Adjustment of UARS, POGS, and DE-1 Satellite Magnetic Field Data for Modeling of Earth’s Main Field

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In the absence of Magsat quality satellite magnetic field measurements, the use of data of lesser quality is sought. The DE-1 and UARS satellite magnetic field experiments were not designed for the purpose of modeling Earth’s main field. The POGS satellite acquired data for modeling of Earth’s main field, but at a lower accuracy than Magsat. All of these data were acquired with fluxgate magnetometers, which are subject to calibration drifts. On Magsat the fluxgate magnetometer was calibrated in-flight by comparison with a Cesium-Vapor scalar magnetometer. Such calibration is not possible on the satellites considered here, leaving uncertainty as to the accuracy of the resulting data. A formalism is developed to compare the data from these satellites with a field model derived from all other available data. This model included data from Magsat, so it is highly accurate at 1980. Its accuracy at the epochs of the satellites considered then depends upon the accuracy with which the field at 1980 can be extrapolated to future epochs. Adjustment of DE-1 data requires estimation of only two parameters for data spanning about 10 years. The resulting adjusted data are in good agreement with the model for those 10 years and exhibit residuals generally interpretable in terms of sources in the ionosphere and magnetosphere. Adjustment parameters of the POGS data vary substantially over the three years of available data. The resulting residuals indicate that the adjusted data set is suitable for main field modeling up to about degree 10, as used for the International Geomagnetic Reference Field. However, the resulting residuals are considered to be due mainly to error in measurement and not to geophysical sources. Adjustment of the UARS data is more difficult. The data used are not sufficient to resolve all of the adjustment-model parameters. If a priori information regarding the magnetic field from attitude torquer rods is included, the ambiguity is mostly resolved. Residuals after adjustment are of comparable magnitude and quality to those from POGS.

1. Introduction

Near-Earth magnetic field measurements have been acquired by many satellites (Langel, 1992). However, only those from Kosmos 49, the POGO series, and Magsat have been used without reservation for what are termed solid-Earth studies, i.e., study of the field from Earth’s core (main field) and lithosphere. The reason is that these spacecraft were equipped with scalar instruments that take measurements considered absolute because their accuracy depends only on knowledge of atomic constants. Data from other near-Earth spacecraft have been acquired only with fluxgate magnetometers, which are subject to drift, e.g., from changes in electronic components due to vibration or varying temperature. Magsat acquired data from both a Cesium vapor (absolute, scalar) magnetometer and a three-axis fluxgate. The data from the Cesium magnetometer were used in-flight to calibrate the data from the fluxgate (Lancaster et al., 1980; Langel et al., 1981).

Data from missions with only fluxgate magnetometers have been used to study fields from ionospheric, magnetospheric, and field-aligned currents, but, with two exceptions, not for solid-Earth studies. The two exceptions are that models of the main field have been derived from data from the DE-2 satellite (Langel et al., 1988) and from a combination of data from the POGS satellite and data from other
Because of the scarcity of absolute data from spacecraft, it seems useful to investigate the possibilities and dangers in utilizing data from missions that acquire data only from fluxgate instruments. This paper reports on an adaptation of the in-flight calibration method used for Magsat data applied to three-axis fluxgate data from the DE-1, POGS, and UARS spacecraft. Because of lack of, or limitations of, attitude information on these spacecraft, only the scalar magnitude of the fluxgate is utilized, although the procedure operates on the individual components. Magsat in-flight calibration required an absolute standard, the field from the scalar magnetometer. No such standard is available for data from the spacecraft considered here. A substitute must be utilized and the results carefully evaluated. The substitute chosen is the field computed from the GSFC (S95-sc) magnetic field model (Sabaka et al., 1996). Without an absolute standard, the results are difficult to evaluate. As will be shown, it is considered that the methods to be described worked very well for DE-1 data, acceptably for some solid-Earth studies for the POGS data, and not very acceptably for the UARS data.

In the following sections pertinent spacecraft characteristics are outlined, the formalism used is summarized, its application to the data described, and the results presented and evaluated. This study is considered “final” only for the DE-1 data. With further work, the accuracy of both POGS and UARS data should be improved over that reported here.

2. Satellite Descriptions and Data Selection

Table 1 summarizes the characteristics of the spacecraft considered. In all cases the magnetometer was at the end of a boom. In spite of that, significant spacecraft fields are present at the UARS magnetometer. It is claimed that such fields are absent for DE-1 (J. Slavin, 1996, personal communication) and POGS, except for a bias correction of 7 nT along one axis (Quinn et al., 1993).

Descriptions of the DE-1 spacecraft and experiments may be found in Hoffman (1981, 1988). The spacecraft is spin-stabilized along the axis antiparallel to the orbit normal at about 10 RPM. For these studies one data point per second is selected from times when the spacecraft is below 1000 km altitude and when the Kp index is $\leq 2^-$. The data are smoothed to eliminate vestiges of a signal at the spin frequency of the satellite, which has a magnitude of $\pm 20$ nT. It is thought that up to 2–3 nT magnitude residual error remains after the smoothing process.

The Polar Orbiting Geomagnetic Satellite, or POGS, mission was conducted by the U.S. Naval Oceanographic Office (NAVOCEANO). Descriptions of the POGS spacecraft and magnetometer may be found in Quinn et al. (1993, 1995). An attempt was made to calibrate the data by indirect comparison with magnetic observatory data as follows (Quinn et al., 1995). A high quality model of the main field was derived from magnetic observatory data and other, non-POGS, data. Because of the concentration of observatories in Europe, this model is regarded as highly accurate between 40° and 35°N latitude and 5°W and 35°E longitude. Residuals of POGS data in this area are minimized with respect to a model of

| Satellite | Launch | Orbit | Data rate | Boom length | Data acquisition period |
|-----------|--------|-------|-----------|-------------|------------------------|
|           | (km)   | (km)  | (Hz)      | (m)         |                        |
| DE-1      | 8/81   | 570   | 23127     | 16          | 6.0                    |
|           |        |       |           |             | 9/81–3/91             |
| POGS      | 4/90   | 700   | 750       | 0.1         | 2.4                    |
|           |        |       |           |             | 1991–1993 (Partially intermittent) |
| UARS      | 9/91   | 585   | 585       | 0.2         | 5.8                    |
|           |        |       |           |             | 9/91–3/95 (Intermittent afterward) |
magnetometer bias and drift to yield the correction

\[ \Delta B = 11.620 - 16.167(t - t_m) \text{ nT} \]  (1)

where \( t_m = 1992.506748293 \). In the course of processing and calibration, an error in timing determination was discovered for data with \( 1991.0 \leq t \leq 1991.4 \) and a correction algorithm determined. A correction for instrument temperature variation was also applied. Except for temperature variations, the corrections assume strictly long-term, linear drift. Any short term or non-linear drift remains unknown.

