Galileo constraints on the secular variation of the Jovian magnetic field

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[1] The variations of the terrestrial magnetic field place important constraints on the behavior of the fluid in the Earth’s magnetic dynamo. Jupiter is currently the only other planet for which magnetic measurements exist over a sufficiently long baseline to enable a study of the secular variation of the field to be undertaken. The average magnetic moment during the Galileo epoch was 4.334 ± 0.010 Gauss R\textsuperscript{3} or 1.584 ± 0.004 × 10\textsuperscript{20} Tm\textsuperscript{3}. The tilt angle of the dipole was 9.71° ± 0.05°. We examine both the change in the magnetic field during the period in which Galileo operated in Jovian orbit and the change in the field between the initial observations with Pioneer 11 and the Galileo epoch. Neither approach definitively identifies secular change in the Jovian field but rather puts a limit on that rate of change. The only significant change is associated with the current imprecision of the International Astronomical Union-defined System III period.


1. Introduction

[2] The existence of Jupiter’s magnetic field was first inferred from its polarized radio emissions detected by Burke and Franklin [1955] with radio telescopes operating at megahertz frequencies. Radio measurements showed that the Jovian magnetic dipole moment was directed northward opposite the terrestrial moment [Dowden, 1963; Berge, 1965], and that it was tilted with respect to the rotation axis by close to 9.5° [Roberts and Komesaroff, 1965; Komesaroff and McCullough, 1967]. The field strength was estimated to be 40,000 nT < B < 100,000 nT in the radiating region [Komesaroff et al., 1970]. The field was originally assumed to be generated in a liquid metallic hydrogen core containing helium [cf. Hide and Stannard, 1976] with the metallic state expected below about 0.73 R\textsubscript{J} [Stevenson and Salpeter, 1976], but current estimates of the extent of the dynamo region can be as large as 0.85 R\textsubscript{J} [e.g., Guillot et al., 2004].

[3] The first spacecraft to reach Jupiter was Pioneer 10, flying by on 4 December 1973, passing within 2.9 R\textsubscript{J} (Jovian radii) of the planetary center [Smith et al., 1974]. Pioneer 11 arrived one year later on 3 December 1974, approaching within 1.6 R\textsubscript{J} of the center of Jupiter on a retrograde orbit so that all longitudes were covered close to the planet [Smith et al., 1975]. Both spacecraft carried accurate vector helium magnetometers. Pioneer 11 carried a redundant fluxgate magnetometer. The consensus dipole-to-quadrupole pseudomoments were 1.00:0.24:0.21, in contrast to the terrestrial 1.00:0.14:0.10 ratio. The dipole moment was found to be 1.55 × 10\textsuperscript{20} Tm\textsuperscript{3}, 20,000 times larger than the terrestrial moment. Voyager 1 arrived at Jupiter on 5 March 1979, passing within 4.9 R\textsubscript{J} and Voyager 2 on 20 August, passing within 10.1 R\textsubscript{J} [Ness et al., 1979]. Both Voyager spacecraft carried only fluxgate magnetometers. Finally, on February 1992, Ulysses flew by Jupiter on its way to a high-inclination solar orbit, passing within 6 R\textsubscript{J} of the planet [Balogh et al., 1992], but the dipole moment was not constrained sufficiently to define the secular variation [Dougherty et al., 1996]. Nevertheless, while these measurements did not identify the secular variation, they do provide a baseline for Galileo that arrived on 7 December 1995 and orbited Jupiter until it was commanded to self-destruct by plunging into Jupiter on 21 September 2003. The range of the Galileo magnetometer extended only to ±16,000 nT so that the field could not be measured all along this trajectory even if telemetry had been available.

