In-Flight Calibration of the NEAR Magnetometer

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Abstract—The science objectives for the Near Earth Asteroid Rendezvous (NEAR) Magnetometer Experiment (MAG) are to measure a possible magnetic field of 433 Eros to 0.1 nT accuracy and secondarily to detect asteroid–solar wind interaction signatures. Between June and November 2000, achieving this accuracy required detailed analysis of spacecraft magnetic fields during cruise. Sources of magnetic contamination identified prior to launch and during cruise are propulsion latch valves, fixed 190 nT residual field, solar arrays and power harness, variable 15 to 60 nT field, power distribution terminal board, ~30 nT field with ±5 nT variations, power shunting circuitry, 1-5° T variations, the MAG sensor survival heater, 6 nT steps and attitude control momentum wheels, and 1 nT amplitude at 0.2 to 10 Hz from each of four wheels. Analysis of cruise data was used to create accurate ±1 nT models for the fixed and variable fields with signals below 0.5 Hz to provide correction of the raw data. The spacecraft field corrections and MAG calibration were validated with data from the Earth swing-by of January 1997. Comparison of solar wind magnetic field measurements from the WIND spacecraft and NEAR from January 22-24, 1997, before and after the Earth swing-by maneuver, confirm that the resulting NEAR magnetic field measurements are accurate to 1–2 nT.

Index Terms—Calibration, extraterrestrial measurements, magnetometers.

I. INTRODUCTION

The NEAR Earth Asteroid Rendezvous (NEAR) Mission is the first in the Discovery Program of low-cost planetary and space science missions. Its objective is to characterize the S-type near-Earth asteroid 433 Eros to determine its composition and structure to help understand the origin of Eros and near-Earth asteroids in general and to clarify the relationship between asteroids and chondritic meteorites. After achieving rendezvous, NEAR will orbit Eros for one year, conducting extensive observations using infrared and visible spectroscopy, imaging, X-ray and γ-ray fluorescence spectroscopy, laser ranging, and in situ magnetic field measurements [4]. The magnetic field experiment (MAG) will be used to characterize the magnetization intensity and geometry of 433 Eros, as described in detail by Acuña et al. [1]. This paper describes the in-flight calibration activities for MAG including analysis of spacecraft magnetic fields and the post-reception processing steps developed to remove these effects prior to scientific study. Because Eros is immersed in the magnetized plasma of the solar wind, the performance requirements of the MAG instrument are related to the orbit distances and the solar wind perturbation signatures associated with the asteroid. During the one-year rendezvous, the NEAR spacecraft will execute a variety of orbits at Eros to optimize the imaging, composition and ranging measurements. The planned orbit radii will range from 400 km down to 35 km, as low as 15 km from the asteroid surface. Assuming for the moment that the plasma behaves hydrodynamically at the small scales of the asteroid, for NEAR to directly sample Eros’s magnetic field, the field would have to stand off the solar wind dynamic pressure which will average ~2.5 nPa at perihelion (1.13 AU) and ~1 nPa at aphelion (1.78 AU), corresponding to magnetic field strengths of 80 nT and 50 nT at perihelion and aphelion, respectively. The goal for MAG is to achieve 10% accuracy in a direct detection of Eros’s magnetic field, which is therefore provided by an accuracy of 5 nT. This is a factor more than 50 less demanding than for space probes designed for solar wind studies. Achieving better than 5 nT accuracy is important for several reasons. Signatures of the solar wind interaction due to whistler waves should be present near the asteroid [13] but are expected to be only a few nT in magnitude. Such indirect observations were used to infer the magnetic character of Gaspra [6] and Ida [7]. In addition, if Eros presents a small obstacle, < 100 km in size, to the solar wind, one expects other kinetic plasma interactions to play a prominent role in the interaction because solar wind protons have gyroradii of ~50 km. Signatures of a kinetic effect are likely to be a few nT or smaller. In this case, one also expects that Eros’s magnetic field will not stand off the solar wind in a magnetohydrodynamic sense, but will be approximately superimposed on the solar wind field and may be detectable at smaller values than 50 nT. Reasonable efforts within cost and schedule constraints were therefore made to achieve noise levels below 5 nT. The net dynamic magnetic field of the spacecraft field is roughly ten times larger than this (the static field is roughly 200 nT), so that a thorough characterization of spacecraft magnetic fields was required. A detailed model of the spacecraft magnetic contamination was developed that makes extensive use of spacecraft engineering data and describes dynamic as well as static field sources. Because of cost limitations, a detailed magnetic survey of the NEAR spacecraft was not performed on the ground and the analysis was performed using data obtained during cruise. This paper documents the methods and results of this analysis, showing that the ultimate accuracy of the magnetic field data returned from NEAR is 1–2 nT. The NEAR magnetic fields ex-