From the corrected data, NAVOCEANO extracted data sets for 14 10-day intervals as suitable for spherical harmonic modeling. For this study, POGS data are extracted from those 10-day data sets for conditions when the \( K_p \) index is \( \leq 2^+ \) and the \( Dst \) index is between \(-50 \) and \(+40 \) nT.

The UARS spacecraft and its experiments are described by Reber (1985). Magnetic field data acquisition was not part of a primary UARS investigation but was included as part of the Particle Environment Monitor (PEM). UARS is a large spacecraft (15,000 lb), and in spite of the length of the boom, magnetic fields at the magnetometer from the spacecraft were significant. In particular, the attitude of UARS is controlled by three near-orthogonal torquer rods which cause a magnetic field at the magnetometer of the order of 200 nT. The torquer rod field at the magnetometer was characterized and a model developed before launch at the GSFC magnetic test facility (Anderson et al., 1991). Based on that model, the field, \( B_t \), from the torquer bars at the magnetometer is given by (Brian Anderson, personal communication, 1994)

\[ B_t = T i_t \]  (2)

where \( i_t \) is the measured current in the three torquer bars, \( B_t \) is in the magnetometer coordinate system, and \( T \) is the matrix

\[
T = \begin{pmatrix}
0.65 & 0.25 & 2.28 \\
0.37 & -2.10 & 0.29 \\
2.44 & 0.25 & 0.51
\end{pmatrix}
\]  (3)

The current is measured and its values telemetered to ground with the data.

Approximately every 36 days, the UARS spacecraft is rotated 180° around its \( Z \), or yaw, axis. This maneuver can cause boom bending and thermal changes at the magnetometer, so data are separately analyzed in segments between maneuvers. The GSFC UARS data base consists of data from selected magnetically quiet days, determined from the 3-hourly \( K_p \) index, between September, 1991, and April, 1992.

3. Adjustment Formalism

Although the underlying principles are the same, the formalism utilized for DE-1 differed from that used for POGS and UARS. That for DE-1 is simpler and will be described first. Both formalisms operate on the component data from the magnetometers. However, no attitude information is required, i.e., the algorithms do not depend upon the magnetometer coordinate system. The reference field used here is GSFC (S95-sc), described by Sabaka et al. (1996).

3.1 DE-1 formalism

Preliminary comparison of the scalar DE-1 data with a field model indicated the presence of a bias of about 20 nT between data and model over the entire 1981–1991 time period of the data. Since there are
essentially two data components, along and normal to the spin axis, the simplest assumption is that the scale factors of the measurement along one or both axes are slightly in error. Accordingly, small corrections are sought to those scale factors. Suppose

\[ x_i^k = (1 + \alpha^k)x_i^o \]  
\[ y_i^k = (1 + \beta^k)y_i^o \]  

where \( \{x_i^o, y_i^o\} \) are the measured components in and normal to spin axis, \( \{x_i^k, y_i^k\} \) are the corrected components in and normal to spin axis after the \( k \)-th iteration, \( \alpha^k, \beta^k \) are the correction factors after the \( k \)-th iteration.

Set

\[ \alpha^{k+1} = \alpha^k + \delta\alpha^k \]  
\[ \beta^{k+1} = \beta^k + \delta\beta^k \]  

\[ (F_i^k)^2 = (x_i^k)^2 + (y_i^k)^2 \]  

\[ \chi = \Sigma_i [F_i^k - B_i]^2, \]  

where \( B_i \) is the field magnitude from the reference field model. The procedure is to linearize \( \chi \) with respect to \( \delta\alpha^k \) and \( \delta\beta^k \) and find the least squares solution that minimizes \( \chi \). Because of the non-linearity of Eq. (6) with respect to \( \delta\alpha^k \) and \( \delta\beta^k \) the procedure is iterated; in practice convergence occurs at the first iteration.

3.2 POGS and UARS formalism

Adequate results are not achieved for POGS or UARS data with simple scaling as used for DE-1. In both cases it is found necessary to also solve for offsets along each measurement axis and for non-orthogonality between the magnetometer axes. The notation used is:

- \( N \) is the number of measurements used for the adjustment estimation,
- \( \{v_i; i = 1, ..., N\} \) are the measured field values along the actual magnetometer axes,
- \( \{y_i; i = 1, ..., N\} \) are the actual field values along the actual magnetometer axes,
- \( \{x_i; i = 1, ..., N\} \) are the corresponding magnetic field values along orthogonal magnetometer axes,
- \( \{B_i; i = 1, ..., N\} \) are the corresponding set of scalar field values from a field model,
- \( b \) is any offset in the vector magnetometer,
- \( \mu_{12} \) is the cosine of the angle between the 1st and 2nd magnetometer sensor axes,
- \( \mu_{23} \) is the cosine of the angle between the 2nd and 3rd magnetometer sensor axes,
- \( \mu_{13} \) is the cosine of the angle between the 1st and 3rd magnetometer sensor axes.

Then define

\[ \gamma_y = \cos^{-1}(\mu_{12}), \quad \gamma_y' = \gamma_y - \pi / 2. \]
For UARS, \( i \), the torquer currents, and \( B_n \), the field from the torquer bars at the magnetometer, are also needed.