[4] The harmonic content of the Jovian magnetic field is rich when compared to the terrestrial moment. This harmonic richness has been interpreted as due to the relatively larger size of the electrically conducting core of Jupiter in comparison with that of the Earth [Elphic and Russell, 1978]. The reason for the control of the harmonic structure by the relative size of the core is simple. The terrestrial dynamo produces an almost flat energy spectrum at all harmonics of the field as measured in the outer part of the core. However, the strength of the field falls off with distance from the center of the planet with a power law whose index depends on the degree of the field. The dipole field falls off as the cube of the radius from the center of the planet. The quadrupole falls off as the fourth power, etc. Thus, if the surface is relatively far from the core, then the...
magnetic field above the surface will be mainly dipolar in nature, even though this is not true close to the core.

[5] The time scales of the terrestrial dynamo are very long for changes in the dipolar moment, but for higher orders (e.g., \( n = 2 \) and \( 3 \)), the time scale is in the range of 100–200 years [e.g., Hulot and LeMouel, 1994]. We can easily measure these changes, and their values are very enlightening. Since the magnetic field is frozen into the highly electrically conducting fluid of the interior, the field changes in response to these motions and by monitoring the changes in the vector field we can follow them. What we know about the terrestrial secular variation cannot be easily scaled to Jupiter, but considering the larger scales involved in this bigger body, we might expect even longer times for change than on Earth if the velocities were similar, but since the Jovian energy flux is much larger than that from the Earth’s core, this velocity may be larger [Christensen et al., 2009a, 2009b]. The net result is that we do not know whether to expect a faster or slower secular variation at Jupiter. On Earth, we can detect the secular variation by observing over a period of only one or more decades. While it is possible that we could detect the secular changes at Jupiter over the seven years of Galileo data or the 30 years from Pioneer to Galileo, Jupiter’s larger size and sparser magnetic coverage could mitigate against their detection.

2. Galileo Orbiter Measurements

[6] The Galileo orbiter carried two fluxgate magnetometers with flippers mounted on booms on the spinning portion of the spacecraft. This configuration allowed determination of the zero levels of the magnetometers continuously in the spin plane. The sensor along the spin axis could be interchanged with one in the spin plane to allow its zero level to be monitored [Kivelson et al., 1992]. The outbound sensor had dynamic ranges of ±32 nT and ±512 nT and ±16,384 nT. The early orbits, G1 to C9, where the letter designates the moon visited (Ganymede, Europa, and Callisto) and the number indicates the orbit, did not venture inside \( 9 \) R\(_J\) except on the insertion pass I0, where the spacecraft traveled far inside Io’s orbit, but orientation data were unavailable throughout much of this pass. On orbits G10 to C20, the spacecraft again stayed at or beyond \( 9 \) R\(_J\). Figure 1 shows the rotation of these orbits into the Z-R plane. Generally, Galileo flew close to the rotational equator.

3. Inverting the Measurements to Determine Multipole Moments

[7] Most studies of the Jovian magnetic field have followed a very similar rubric, solving an overdetermined linear system

\[
y = Ax,
\]

where \( y \) is a column matrix of the 3N magnetic field observations (three components observed N times) and \( A \) is a 3N by M matrix relating the observation to the model.
parameters \( x \). The vector \( x \) is arranged as a column vector of length \( m \).

The magnetic field at any point is a sum of coefficients dependent on locations and Schmidt-normalized Legendre polynomials

\[
B_x = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} (n+1) \left\{ \left( \frac{\alpha}{r^n} \right)^{n+2} \left[ g_n^m \cos(m\phi) + h_n^m \sin(m\phi) \right] P_n^m(\cos \theta) \right\}
\]

\[
B_y = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} (n+1) \left\{ \left( \frac{\alpha}{r^n} \right)^{n+2} \left[ g_n^m \cos(m\phi) + h_n^m \sin(m\phi) \right] \frac{dP_n^m(\cos \theta)}{d\theta} \right\}
\]

\[
B_z = \frac{1}{\sin(\theta)} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \left\{ m \left( \frac{\alpha}{r^n} \right)^{n+2} \left[ g_n^m \sin(m\phi) - h_n^m \cos(m\phi) \right] P_n^m(\cos \theta) \right\}
\]