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periment will therefore return direct measurements Eros's magnetic field, if its magnetic moment is sufficiently large, as well as signatures of the solar wind interaction.

II. INSTRUMENT DESCRIPTION

The NEAR magnetometer is described in detail by Lohr et al. [3] and essential instrument characteristics are summarized in Table 1. The instrument consists of a triaxial fluxgate sensor, drive and sense electronics with separate 20-bit A/D converters for each axis. The instrument includes eight ranges covering full scale sensitivities from ±4 nT to ±65536 nT. Preflight sensor calibration provided absolute gain calibrations to 0.1% (0.5%) in the least (most) sensitive range and orientation to 1 arc minute. Range control can be selected to be either manual or automatic. Automatic range control provides transition to less sensitive ranges when any one axis exceeds 87.5% of full scale for 0.25 s and shifts to a higher sensitivity when the field on all three axes falls below 17% of full scale continuously for 1 min. This ensures that the instrument will follow rapid increases in field strength without rapidly toggling between ranges.

The internal instrument sampling is fixed and variable output rates are accomplished by a combination of digital filtering and sub-sampling. The analog voltage outputs are anti-alias filtered with a combination of a single pole analog Butterworth low pass filter, 3 dB attenuation at 10.7 Hz at the input of each A/D, and an IRK filter built into the A/D, 3 dB attenuation at 16.7 Hz. The analog signals are sampled continuously by the A/D converters at 20 samples/axis and output to the instrument data processing unit (DPU) via gate arrays. The same DPU services both the MAG and the Near Infrared Spectrometer (NIS) instruments. Subsequent digital filtering, range control, noise rejection, time tagging, formatting, and other pre-processing and logic control are performed in the DPU. Intrinsic instrument sensor noise is about 57 fT rms (0-1 Hz). Time tagging is provided to 0.05 s accuracy, and the inertial timing latency of the instrument including both analog delays and digital processing is 0.64 s. Additional known latencies are introduced by the onboard digital filters and vary with the output sample rate.

To accommodate the data collection strategies of NEAR, the instrument sample rate is commandable from 0.01 to 20 samples. Digital filtering commensurate with the output rate is applied for rates down to 1 sample/s. The filtering calculations are performed on the internal 20 bit resolution data. To avoid integer roundoff calculations in the filtering, the data are padded with five zeros and the resulting 25-bit integers are carried forward in the 32-bit processor. The output is rounded to 16-bit resolution providing digitalization step sizes from 0.2 pT to 2 nT. To avoid undesirably low averaging and to ensure that data are not smeared significantly in position relative to Eros, sample rates from 0.5 samples/s to 0.01 samples/s are subsamples of the 0.5 Hz filtered time series. During cruise, the instrument is operated in range 3 at the 0.01 samples/s rate and checkouts consisting of a calibration with the internal bias current, 20 samples/s data collection (5 min) and anti-alias filter turn-off are performed approximately weekly as spacecraft operations allow. The sampling rate at rendezvous will be 1 sample/s and checkouts performed weekly.

