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MAGNETIC TEST PERFORMANCE CAPABILITIES
AT THE GODDARD SPACE FLIGHT CENTER
AS APPLIED TO THE GLOBAL GEOSPACE SCIENCE INITIATIVE

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ABSTRACT

Goddard Space Flight Center's (GSFC) Spacecraft Magnetic Test Facility (SMTF) is a historic test facility that has set the standard for all subsequent magnetic test facilities. The SMTF was constructed in the early 1960's for the purpose of simulating geomagnetic and interplanetary magnetic fields. Additionally, the facility provides the capability for measuring spacecraft generated magnetic fields as well as calibrating magnetic attitude control systems and science magnetometers. The SMTF was designed for large, spacecraft level tests and is currently the second largest spherical coil system in the world.

The SMTF is a three-axis Braunbek system composed of four coils on each of three orthogonal axes. The largest coils are 12.7 meters (41.6 feet) in diameter. The three-axis Braunbek configuration provides a highly uniform cancellation of the geomagnetic field over the central 1.8 meter (6 foot) diameter primary test volume. Cancellation of the local geomagnetic field is to within ±0.2 nanoTesla with a uniformity of up to 0.001% within the 1.8 meter (6 foot) diameter primary test volume. Artificial magnetic field vectors from 0-60,000 nanoTesla can be generated along any axis with a 0.1 nanoTesla resolution. Oscillating or rotating field vectors can also be produced about any axis with a frequency of up to 100 radians/second.

Since becoming fully operational in July of 1967, the SMTF has been the site of numerous spacecraft magnetics tests. Spacecraft tested at the SMTF include : the Solar Maximum Mission (SMM), Magsat, LANDSAT-D, the Fast Auroral Snapshot (FAST) Explorer and the Sub-millimeter-Wave-Astronomy Satellite (SWAS) among others. This paper describes the methodology and sequencing used for the Global Geospace Science (GGS) initiative magnetic testing program in the Goddard Space Flight Center's SMTF. The GGS initiative provides an exemplary model of a strict and comprehensive magnetic control program.

INTRODUCTION

The GGS Initiative is part of the International Solar Terrestrial Physics (ISTP) science initiative. The GGS Initiative consists of the two NASA managed spacecraft, WIND and POLAR, and the Japanese Institute of Space and Astronautical Science's (ISAS) Geotail satellite. The purpose of the GGS mission is to study the physical mechanisms and various regions controlling the transport of mass, energy and momentum between the Sun and Earth in geospace.

Due to the extreme sensitivity of many of the science instruments onboard WIND and POLAR to magnetic disturbances, the GGS project imposed highly stringent magnetic test limits on both spacecraft at the instrument level. Table 1 shows the GGS instrument level magnetic test limits. This approach relies on the minimization of contributions from individual sources at the component and instrument levels, coupled with the net vectorial cancellation of residual fields at the fully integrated spacecraft level, to produce a magnetically ultra-clean spacecraft.

The severity of the GGS magnetic test limits was evidenced when only three of the boxes tested for WIND and POLAR were able to meet the GGS test specifications. None of the fully assembled instruments on WIND or POLAR tested at GSFC were able to meet the magnetic test limits set forth in table 1 in its entirety. On the other hand, the majority of instruments flown on the POLAR spacecraft were able to meet their generally more lenient POLAR magnetic allocations.

Magnetic control specifications on the POLAR spacecraft were handled in a different manner than those for the WIND spacecraft. A set of magnetic allocations was setup for each instrument on POLAR. Each instrument was still to attempt to meet the GGS test limits, but levels within the given allocation were deemed acceptable. Where the GGS magnetic test limits were generated from limits formerly established on the International Sun-Earth Explorer (ISEE) spacecraft, the POLAR magnetic allocations were generated by taking into account the position of each instrument on the spacecraft with respect to the position of the science magnetometer probe. Using an inverse cubed fall-off rate, maximum field levels at 1.0 meter and 0.5 meters from each instrument were calculated that would result in levels below the science magnetometer's sensitivity at the magnetometer probe . Magnetic allocations for instruments flying on the POLAR spacecraft are given in table 2.

