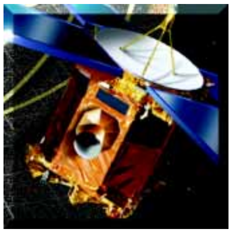


The NEAR Magnetic Field Instrument

David A. Lohr, Lawrence J. Zanetti, Brian J. Anderson, Thomas A. Potemra, and Mario H. Acuña

The primary objective of the Magnetic Field Instrument on the Near Earth Asteroid Rendezvous (NEAR) spacecraft is to search for and characterize the magnetic field of the asteroid Eros to better understand the origin and evolution of this planetary body. The instrument consists of a three-axis fluxgate magnetometer with a sensor mounted on the high-gain antenna feed structure of the NEAR spacecraft. It is currently operating in space and is providing measurements of the interplanetary magnetic field with a resolution of better than 1 nT. The Magnetic Field Instrument is capable of detecting a surface field at Eros of 10 nT at the 35-km altitude that will be the eventual orbit of NEAR.
(Keywords: Asteroids, Eros, Magnetic fields, NEAR, Space physics.)

INTRODUCTION AND OBJECTIVES

The magnetic field measurements of the Near Earth Asteroid Rendezvous (NEAR) spacecraft play a fundamental role in the remote sensing of the composition and internal structure of the asteroid Eros and are relevant to understanding the early processes of formation, evolution, and differentiation of planetary bodies. If Eros was originally part of a parent body with an internal magnetic dynamo, such as the Earth, Mars, or Mercury, then it should have a coherent natural remnant magnetization, possibly characterized by a simple dipole field. If it possesses a strong magnetic field, then it will interact with the solar wind plasma in a profound manner and produce a wealth of magnetohydrodynamic phenomena.[1] If Eros is a "rubble pile" composed of smaller magnetized pieces, its magnetic field will be much more complicated. If it is a permeable body but without significant permanent magnetization, there will be an induced magnetic field in it that bears a definite relationship to the solar magnetic field, called the interplanetary magnetic field, both in direction and magnitude. The long-term magnetic field measurements that will be conducted by NEAR will allow us to sort out these various cases and will contribute to the understanding of the composition, formation, and evolution of Eros.

Magnetic field disturbances associated with the asteroid Gaspra were detected during the flyby of the Galileo spacecraft.[2] Kivelson et al.[2] extrapolated magnetic field measurements obtained at the closest approach of Galileo at 1600 km or 230 Gaspra radii, and estimated the surface field to be between 4000 and 140,000 nT (the surface field of the Earth is between

30,000 and 50,000 nT). If Eros has a similar magnetic field, it would produce a magnetic field at a 35-km altitude (approximately the mean Eros radius) of 500 to 18,000 nT, readily detectable with the NEAR Magnetic Field Instrument (MFI).* If Eros possesses such a large magnetic field, it would interact with the solar wind to produce a complicated magnetosphere characterized by various plasma boundaries. Special bandpassed channels are included in the NEAR MFI, which are based on the identification of plasma boundaries in the Earth's magnetosphere,[3–5] to study the possible Eros plasma boundaries.

