AN INVESTIGATION OF THE SHIELDING PROPERTIES OF MOLY PERMALLOY[R] SHIELDS DESIGNED FOR USE WITH A HYDROGEN MASER

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Introduction

Hydrogen masers are being considered for use as the frequency standard in the next generation of navigational satellites (NAVSTAR GPS). For these masers to achieve the required frequency stability (1 part in 10^{14}), the magnetic field environment in which the maser operates must be accurately known and stable to 1 nT for ambiant magnetic field changes of 100,000 nT. (The earth's magnetic field is approximately 50,000 nT). The usual procedure is to surround the hydrogen maser by one or more concentric magnetic shields. The objective of this study is to verify the shielding characteristics of the magnetic shield system (Fig. 1) that has been designed for use with the VLG-11 ground based hydrogen maser.

Measurements were made in the 11.3 meter diameter Braunbek coil system at the Spacecraft Magnetic Field Site, Goddard Space Flight Center, Greenbelt, Md. (See Fig. 2). This coil system actively compensates for changes in the Earth's magnetic field and is capable of nulling the earth's field to better than 1 nT over a 1.3 m diameter sphere. In addition, this system has the capability of applying a field, known to an accuracy of 1 nT over this volume, with a magnitude as large as 60,000 nT.

Both the transverse and axial shielding factors of a single layer shield and a four layer nested shield were determined using a fluxgate magnetometer with 0.1 nT resolution and a Superconducting QUantum Interference Device (SQUID) magnetometer with 0.001 nT resolution. Attenuation was studied as a function of external magnetic field, position within the shield, zero field magnetic moment (perm), and thermal cycling.

Single Shield Results

A single layer shield of Moly Permalloy[R*] of the type shown in Fig. 1 was placed at the center of the coil facility. Data were taken primarily with a three axis fluxgate magnetometer, however a limited number of measurements were also taken with a flip coil SQUID magnetometer.

Measurements were made of the internal field and the differential shielding factor (the change in external field divided by the change in internal field) as a function of: applied field, axial distance from the center of the shield, and "zero" field magnetic moment (perm) of the shield.

These measurements basically fell into three categories characterized by the magnitude of the applied field:

(a) Low magnetic fields (50 to 500 nT): Here the changes in the internal field in a given direction for a given change in the external field in the same direction was constant, reproducible, and reversible, i.e., the "zero" field readings which were taken after each application and removal of the external field were reproduced to within 1 nT. These results were independent of the perm that the shield had before initiating the measurements. Figure 3 displays the transverse and axial shielding factors as a function of axial distance from the center of the shield. The shielding factor at the center of the shield varied from 33 in both transverse directions to 20 in the axial direction.

(b) Intermediate magnetic fields (500 to 30,000 nT): These data are characterized by internal fields and shielding factors which are dependent on the recent magnetic history of the shield and the initial perm. In this field region, the perm of the shield is dependent on the magnetic history. Figure 4 illustrates a typical hysteresis loop where the perm in the axial direction was initially small[1]. In this range of magnetic fields, the shielding factor always exceeded the low-field shielding factor.

(c) High magnetic fields (30,000 to 55,000 nT or a field comparable to the Earth's magnetic field): In this range, the magnitude of the applied field is sufficiently large that the perm and previous magnetic history are not important. In this field range, an absolute shielding factor was determined rather than the differential one. Results for the two orientations are included in Figure 3. For a maximum applied field of 55,000 nT, the internal field never exceeded 1000 nT at the center and 3400 nT at axial distance of 200 mm from the center of the shield.

Aside from the determination of the details of the shielding characteristics of this shield, another significant result is that the perm of the sample shield was unaffected (to the 1 nT level) by uniform fields of up to 500 nT. Thus in any shield design where the perm must remain stable to this level, an upper limit on the fields that a similarly fabricated shield can be exposed to and have the perm remain unchanged has been established.

Four Layer Nested Shield Set Results

These measurements were made on a set of four shields acquired from Allegheny Ludlum Corp. and built to SAO specifications. The outermost shield of this set is essentially of the same design as the single shield discussed above. To preserve the high permeability of these shields they were "nested" using carved balsa wood spacers and foam rubber between successive layers. The spacing of the shields was in conformance with specifictions supplied by

SAO. These spacers and foam seperators were fashioned so that the four layer set could be placed on its side or inverted without changing the relative orientations of the shields.

Prior to each of the measurements, the shields were depermed using a combination of techniques[2]. The shields were placed at the center of the 11.3 m coils and the ambient field was nulled to approximately one nT. Before the initial deperm, the internal field was at most 67 nT. A pair of 3.05 m diameter coils spaced 2.24m apart were placed on opposite sides of the shields. (See Fig. 5) A 60 Hz current in the coils was raised to 100 amps (corresponding to a field at the shields of $3x10^6$nT) and lowered in 10 seconds. The shield was then rotated 90^o about the vertical axis and the current was again brought to 100 Amps and decreased at the same rate. As a result of this phase of the deperm sequence, the internal field was now typically approximately 5 nT. A cable was then run axially through the shield forming a single loop, and a 250 amp 60 Hz current was passed through the cable. The current was then reduced from 250A to 30 A in 2 minutes time, then increased to 60 A and reduced to zero again in 2 minutes. The remnant internal field was consistently below 0.1 nT.