The \( i \)th observation, \( y_i \), is related to the model parameters by the function \( P(x_i) \). The functions \( P(x_i) \) can be Taylor expanded around some initial parameter set, \( x_j \)

\[
y_i = P(x_i^0) + \frac{\partial P}{\partial x_j} x_j + \ldots
\]

We can proceed by calculating the residual from an existing model, e.g., the O6 model of Connerney [1992]

\[
\Delta y_i = y_i - P(x_i^0) = A' \Delta x_j
\]

where \( A' = \frac{\partial P}{\partial x_j} x_j \).

Figure 2. Condition numbers for the spacecraft trajectories of Pioneer 11, Voyager 1, Voyager 2, Ulysses, Galileo’s Ganymede 1 orbit, Callisto 10 orbit, and Io 27 orbit. Condition numbers for 15 eigenvalues (dipole, quadrupole, and octupole) and 8 eigenvalues (dipole plus quadrupole) are shown.

[10] Multiplying both sides of the equation by \( U^T \), we obtain

\[
(U^T y) = S(V^T x).
\]

Since \( S \) is an \( M \times M \) diagonal matrix, we regard the above equation as \( M \)-independent equations relating eigendata (on the left), through the eigenvalues \( s_v \), to eigenvectors of parameter space, the linear combination of the original parameters \( P \). The solution to \( y = Ax \), that is, the parameter vector \( x \) minimizing in a least squares sense [Lanczos, 1971] the difference between the model and the observations, is given by

\[
x = V S^{-1} y.
\]

Writing \( \beta = U^T y \), the solution can be constructed by a summation over the orthonormalized \( V_i \) of parameter space

\[
x = \sum_{i=1}^{M} (\beta_i / s_{v_i}) V_i.
\]

Magnetic field observations along a certain trajectory are insensitive to certain linear combination of parameters. One advantage of the SVD is that the parameter vectors which are poorly constrained by the available observations are explicitly identified. They are the eigenvectors associated with the small eigenvalues of \( A' \).

[11] One way to examine the condition, or stability, of a linear system is to calculate the “condition number,” \( CN \), defined as the ratio of the largest and smallest singular value (the square root of the eigenvalue) [Lanczos, 1971]

\[
CN = \frac{s_{v_1}}{s_{v_m}}.
\]

Errors in the \( mth \)-generalized parameter can be expected to be about \( CN \) times larger in magnitude than errors in the first generalized parameter. So, the condition number gives a very good estimate of the “quality of inversion” for a system.

[12] Figure 2 shows the condition number for different spacecraft trajectories with different eigenvectors included. The 15ev solutions include the octupole terms while the 8ev solutions contain up to the quadrupole.
Table 1. Octupole Model From Galileo Observations