MAGNETIC TESTING

Purpose

Magnetic testing furnishes a means for advance mitigation of unwanted orbital torques produced by the interaction of a spacecraft's magnetic moment with ambient magnetic fields. Also, as in the GGS case, magnetic testing provides a mechanism for the characterization and minimization of magnetic fields generated by a spacecraft when flying instrumentation sensitive to magnetic disturbances, such as magnetometers and particle detectors.

The effect of a spacecraft magnetic disturbance torque was first observed on the Vanguard I satellite which was launched in late 1958. Interaction of the geomagnetic field with eddy currents generated in the spacecraft's rotating outer shell caused Vanguard I to be continuously despun. As a result the satellite's spin rate was reduced from an initial value of 2.7 revolutions/second at launch, to less than 0.2 revolutions/second two years later. Reference 1 gives a detailed analysis of this effect.

Magnetic disturbance torques can be generated by one of three mechanisms. The spacecraft's permanent magnetic dipole component can create perturbations as it attempts to align itself with the ambient magnetic field. Materials with large permeability values can generate torques due to hysteresis effects. Finally, as in the case of Vanguard I, eddy currents induced in conductive materials by changing flux levels on orbit can create eddy current damping torques.

The general equation governing magnetic disturbance torques is very straightforward :

$$\bar{T}_{S/C} = \bar{M}_{S/C} \times \bar{B} \quad (1)$$

where

$\bar{T}_{S/C} =$ spacecraft magnetic disturbance torque vector in dyne-cm

$\bar{M}_{S/C} =$ spacecraft magnetic dipole moment vector in gauss-cm^3

$\bar{B} =$ ambient magnetic induction vector in gauss

A detailed explanation of the application of this equation to the cases of hysteresis and eddy current damping torques can be found in reference 2.

The detriment posed by spacecraft magnetic torques is the additional load imposed on the attitude control system. Averaged over numerous orbits the energy loss due to correction of magnetic torques can become very significant. With power consumption always a major concern onboard spacecraft, the need for minimizing unnecessary magnetic torques is obvious.

Present day state-of-the-art magnetometers exhibit sensitivities of 0.1 nanoTeslas or better. Controlling the magnetic properties of large spacecraft such as WIND and POLAR in order to minimize biases at the magnetometer probe can therefor become a major concern. This problem is distinct from magnetic disturbance torque considerations in that it focuses on the field at a particular location on the spacecraft rather than emphasizing the equivalent dipole moment of the entire spacecraft. However, enacting procedures for maintaining magnetic cleanliness in a spacecraft also generally result in a minimization of the spacecraft's dipole moment.

Data Acquisition and Analysis

Data acquisition at the SMTF is achieved utilizing an array of four triaxial fluxgate magnetometers interfaced to a personal computer. During the tests of the GGS instruments at the SMTF a Hewlett Packard model HP86 computer and model 9427A data acquisition/control unit were used for data acquisition. The magnetometers used were developed and built by Doctor Mario Acuña of GSFC code 695. The test hardware has recently been updated with a Macintosh Quadra 800 computer and National Instruments SCXI signal conditioning box. The newer data acquisition system provides many enhanced capabilities not available in the older setup including : improved resolution; continuos sampling; higher data processing speed and increased options for data representation.