Axial measurements were made with both a fluxgate and a SQUID magnetotmeter, with the shields depermed prior to either measurement. Data were obtained by increasing the applied field in incremental steps from 0 to 60,000 nT parallel to the Z axis (up direction), then incrementally decreased to zero and then again increased incrementally to 60,000 nT directed antiparallel to the Z axis (down direction) and thence back to zero.

The fluxgate magnetometer was suspended at the center of the shield with its sensing axis along the Z axis. The SQUID magnetometer had a sensing coil which could be rotated 360° in the horizontal plane and 270° in the vertical plane, permitting arbitrary field directions to be evaluated. Transverse measurements with the fluxgate magnetometer were inconclusive due to a lack of sensitivity, the SQUID magnetometer performed with satisfactory precision. Results for the axial fields are shown in Fig. 6 and the transverse measurements are shown in Fig. 7. In Fig. 6, we see that for a total field change of 120,000 nT (+60,000 to -60,000 nT) the total internal field change was approximately 2nT, resulting in a shielding factor of 6×10^{4}. The residual moment or perm after traversing this one cycle changed by 0.25 nT. The transverse shielding factor was determined to be 3.75×10^{5} and the change in perm was 0.05 nT.

Shielding factors as a function of axial distance from the center of the shield were determined in the following fashion. Axial fields of $\pm$ 60,000 nT were applied to the shields and the internal fields at the center of the shield were determined. The fields were monitored by the stationary magnetometers as the shields were raised by discrete amounts. (Fig. 8). The shields were then inverted and the measurements were repeated. In this manner any asymmetry introduced by the magnetometer probe itself is removed from the final results. Note the large asymmetry in the internal fields towards the welded end as compared to the press fit end. This could be due to the fact that there are larger access holes at the press fit end than at the welded end, the incomplete ferromagnetic circuit due to a lack of continuity of the shields, the stress of assembly at the press fit end, or any combination of these factors.

Thermal Shock Test

The shields were placed in a thermostatically controlled oven and maintained at 65C for two hours and allowed to cool to 25C in 40 minutes. The magnetic shielding measurements detailed above were repeated. No difference was detected from the earlier results.

Discussion of Results

These results reflect significantly on the performance of a hydrogen maser since the effect of a magnetic field is to change the frequency of the maser according to the following equation[3]

$$\Delta\nu/\nu = 3.9\times10^{-16} H \Delta H$$

where ν is the frequency and H is the field in nT required to provide the quantization direction. For state-of-the-art masers, H is in the range 10 to 50 nT. Thus an axial ΔH of 2 nT as measured at the center of the shield would produce a frequency shift of from 0.7 part in 10^{14} for a field of 10 nT and one of 3.5 parts in 10^{14} for a field of 50 nT. The large measured anisotropy in the shielding factor indicates that this estimate of frequency stability is optimistic, since the maser cavity takes up a significant portion of the inner shield volume and therefore the effective shielding factor will undoubtedly be less than the value at the center. The lack of any measurable effect of the mild thermal shock was not unexpected but is encouraging since no degradation of the shielding was observed.

Conclusions

The present configuration of four shields designed for use with ground based masers provides only marginally adequate field attenuation for ambient excursions of 60,000 nT. This is based on the stability requirement of one part in 10^{14}. If space applications require shielding of 60,000 nT ambient fields, some modifications in the shield design appear necessary in order to assure the required performance.

Acknowledgements: The authors wish to thank William Brown, Charles Harris, Ralph Ricucci and William Pruett of the Spacecraft Magnetic Field Site, NASA, for their hospitality and assistance.

References

1. 3.05 m diameter deperming coils were used in one transverse direction only. The result was to reduce the "zero" field moment of the shield in the two perpendicular directions. The perpendicular transverse direction had a very small perm (<3nT) after running the 60 Hz field in the deperming coils to $3x10^6$ nT and slowly reducing it.

2. Private Communications, Charles Harris of NASA-Goddard and Robert Vessot of SAO.

3. D. Kleppner, H. M. Goldenberg and N. F. Ramsey, Phys. Rev. 126, 603(1962).

*R Allegheny Ludlum Corp.

FIGURE CAPTIONS

1. Four shield nested array.

2. Artists conception of NASA-Goddard Spacecraft Magnetic Test Facility.

3. Transverse and axial shielding factors as a function of axial distance from the center of the shield for a single Moly Permalloy[R] shield. For the upper two curves, the shielding factor was calculated by dividing the applied field by the internal field. For the lower two curves, the shielding factor was calculated by dividing the applied field by the change in the internal field parallel to the applied field. The filled circles are the SQUID data.

4. The internal axial field as a function of the external axial field 150 mm from the center of the single shield. The data were taken as follows: the field was increased from "zero" with the axial perm small until 55,000 nT was reached (the maximum field that could be uniformly applied). The field was then decreased to zero and then increased to 55,000 nT in the opposite direction. The field was decreased to zero again and reversed and increased to 55,000 nT in the original direction. The field was decreased to zero again and reversed and increased to 55,000 nT. This cycle is shown by the solid curve. The field was then decreased to zero and increased to 55,000 nT in the same direction as it had just been before. This last cycle is illustrated by the dashed curve. Notice that the internal field at 55,000 nT always reproduces.

5. (a) Deperming coils used to reduce the internal field to approximately 5 nT.