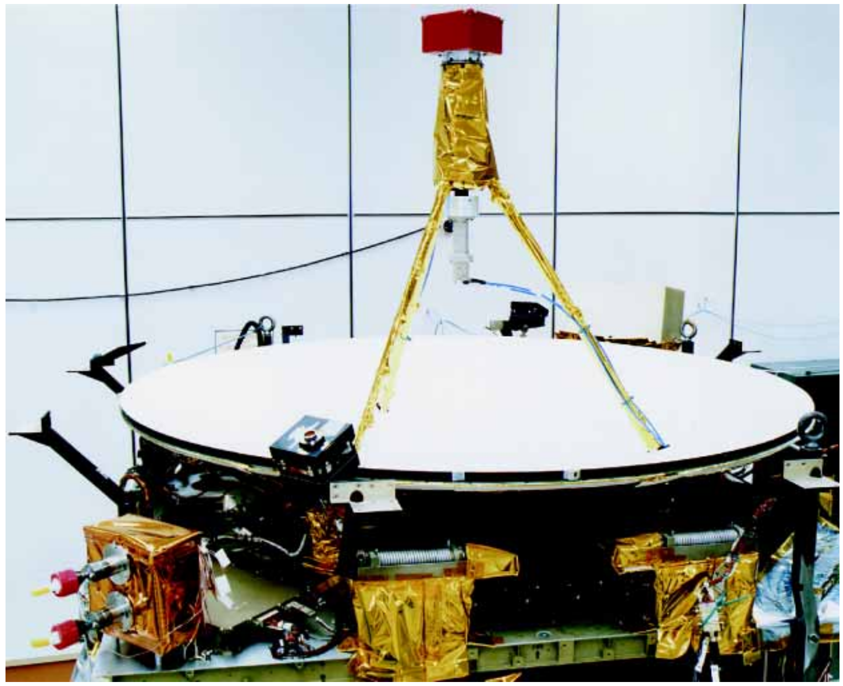


Figure 1. The NEAR Magnetic Field Instrument. The sensor for the instrument is mounted inside the tube covered with gold foil, just below the red box at the top of the antenna feed for NEAR's telemetry antenna.

INSTRUMENT DESCRIPTION

The NEAR MFI consists of a three-axis fluxgate magnetometer with the sensor mounted on the high-gain antenna feed structure as shown in Fig. 1. It has eight automatically switchable ranges: ±4, ±16, ±64, ±256, . . . , ±65,536 nT. The sensor coils are sampled internally at 20 Hz, and the analog-to-digital converter has 20-bit resolution. The three-axis vector data are transmitted to the ground with 16-bit resolution, and the additional bits are used onboard for the AC bandpassed channel. For example, the resolution of measurements in the ±1024-nT range is 31 pT and in the ±256-nT range is 8 pT. Various parameters such as filtering coefficients, frequency ranges, offsets, and calibration factors are included in the onboard processing and can be uploaded during flight.

The heritage of the NEAR fluxgate magnetometer includes NASA[6,7] and APL[8] instruments aboard Voyager, Freja, Wind, Mars Observer, Geotail, Giotto, Magsat, Viking, Pioneer, AMPTE/CCE (Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer), UARS (Upper Atmosphere Research Satellite), and DMSP/F7 (Defense Meteorological Satellite Program). The magnetometer sensor mounting on the high-gain antenna feed structure is similar to that used on the successful Giotto mission to Comet Halley and has proven to be satisfactory in terms of reducing spacecraft magnetic noise.

The MFI shares a digital processing unit (DPU), located on the lower deck, with the Near-Infrared Spectrometer (NIS). This NIS/MFI data processing unit collects digital data from the magnetic sensor electronics, processes and stores the data from the instruments, controls the experiments, and transmits the data to the spacecraft for transmission to Earth. The DPU contains a general-purpose processor, a special-purpose 1553 processor, memory, and interfaces to complete the magnetometer system. The program for controlling the processor is contained in electrically erasable programmable read-only memory (EEPROM), which is copied to random access memory (RAM) for execution. The use of EEPROM permits changes in the programming after launch should the need arise from unforeseen requirements. The DPU also contains a specialized processor to handle the interface with the 1553 bus used to transmit the data to the spacecraft. This interface is bidirectional and is used to receive commands sent to the instrument.

The DPU receives vector magnetic field samples, 20 bits per axis, from the magnetometer electronics at 20 Hz. It filters and subsamples this 20-Hz data to generate the following output rates per second: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 5, 10, or 20. The nominal data rate is 1 vector sample/s. The DPU output data include the range setting for each vector sample so that the absolute magnetic field strengths may be determined.

In addition to the vector field values, the DPU also computes a 9-bit AC amplitude value for each sample. It computes this value by filtering the *x*-, *y*-, or *z*-axis

* Other articles in this issue of the *Digest* refer to the Magnetometer (MAG) rather than to the Magnetic Field Instrument (MFI) when discussing the major instruments aboard NEAR. In this article, we have chosen to refer to the instrument as the MFI, of which the MAG is the major component.

field values (after noise rejection) with a 1–10 Hz passband digital filter. To produce an output value to include with each subsampled magnetic field vector, the DPU computes the root-mean-square amplitude of this filtered signal over the subsampling interval. It then codes the resulting value into a 9-bit data item with a pseudo-logarithmic representation. The DPU also generates the magnetometer's real-time housekeeping data.