III. INSTRUMENT CALIBRATIONS

In-flight calibration for the NEAR magnetometer involved measurements specific to the magnetometer per se as well as analysis to characterize the spacecraft magnetic fields. Spacecraft magnetic fields were characterized using cruise measurements both before and after the Earth fly-by on January 23, 1998. Prelaunch calibrations are described by Lohr et al. [3].

A. Checkout Sequences

Several aspects of instrument performance are monitored using checkout sequences executed in flight. A calibration can be commanded which adds a bias field to each of the three fluxgate ring cores and is used to monitor any drift in the magnetometer gain and A/D conversion scaling. Other sequences consist of commanding various instrument modes including changing ranges to monitor level shifts, rate changes (especially to 20 samples/sec), turning the digital anti-alias filter off, and turning noise rejection off. The latter three are used to monitor the level and character of spacecraft magnetic noise.

B. Earth Swing-By

The primary in-flight instrument calibration was associated with the Earth swing-by that occurred on January 22–23, 1998. Because the NEAR spacecraft was not characterized in a magnetically facility the Earth swing-by was the only means of establishing the precise sensor orientation with respect to the spacecraft coordinate system. In addition, the instrument auto-ranged from range 3 up through 7 and back to 3 providing an opportunity to determine range dependent offsets. Fig. 1 shows GSE coordinates of the NEAR trajectory, and Fig. 2 gives the field in spacecraft coordinates and the residual in spacecraft coordinates after scale factor and sensor spacecraft
and magnetospheric [12] contributions, and transforming it into spacecraft coordinates. Secular variations lead to variations in the main field of roughly 0.1% per year and the IGRF-1995 model extrapolates the secular variations to the date of the Earth swing-by. The IGRF model is an average reference field which departs from other models by as much as 1% in specific regions. A least squares fit of the measurements from each component to the three axes of the model field in spacecraft coordinates determined a correction matrix from which we derive the rotation between sensor and spacecraft coordinates. The largest orientation adjustment is a 1.8° rotation in the X-Y sensor plane, about the axis of the tube in which the sensor is mounted. The only other statistically significant orientation adjustment was a 0.2° rotation in the X-Z sensor plane. The swing-by derived matrix also contained gain factors slightly different from unity—the model field was 0.3% to 0.4% smaller than the observed field. All three instrument axes showed the same relative departure from the model field, to within 0.1%, indicating that relative drifts in the pre-launch calibrations were very small. Whether the scalar discrepancy with the model field is due to errors in the secular variation predictions in the IGRF-1995 model or due to a uniform calibration drift in all three axes has not been determined. Without compelling evidence for a large calibration drift, we multiplied the swing-by derived calibration correction matrix by 1.0036 to preserve the pre-launch gain calibrations. Calibrated data are obtained by first converting the data to physical units, nT, accounting for instrument range, fixed offsets and spacecraft fields. The final calibration adjustment is then applied in spacecraft coordinates as follows:

\[
\begin{pmatrix}
B_x' \\
B_y' \\
B_z'
\end{pmatrix}
= \begin{pmatrix}
1.0005 & 0.0034 & 0.0018 \\
-0.0035 & 0.9999 & 0.0073 \\
-0.0039 & -0.0038 & 0.9996
\end{pmatrix}
\begin{pmatrix}
B_x \\
B_y \\
B_z
\end{pmatrix}
\]

(1)

The remaining residuals are less than ±0.50 nT in a main field of > 20000 nT and are within limits of knowledge of the contributions due to magnetospheric currents (e.g., [12]) and are attributed to real contributions not accounted for in the field models. Portions of the residuals displaying rapid oscillations of a few nT are due to the effects of subtracting the model field from the 2 nT LSB resolution in the least sensitive range during portions of the swing-by when the field changed most rapidly. Finally, the Earth swing-by also validated the coordinate transformation software from spacecraft to inertial coordinates since these same routines were used to transform the model field into spacecraft coordinates.

