological Survey (NERC).

REFERENCES

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

Cain, J. C., Z. Wang, K. Kluth, and D. R. Schmitz, Derivation of a geomagnetic model to \( n = 63 \), Geophys. J., 97, 431–441, 1989.

Coleman, R. J., Project MAGNET high-level vector data reduction, NASA Conference Publication 3153, edited by R. A. Langel, pp. 215–248, 1992.

Department of Defense World Geodetic System 1984, Defense Mapping Agency, Technical Report TR 8350.2, 2nd ed., 1991.

Department of Defense Military Specification: World Magnetic Model (WMM), Defense Mapping Agency, MIL-W-89500, 1993.

Kelley, M. C., The Earth's Ionosphere: Plasma Physics and Electrodymanics, Academic Press, Inc., New York, 1989.

Langel, R. A. and R. H. Estes, The near-earth magnetic field at 1980 determined from MAGSAT data, J. Geophys. Res., 90, 2495–2509, 1985.

Lowes, F. J. and J. E. Martin, Optimum use of satellite intensity and vector data in modelling the main geomagnetic field, Phys. Earth Planet. Inter., 48, 183–192, 1987.

Macmillan, S., The 1994 Revision of the Models of Geomagnetic Secular Variation, British Geological Survey, Edinburgh, Scotland, Technical Report # WM/94/25C, 1994.

Macmillan, S., D. R. Barraclough, J. M. Quinn, and R. J. Coleman, The 1995 revision of the joint US/UK geomagnetic field models. I: Secular variation, J. Geomag. Geoelectr., 49, this issue, 229–243, 1997.

Quinn, J. M., D. L. Shiel, M. H. Acuna, and J. Scheiffe, Initial Analysis and Modeling Results from the Polar Orbiting Geomagnetic Survey (POGS) Satellite, Naval Oceanographic Office, Stennis Space Center, MS; Technical Report #311, 1993.

Quinn, J. M., R. J. Coleman, D. L. Shiel, and J. Nigro, The Joint US/UK 1995 Epoch World Magnetic Model, Naval Oceanographic Office, Stennis Space Center, MS; Technical Report #314, 1995.

Stern, D. P., R. A. Langel, and G. D. Mead, Backus effect observed by MAGSAT, Geophys. Res. Lett., 7, 941–944, 1980.