The instrument includes a calibration circuit that can inject a known bias current into the front-end detector electronics, simulating a magnetic field offset of approximately one-half of full scale in each axis. The DPU controls this calibration circuit by means of a command.

The MFI was calibrated at NASA's 40-ft magnetics facility. The objective of this calibration was to test the various ranges to as sensitive a level as possible. The most important aspect of this test was to evaluate the linearity, orthogonality, and cross talk of the sensor block for each axis and for each range. The linearity was calibrated down to ±256 nT, at which point the NASA magnetics facility was at a comparable digitization noise level. The linearity procedure was continued at APL by placing the sensor in concentric Permalloy shield cans to exclude the ambient field (below 1 nT) as well as external noise. The linearity tests in the shield cans were performed with a finely varied, calibrated current source exciting a solenoid surrounding the sensor.

MAGNETIC CLEANLINESS PROGRAM

It is crucial that noise magnetic fields produced by spacecraft systems are identified and characterized so that they can be modeled and removed from the MFI observations. In an effort to reduce spacecraft magnetic noise, internal wiring loops on the spacecraft terminal connection board for the heater circuits were individually compensated with current reverse loops. A single-point grounding scheme was implemented to reduce noise from unintended ground loops. Magnetic fields created by commanded, traceable subsystem loads were modeled and removed using housekeeping monitors of subsystem currents. Thermal-vacuum testing at NASA was performed with small "Helmholtz" coils rigged around the high-gain antenna tube and driven by constant current supplies. These techniques reduced the spacecraft magnetic noise at the sensor to less than 1 nT so that the MFI could be calibrated in the test chamber.

Interference from the solar arrays was minimized by taking advantage of the symmetry of the four panels that surround the center-axis location of the magnetometer sensor on the high-gain antenna feed structure. The MFI sensors are approximately 1.5 m from the centers of the solar panels. The shunting sequences were balanced from one side to the other to maintain the symmetry. The solar cell strings were not individually backwired, but levels below 1 nT were determined from this balanced cancellation.

Static magnetic fields were individually checked, and it was determined that most subsystems would not interfere with the measurement objectives. The major contributors to residual magnetization levels are the latch valves (which include a total of nine permanent magnets) in the propulsion system. Approximately 800–900 nT of static field from the NEAR propulsion system latch valves was eliminated with the careful placement of compensation magnets on the spacecraft.

FIRST NEAR MAGNETOMETER DATA

About three months of 1-min resolution magnetic field data have been acquired to date by NEAR, centered around the Sun–Earth heliocentric longitude location of NEAR (1.2 to 1.7 AU) from 27 April to 8 August 1996. Figure 2 shows magnetic field data obtained by NEAR on 27 and 28 April 1996, when the spacecraft was approximately 1.25 AU from the Sun.

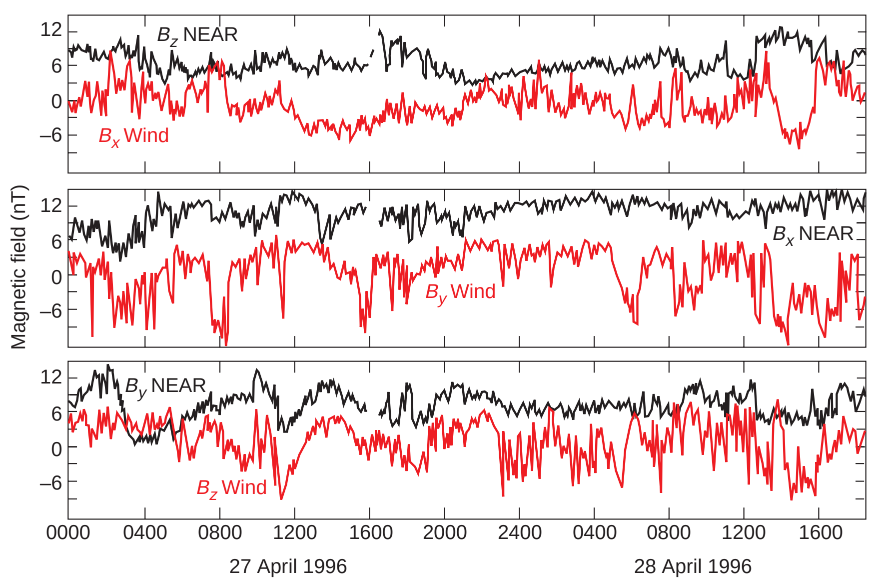


Figure 2. Comparison of early magnetic field data acquired by NEAR with data from the NASA Wind spacecraft. The Wind data are delayed by 18.4 h to provide the best fit between the data sets. (Wind data are courtesy of Ronald Lepping, Wind Principal Investigator.)