For the \( i \)-th measurement, the adjustment model is

\[
y_i = Sv_i + b + T(i)I_i, \tag{9}
\]

\[
x_i = Hy_i, \tag{10}
\]

where \( S \) is the matrix of instrument scale factors and \( H \) is the transformation matrix to the orthogonal magnetometer coordinate system. \( S \) is assumed diagonal and its diagonal elements, \( \{S_{ij}, j = 1, 3\} \) are to be determined. \( H \) is not diagonal, but its elements depend only upon the three \( \mu_j \) defined above. The quantities \( T^k \) and \( \chi \) are defined as for DE-1, noting that \( T^k = |x_i| \).

Set

\[
b^{k+1} = b^k + \delta b^k, \tag{11a}
\]

\[
S^{k+1} = S^k + \delta S^k, \tag{11b}
\]

\[
H^{k+1} = H^k + \delta H^k, \tag{11c}
\]

\[
T^{k+1} = T^k + \delta T^k. \tag{11d}
\]

Then the procedure is to linearize \( \chi \) with respect to the perturbation variables, \( \delta b^k, \delta S^k, \delta H^k, \) and \( \delta T^k \), a total of 18 variables for UARS and 9 variables for POGS, and find the least squares minimum of \( \chi \) with respect to those perturbed quantities.

Definitions of \( b^k, \delta b^k, (y_i)^k, (\delta y_i)^k, S^k, \delta S^k, T^k, \) and \( \delta T^k \) are straightforward. The matrix \( H \) transforms the vector \( y \), with unit vectors in the non-orthogonal directions \( \hat{y}_i, i = 1, 2, 3 \), to an orthogonal system with unit vectors \( \hat{x}_i, i = 1, 2, 3 \), defined as follows. The \( \hat{x}_1 \) axis is taken to be equal to the \( \hat{y}_1 \) axis; the \( \hat{x}_2 \) axis is taken to be in the plane formed by the \( \hat{y}_1 \) and \( \hat{y}_2 \) axes and oriented as near as possible to the \( \hat{y}_2 \) axis; and the \( \hat{x}_3 \) axis is taken such as to form a right handed system. \( \hat{x}_3 \) will be nearly along the \( \hat{y}_3 \) axis because the \( \hat{y} \) axes are themselves nearly orthogonal.

By the above definitions

\[
\hat{y}_2 \cdot \hat{x}_3 = 0, \quad \hat{y}_1 \cdot \hat{x}_1 = \hat{x}_1 \cdot \hat{x}_1 = 1. \tag{12}
\]

Noting that

\[
x = x_1\hat{x}_1 + x_2\hat{x}_2 + x_3\hat{x}_3 = y_1\hat{y}_1 + y_2\hat{y}_2 + y_3\hat{y}_3, \tag{13}
\]

and using (12), it can be shown that

\[
H_{11} = 1.0, \quad H_{12} = \mu_{12}, \quad H_{13} = \mu_{13}, \tag{14a}
\]

\[
H_{21} = H_{31} = H_{32} = 0.0, \tag{14b}
\]

\[
H_{22} = \left[1 - \mu_{12}^2\right]^{1/2}, \tag{14c}
\]
\[ H_{23} = \left[ \mu_{23} - \mu_{12} \mu_{13} \right] / \left[ 1 - \mu_{12}^2 \right]^{1/2}, \]  
\[ H_{33} = \left\{ 1 - \mu_{13}^2 - \left[ \mu_{23} - \mu_{12} \mu_{13} \right]^2 / \left[ 1 - \mu_{12}^2 \right] \right\}^{1/2}. \]

In practice it is easier to work with the \( \gamma_y' \). In particular, if the \( \gamma_y' \) are very small

\[ \mu_y = \cos(\gamma_y') = \cos(\gamma_y' + \pi / 2) = -\sin(\gamma_y') = -\gamma_y', \]  
\[ \left[ 1 - \mu_y^2 \right]^{1/2} = \sin(\gamma_y') = \cos(\gamma_y') = 1 - \left( \gamma_y' \right)^2 / 2, \]

\[ \left[ 1 - \mu_y^2 \right] = 1 - \left( \gamma_y' \right)^2. \]

A good approximation is

\[ H = \begin{pmatrix}
1.0 & -\gamma_{12}' & -\gamma_{13}' \\
0.0 & 1 - \frac{\left( \gamma_{12}' \right)^2}{2} & -\gamma_{23}' - \gamma_{12}' \gamma_{13}' / 2 \\
0.0 & 0.0 & 1 - \left( \gamma_{13}' \right)^2 - \left[ \gamma_{23}' + \gamma_{12}' \gamma_{13}' \right]^2 / \left[ 1 - \left( \gamma_{12}' \right)^2 \right]^{1/2}
\end{pmatrix}. \]

Consider the definition of \( \delta H^k \). From Eq. (18), it is clear that

\[ \delta H_{11}^k = \delta H_{21}^k = \delta H_{31}^k = \delta H_{32}^k = 0.0 \]  
\[ \delta H_{12}^k = -\left( \delta \gamma_{12}' \right)^k, \quad \delta H_{13}^k = -\left( \delta \gamma_{13}' \right)^k. \]

Determination of the elements \( \delta H_{22}^k, \delta H_{23}^k, \) and \( \delta H_{33}^k \) requires some care.

Consider

\[ H_{22}^{k+1} = 1 - \left( \gamma_{12}' + \delta \gamma_{12}' \right)^2 / 2 = 1 - \left( \gamma_{12}' \right)^2 / 2 - \left( \gamma_{12}' \right)^2 \left( \delta \gamma_{12}' \right)^k + \text{higher order terms}. \]

Neglecting the higher order terms, define

\[ H_{22}^k = 1 - \left( \gamma_{12}' \right)^2 / 2. \]
\[ \delta H_{22}^k = -\left(\gamma_{12}'\right)^k (\delta \gamma_{12}')^k. \]  