Since the early 1970's field mapping techniques have been used at the SMTF for determination of magnetic dipole moments. Figure 1 shows a typical test configuration. Data is obtained while rotating the test item past an array of triaxial magnetometer probes. All probes are located in a plane at radial distances D_n from the centroid of the test item. Data is taken in the near-field region in order to maintain a high signal-to-noise ratio. The algorithm used to analyze the data is based on the assumption that the test item's magnetic field can be modeled by the summation of its constituent multipole fields. The test data is inputted into a set of fourier equations to calculate an equivalent dipole moment. Detailed derivations of the equations used for the analysis are given in references 3 and 4. The general equations used to analyze the test data are :

$$\frac{1}{18}\sum_{\theta=0^\circ}^{360^\circ} B_{xn}(D_n,\theta)\cos\theta = \left(\frac{2A_{11}}{D_n^3} - \frac{6A_{31}}{D_n^5} + \frac{45A_{51}}{4D_n^7} - \frac{35A_{71}}{2D_n^9}\right) \quad (2)$$

$$\frac{1}{18}\sum_{\theta=0^\circ}^{360^\circ} B_{xn}(D_n,\theta)\sin\theta = \left(\frac{2B_{11}}{D_n^3} - \frac{6B_{31}}{D_n^5} + \frac{45B_{51}}{4D_n^7} - \frac{35B_{71}}{2D_n^9}\right) \quad (3)$$

$$\frac{1}{18}\sum_{\theta=0^\circ}^{360^\circ} B_{yn}(D_n,\theta)\cos\theta = -\left(\frac{B_{11}}{D_n^3} - \frac{3B_{31}}{2D_n^5} + \frac{15B_{51}}{8D_n^7} - \frac{35B_{71}}{16D_n^9}\right) \quad (4)$$

$$\frac{1}{18}\sum_{\theta=0^\circ}^{360^\circ} B_{yn}(D_n,\theta)\sin\theta = \left(\frac{A_{11}}{D_n^3} - \frac{3A_{31}}{2D_n^5} + \frac{15A_{51}}{8D_n^7} - \frac{35A_{71}}{16D_n^9}\right) \quad (5)$$

$$\frac{1}{36}\sum_{\theta=0^\circ}^{360^\circ} B_{zn}(D_n,\theta) = -\left(\frac{A_{10}}{D_n^3} - \frac{3A_{30}}{2D_n^5} + \frac{15A_{50}}{8D_n^7} - \frac{35A_{70}}{16D_n^9}\right) \quad (6)$$

where :

n	=	magnetometer number (1 to 4)
A_{11}	=	X axis dipole moment coefficient
B_{11}	=	Y axis dipole moment coefficient
A_{10}	=	Z axis dipole moment coefficient
A_{31} A_{51} A_{71}		
B_{31} B_{51} B_{71}	=	multipole moment coefficients
A_{30} A_{50} A_{70}		
B_{xn}, B_{yn}, B_{zn}	=	X,Y and Z components of magnetic field at probe n
D_n	=	magnetometer distance
θ	=	rotation angle

Test Sequence

A complete magnetic test sequence as implemented on WIND and POLAR consists of permanent magnetism, induced magnetism and stray field measurements as outlined below. Figure 2 shows a typical test data printout. Results from some of the tests run for instruments flying on the WIND spacecraft are summarized in figure 3.

Permanent Magnetism

The permanent magnetism test sequence is comprised of three distinct measurement conditions. Data for all three test conditions is acquired in an identical manner. The test item is rotated about it's vertical axis in the center of the facility coils while an array of magnetometers collects the magnetic field data. See figure 1 for details. The distinction between measurements comes from the magnetic state of the test item during each test.

Initial perm measurements characterize the test item "as received", i.e., before exposing the test item to any influences that might alter the magnetic state of the item. The "as received" magnetic state of the test item indicates:

(a) A possible level of perm that the newly assembled item might be expected to maintain.

(b) A relevant magnitude of field that can be used to determine the effectiveness of the deperm treatment.

(c) The stability of the items perm field by initiating a record of its magnetic history.

Post exposure (perm) measurements determine the magnetic state of the test item after exposure to a 15 Gauss steady state field along one of the horizontal axes. Post exposure measurements give an indication of the extent of soft magnetic materials present on the test item, as well as a possible level of perming the test item may attain during the environmental test sequence.