Also shown in this figure are the magnetic field data acquired with the NASA Wind spacecraft located near the Earth. The Wind magnetic field data are shown in geocentric solar ecliptic (GSE) coordinates with *x* radially away from the Sun, *z* upward (northward) at the Earth, and *y* completing the orthogonal system. The Wind observations are delayed by about 18.4 h in Fig. 2 to compensate for the 0.25 AU separation of NEAR and to provide the best fit of the two data sets. The top panel shows the magnetic field component measured by NEAR parallel to the spacecraft's spin axis directed toward the Sun. The magnetic field component oriented in the same direction measured with the Wind spacecraft is shown directly below the NEAR data. The magnetic field components measured in the plane perpendicular to the Sun's direction are shown in the middle and bottom panels of Fig. 2.

At this early date in the processing effort of the NEAR data, it has not been possible to accurately transform the measured components into GSE coordinates, so the NEAR data shown in spacecraft coordinates in Fig. 2 provide only an approximate comparison of the measured magnetic field components between the two spacecraft. The good correlation between the delayed Wind and NEAR measurements in the bottom panel suggests that the *y* component of the NEAR data may be close to the GSE *z* component measured by Wind. There are some features in the Wind and NEAR data that are well correlated in the middle panel, whereas the data in the top panel show the poorest correlation. The delay of 18.4 h over the 0.25 AU (3.8×10^7 km) provides a solar wind speed of 566 km/s, which is a reasonable value. Consequently, the time delay between the observations is appropriate to obtain the best correlation between the two data sets for this first try. When the processing of these data is more advanced to the state when the NEAR data can be rotated into the proper coordinate system, the comparison of these data sets will provide a very powerful tool for exploring the propagation of the interplanetary magnetic field throughout the solar system.

Figure 3 is a power spectrum of 10-min data from the MFI *x*-axis sensor for the 6-day period, 18–23 June 1996. The spectrum can be characterized by a decreasing power law function with possible event peaks at about 0.02 and 0.05 mHz (corresponding to 14- and 5-h periods). The higher frequency part (above 0.05 mHz) of the MFI spectrum in Fig. 3 shows a frequency dependence of $f^{-(5/3)}$, which is the representative spectrum for turbulence,[9] and which is typically found for magnetic field fluctuations in the solar wind.[10] This finding provides further evidence that the magnetic field fluctuations measured by NEAR are caused by the interplanetary environment and not by the spacecraft itself.

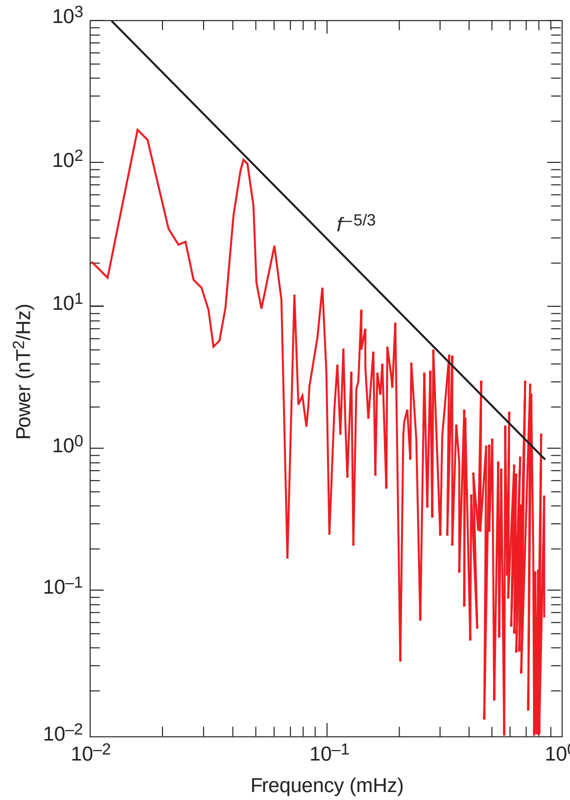


Figure 3. Power spectrum of 10-min data from the *x*-axis sensor of the Magnetic Field Instrument for the 6-day period, 18–23 June 1996. The higher frequency part of the spectrum shows a frequency dependence of $f^{-(5/3)}$, which is the representative spectrum for turbulence, and which is typically found for magnetic field fluctuations in the solar wind.