If the first two terms of the Taylor series are retained

\[
\begin{align*}
\left(1 - \frac{\left[\gamma_{12}' + \delta \gamma_{12}'\right]^2}{2}\right)^{-1} &= \frac{1}{1 - \frac{\left[\gamma_{12}'\right]^2}{2}} + \frac{(\gamma_{12}')^k (\delta \gamma_{12}')^k}{1 - \frac{\left[\gamma_{12}'\right]^2}{2}}, \\
\left[1 - \left(\gamma_{12}' + \delta \gamma_{12}'\right)^k\right]^2 &= 1 + 2 \left(\gamma_{12}'\right)^k (\delta \gamma_{12}')^k \\
\left(\gamma_{23}' + \delta \gamma_{23}'\right)^k + \left(\gamma_{13}' + \delta \gamma_{13}'\right)^k (\gamma_{12}' + \delta \gamma_{12}')^k &= \frac{1}{1 - \frac{\left[\gamma_{12}'\right]^2}{2}} + \frac{(\gamma_{12}')^k (\delta \gamma_{12}')^k}{1 - \frac{\left[\gamma_{12}'\right]^2}{2}}, \\
\end{align*}
\]

\[H_{23}^{k+1} = -\left(\gamma_{23}' + \delta \gamma_{23}'\right)^k + \left(\gamma_{13}' + \delta \gamma_{13}'\right)^k (\gamma_{12}' + \delta \gamma_{12}')^k \]

\[= H_{23}^k + \delta H_{23}^k.\]

To first order in the \(\delta \gamma_{ij}'\)

\[H_{23}^k = -\left(\gamma_{23}'\right)^k + \left(\gamma_{13}'\right)^k (\gamma_{12}')^k \left(\frac{1}{1 - \frac{\left[\gamma_{12}'\right]^2}{2}}\right)\]  

\[= \left(\gamma_{23}'\right)^k + \left(\gamma_{13}'\right)^k (\gamma_{12}')^k \left(\frac{1}{1 - \frac{\left[\gamma_{12}'\right]^2}{2}}\right).\]
\[ \delta H_{23}^k = -\left( (\gamma_{23}')^k + (\gamma_{12}')(\delta_{13}')^k + (\gamma_{13}')^k(\delta_{12}')^k \right) \frac{1}{1 - \left( \frac{(\gamma_{12}')^k}{2} \right)^2} \]

\[ -\left( (\gamma_{23}')^k + (\gamma_{12}')(\delta_{13}')^k \right) \frac{1}{1 - \left( \frac{(\gamma_{12}')^k}{2} \right)^2} \]  

Using (25),

\[ H_{33}^{k+1} = \left( 1 - \left( \gamma_{13}' + \delta_{13}' \right)^k \right)^2 - \left( (\gamma_{23}' + \delta_{23}' + (\gamma_{13}')^k(\delta_{12}')^k + (\gamma_{13}')^k(\delta_{12}')^k \right)^2 \]

\[ 1 - \frac{1}{1 - \left( \frac{(\gamma_{12}')^k}{2} \right)^2} + \frac{2(\gamma_{12}')^k(\delta_{12}')^k}{1 - \left( \frac{(\gamma_{12}')^k}{2} \right)^2} \]

\[ \delta H_{33}^k = -1 \left[ \frac{1}{H_{33}^k} \left( (\gamma_{23}')^k + (\gamma_{13}')^k(\gamma_{12}')^k \right) \left( \delta_{12}' \right)^k \left( \delta_{13}' \right)^k \right] \]

Again to first order,

\[ \delta H_{33}^k = -1 \left[ \frac{1}{H_{33}^k} \left( (\gamma_{23}')^k + (\gamma_{13}')^k(\gamma_{12}')^k \right) \left( \delta_{12}' \right)^k \left( \delta_{13}' \right)^k \right] \]
4. DE-1 Results

When applying the above formalism, the DE-1 data are first decimated and subdivided into two data sets. This is accomplished by first subdividing the Earth into equal area bins of size about equal to $20^\circ \times 20^\circ$ at the equator. One DE-1 data point is selected from each bin in each year, as available. Each bin is examined to see if a magnetic observatory is present. DE-1 data from bins that do contain such data are placed in data set A, containing 1525 data points. DE-1 data from bins that do not contain such data are placed in data set B. The reference field model includes parameters describing the large scale field of magnetospheric origin, i.e., due to the ring current, magnetopause currents, and magnetotail currents. Adjustments were computed both with and without the external fields computed from those parameters. Inclusion of the external field in the model resulted in a significant reduction in residuals for the calibrated data. The adjustment formalism is initially applied to data set A and the correction values determined are

$$\alpha = 5.71 \times 10^{-4} \left(2.1 \times 10^{-5}\right), \quad \beta = 7.41 \times 10^{-3} \left(1.7 \times 10^{-3}\right), \quad (31)$$

where the numbers in parentheses are the formal $1\sigma$ error estimates. Table 2 shows the statistics of the data sets with respect to the reference model before and after application of the correction.

The procedure is repeated after elimination of 78 outliers with residuals greater than 45 nT, this time with data sets A and B concatenated, with the results

$$\alpha = 5.61 \times 10^{-4} \left(2.0 \times 10^{-5}\right), \quad \beta = 5.63 \times 10^{-3} \left(1.5 \times 10^{-3}\right), \quad (32)$$

and corresponding data statistics for the whole data set and by year as shown in Table 2.

It is concluded that the data have a scale error that is nearly constant throughout the mission. The resulting field error, evident in the uncorrected mean values in Table 2, is about 20 nT. The correction is not absolute because it assumes field magnitudes from a reference model and any model error will be transferred directly to the corrected data. However it is remarkable that with the simple correction of Eq. (32) the data can be brought into good agreement with the reference model over the entire ten year period. This argues, first, that the underlying model is consistent for the entire time period, i.e., its geographic and temporal distribution of error must be constant to within about the corrected rms, or 22 nT. Second, it argues that the magnetometer onboard DE-1 has good long-term stability.

Figure 1 shows polar plots of the corrected residuals for two DE-1 passes over the south pole. The variations shown are indicative of ionospheric currents, sometimes called electrojets, flowing beneath the satellite. Note that a westward (eastward) current flows counterclockwise (clockwise) on the plot giving, by the right-hand-rule, a radially inward field to its north (south) and radially outward field to its south (north). Since the radial component of the main field in the south is outward, an inward (outward) disturbance field results in negative (positive) scalar residual. On the plot, the short line perpendicular to the satellite track is a scale line of length equal to 50 nT and drawn in the direction of positive scalar residual. In the left figure, the current is flowing eastward centered roughly at the latitude where the residual changes from positive to negative resulting in a positive residual to the north of the current and a negative residual to the south. In the right figure, the current is flowing westward resulting in a negative residual to the north and positive residual to the south.