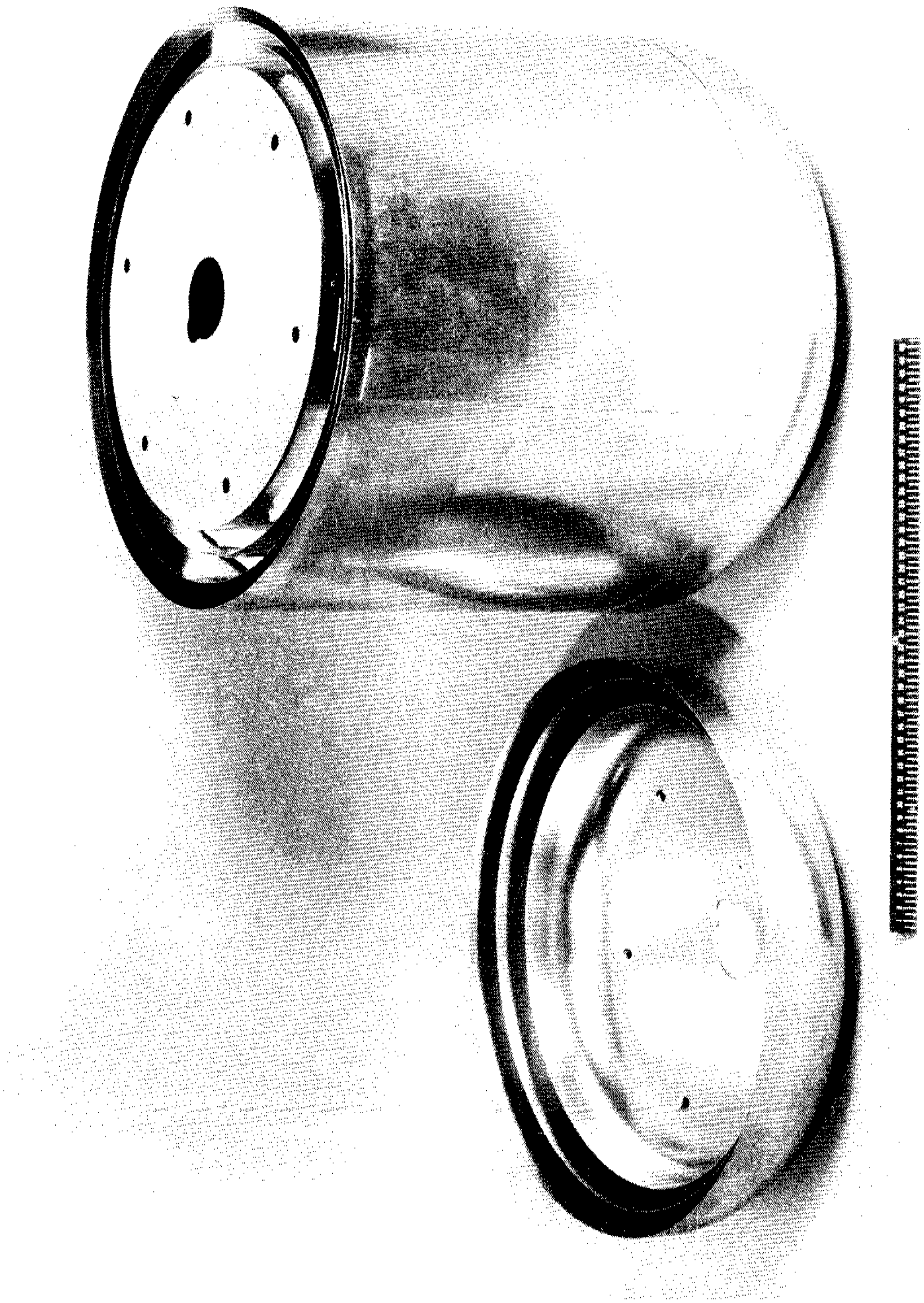
   (b) The 250 amp cable used to reduce the remmant internal field to 0.1 nT is visible as it is passed axially through the shields in the box.