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>g10</td>
<td>4.242</td>
<td>4.258</td>
<td>4.273</td>
</tr>
<tr>
<td>g11</td>
<td>-0.059</td>
<td>-0.725</td>
<td>-0.716</td>
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<tr>
<td>h11</td>
<td>0.241</td>
<td>0.237</td>
<td>0.235</td>
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<tr>
<td>g20</td>
<td>-0.022</td>
<td>0.212</td>
<td>0.270</td>
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<tr>
<td>g21</td>
<td>-0.711</td>
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<td>-0.593</td>
</tr>
<tr>
<td>g22</td>
<td>0.487</td>
<td>0.517</td>
<td>0.523</td>
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<tr>
<td>h21</td>
<td>-0.403</td>
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<td>-0.442</td>
</tr>
<tr>
<td>h22</td>
<td>0.072</td>
<td>0.152</td>
<td>0.157</td>
</tr>
<tr>
<td>g30</td>
<td>0.076</td>
<td>-0.013</td>
<td>-0.092</td>
</tr>
<tr>
<td>g31</td>
<td>-0.155</td>
<td>-0.764</td>
<td>-0.155</td>
</tr>
<tr>
<td>g32</td>
<td>0.198</td>
<td>0.292</td>
<td>0.274</td>
</tr>
<tr>
<td>g33</td>
<td>-0.180</td>
<td>-0.095</td>
<td>-0.096</td>
</tr>
<tr>
<td>h31</td>
<td>-0.388</td>
<td>0.950</td>
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<tr>
<td>h32</td>
<td>0.342</td>
<td>0.521</td>
<td>0.506</td>
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<tr>
<td>h33</td>
<td>-0.224</td>
<td>-0.309</td>
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<tr>
<td>tilt</td>
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<tr>
<td>long</td>
<td>159.9</td>
<td>161.9</td>
<td>161.8</td>
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\*Full octupole model with 15 coefficients and partial octupole model with 13 coefficients are compared with the NASA Goddard Space Flight Center O6 model, which is mainly inverted from Pioneer 11 observations. In the Galileo 13 model, the g31 and h31 coefficients that have minimum field contributions near the orbital plane of Galileo are held fixed at their O6 value.

4. Postlaunch Calibration of the Galileo Magnetometer

The Galileo magnetometer was carefully calibrated at the Ames Research Center prior to launch with one of the authors (CTR) among others in attendance, using the standard field generators of the facility operated by experienced personnel. There was no reason to mistrust the calibration of the magnetometer after these tests. The misfortune of Galileo’s inability to launch directly to Jupiter after the Challenger disaster in 1986 required Galileo to obtain three gravity assists: one from Venus and two from Earth in 1990 and 1992. The two Earth flybys provided an opportunity to perform postlaunch calibrations against the Earth’s magnetic field. The Galileo magnetometers could be set in either one of two flip states in which the sensor along the spin axis could be moved into the spin plane while a spin plane sensor was moved to point along the direction of the spin axis. These two flip states were designated flip right and flip left. The 1990 Earth flyby was undertaken with the flip right state and the 1992 flyby in the flip left state. The magnetometer was generally operated in the flip left state at Jupiter.

These flybys were used to improve the pointing and orthogonalization of the magnetometer using the techniques described by Kepko et al. [1996], but were not used to adjust the gain of the magnetometer (E. L. Kepko, personal communication, 2009). In preparation for the secular variation project. The 15 terms of the full octupole inversion agree moderately well with O6 except for the g31 and h31 terms. Since Galileo measurements are obtained in the rotational equator, they cannot resolve well the g20, g31, or h31 terms. Thus, in the solution in Table 1, we have fixed the g31 and h31 coefficients at their O6 values. We note that the longitude of the dipole axis has changed 2° between 1975 and the Galileo epoch. This is due to a slight inaccuracy of the 1965 International Astronomical Union (IAU)-defined system III period [Yu and Russell, 2009]. This small period shift may mask small changes in the other coefficients. We have used the IAU 1965 defined period of 9h 55m 29.71s throughout this paper. For future studies, a better value would be 9h 55m 29.706 ± 0.003s [Yu and Russell, 2009]. We note also that since the work of [Yu, 2004], we have found that the Galileo magnetometer was slightly miscalibrated. Table 1 has been adjusted for this miscalibration. How we corrected the data is described in section 4.

Table 2b. Calibration Matrix After Earth Field Comparison

<table>
<thead>
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<th>a_{x3}</th>
</tr>
</thead>
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<tr>
<td>a_{1x}</td>
<td>1.0089</td>
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<td>-0.0545</td>
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<tr>
<td>a_{2x}</td>
<td>0.0088</td>
<td>0.9820</td>
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<tr>
<td>a_{3x}</td>
<td>0.0535</td>
<td>0.0007</td>
<td>0.9971</td>
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</table>