A large volume of absolute accuracy scalar data were collected by the OGO-2, OGO-4, and OGO-6 spacecraft, also known as POGOs. These data were acquired between October of 1965 and May of 1971, under all magnetic conditions, and covering nearly the same orbital conditions (altitude, inclination, etc.) as the data from DE-1, POGS, and UARS considered in this paper. Of the three, the orbital conditions of DE-1 differ most from the POGO spacecraft. Residual plots of all of these data are available. For example,
Table 2. Statistics of DE-1 data with respect to reference model.

| Data set      | Points | Uncorrected  | Corrected  |
|---------------|--------|--------------|------------|
|               |        | Mean | σ      | Mean | σ     |
| A             | 1525   | 20.4  | 31.1  | -0.4 | 22.7  |
| B             | 702    | 17.4  | 28.0  | -1.3 | 21.5  |
| Combined (with outliers deleted) | 2149 | - | - | -1.0 | 16.9 |
| 1981          | 225    | -     | -     | -3.1 | 15.0  |
| 1982          | 606    | -     | -     | -0.5 | 15.4  |
| 1983          | 607    | -     | -     | 0.1  | 16.6  |
| 1984          | 48     | -     | -     | -9.2 | 16.0  |
| 1985          | 4      | -     | -     | -4.8 | 5.4   |
| 1986          | 188    | -     | -     | -1.7 | 17.8  |
| 1987          | 95     | -     | -     | -2.8 | 17.3  |
| 1988          | 244    | -     | -     | 0.6  | 19.4  |
| 1989          | 88     | -     | -     | 0.1  | 19.8  |
| 1990          | 44     | -     | -     | -5.9 | 24.8  |

Data set A: From blocks in which a magnetic observatory is located.
Data set B: From blocks in which a magnetic observatory is not located.

Fig. 2 shows two south polar residual plots from the OGO-4 satellite in the same format as the DE-1 residuals of Fig. 1. The left plot of Fig. 2 is very similar to the left plot of Fig. 1. Residuals due to ionospheric and magnetospheric effects should have the same characteristics for all near-Earth satellite measurements. For example, scalar residual plots from the Magsat satellite data show the same characteristics as those from POGO for the same local times and magnetic conditions.

High latitude residuals were extensively studied by Langel (1974a, b). He showed that those residuals were predominantly negative from 13 hr to 20 hr, magnetic local time (MLT), i.e., in the evening sector, and predominantly positive from 0 hr to 9 hr MLT, and concluded that they could not be from field-aligned currents. Negative $\Delta B$ in the evening local time sector was shown to be due to ionospheric currents. During extremely quiet magnetic periods, considerable variation from the dominant trends are found. The source of the positive $\Delta B$ in the morning sector was undetermined. Fukushima (1975) showed that it is possible that part of the positive $\Delta B$ is due to field-aligned currents. It is also likely that part is due to magnetospheric currents.

The residuals in Fig. 1 correspond to the residual patterns found by Langel (1974a, b) from the POGO satellites. Close similarities to POGO residuals are found in many, though not all, such plots, confirming the quality and usefulness of the corrected DE-1 data.

5. POGS Results

The formalism of Subsection 3.2 was applied to POGS data selected from magnetically quiet periods. Table 3 lists these periods, the resulting adjustment parameters, and the residuals of the data with respect to the field model before and after the adjustment parameters were applied. Typical formal error estimates were $3 \times 10^{-5}$ to $6 \times 10^{-5}$ for scale factors, 0.24 to 0.35 min for the non-orthogonality angles, and 1 to 2 nT for the biases. Actual errors are undoubtedly higher and are dependent upon the accuracy of the reference model. Figure 3 shows the variation of the scale factors, non-orthogonality angles, and biases as a function of time. The abscissa is Modified Julian Day, where Jan. 1, 1991 = 48257, Jan. 1, 1992 = 48622, and Jan. 1, 1993 = 48988. All parameters exhibit apparent long term trends with shorter term
Adjustment of UARS, POGS, and DE-1 Satellite Magnetic Field Data

Fig. 1. South polar plots of residuals from the DE-1 satellite. The coordinates are magnetic local time and dipole latitude. The satellite track is shown as a continuous line and is the baseline for the residual plot. Scale lines orthogonal to the satellite track are in the direction of positive residual and their length corresponds to a residual of 50 nT.
Fig. 2. South polar plots of residuals from the OGO-4 satellite. The coordinates are magnetic local time and dipole latitude. The satellite track is shown as a continuous line and is the baseline for the residual plot. Scale lines orthogonal to the satellite track are in the direction of positive residual and their length corresponds to a residual of 50 nT.
variations. For the biases and, especially, the non-orthogonality angles, the trends are clearer if the March 11 to March 18, 1991, and January 21 to January 24, 1993, time periods, circles on the middle plot, are eliminated. Their elimination has little effect on the scale value plots. From Table 3, these time periods have the largest residuals both before and after adjustment, but the reason is not known; neither of the periods is lacking data points.

Reasons for changes in the POGS adjustment are not readily apparent. Because the standard of comparison is not absolute, all results should be viewed with some caution. The magnetometer itself should be accurate to about 20 nT after application of pre-launch calibration and the only anticipated source of in-flight calibration change are temperature variations (M. Acuna, personal communication, 1995). Though the effect on the magnetic field measurements, if any, is uncertain, it is noted that the spacecraft often went into a low power mode in which all instruments, including the magnetometer, were turned off. Only those systems necessary for the health or recovery of the spacecraft remained on. The times of these shut-downs are indicated on Fig. 3 with asterisks.

Figure 4 shows plots of uncorrected and corrected residuals for four orbits in early 1992. Comparison with the magnetic field from the lithosphere as computed from the determination of Arkani-Hamed et al. (1994) shows clearly that the residuals are due to some cause other than crustal fields. Quinn et al. (1995) state with regard to the residuals found in their analysis, which are similar to the uncorrected residuals of Fig. 4, that they are "tentatively attributed to equatorial and mid-latitude Spread-F effects (Kelley, 1989).", italics theirs. Some variations they attribute to the effects of field-aligned currents. We consider the first of these explanations implausible and that the second should be qualified.