6. Internal fields of a 4 layer nested Moly Permalloy[R] shield set as a function of applied axial fields.

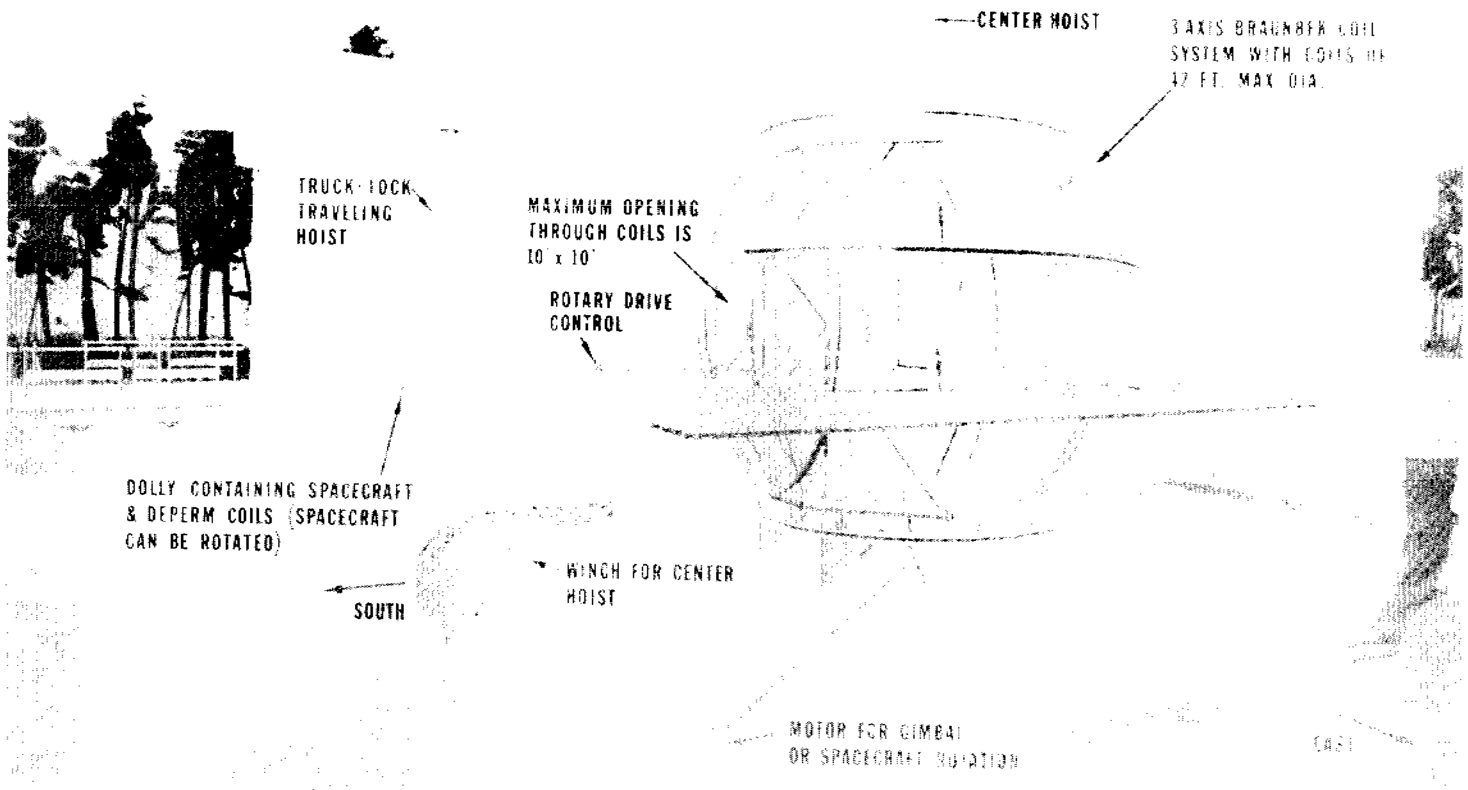
7. Internal fields of a 4 layer nested Moly Permalloy[R] shield set as a function of applied transverse field.

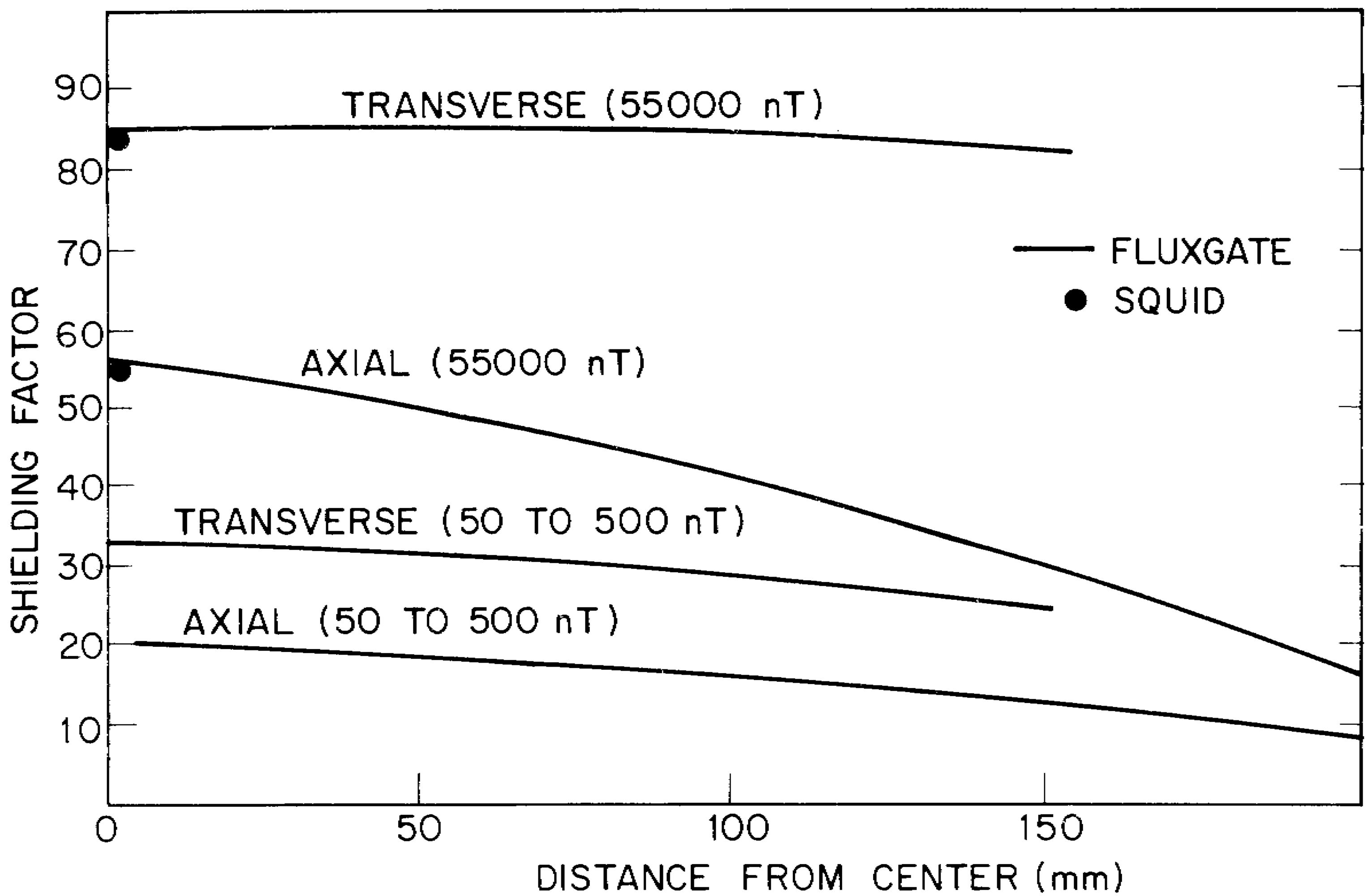
8. Shielding factors as a function of axial distance from