C. Sensor Survival Heater

The instrument includes a sensor heater that cycles autonomously for probe temperatures below −15 °C to prevent possible deformation damage. For sun-pointing operations on NEAR, the range of heliocentric distances over which the heater cycles on and off is 1.53 AU to 1.72 AU. Beyond 1.72 AU the heater remains on and runs in proportional closed loop.
NEAR Magnetometer Sensor Heater Correction

![Graph showing corrected and uncorrected data](image)

Correction for the heater signal is applied in ground processing and requires determination of heater turn on and turn off times together with an accurate model of the heater field perturbation. Because the heater cycles autonomously and draws negligible current, the times of heater turn on and turn off must be identified in the magnetometer data. The heater cycle signal is quite well defined. The heater step size is known, a negative step must be followed by a positive step, and the separation between cycles and the duration of a heater cycle varies slowly with time. An analysis tool was developed that first flags all first point differences larger than 4 nT and then allows graphical, interactive editing of the heater on/off time series. Determining the heater cycle times for a day’s data requires about 30 min, including file handling and is the only aspect of data processing that is not automated. The heater on and off times are assigned times midway between the two points defining each jump (on or off) to guard against roundoff in software logic when corrections for the heater signal are applied.

Because the heater signal is not a simple square-wave, extensive statistical analysis was required to model it. For on/off cycling operations, the heater signal was characterized by extracting all heater on/off cycles from the cruise data through May 1999. The details of the heater profile were determined from the Y component in which the signal was strongest. Data for each heater cycle were binned according to the cycle duration. The on/off steps were averaged and the profile fit with a three degree polynomial for each duration bin. The on/off steps and profile coefficients for the heater were then fit to continuous functions of heater on duration to construct an empirical model of heater signal. Corrections in the X and Z components were smaller <1 nT and were simply a fraction of the Y correction determined from the ratio of the average on/off step in Y to X and Z. The corrected signal for Y is shown in Fig. 3. For heater on cycles longer than 2700 s, including continuous operation, the profile correction for the first 2700 s is applied and the value at 2700 s used for times longer than this since heater turn on.

IV. SPACECRAFT FIELDS

Because the primary magnetic fields science objective requires only 5 nT precision, the sensor was mounted just under the high gain antenna feed, 1.2 m above the spacecraft top deck rather than on a boom. Prelaunch assessments of the sources of spacecraft magnetic fields and activities undertaken to address these sources are summarized in Lohr et al. [1, Table A3]. Fig. 4 is a schematic of NEAR showing the systems and components responsible for spacecraft magnetic fields. The largest component of the spacecraft field measured by the sensor is BZ, along the spacecraft axis of symmetry and varies from 150 nT to 180 nT. Most of the variation is due to changes in the total current in the solar panels. With these values the instrument operates in range 3 with full scale of 256 nT, 8 pT resolution.
the accuracy of the cancellation was limited to the background environment variability. Long-term cruise measurements were used to determine the fixed field to an accuracy of 0.5 nT (see Section V). The presence of magnetically permeable materials (e.g., non-ferromagnetic magnets) did not prove a severe problem because the satellite does not operate in a strong magnetic field environment (i.e., NEAR is not an Earth orbiting spacecraft). Nonetheless, highly permeable materials were avoided wherever possible. The most notable exception was the spacecraft battery which uses nickel–cadmium cells [2]. The battery was not an issue since it is mounted on the opposite end of the spacecraft from the magnetometer.