Examination of residual plots from the POGO satellites fails to reveal residual patterns that have the same characteristics found in Fig. 4. For example, Fig. 5 shows a set of residual plots from the OGO-4 satellite selected because the orbit characteristics, altitude, local time, etc., are close to those for the POGS data in Fig. 4. In Fig. 5, plots A–D are from particularly quiet time periods, similar to those chosen for Fig. 4, while plots E–H are from more disturbed times. In particular plot D is from an extremely quiet magnetic period and most of the $\Delta B$ variations are clearly due to fields from the Earth's lithosphere, as can be seen by comparison with published satellite magnetic anomaly maps, e.g., Ravat et al. (1995). Each pass has a different level of magnetospheric field, as measured by the $Dst$ index. The salient characteristic of that magnetospheric field is a depression in $\Delta B$, i.e., the residual, at the magnetic equator and a smaller corresponding positive $\Delta B$ at the poles. The variation of the equatorial depression with $Dst$ is clearly evident in the plot in Fig. 5 but there are no such corresponding variations in the POGS residuals of Fig. 4.

Data in auroral and polar regions generally exhibit $\Delta B$ of higher amplitude than at lower latitudes. This is clearly seen in Fig. 5. However, even in polar and auroral regions, the $\Delta B$ from OGO-4 in plots A–D of Fig. 5 reach only 40 nT. Examination of the corrected residuals of Fig. 4 in the polar regions shows some resemblance to such residuals in Fig. 5, though not a good correspondence. To illustrate this, Fig. 6 shows a polar residual plot from POGS chosen specifically because the residual variations are similar to those in the right plot of Fig. 2, from OGO-4. Most POGS passes are not this similar to patterns found in POGO data. In some cases, meaningful variations probably associated with magnetospheric/ionspheric currents and crustal anomalies (Kotze and Barraclough, 1995) can be extracted by suitable filtering.

In view of the comparison between Figs. 4 and 5, and the above discussion, it is concluded that the residuals of Fig. 4 are predominantly due to measurement error, with some contribution from ionspheric and crustal sources. The adjustment parameters of this study do not correspond to the design parameters of the magnetometer. Proper readjustment, beyond the scope of this study, would return to the raw magnetometer data and use a formalism corresponding to the magnetometer design.

In spite of the presence of suspected measurement error in the POGS data, the adjusted data are of high enough quality for use in some main field modeling. Considering the estimated amplitude of the error, i.e., corresponding to the residuals of the adjusted data, such models should be regarded with caution for spherical harmonic degree above about ten, and should be used only with great care when analyzing satellite data in terms of quiet time ionospheric or lithospheric fields. The same can be concluded for the corrections applied by Quinn et al. (1995).
Table 3. Summary of POGS adjustment results.

| Time          | Scale factors | Non-orthogonality angle (min) | biases (nT) | residual (nT) |
|---------------|---------------|-------------------------------|-------------|---------------|
|               | axis 1 | axis 2 | axis 3 | axis 1 | axis 2 | axis 3 | axis 1 | axis 2 | axis 3 | after | before |
| Jan. 14-Jan. 23, 91 | 1.0001400 | 1.0012600 | 0.9992367 | 1.7 | 1.0 | -1.2 | -27.1 | 0.3 | 2.6 | 1.1 | 36.8 | -7.5 | 42.7 |
| Mar. 11-Mar. 18, 91 | 0.9995958 | 1.0002200 | 0.9987962 | 5.5 | -0.0 | 12.3 | -32.1 | 16.7 | 2.8 | 0.6 | 40.0 | -29.0 | 61.8 |
| May 11-May 21, 91 | 0.9992810 | 1.0008800 | 0.9984872 | 1.3 | 2.4 | -2.0 | -23.2 | 8.3 | 12.5 | 1.0 | 29.5 | -34.3 | 51.7 |
| Jan. 18-Jan. 26, 92 | 0.9995151 | 0.9996777 | 0.9982743 | 0.2 | -0.7 | 0.6 | -15.3 | -2.4 | -7.2 | 1.2 | 28.7 | -32.8 | 47.4 |
| Feb. 13-Feb. 16, 92 | 0.9996526 | 0.9994098 | 0.9977189 | 1.1 | 0.0 | 1.4 | -8.2 | 1.9 | 3.9 | -0.3 | 23.3 | -28.9 | 40.1 |
| Apr. 10-Apr. 17, 92 | 0.9998392 | 0.9990084 | 0.9982045 | 0.2 | -0.5 | 0.0 | -19.3 | 0.9 | -23.0 | -1.1 | 27.2 | -37.8 | 49.5 |
| Jun. 1-Jun. 6, 92 | 0.9996137 | 0.9991540 | 0.9988288 | 0.4 | 0.6 | 2.4 | -16.9 | 9.1 | -22.1 | 0.6 | 28.8 | -30.5 | 45.5 |
| Jul. 3-Jul. 10, 92 | 0.9998029 | 1.0002900 | 0.9988687 | -0.3 | -0.7 | 0.0 | -10.5 | 8.7 | -12.4 | 2.0 | 30.9 | -17.1 | 39.4 |
| Aug. 30-Sep. 1, 92 | 0.9997915 | 1.0001700 | 0.9988930 | -2.6 | 0.1 | 1.8 | -7.8 | -2.3 | -10.1 | 0.8 | 27.9 | -15.4 | 35.8 |
| Sep. 21-Sep. 24, 92 | 0.9993609 | 0.9995124 | 0.9985044 | 3.4 | 5.9 | 5.2 | 11.4 | 16.4 | 1.9 | 0.3 | 44.0 | -26.1 | 57.8 |
| Sep. 23-Sep. 27, 93 | 0.9997845 | 0.9998503 | 0.9991336 | -3.4 | -2.6 | 0.4 | -10.2 | -4.9 | -22.0 | 0.5 | 28.6 | -17.1 | 37.1 |
| Oct. 28-Nov. 13, 93 | 0.9998478 | 1.0000100 | 0.9991061 | -2.2 | -0.5 | 1.9 | -9.3 | -4.7 | -22.4 | -0.9 | 30.0 | -16.6 | 37.7 |
| Nov. 21-Nov. 25, 93 | 0.9994419 | 0.9997776 | 0.9991282 | -1.7 | 0.4 | 2.5 | -1.3 | -1.6 | -16.1 | 0.6 | 31.3 | -18.6 | 38.7 |
| Dec. 30-Jun. 22, 93 | 0.9992942 | 1.0000100 | 0.9989365 | -1.2 | 1.3 | 1.0 | -0.9 | 6.6 | -17.2 | 0.6 | 28.6 | -17.6 | 37.1 |
| Jul. 12-Jul. 18, 93 | 1.0000800 | 1.0004900 | 0.9989533 | -2.0 | -1.0 | 2.9 | -12.6 | -4.3 | -17.7 | 0.4 | 33.9 | -9.5 | 39.2 |
Fig. 3. Parameter values from POGS adjustment calculation as function of Modified Julian Day. Top: Scale values; Middle: Non-orthogonality angles; Bottom: Bias values. The three axes are shown as solid, dotted, and dashed lines. Labeling of the axes is arbitrary. Asterisks indicate times when the spacecraft went into low-power mode. Large circles explained in text.
Fig. 4. Residuals of data from the POGS satellite relative to the GSFC (S95-sc) field model. Uncorrected residuals are from data as received from NAVOCEANO. Corrected residuals are from data after application of the formalism of Subsection 3.2. The abscissa is in units of latitude where the left of the plot is the geographic equator and the data proceed over the north pole, across the equator again, over the south pole and back to the equator. On the right are the longitudes at which the track crosses the equator, i.e., at 0°, 180° and 360°, as well as the time (hh:mm:ss), Dst, and local time at the 180° equator crossing. The ordinate is in nT.
6. UARS Results