Table 2c. Previously Used Calibration Matrix

<table>
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<tbody>
<tr>
<td>a_{1x}</td>
<td>1.0174</td>
<td>0.0052</td>
<td>-0.0558</td>
</tr>
<tr>
<td>a_{2x}</td>
<td>-0.0048</td>
<td>0.9916</td>
<td>-0.0049</td>
</tr>
<tr>
<td>a_{3x}</td>
<td>0.0554</td>
<td>0.0008</td>
<td>1.0055</td>
</tr>
</tbody>
</table>
study, we compared the Galileo measurements with terrestrial field models and found an approximate 1% difference, but in order to do a proper recalibration, we need to work in sensor coordinates in the rotating spacecraft frame. First, we orthogonalized the sensor triad numerically by minimizing the first and second harmonics in the spin plane as well as the first harmonic along the spin axis using the Kepko et al. [1996] algorithm. This attempt failed because the algorithm did not converge toward stable solutions. Thus, a new procedure was developed using high-order Butterworth filters with zero phase shift. This procedure can describe the phase and amplitude of the spin harmonics for every point in time during the Earth 1 and Earth 2 flybys and had no trouble with the rapidly changing field. The solutions for both Earth flybys converged rapidly. This process yielded the relative gain of the sensors in the spin plane, the regular angular correction around the axis for the spin plane sensors, the three elevation angles of the sensors, the azimuthal angle of the projection of the spin axis sensors on the spin plane, as well as the spin plane offsets. With the new orthogonalization matrix given in Table 2a, we compared with the Earth field model to obtain absolute gain corrections and absolute orientation of the sensor triad. When we compared our new calibration matrix (given in Table 2b) with the matrix that was previously used (given in Table 2c), the results were that the three sensors for the flip left state had been assumed to have a gain 1% too large. The other two sensors in flip right had different gain errors, but in the same range. It is moot what gain these sensors had since this flip state was rarely used. It is fortunate that in the flip left state, all three sensors had the same gain correction of 0.9911 ± 0.0008. Thus, we could use the results obtained by Yu [2004] with just a simple gain adjustment and not have to either reprocess the Galileo data or reinvert the processed Galileo data. Tables 1–5 have been so adjusted.

5. Secular Variation During the Galileo Mission

The accuracy with which the Jovian field could be measured with Pioneer 10 (1974) and 11 (1979) and Voyager 1/2 (1980) was not sufficient to resolve any small change in the field between these two pairs of missions [Connerney and Acuna, 1982]. The 1992 Ulysses encounter provided too little coverage to provide a statistically significant update to the Jovian field model [Dougherty et al., 1996]. In contrast, the available 7 years of Galileo orbital data have greater potential because of coverage and longevity to detect any significant secular variation. If a significant variation during the Galileo mission is not found, we can then go to the longer baseline between Pioneer and

<table>
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<th>Table 3. Orbits and Time Space in Each of Six Groups</th>
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<td>Group</td>
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<td>-------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

Figure 3. (top) Model magnetic field strength and vector components during the closest approach phase of the Earth 2 flyby in December 1992 from Tsyganenko [2002a, 2002b]. (bottom) The percent of spin-averaged residual field remaining after optimizing the gain in each of the three despun spacecraft coordinate directions. The residual percentage deviations are strongest where the field is low and poorly determined by the model. In highest fields, the residuals are consistent with the expected 0.1° accuracy of the orthogonality matrix.
Galileo to search for any changes in the main field. In this section, we examine the Galileo epoch.