B. Variable Fields

The sources of variable spacecraft magnetic fields, their approximate magnitude, characteristic time scale, type of signal, and the approach used to address its contamination are listed in Table II. Sources either discovered after launch or found to be considerably stronger than indicated by prelaunch tests are indicated (cf. [13]). Many of the dynamic magnetic fields are linked together so that step changes in the spacecraft field result from combinations of factors. Thus, analysis proceeded in a series of steps removing the largest or easiest isolated contribution to the contamination field before proceeding to analysis of the next factor. The sequence of analyses was the following. First, the magnetometer heater signals were removed as described above. Second, the field from the terminal board was modeled using a Biot–Savart calculation based on prelaunch measurements of the board's current loops. This model was tested in the laboratory with a mockup. Third, the solar array current was correlated with long-term averages of the field to remove the field due to the power system. Fourth, cruise data from a given power system digital shunt configuration were used to correlate the analog shunt current with the field measurements to determine the analog shunt loop coefficients. Fifth, the steps between different digital shunt configurations were analyzed to determine the field change resulting from each shunt switch. 

1) Terminal Board: One source of dynamic magnetic fields is the power system terminal board through which all loads on the spacecraft are powered and where their currents are measured. This board was chosen from an existing design to meet the NEAR launch schedule. Unfortunately, the wiring is laid out in uncompensated loops [8] ranging in area from 100 cm² to 600 cm² carrying currents ranging from a few tens of milliamperes to a few amperes. The net terminal board field has a total magnitude of 30 to 50 nT with typical step-wise variability of 1 nT to 5 nT. 

Nearly all of the currents in the board’s loops are monitored in spacecraft housekeeping. During spacecraft assembly the positions and geometry of the loops were carefully measured to allow explicit calculation of the field from each loop. Corrections for the 23 loops whose currents are monitored in spacecraft housekeeping are applied in ground processing to an accuracy of a few percent (5-bit resolution current monitors). There are three autonomous heaters with loops on the terminal board whose currents are not monitored in spacecraft housekeeping. These loops were cancelled by adding compensation loops which trace the current path backward on the board [3].
### Table II

<table>
<thead>
<tr>
<th>Source</th>
<th>Magnitude</th>
<th>Time scale</th>
<th>Type of output</th>
<th>Mitigation approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation vector events</td>
<td>~0.001 E</td>
<td>Polarizations</td>
<td>Direct proportion, no net</td>
<td>Big propagation events. Correcting data during propagation events not necessary.</td>
</tr>
<tr>
<td>Terminal board, spacecraft setup load</td>
<td>25 mT</td>
<td>0.01-0.10 ma (hours -1.6.0.4)</td>
<td>Direct proportion, no net</td>
<td>Half-propagation events. Correcting data during propagation events not necessary.</td>
</tr>
<tr>
<td>Digital power system shutdown*</td>
<td>5-10 Hz</td>
<td>Hours to months</td>
<td>Direct proportion</td>
<td>Direct proportion to shutdown current corresponding to number of devices turned off.</td>
</tr>
<tr>
<td>Analog power system shutdown*</td>
<td>5 mT</td>
<td>Minutes</td>
<td>Direct proportion</td>
<td>Direct proportion to shutdown current corresponding to number of devices turned off.</td>
</tr>
<tr>
<td>Solar array</td>
<td>30 mT</td>
<td>Hours to months</td>
<td>Direct proportion</td>
<td>Direct proportion to shutdown current corresponding to number of devices turned off.</td>
</tr>
<tr>
<td>Mission where*</td>
<td>1-2 mT</td>
<td>0.6 to 10 Hz, exc. &gt;0.5 Hz</td>
<td>Direct proportion</td>
<td>Direct proportion to shutdown current corresponding to number of devices turned off.</td>
</tr>
</tbody>
</table>

*Source either discovered after launch or found to be stronger than expected.