Post deperm measurements determine the magnetic state of the test item after exposure to a slowly diminishing 30 Gauss AC field. The deperm treatment is conducted inside the zero-field environment. The deperm must be conducted in zero-field in order to reach the lowest remanence level possible. Deperm treatments performed in the geomagnetic field can result in a net increase in the test item's magnetic field. When performed properly, post deperm measurements represent the lowest level of remanence field for the test item.

If following the deperm treatment the test item still exceeds it's test specification, then magnetic compensation can be applied as a corrective measure. Magnetic compensation involves affixing a small bar magnet to the test item to reduce its dipole moment. The compensation magnet is oriented on the test item such that its dipole moment is in opposition to the test item's dipole moment. This results in a net cancellation between the fields produced by the two moments in the far-field region.

Induced Magnetism

Induced field measurements attempt to measure the presence of any soft ferromagnetic materials present within the test item. Induced moments can be generated by the interaction of soft ferromagnetic materials onboard a spacecraft with ambient magnetic fields. If present, induced moments can create hysteresis damping torques on the spacecraft as discussed previously.

For the induced field test, a field vector is generated inside the SMTF coils to simulate the magnetic field environment the test item will experience while on orbit. A 0.3 gauss field is typically used to simulate low earth orbit. The test item is placed inside the magnetic field and data is acquired in a similar manner to that of the permanent magnetism test. The magnetometers used in the SMTF have the capability to internally bias out fields of up to 1.0 gauss. This capability enables the magnetometers to maintain the sensitivity needed to discern the induced fields in the much larger artificial field. Test results are then compared to the post deperm results with any differences attributable to induced moments.

Induced magnetic moments are not as easily corrected as are those due to permanent magnetism. The only means for correcting induced magnetic moments is replacement of the offending material. Neither deperming or compensation magnets are effective cures for this problem. Since moments generated by soft materials are variable with ambient field strength and direction, a fixed permanent magnet can not effectively compensate for an induced moment which varies continuously with orbital position.

Stray Field Magnetism

Stray field measurements are taken in order to characterize magnetic fields generated by circulating currents within the test item. Current loops of large cross sectional area and electric motors are the most common causes of stray magnetic fields. Measurements are made of both static and dynamic magnetic fields. Dynamic measurements are conducted over a frequency range of 1 to 30 hertz.

Baseline measurements are made with the test item powered off. Successive measurements are taken as the test item is powered on and then switched to various operational modes. This process is performed separately for static and dynamic field measurements.

Static field measurements can be acquired by up to 4 triaxial magnetometers in any configuration desired. For dynamic fields only one single axis probe is used. Output from the test magnetometer is sent to either a Hewlett Packard model 3562A signal analyzer or strip chart recorder depending on the spectral resolution desired. Due to the long acquisition time required by the signal analyzer for frequencies below 1 hertz, measurements below 1 hertz are typically made using a strip chart recorder and a series of low and high pass filters.

Magnetometer Calibration

The SMTF provides a controllable, high precision magnetic field environment perfectly suited for calibrations of magnetic attitude control systems and science magnetometers. In addition to calibration data, sensor orthogonality and magnetometer frequency response can be measured. A laser or theodolite is used for mechanical alignment to facility coils. Facility calibration is achieved using a proton magnetometer.

Artificial magnetic fields can be generated with magnitudes of 0 to 60,000 nanoTesla along any facility axis. Maximum field resolution is 0.1 nanoTesla. Static field vectors are stable to $\pm$ 1.0 nanoTesla over a 48 hour period. Rotating fields are produced with magnitude uniform to within 2% or 0.5 nanoTesla, whichever is larger, over a 48 hour period. Rotation rates are variable from 0 to 100 radians/sec with an accuracy of 0.03 radians/sec or 3% of the value, whichever is larger. Resolution is 0.01 radians/sec or 1%, whichever is larger.

RESULTS

Measurements conducted on the WIND and POLAR spacecraft at the Martin Marietta facility in East Windsor, New Jersey indicate that the magnetic control programs implemented on both spacecraft were highly successful. Measurements of WIND at the spacecraft level indicated an estimated dipole moment of 2200 pole-cm. A moment of 2200 pole-cm magnitude generates a resultant field at the outer Magnetic Fields Investigation (MFI) sensor of 0.1 nanoTesla. This is within the project goal of 0.5 nanoTesla.