[19] We have 22 orbits of Galileo to analyze for the secular variation study. These orbits are shown above in Figure 1. Measurements were not available inside of 8 R_J until C21 in mid-1999. Perijove was gradually lowered until it reached 5.78 R_J on I32. The condition number is useful for assessing the ability of a particular orbit to produce a high-quality inversion and this depends on spatial coverage. Figure 4 shows the condition number for the orbits available to us for the study for a full octupole (15ev) and a full quadrupole fit (8ev). The condition numbers for the 8ev fit are more stable and smaller and should provide a more even inversion quality over the course of the mission, one more suitable for a study of the secular variation. We note that all orbital periods studied lie entirely within 15 R_J and each included at least 3 complete Jovian rotations. There is one quadrupole coefficient that it is difficult for Galileo to measure accurately. This is the g20 coefficient where the field is minimized in the equatorial plane. We can improve the reliability of the inversion results if we use only 7 coefficients. Since we analyze the difference between our observations and the O6 model on the way to creating a better model, this truncation is equivalent to assuming that the g20 coefficient in the O6 model is accurate. Moreover, since we used the full O6 octupole field model including its octupole terms to calculate the residuals that we inverted to obtain the Galileo model, we have accepted the octupole terms as fixed and not spread their power into the lower-degree coefficients, as we studied the possible secular changes in the dipole and quadrupole terms. The fractional accuracy for the dipole term from this procedure is expected to be 0.2%, and for the quadrupole terms 20% in each of those 22 data sets based on the condition numbers and the observation noise through the resolution matrix [Jackson, 1972]. The standard deviation of the coefficients from our 22 independent inversions, shown later, confirms this estimate. Thus, we concentrate our attention on the dipole terms.

[20] To proceed with our testing of the significance of any trends in the dipole term, we use a technique called the one-way analysis of variance (ANOVA). This technique is

Figure 4. Condition numbers for Galileo orbits together with each orbit’s perijove distance. Light-colored bars represent the condition numbers of a full octupole internal field model with 15 coefficients; dark-colored bars represent the condition numbers of a full quadrupole internal field model with 8 coefficients.

Figure 5. One-way analysis of variance (ANOVA) plot of coefficient g10. Data are divided into six groups by time of acquisition. The upper and lower lines of the box are the upper and lower quartiles. The line in the middle of the box is the median. The bars whiskers up and down indicate the range of the sample.

Figure 6. Same as Figure 5 but for coefficient g11.
designed to determine whether groups have a common mean or are different. The linear model that is being tested is

\[ Y_{ij} = x_j + E_{ij}, \]

where \( Y_{ij} \) is a matrix of observations in which each column represents a different group. The \( X_{ij} \) matrix has columns that are the group means. The notation “\( \text{dot } j \)” means that \( x \) applies to all the rows of the \( j \)th column and the value \( x_{ij} \) is the same for all \( i \). \( E_{ij} \) is a matrix of random disturbances. The model posits that the columns of \( y \) are a constant plus a random disturbance. The objective is to determine if all the constants are the same.

We proceed by examining the dipole coefficients and the dipole tilt. We take our 22 data points and analyze them in 6 groups of 4. The orbit numbers for each group and their start and end dates and midtimes are given in Table 3. The last group overlaps with the fifth group and is not an independent sample.

ANOVA allows us to test if the groups have a common mean (the null hypothesis). The first parameter we examine is the F statistic and the probability of the null hypothesis being true. For our 6 groups and the dipole coefficient \( g_{10} \), we obtain a probability of 0.05, giving us 95% confidence that there is a real change in the moment over the Galileo period, but there is more to ANOVA than just the F statistic test.

A way of visualizing this is the box plot shown in Figure 5. This plot has several graphic elements. The lower and upper lines of the “box” are the 25th and 75th percentiles of the sample. The distance between the top and bottom of the box is the interquartile range. The line in the middle of the box is the sample median. If the median is not centered in the box, this is an indication of skewness. The “whiskers” are lines extending above and below the box. They show the extent of the rest of the sample (unless there are outliers). Assuming no outliers, the maximum of the sample is the top of the upper whisker. The minimum of the sample is the bottom of the lower whisker. By definition, an outlier is a value that is more than 1.5 times the interquartile range away from the top or bottom of the box. A plus sign at the top of a plot would be an indication of an outlier in the data. Such a point may be the result of a data entry error, a poor measurement or a change in the system that generated the data. Figures 5 and following have no outliers.