The data at http://sd-www.jhuapl.edu/NEAR/SDC/SDC_HDF/MAG will be archived by year and day of year. The Hierarchical Data Format files organization is based on the experiment data record defined in the instrument DPU requirements.[11,12] Each record contains time tag information, housekeeping values, and sets of 44 samples of magnetic field values, AC field values, and noise flags.

SUMMARY

The NEAR spacecraft has been launched successfully, and the MFI has demonstrated that it can obtain measurements in the interplanetary medium with a sensitivity of about 1 nT. This sensitivity has been achieved by a comprehensive magnetic cleanliness program during the development of the spacecraft and the development of a successful predictive model of spacecraft noise. Even with the uncertainties associated with early processing, fluctuations in the interplanetary magnetic field measured by NEAR show features that are correlated with fluctuations measured by the Wind spacecraft when reasonable time delays in the solar wind speed are included in the analysis. The frequency spectrum of the NEAR magnetic field fluctuations is close to what has been previously measured in the interplanetary medium, strengthening the validity of the NEAR measurements. With the 1-nT sensitivity, the MFI will be able to detect a 10-nT surface field for Eros at a distance of 1 Eros radius from its surface. The surface field of Gaspra was estimated from the Galileo flyby to range between 4000 and 140,000 nT.[2] If the magnetic field of Eros is similar in strength to that estimated for Gaspra, then the NEAR mission will provide the first opportunity to explore a complicated miniature planetary magnetosphere. The MFI was developed, tested, and calibrated with approximately 4% of the resources allotted to the entire NEAR instrument suite. It is a significant example of the better, faster, cheaper paradigm.

REFERENCES

[1]Baumgartel, K., Sauer, K., and Bogdanov, A., "A Magnetohydrodynamic Model of Solar Wind Interaction with Asteroid Gaspra," *Science* 263, 653–655 (1994).

[2]Kivelson, M. G., Bargatze, L. F., Khurana, K. K., Southwood, D. J., Walker, R. J., and Coleman, P. J., Jr., "Magnetic Field Signatures near Galileo's Closest Approach to Gaspra," *Science* 271, 331–334 (1993).

[3]Anderson, B. J., Takahashi, K., Erlandson, R. E., and Zanetti, L. J., "Pc1 Pulsations Observed by AMPTE/CCE in the Earth's Outer Magnetosphere," *Geophys. Res. Lett.* 17, 1853 (1990).

[4]Anderson, B. J., Potemra, T. A., Bythrow, P. F., Zanetti, L. J., Holland, D. B., and Winningham, J. D., "Auroral Currents During the Magnetic Storm of November 8 and 9, 1991: Observations from the Upper Atmosphere Research Satellite Particle Environment Monitor," *Geophys. Res. Lett.* 20, 1327 (1993).

[5]Zanetti, L. J., Potemra, T. A., and Anderson, B. J., "Boundary Determinations Based on Low Frequency Magnetic Field Measurements," Proc. Int. Conf. on Comparative Planetology, in *Earth, Moon and Planets* 67, 175–178 (1995).

[6]Acuña, M. H., "Fluxgate Magnetometers for Outer Planets Exploration," *IEEE Trans. Magnetics* Mag-10, 519 (1974).

[7]Acuña, M. H., Connerney, J. E. P., Wasilewski, P., Lin, R. P., Anderson, K. A., et al., "Mars Observer Magnetic Fields Investigation," *J. Geophys. Res.* 97, 7781–7798 (1992).

[8]Zanetti, L., Potemra, T., Erlandson, R., Bythrow, P., Anderson, B., et al., "Magnetic Field Experiment for the Freja Satellite," *Space Sci. Rev.* 70, 465–482 (1994).