Because the spacecraft housekeeping currents are integral to generating science magnetic field data, the housekeeping data collection times were synchronized with magnetic field observations. During cruise the magnetic field was usually sampled once every 100 s. To ensure that each housekeeping sample corresponded as nearly as possible to a simultaneous magnetic field sample, the spacecraft software was changed to accommodate a signal from the magnetometer DPU to the spacecraft computer when a magnetic field reading was about to be taken. This signal was used as a trigger for the next spacecraft housekeeping sample. These changes were implemented by uploading revised magnetometer and spacecraft flight code on days 255 and 256 of 1997. The magnetic field will be recorded at a 1 Hz rate during an encounter, corresponding to the finest timing control of housekeeping readings, so this synchronization will not be needed during encounter.

2) **Power Management System:** The power system includes the solar arrays and cables, and the power shunt control circuitry. Each solar panel has 24 strings of solar cells organized into five circuits, as shown in Fig. 4 [2]. Each circuit consists of either four or five strings operating in parallel. The sequence for digital shunting (see below) is indicated by the number for each circuit; the lowest numbers being shunted first. Because the backs of the panels are occupied by shunt heaters, backing the panels was not possible. In addition, the need to maximize collection area meant that there was no room to lay cancellation loops on the front of the panels. With neither of these techniques available, a predictive model of the solar panel fields was developed and used to design the array current paths to minimize the field produced at the sensor by ensuring that current loops produced opposite directions and that the field parallel to the plane of the arrays from strings on opposite panels cancelled at the sensor location. This dictated the four-string pattern of current flow used (Fig. 4 bottom), which ensures that every line of current has a neighbor of opposite flow sense. It is not possible to cancel both the in-plane and out of plane components. For uniform current in all strings the field at the sensor from the arrays is only parallel to the spacecraft Z axis.

We therefore expected a significant field at the sensor proportional to solar array current. Averages of the field in spacecraft coordinates from 1997-225-365 were correlated with solar array current and found to depend linearly on solar array current and the correlated field contributions are given by

\[
\begin{align*}
\Delta B_X & = -0.002 \gamma + 0.011 n\text{Ci}^{-1} \\
\Delta B_Y & = +0.163 \gamma + 0.016 n\text{Ci}^{-1} \\
\Delta B_Z & = -0.259 \gamma + 0.011 n\text{Ci}^{-1}
\end{align*}
\]

where one ampere equals 3.4 counts. The largest contribution is along the Z axis, but there is a significant contribution along Y, indicating that a major fraction of this current is due to current loops associated with the power harness and switching unit. The net field would correspond to a current loop on the top deck of area of 0.019 m², 15 cm diameter. The total array current ranges from 15 to 60 amperes, giving a variation in the observed field as large as 31 mT in Z. This variation corrected to a precision of about 1.5 mT in each component.

The shunting state of the array also affects the magnetic field. Because the solar panels generate more current than the spacecraft will use, excess current must be shunted. On NEAR, the resistive shunt elements are on the anti-sunward side of the solar panels. The current path in these heaters generates negligible moment but imbalances in the current between shunted and non-shunted strings together with the current loops in the power switching electronics and wiring cause magnetic fields. Current shunting is done in two levels, digital (seapwise) and analog (continuous) (cf. [2]). If one of the current from a given string is needed, its entire current is shunted to a resistive load. The sequence of digital shunting is fixed, and there are twenty possible digital shunt states (cf. Fig. 4). Because a solar cell string that is being shunted operates at a slightly lower voltage than one that is powering the spacecraft there is a slight imbalance in the field cancellation between strings of the solar array if one is shunted and its opposite is not. In addition, there are current loops within the power switching unit so that changes in the digital shunt configuration correspond to changes in current inside the switching unit.

Within each digital shunt level, fine control is achieved by diverting the residual excess current to one or more of six heaters engaged sequentially in even current steps. The analog shunt
current flow in the switching unit and through the harness is different depending on the analog shunt resistors being used. The current loops associated with the digital and analog shunt circuits are independent.