A similar test of the POLAR spacecraft measured a field strength at the outboard Magnetic Fields Experiment (MFE) probe of 0.3 nanoTesla. This is also within the project goal of 0.5 nanoTesla. Detailed reports of both tests are given in references 5 and 6.

Due to the enforcement of extremely rigorous instrument level test requirements, both spacecraft were able to meet their test specifications. The success of the magnetic control program on these two spacecraft illustrates the effectiveness of a stringent and comprehensive magnetic control program monitored in a properly equipped test facility.

REFERENCES

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2. Fischell, Robert E., " Magnetic Damping of the Angular Motions of Earth Satellites," ARS Journal, September, 1961

3. W.L. Eichhorn, "Magnetic Dipole Moment Determination by Near-Field Analysis," NASA Technical Note TN D-6685, July, 1972

4. W.L. Eichhorn, "A New Method for Determining the Magnetic Dipole Moment of a Spacecraft from Near-Field Data," NASA Document X-325-69-350, August, 1969

5. *GGS WIND Static Magnetics Test Report.* GGS-54-163, Martin Marietta Astro Space, September 1994.

6. *Performance Verification Report POLAR Static Magnetics Test.* GGS-95-134, Martin Marietta Astro Space, October 1995.

Table 1 GGS Magnetic Limits

Magnetization	Background Tesla (Gauss x 10E+04)	Maximum Magnetic Field in Nanotesla (gamma) 50 cm	Maximum Magnetic Field in Nanotesla (gamma) 100 cm	GEVS Ref. ¶
Initial Perm	0	6.40	0.8	2.5.4.1
Permanent				
Post 15E-04 Tesla Exposure (15 gauss)	0	24.00	3.00	2.5.4.2
Post 50E-04 Tesla Deperm (50 gauss)	0	1.60	0.2	2.5.4.3
Induced	3.00E-05	1.60	0.2	2.5.4.4
Stray Field				
DC	0	1.60	0.2	2.5.4.5
0.0001-0.1 Hz AC	0	0.40	0.05	2.5.4.5
0.1-1.0 Hz AC	0	0.40	0.05	2.5.4.5
1-3 Hz AC	0	0.30	0.04	2.5.4.5
3-10 Hz AC	0	0.22	0.03	2.5.4.5
10-30 Hz AC	0	0.07	0.01	2.5.4.5

Table 2. GGS POLAR Magnetic Allocations

ITEM	STATIC nT @ 1m	STATIC nT @ 50 cm	VARIABLE nT @ 1m peak-to-peak	VARIABLE nT @ 50 cm peak-to-peak
HYDRA				
DPU	1.0	8.0	0.2	1.6
Sensor A	1.6	12.8	0.2	1.6
Sensor B	1.6	12.8	0.2	1.6
MFE				
Electronics	1.4	11.2	0.2	1.6
Lanyard Boom	1.4	11.2	0.2	1.6
TIMAS	20.0	160.0	2.0	16.0
EFI				
Main Electronics	5.4	43.2	0.6	4.8
Motors	1.6	12.8	0.24	1.9
PSI				
Electronics	4.8	38.4	31.6	252.8
PWI				
Electronics	32.4	259.2	3.2	25.6
Search Coil	0.4	3.2	0.2	1.6
Loop Antenna	0.4	3.2	0.2	1.6
Lanyard Boom	1.4	11.2	0.2	1.6
CEPPAD				
DPU	5.6	44.8	0.6	4.8
IES DPU	2.4	19.2	0.2	1.6
VIS	TBD	TBD	24.6	196.8
PIXIE				
Camera	TBD	TBD	6.0	48.0
Electronics	TBD	TBD	5.6	44.8
UVI				
Sensor	TBD	TBD	10.0	80.0
Electronics	TBD	TBD	6.6	52.8
SEPS	TBD	TBD	7.4	59.2
CAMMICE				
HIT	1.6	12.8	0.2	1.6
MICS	1.6	12.8	0.2	1.6
TIDE	8.0	64.0	0.8	6.4