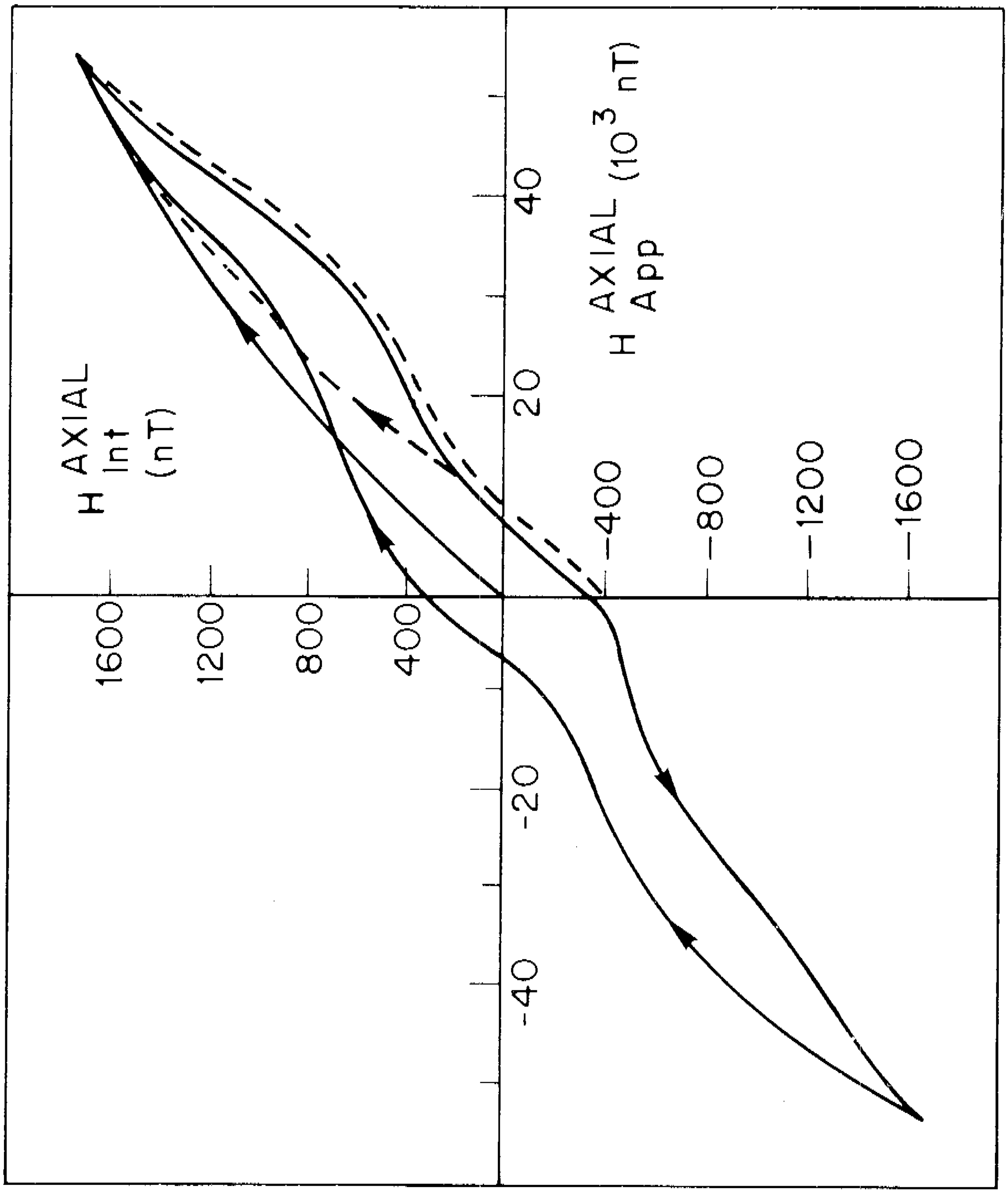
the center of the shield for applied axial field. Shielding at the welded end is much more effective than at the press fit end.