The contamination fields can be removed because the total solar array current as well as the digital and analog shunt currents are recorded. The first step in correcting imbalances due to the shunt currents is to identify the digital shunt level. Fig. 5 shows the distribution of digital shunt current to total solar array current including data from 1996, 1997, 1998, and 1999, covering the full range of heliocentric distances to be spanned at Eros. The vertical dashed lines correspond to the expected boundaries between digital shunt steps assuming that the current in each circuit is proportional to the number of strings. These boundaries correspond very well to the observed gaps in the distribution.

The field due to the analog shunt circuitry was determined by binning data according to both digital shunt level and analog shunt current. The results for averages using all data from 1996, 1997, and 1998 are shown in Fig. 6. Separate traces are shown for each digital shunt level and the solid dark trace is the average over all digital shunt levels. The data were renormalized by subtracting the average within each digital shunt level to allow use of all data to determine the analog shunt field model. The analog shunt uses six heater shunt circuits which are engaged sequentially with the boundaries occurring at 17, 34, 51, 68, and 85 counts (28.5 counts/ampere). We modeled the field as a set of six contiguous linear segments with boundaries at shunt currents of 17a counts. The model is shown in Fig. 6 by the thick gray trace with circles at the line segment endpoints. The rms deviations between the model fit and the average of the data are 0.22 nT, 0.40 nT, and 0.21 nT for BX, BY, and BZ, respectively.

To determine the digital shunt effects, the analog shunt corrections just described were applied, and the jumps in the magnetic field associated with digital shunt level changes between adjacent shunt steps were recorded. Because the field from the solar array is proportional to total solar array current, only those jumps for which the solar array current was constant to within 2% were used and the field jumps were normalized to the solar array current. The top panel of Fig. 7 shows the steps in BY per unit solar array current between shunt levels i and i + 1 versus i, where i is the digital shunt level, together with the average and standard deviation. Shunt level i = 13 was chosen as an arbitrary reference level and the net field correction in other shunt levels were determined by summing the magnetic field jumps up or down in i. The spacecraft offset field is then referenced to shunt level 13. The bottom panel of Fig. 7 shows the digital shunt correction for BY plus the standard error in the mean computed from the standard errors of each step combined in quadrature. The uncertainties in these steps are generally 0.002 nT/count which gives uncertainties of 0.3 nT for typical solar array currents of ~35 amperes (~125 counts).

3) Momentum Wheels: The spacecraft attitude control system includes four momentum wheels for three axis stabilization and precision pointing [11]. The wheels are mounted on the bottom deck in pairs on two A-frames (Fig. 4). During diagnostic periods, the magnetic field data were recorded at 20 samples/s, and excellent correlation between frequency peaks and the reaction wheel spin tones were found, indicating that residual dipole moments in each wheel are present. Fig. 8 shows power spectra for one such interval, showing excellent agreement between the engineering data wheel speeds and the
special peaks in the magnetic field data. The wheels give about 1 nT peak to peak sinusoidal signals (about five times larger than expected from prelaunch tests [3]) but are filtered out in all instrument ranges from 0.01 to 1 samples unless the wheels operate below 30 rpm. This slow wheel condition happens occasionally and to avoid aliasing the magnetometer will run at 1 sample/during rendezvous.

4) Science results (NLR): Diagnostic magnetic field data at 20 samples were recorded during selected operations of other science instruments to assess whether they generated significant magnetic fields. The only instrument that displayed a detectable magnetic signature was the NASA Laser Rangefinder (NLR). The 1-kHz NLR pulses show up in the BY (2) data as single point downward spikes >2 nT in 20 Hz data.

V. VALIDATION
Because the desired accuracy is less than 10% of the corrections applied, it is crucial to verify the resulting science data. The Earth swing-by was an excellent opportunity to do this, because there were other spacecraft measuring the interplanetary magnetic field (IMF). Fig. 9 shows NEAR magnetic field data to which all of the above described corrections have been applied and WIND magnetic field data (data provided courtesy of R. Lepping, GSFC, Greenbelt, MD) for the Earth swing-by when WIND was located at the L1 point. The WIND data have been time shifted using the measured solar wind speed at WIND divided into the difference in heliocentric distance between NEAR and WIND. The WIND and NEAR data agree within 1 to 2 nT.