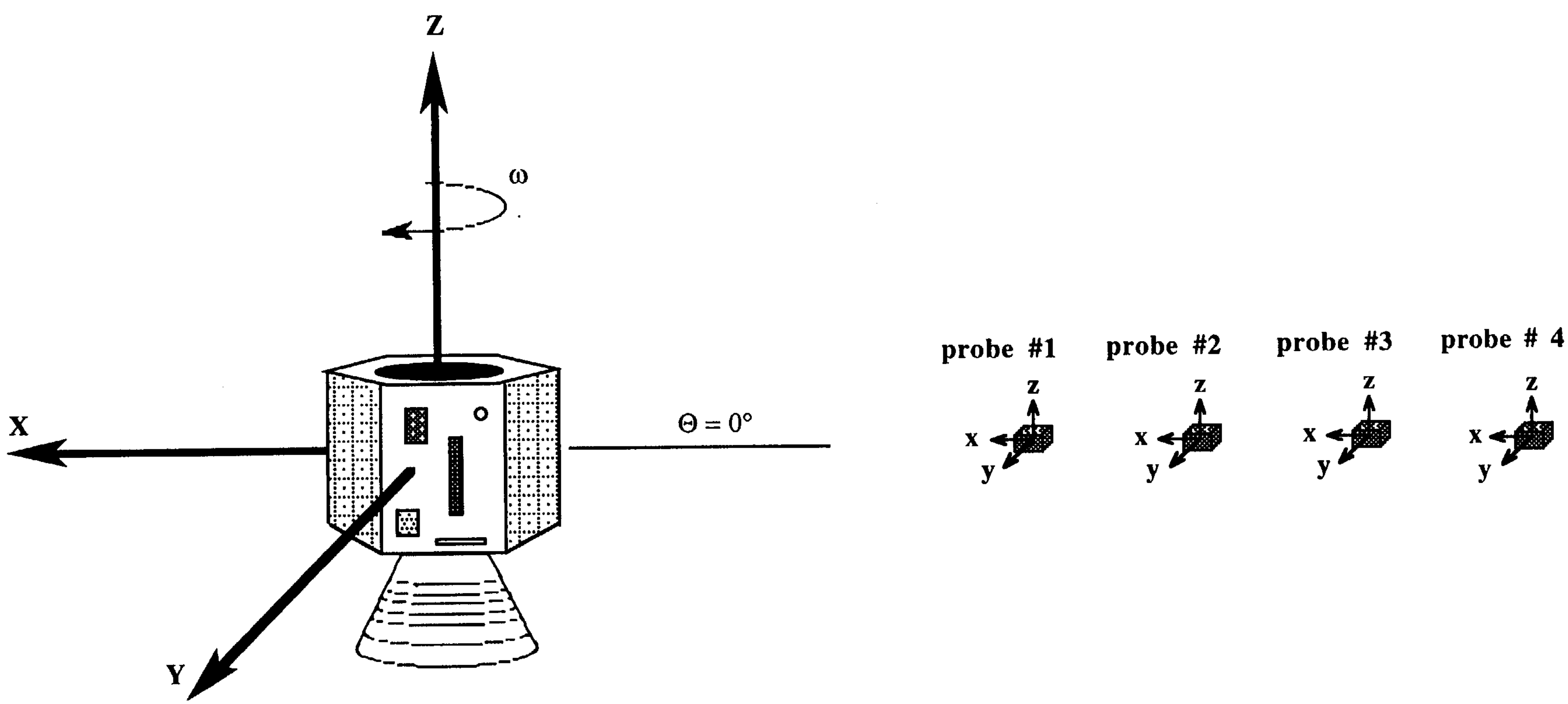

Figure 1. Spacecraft Orientation for Magnetic Testing

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ISTP/WIND MFI 02

MAGNETIZATION DISTANCE (M)