The formalism of Subsection 3.2 was applied to 49,824 UARS data points from the period January 19–24, 1992. In the initial analysis the pre-flight calibration of the torquer bars was not taken into account. For this case, high correlations were found between some of the solution parameters, as summarized in Table 4.

To explore the effect of incorporating the parameters determined in the pre-flight calibration, the formalism was modified to permit their inclusion as weighted a priori information. If $p$ is the vector of parameters to be determined, $p_o$ the vector of a priori values for $p$, with covariance $P_o$, on $p_o - p$, $p^k$ the estimate after the $k$-th iteration, $A^k$ the matrix of linearized partial derivatives after the $k$-th iteration, and $r^k$ the residuals of the model after the $k$-th iteration, then (Tarantola and Valette, 1982)

$$
\delta p^k = \left[ (A^k)^T (A^k) + P_o^{-1} \right]^{-1} \left[ (A^k)^T r^k + P_o^{-1} (p_o - p^k) \right].
$$

The solution covariance is given by

$$
\text{Cov} = \delta^2 \left[ (A^k)^T (A^k) + P_o^{-1} \right]^{-1},
$$

where, because the number of data is much greater than the number of parameters in the solution, for all data weighted equally, $\delta^2$ is equal to the a posteriori standard error of the data to the model.

Table 5 summarizes the results for three cases. A priori information is included for the $S_{ii}$ and for the elements of $T$. The a priori values for the $S_{ii}$ are taken to be 1.0, those for $T$ are the values given in Eq. (3). The corresponding values of the (diagonal) elements of $P_o$ are given by the square of $\sigma_S$ for the $S_{ii}$ or $\sigma_T$ for $T$, as given in Table 5. Correlations involving the elements of $T$ become small (<0.5) when a priori is added. From Table 5, as the weight of the a priori is increased, the quality of the fit to the data is nearly unchanged. For Model 3, the final $T$ is equal to its a priori. Some, but not drastic, change occurs in other solution parameters as the values of $T$ are constrained, particularly in the values of $\gamma$. High correlation indicates that the data considered are not sufficient to resolve all of the adjustment parameters. Also,

### Table 4. High correlations in UARS analysis.

| Parameters correlated | Correlation | Parameters correlated | Correlation |
|-----------------------|-------------|-----------------------|-------------|
| $S_{22} - b_2$        | 0.89        | $S_{22} - b_2$        | 0.96        |
| $b_1 - \gamma_1$     | -0.77       | $b_1 - \gamma_1$     | -0.96       |
| $b_3 - \gamma_3$     | -0.55       | $b_3 - \gamma_3$     | -0.95       |
| $S_{11} - T_{13}$     | -0.74       | $S_{33} - b_2$        | 0.61        |
| $S_{11} - T_{23}$     | -0.61       |                       |             |
| $S_{33} - T_{32}$     | -0.74       |                       |             |
| $b_3 - T_{31}$        | -0.77       |                       |             |
| $\gamma_2 - T_{12}$  | -0.66       |                       |             |
| $T_{11} - T_{22}$     | 0.86        |                       |             |
| $T_{11} - T_{33}$     | 0.93        |                       |             |
| $T_{22} - T_{33}$     | 0.93        |                       |             |
Fig. 5. Residuals of data from the OGO-4 satellite plotted versus latitude. On the right are the longitudes at which the track crosses the equator, i.e., at 0°, and 180°, as well as the time (hh:mm:ss), $Dst$, and local time at the leftmost equator crossing. The ordinate is in nT.
Fig. 5. (continued)
Fig. 6. South polar plot of residuals from the POGS satellite. The coordinates are magnetic local time and dipole latitude. The satellite track is shown as a continuous line and is the baseline for the residual plot. Scale lines orthogonal to the satellite track are in the direction of positive residual and their length corresponds to a residual of 50 nT.

examination of only one time period gives no indication of adjustment stability. Further analysis, with data from other time periods, is required both to examine stability and to try to resolve all adjustment parameters.