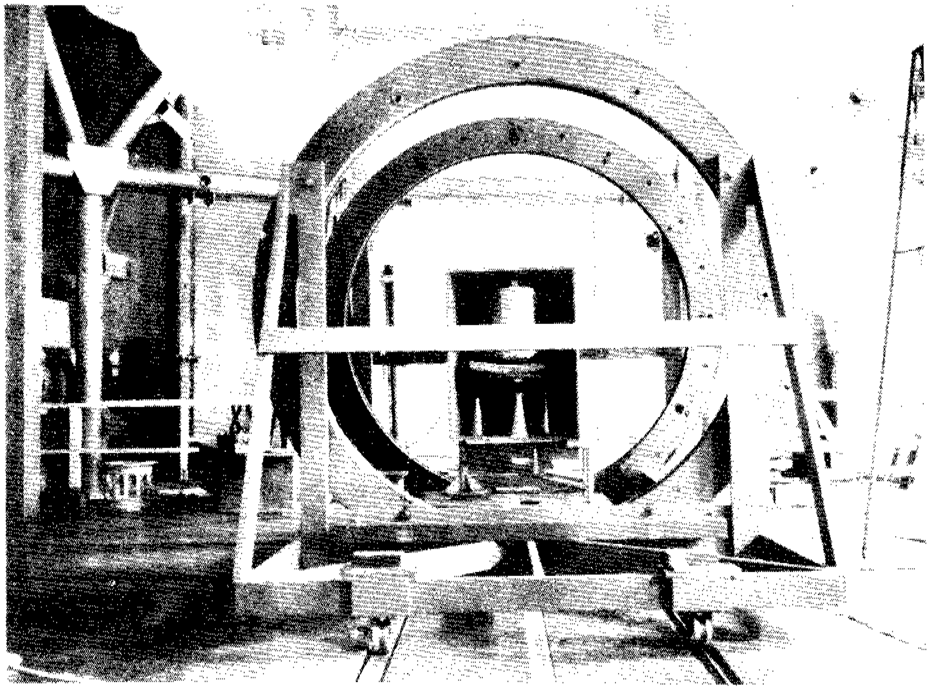


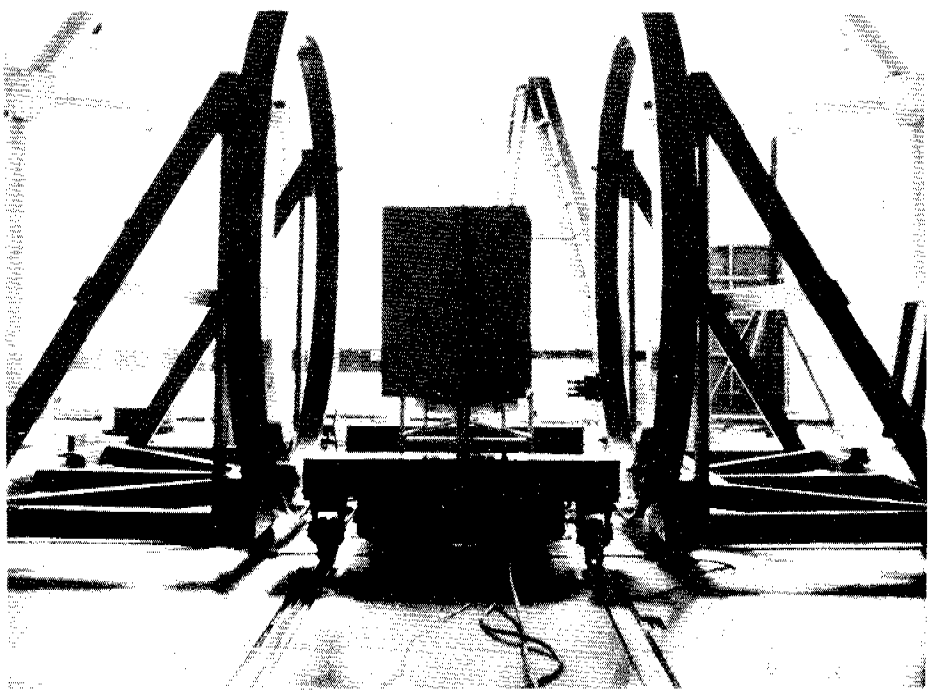
SPACECRAFT MAGNETIC TEST FACILITY

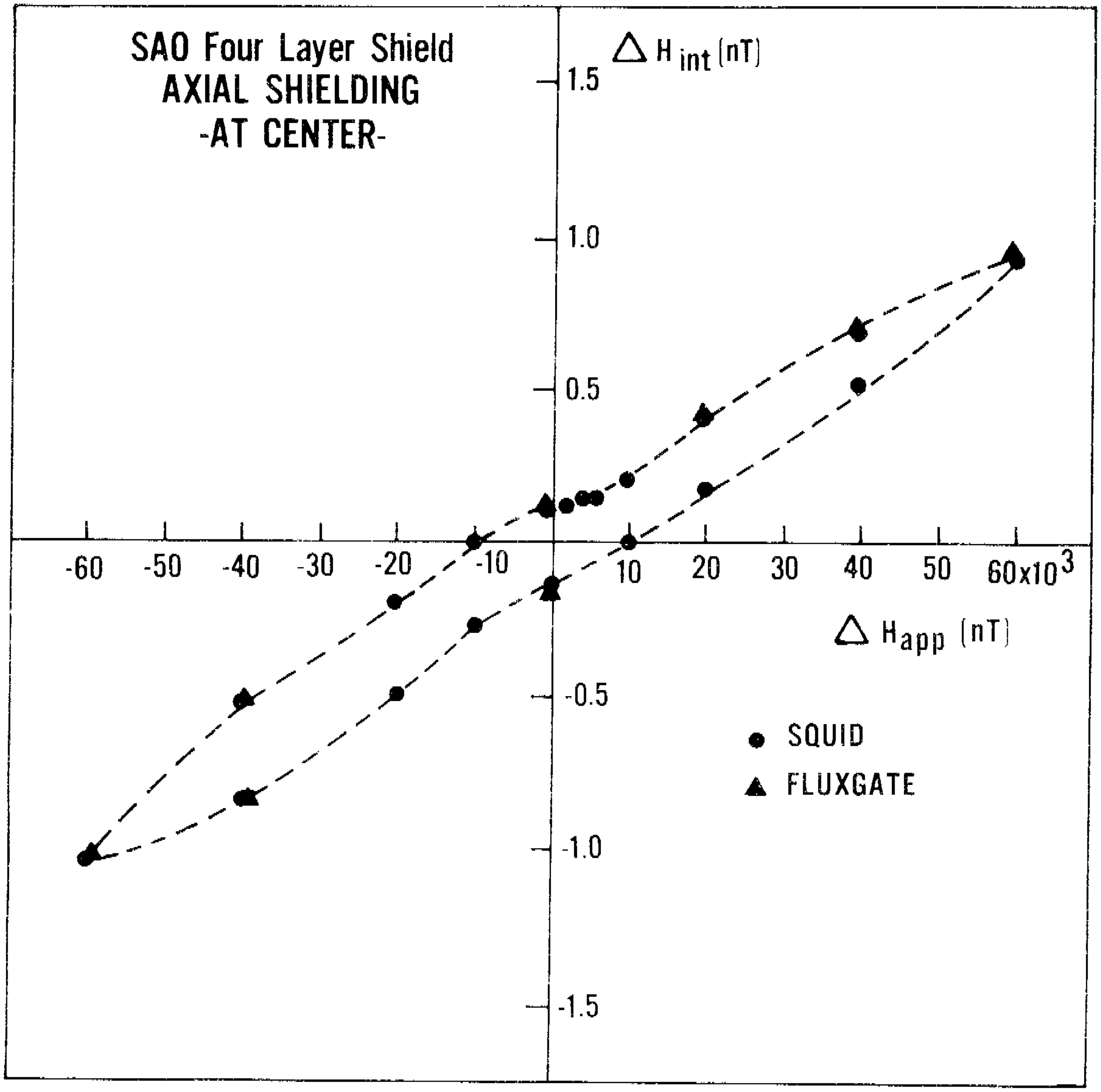


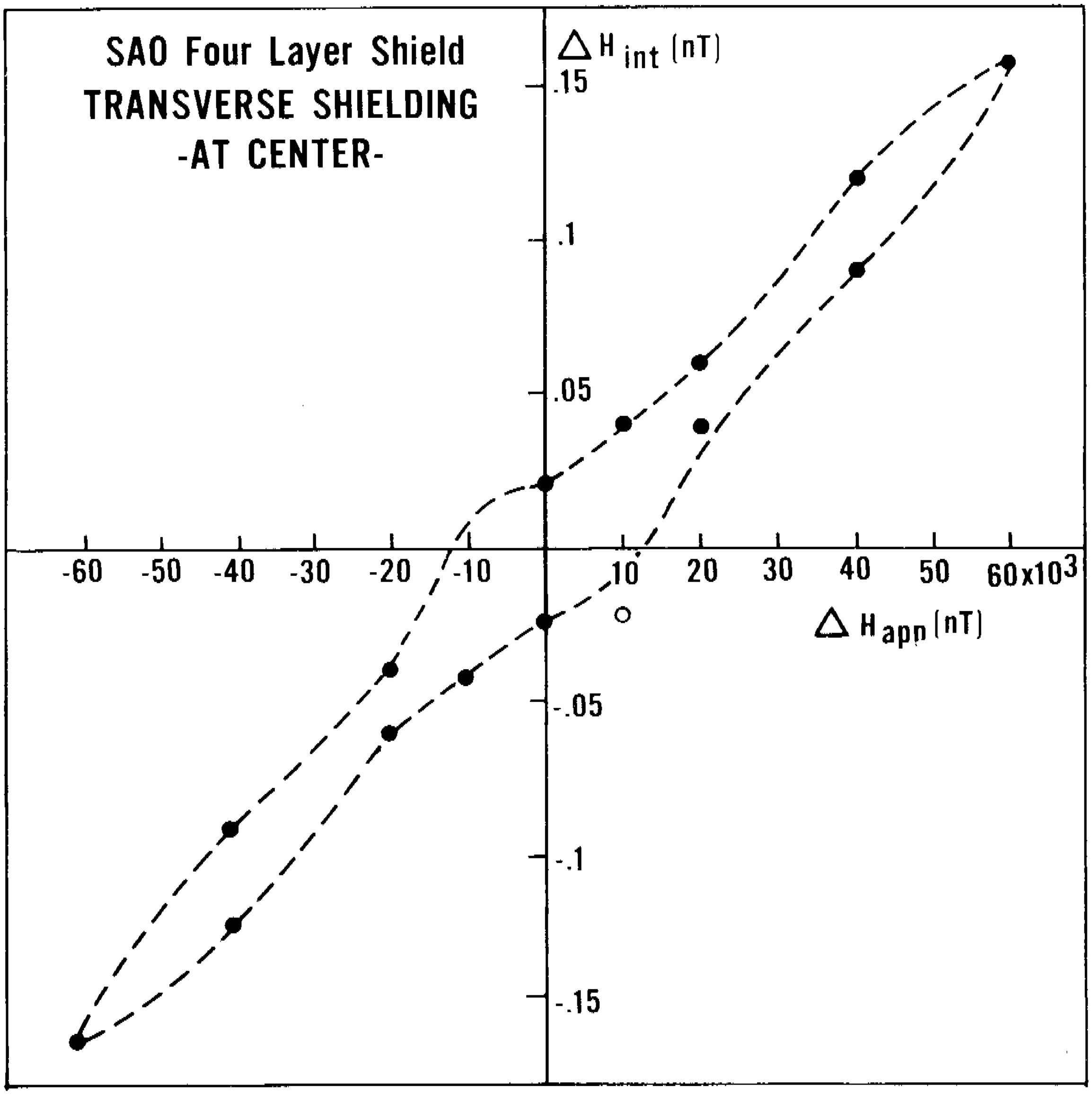

SHIELDING FACTOR
90
80
70
60
50
40
30
20
10
0
50
100
150
DISTANCE FROM CENTER (mm)