From Figure 5, we can clearly see that for the dipole coefficient, group 2 has a very large variation compared with other groups. Moreover, there is not a monotonic trend in the data and the spread around the mean solution (G7) is close to what one would expect at random. Thus, the ANOVA analysis does not make a strong case for a secular trend here, even though the F statistic gives a positive indication.

We repeat this analysis for the \( g_{11} \) coefficient in Figure 6. Here, the probability of the null hypothesis being true from the F statistic is 40%. Four of the six boxes intersect the mean (G7) solution and the remaining two are very close. There clearly is no secular change in \( g_{11} \) within our detection level. Figure 7 shows the box plot for the \( h_{11} \) coefficient. The null hypothesis here has a 15% chance of being true and four of the boxes intersect the mean solution. Again, this is not strong support for secular change but what one would expect for a noise-dominated variation.

In Figure 8, we show the box plot for the dipole tilt. The F statistic here gives a 49% chance of the null hypothesis being true and five of the six boxes intersect the mean solution. Clearly, there is no evidence for secular variation of the dipole tilt angle during Galileo’s tour of duty.

Table 4 shows the F statistics for the dipole and quadrupole solutions for our 6 groups. Of the dipole terms, only the \( g_{10} \) term appears to have a possible secular change and as we noted above in the ANOVA analysis, the trend is not monotonic. In the quadrupole terms, a strong dichotomy
exists. Three of the coefficients are clearly dominated by noise, but one, the g22 term, is very likely changing. As we discuss in section 6, there is reason for this term to be changing that does not fall into the usual category of secular change. We conclude that the measurements obtained by Galileo found no significant secular change over the period it was in orbit. In order to improve our search, we must look over a longer baseline.

6. Longer-Term Trends

[28] On Figures 5–8, we included the O6 and the G7 solution. The G7 solution is the inversion of all the Galileo orbits discussed above. Table 5 includes the 7 coefficients of the O6 model that Galileo can detect, plus refits of the Pioneer 11, Voyager 1, Voyager 2, and Ulysses data using the same algorithm for consistency. The O6 model is appropriate to an epoch of 1974 because it depended most heavily on the Pioneer 11 observations, and the latter with an epoch of about 2000 in the middle of the Galileo orbital operations. We also include an estimate of the probable error of the mean of each of the G7 coefficients based on the 22 independent inversions of the Galileo data that contribute to the G7 solution. This statistical error is quite small. The dipole moment is \(1.584 \pm 0.004 \times 10^{20} \text{Tm}^3\), and the dipole tilt is \(9.71° \pm 0.05°\). If we assume the O6 and G7 estimates have no error, the secular change in g10 is 0.03% per year, and if we assume that the Pioneer 11 value is a more accurate starting point, the change is 0.006% per year. However, it is unlikely that O6 or P11 values are sufficiently accurate to resolve a rate this small. Unlike the values for g10, the O6 and G7 values for g11 and h11 with epochs of 1974 and 2000, respectively, appear to be measurably different. There is a very simple reason for this that has nothing to do with the secular variation. Since 1965, when the IAU defined the period of Jupiter’s rotation to an accuracy of 10 ms, Jupiter has rotated a sufficient number of times that the accuracy of the IAU period is insufficient to predict the location of the projected dipole in the spin plane to accuracy with which we can measure it. What we are seeing in Figures 6 and 7 is the 2° that the defined coordinate system has rotated in the ensuing years, relative to the true body-fixed system. We note that two of the quadrupole terms should be even more affected by this slippage of the coordinate system due to the inaccuracy of the spin period. These are the g22 and h22 terms, which are not rotationally symmetric and have a half the spatial (longitudinal) scale of the dipole variation. In fact, g22 was identified in the ANOVA analysis as possibly having secular variation. In both cases, the G7 value is markedly different than the O6 value. Hence, an inaccurate rotation rate appears to be a factor in the apparent quadrupole “secular” variation.