[9]Kolmogorov, A. N., "The Local Structure of Turbulence in Incompressible Viscous Fluids for Very High Reynolds Numbers." *Dokl. Akad. Nauk SSSR*, 30, 301 (1941).

[10]Ghosh, S., Siregar, E., Roberts, D. A., and Goldstein, M. L., "Simulation of High-Frequency Solar Wind Spectra using Hall Magnetohydrodynamics," *J. Geophys. Res.* 101, 2493–2504 (1996).

[11]Hayes, J. R., *NEAR Instrument DPU Common Software Requirements Specification*, Report No. 7358-9001, JHU/APL, Laurel, MD (1995).

[12]Hayes, J. R., *NEAR Infrared Spectrograph/Magnetometer (NIS/MFI) DPU Software Requirements Specification*, Report No. 7357-9001 JHU/APL, Laurel, MD (1995).

ACKNOWLEDGMENTS: We are grateful for the contributions of the NEAR engineering teams, particularly given the schedule of 27 months from project go-ahead to launch in February 1996. We thank the NASA/Discovery management of NASA Headquarters for support. We acknowledge the dedicated Mission Operations Team for the data already delivered and those to come. This work was supported under contract N00039-95-C-0002 with the U.S. Navy. The UCLA magnetics group is acknowledged, in particular, Robert Snare, for supporting the Aerojet propulsion magnetics testing.

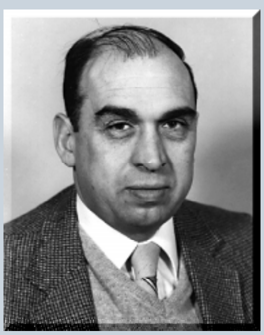
THE AUTHORS

DAVID A. LOHR is a member of APL's Principal Professional Staff. He received a B.S. in physics from the University of Maryland in 1974. Before coming to APL in 1988, he worked at Northrop DSS and Litton Amecom. He was the lead engineer for the Freja Magnetic Field Experiment and lead engineer for the NEAR magnetometer experiment. He is currently the lead engineer for the ACE EPAM particle experiment. Mr. Lohr also participated in the JADE and Flare Genesis programs. His e-mail address is david.lohr@jhuapl.edu.

LAWRENCE J. ZANETTI received a B.A. in physics from the University of Colorado in 1974 and an M.S. and Ph.D. in physics from the University of New Hampshire 1976 and 1978, respectively. He joined APL in 1978 and is a Principal Staff Physicist and Supervisor of the Magnetic Fields Section of the Space Physics Group. Dr. Zanetti was the principal investigator for the Freja Magnetic Field Experiment and instrument scientist for the NEAR magnetometer experiment. He is presently on a special assignment at NASA Headquarters as Program Scientist for magnetospheric missions. His e-mail address is lzanetti@hq.nasa.gov.

BRIAN J. ANDERSON received a B.A. in physics, mathematics, and religion from Augsburg College in 1982 and a Ph.D. in physics from the University of Minnesota in 1987. He was Assistant Professor of Physics at Augsburg College before joining APL in 1988, where he is a member of the Senior Professional Staff. Dr. Anderson is the principal investigator for several NASA and National Science Foundation research grant projects. His e-mail address is brian.anderson@jhuapl.edu.

THOMAS A. POTEMRA received a Ph.D. from Stanford University in 1966 and joined APL in 1965, where he supervises the Space Physics Group. During 1985-86, he worked on special assignment as a Senior Policy Analyst in the Office of Science and Technology Policy, Executive Office of the President. Dr. Potemra is the principal investigator for numerous satellite magnetic field experiments and serves on several advisory committees of NASA and the National Research Council. His e-mail address is thomas.potemra@jhuapl.edu.



MARIO H. ACUÑA received an M.S.E.E. from the University of Tucuman in 1967 and a Ph.D. from the Catholic University of America in 1974. He joined the NASA Goddard Space Flight Center in 1969, where his research interests have centered around instrumentation for geophysical and space research and studies of magnetic fields in space and magnetospheres. Dr. Acuña has been honored by NASA with numerous prestigious awards including the Exceptional Service Medal in recognition of his contributions to magnetometry and space research. He is the principal or co-investigator for magnetic field experiments on many space missions and is the science team leader for the NEAR Magnetic Field Instrument. His e-mail address is mario.acuna@gsfc.nasa.gov.