POST DEPERM 0.5 : 0.75 : 1.0

FIELD MAGNITUDE IN NANOTESLA

ANGLE	X1	Y1	Z1	X2	Y2	Z2	X3	Y3	Z3
DATA SCANS									
0	-0.4	0.6	0.4	0.1	0.8	0.0	-0.1	0.1	0.3
10	-0.5	0.5	0.4	0.0	0.8	0.1	-0.1	0.1	0.2
20	-0.4	0.6	0.4	0.1	0.8	0.0	-0.1	0.1	0.1
30	-0.4	0.5	0.2	0.1	0.7	0.0	-0.1	0.1	-0.1
40	-0.4	0.5	0.2	0.1	0.7	0.0	-0.1	0.1	-0.1
50	-0.3	0.5	0.2	0.1	0.7	0.0	-0.1	0.1	-0.2
60	-0.4	0.3	0.2	0.1	0.7	0.0	0.0	0.1	0.0
70	-0.4	0.3	0.2	0.1	0.7	0.0	0.0	0.1	0.0
80	-0.5	0.3	0.2	0.0	0.6	0.0	-0.1	0.1	0.1
90	-0.4	0.3	0.2	0.1	0.6	0.0	-0.1	0.1	0.1
100	-0.4	0.2	0.3	0.0	0.5	0.0	-0.1	0.1	0.1
110	-0.4	0.1	0.2	0.0	0.4	0.0	-0.1	0.1	0.1
120	-0.3	0.0	0.3	0.0	0.3	0.0	-0.1	0.1	0.0
130	-0.1	-0.1	0.3	-0.1	0.2	0.0	0.0	0.0	-0.1
140	0.0	-0.2	0.2	0.1	0.1	0.0	0.0	0.0	-0.1
150	0.2	-0.3	0.3	0.0	0.0	0.0	0.1	0.0	-0.1
160	0.5	-0.3	0.2	0.1	-0.1	0.0	0.1	0.0	0.0
170	0.6	-0.4	0.3	0.2	0.0	0.0	0.2	0.0	0.1
180	0.8	-0.2	0.4	0.1	0.1	0.0	0.2	0.0	0.2
190	0.9	-0.3	0.4	0.2	0.0	0.0	0.2	0.0	0.2
200	1.1	-0.2	0.4	0.1	-0.1	0.0	0.3	0.0	0.1
210	1.2	-0.1	0.4	0.1	0.0	0.0	0.2	0.0	0.1
220	1.1	0.0	0.8	0.1	-0.1	0.1	0.2	0.0	0.0
230	1.1	0.1	0.9	0.0	-0.1	0.1	0.0	0.0	0.0
240	1.0	0.1	1.0	0.1	0.0	0.1	0.1	0.0	0.1
250	0.9	0.1	1.0	0.1	0.0	0.1	0.1	0.0	0.1
260	0.9	0.0	1.1	0.2	0.0	0.2	0.3	0.0	0.2
270	0.9	0.2	1.1	0.1	0.0	0.2	0.3	0.0	0.3
280	0.7	0.0	1.2	0.2	-0.1	0.3	0.3	-0.1	0.2
290	0.6	0.0	1.2	-0.1	-0.3	0.2	0.3	-0.1	0.2
300	0.4	-0.1	1.2	-0.1	-0.2	0.2	0.2	-0.1	0.1
310	0.4	-0.3	1.1	0.0	-0.5	0.2	0.2	-0.1	0.0
320	0.3	-0.2	1.1	0.0	-0.4	0.2	0.2	-0.1	0.0
330	0.2	-0.3	0.9	0.0	-0.4	0.2	0.1	-0.2	0.0
340	0.2	-0.4	1.0	0.1	-0.5	0.2	0.2	-0.2	0.2
350	0.0	-0.5	0.9	0.1	-0.7	0.2	0.2	-0.2	0.3