Figure 7 shows the UARS residuals from Model 3. Residuals from the other models are very similar to those from Model 3. There is a tendency for the highest magnitude residuals to occur at southern high latitudes, the location where ionospheric currents are expected to be greatest, so perhaps some of the residual variations are ionospheric in origin. However comparison with Fig. 5 shows that there is not good correspondence of the UARS residuals to those found with OGO-4. The UARS data are from magnetically quiet periods, with low Dst, as shown on Fig. 7, yet the residual amplitudes greatly exceed those from OGO-4, except during moderately disturbed periods, e.g., Fig. 5H. But the residual patterns in Fig. 7 do not show the same characteristics as Fig. 5H. It is concluded that the adjustment procedure has failed to account for either fields from the spacecraft or errors in magnetometer calibration.

7. Summary and Discussion

Acquisition of near-Earth satellite data from three component fluxgate magnetometers without accompanying absolute scalar measurements leads to hard choices in data processing, evaluation, and use. On the one hand, fluxgate magnetometer technology has advanced to the point where the best modern
Table 5. Solution parameters for three UARS models.

|                | Model one                        | Model two                        | Model three                       |
|----------------|----------------------------------|----------------------------------|-----------------------------------|
|                | No constraint                     | Moderate constraint               | High constraint                   |
| \( \sigma_s \) | \( \infty \)                      | \( 5 \times 10^{-3} \)           | \( 5 \times 10^{-3} \)           |
| \( \sigma_r \) | \( \infty \)                      | \( 5 \times 10^{-3} \)           | \( 1 \times 10^{-5} \)           |
| Mean           | 0.1                              | 0.2                              | 0.2                               |
| \( \sigma \)   | 26.1                             | 26.5                             | 26.9                              |

|                |                                |                                |                                  |
| S:             | 0.99026 (1 \times 10^{-5})     | 0.99668 (6 \times 10^{-6})     | 0.98923 (5 \times 10^{-6})       |
|                | 1.00108 (4 \times 10^{-5})     | 0.99939 (3 \times 10^{-5})     | 0.99800 (2 \times 10^{-5})       |
|                | 1.00305 (4 \times 10^{-4})     | 1.00347 (2 \times 10^{-6})     | 1.00362 (2 \times 10^{-6})       |
| \( \gamma \)   | \(-6.50 \times 10^{-5} (1 \times 10^{-4})\) | \(-8.82 \times 10^{-5} (1 \times 10^{-5})\) | \(-1.20 \times 10^{-4} (1 \times 10^{-5})\) |
|                | \(-3.61 \times 10^{-3} (5 \times 10^{-5})\) | \(-3.02 \times 10^{-3} (4 \times 10^{-6})\) | \(-2.83 \times 10^{-3} (3 \times 10^{-6})\) |
|                | \(-1.02 \times 10^{-3} (7 \times 10^{-5})\) | \(-4.28 \times 10^{-4} (1 \times 10^{-5})\) | \(-5.73 \times 10^{-4} (1 \times 10^{-5})\) |
| \( b \)        | 25.8 (0.2)                       | 31.5 (0.2)                      | 31.9 (0.2)                       |
|                | \(-437.4 (0.7)\)                | \(-463.4 (0.5)\)               | \(-494.6 (0.4)\)                |
|                | \(-282.9 (0.1)\)                | \(-287.5 (0.1)\)               | \(-289.6 (0.1)\)                |
| \( T \)        | 1.91                             | 0.77                            | 0.65                             |
|                | 1.10                             | 0.39                            | 0.37                             |
|                | 1.71                             | 2.21                            | 2.44                             |

Error estimates for \( T \):
- 0.02
- 0.01
- 0.01
- 0.01
- 0.01
- 0.01

All elements = \( 2 \times 10^{-3} \)

Non-orthogonality of magnetometer axes:
- Without constraint: -13 sec, -744 sec, -210 sec
- With constraint: -25 sec, -583 sec, -118 sec

Instruments are accurate to a few nT or better and are stable over long periods of time. At the same time, they can occasionally exhibit drift of scale parameters and biases of sufficient magnitude to cause error when the data are used to determine the temporal variation of Earth’s main magnetic field. And the dilemma is that one is never certain of the true situation. The methodology developed and used in this study attempts to examine such data and estimate corrections as necessary.

In particular, an adjustment method for rendering satellite fluxgate data suitable for use in main-field modeling is developed and applied to data from the DE-1, POGS, and UARS spacecraft. Because the procedure relies on field magnitudes from a reference model, it is neither absolute nor objective. One must start with a model of Earth’s main field that is independent of the data to be evaluated and corrected. Then the corrected data are assumed to provide independent information for a new generation main field model, at least in geographic areas where other data are lacking. This is a circular argument and any error in the original reference model will most likely be transferred to the corrected data. Therefore the results should be regarded with caution unless clear evidence is available that the procedure is valid.

Of the data examined in this paper, the DE-1 data show such evidence. Because of the simplicity of the adjustment model for DE-1, and because the resulting corrected data are well fit by the reference model for the entire 10 year time span, it is concluded that both the corrected data and the field model itself (for 1981–1990) are reliable with 1σ error ≤ 15–20 nT.

Comparable evidence is lacking for the POGS and UARS data. In contrast to DE-1, no single, simple,
Fig. 7. Residual plots of UARS data after adjustment with Model 3, high constraint on torquer bar parameters. The abscissa is in units of latitude where the left of the plot is the geographic equator and the data proceed over the north pole, across the equator again, over the south pole and back to the equator. On the right are the longitudes, universal times (hh:mm:ss), and Dst values, corresponding to the second equator crossing (180°). An asterisk on the plot indicates the location of the dip equator. The ordinate is in nT.
Adjustment suffices to bring the data into good agreement with the reference model, although more work is needed for UARS. For both POGS and UARS, if shorter spans of data, e.g., a single orbit, are adjusted, much better agreement between model and data is achievable. But the resulting adjustment parameters show little consistency from solution to solution. If such solutions were correct, the implication would be that the instrument parameters are changing significantly over periods of time shorter than an orbital period. This is not considered likely. Further, the residuals in the POGS and UARS data after correction do not generally resemble corresponding residuals found in the POGO absolute magnetometer data. The discrepancy is about the same for the UARS and POGS data. When such variations exceed about 50 nT for POGS or UARS, they may be at least partly geophysical in nature. Errors in the uncorrected data are estimated to be on the order of 20 nT for DE-1, 50–100 nT for POGS, and several hundred nT for UARS.

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