In addition, boundaries associated with Earth's magnetosphere are evident in the NEAR data. On the inbound pass, the bow shock was crossed repeatedly from ~1600 UT on January 21 to 1300 UT on January 22, as evidenced by the sharp jumps in Bz, shown. On the outbound pass, a single bow shock crossing occurred at about 1200 UT on January 23. The magnetopause crossings occurred at 2230 UT on January 22 (inbound) and 1130 UT on January 25 (outbound), both within 15 min of the magnetopause location as specified in the IRI90 magnetospheric field model. These results confirm that the spacecraft contamination field model described here provides correction of these fields to the 1 to 2 nT level.
respectively, so the average baseline uncertainty is in the range 0.3 to 0.5 nT.

Independent validation of the offsets determined in this way is provided by rolling the spacecraft in a slow spin about the Earth-Sun line to determine the baselines in the X–Y plane. Tests of this maneuver were performed on 1997-262 and 1999-198. The spacecraft roll rate used in the 1997-262 test was too high and produced excessive magnetic interference from currents drawn by the momentum wheels. The 1999-198 (mission day 1245 in Fig. 10) roll used a lower roll rate and provided useful data giving residual offsets (relative to those of Fig. 10) in X and Y of −0.10 ± 0.05 nT and 0.20 ± 0.04 nT, respectively. The solar wind field in the X–Y spacecraft plane was 2.9 nT during the roll test. The roll test is consistent with the baseline uncertainties of 0.3 to 0.5 nT estimated above.

VI. DISCUSSION

As a result of the prelaunch and in-flight calibration activities the NEAR Magnetic Fields Experiment yields measurements accurate to ~1 nT, exceeding the design goal of 5 nT. This success indicates the probable limits achievable for body mounted magnetometers on deep space probes. It is important to bear in mind that the requirements for the NEAR magnetic field experiment were very modest. Not only is the required precision level coarse relative to typical interplanetary measurements,
The NEAR magnetic fields experiment required flight calibration and analysis of crust data to ensure valid science data of the accuracy required to achieve the science objectives. There were two fundamental reasons for this. First, the MAG3 sensor is mounted to the body of the spacecraft rather than on a boom so that spacecraft magnetic fields are a much greater concern for MAG than for the Vesta. Second, the NEAR spacecraft was not characterized for magnetic field signatures in a magnetics facility, so it was impossible to measure the spacecraft fixed- and variable-source magnetic fields before launch to the desired accuracy. Thus, prelaunch activities focused on minimizing spacecraft field to the extent possible by advising in-spacecraft design and performing calibrations and texts as possible to identify known sources of magnetic fields including the propulsion valves, solar arrays, and the power terminal board. Additional sources of magnetic contamination were discovered after launch including the MAG sensor heater, analog shunts, momentum wheels, solar array harness, and control electronics, and rapidly varying loads such as the NEAR laser. Identifying these sources and modeling their effects was made possible only by collecting data over prolonged periods during cruise and performing extensive analysis on the ground. The total contamination field includes a fixed field of 190 nT together with the net dynamic field, which varies from 20 to 100 nT. The spacecraft engineering housekeeping data are used to calculate the dynamic spacecraft field and subtract it in ground processing and are therefore an integral element of the science data. Special changes in spacecraft and MAG flight mode were made after launch to ensure time synchronization between the spacecraft engineering sampling and MAG readings during periods of coarse MAG sampling. The combination of prelaunch and in-flight calibration activities enabled the NEAR Magnetic Fields Experiment to achieve a low level and baseline uncertainty from the NEAR spacecraft of 1–2 nT, exceeding the design goal of 5 nT.

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