DIPOLE MOMENTS IN POLE-CM

X	Y	Z	T
-0.2	-0.4	-0.7	0.8

Figure 2. Typical Magnetic Test Data Printout

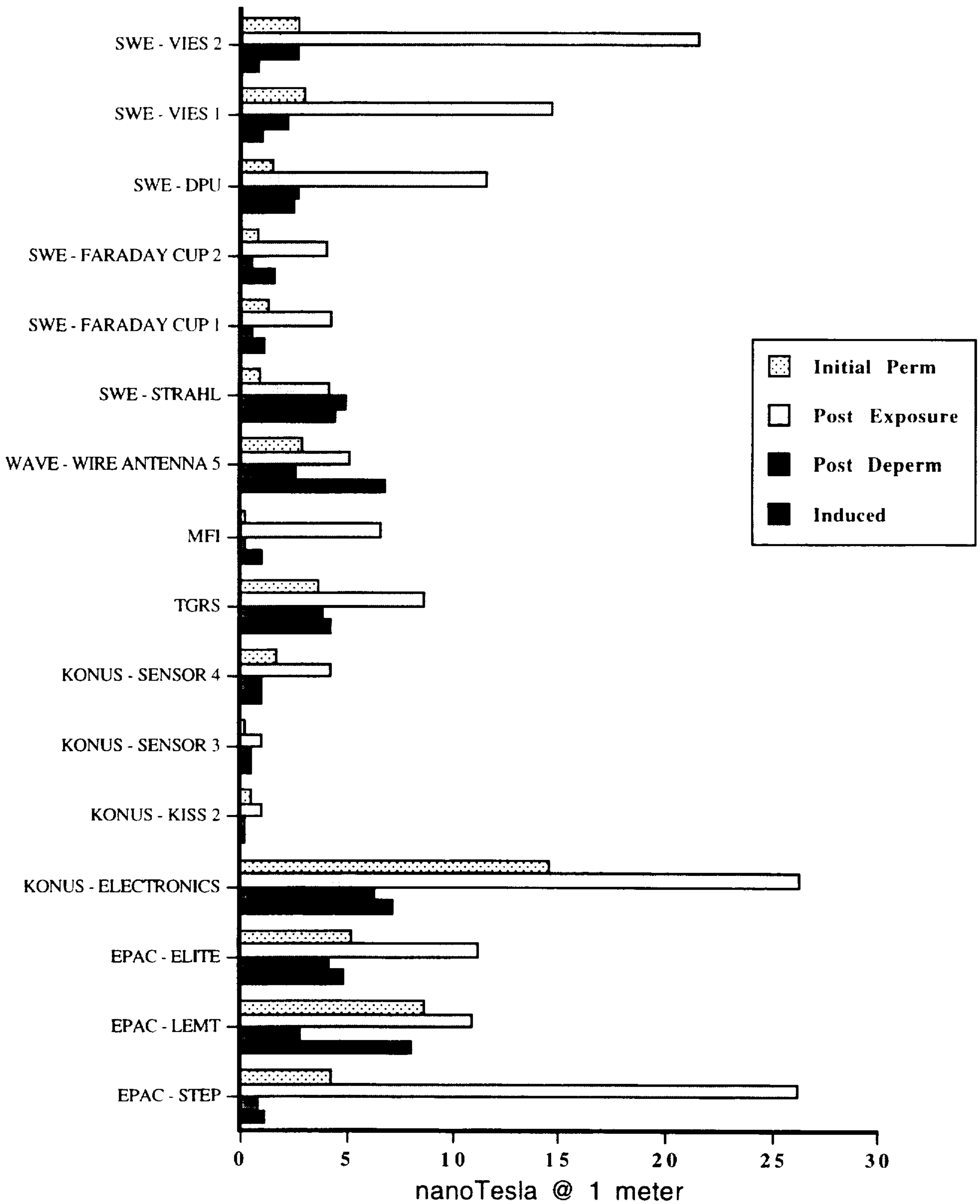

Figure 3. WIND Instruments Static Field Test Results