7. Summary and Conclusions

[29] We have examined the Galileo orbital data for evidence of a secular variation in the magnetic field. We limited our analysis to seven components that Galileo could resolve well and looked for significant trends during the Galileo mission. During the Galileo epoch, the planetary moment was \(4.334 \pm 0.010 \text{ Gauss R}^3\) compared to the 4.330 Gauss R3 given by the P11 fluxgate. The difference is well within the statistical error of the Galileo analysis without even considering the error in the Pioneer 11 solution. The tilt of the dipole during the Galileo epoch was \(9.71° \pm 0.05°\). This value is statistically different than the \(8.81°\) value of the tilt in the Pioneer 11 epoch. But the tilt angle seems to be randomly varying across the various solutions and a trend is not seen. While occasionally a component might appear to have a significant temporal trend, there was no pattern that suggested that the field was changing as a whole. The only clear evidence for change could be explained by the current inaccuracy of the 1965 IAU definition that allows a 2° slip in the dipole longitude since the Pioneer 11 epoch. Perhaps the major contribution this study can make is a firm baseline for later studies.

[30] We note that to perform this analysis, we have recalibrated the Galileo data with a single-scale factor. We have not reprocessed the Galileo data. Future improvements could be made with reprocessing that might improve the pointing a little, as well as the scale factor. The use of an improved rotation period for Jupiter [Yu and Russell, 2009] is highly recommended.

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References


Table 5. Seven Coefficient Fit for Various Measurement Epochs Compared With O6 Model

<table>
<thead>
<tr>
<th>Term</th>
<th>O6</th>
<th>P11-FGM</th>
<th>Voyager 1</th>
<th>Voyager 2</th>
<th>Ulysses</th>
<th>G7</th>
<th>G7 Error</th>
</tr>
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<tbody>
<tr>
<td>g10</td>
<td>4.242</td>
<td>4.279</td>
<td>4.236</td>
<td>4.406</td>
<td>4.116</td>
<td>4.272</td>
<td>±0.009</td>
</tr>
<tr>
<td>g11</td>
<td>−0.659</td>
<td>−0.627</td>
<td>−0.658</td>
<td>−0.659</td>
<td>−0.636</td>
<td>−0.694</td>
<td>±0.003</td>
</tr>
<tr>
<td>h11</td>
<td>0.241</td>
<td>0.217</td>
<td>0.247</td>
<td>0.225</td>
<td>0.223</td>
<td>0.228</td>
<td>±0.002</td>
</tr>
<tr>
<td>g21</td>
<td>−0.711</td>
<td>−0.655</td>
<td>−0.630</td>
<td>−0.355</td>
<td>−0.836</td>
<td>−0.572</td>
<td>±0.026</td>
</tr>
<tr>
<td>g22</td>
<td>0.487</td>
<td>0.435</td>
<td>0.493</td>
<td>0.410</td>
<td>0.463</td>
<td>0.541</td>
<td>±0.011</td>
</tr>
<tr>
<td>h21</td>
<td>−0.403</td>
<td>−0.295</td>
<td>−0.420</td>
<td>−0.524</td>
<td>−0.291</td>
<td>−0.439</td>
<td>±0.022</td>
</tr>
<tr>
<td>h22</td>
<td>0.072</td>
<td>0.004</td>
<td>0.070</td>
<td>0.235</td>
<td>0.183</td>
<td>0.159</td>
<td>±0.007</td>
</tr>
<tr>
<td>Tilt</td>
<td>9.39</td>
<td>8.81</td>
<td>9.42</td>
<td>8.97</td>
<td>9.30</td>
<td>9.71</td>
<td>±0.050</td>
</tr>
</tbody>
</table>

*Units of coefficients are \(10^{-4}\text{T}\), i.e., Gauss, except for tilt which is in degrees.


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