TRANSVERSE (55000 nT)
AXIAL (55000 nT)
TRANSVERSE (50 TO 500 nT)
AXIAL (50 TO 500 nT)
FLUXGATE
SQUID


H AXIAL Int (nT)
H AXIAL App (10^3 nT)
1600
1200
800
400
-400
-800
-1200
-1600
-40
-20
20
40

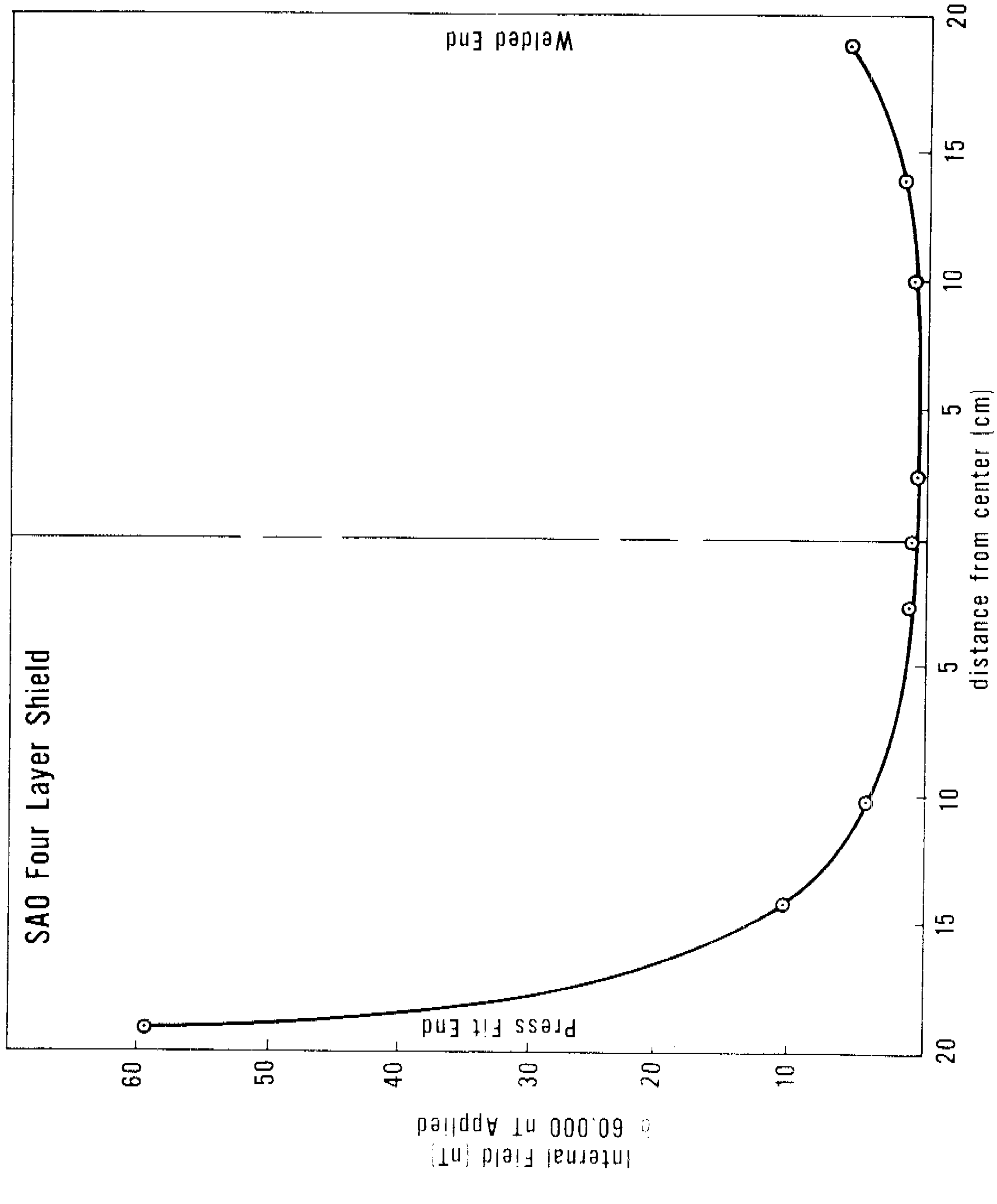





SAO Four Layer Shield
AXIAL SHIELDING
-AT CENTER-
△ H int (nT)
1.5
1.0
0.5
-0.5
-1.0
-1.5
-60
-50
-40
-30
-20
-10
10
20
30
40
50
60x10 3
△ Happ (nT)
SQUID
FLUXGATE



SAO Four Layer Shield
TRANSVERSE SHIELDING
-AT CENTER-
△H int (nT)
.15
.1
.05
-.05
-.1
-.15
-60
-50
-40
-30
-20
-10
10
20
30
40
50
60x10³
△ H app (nT)


SAO Four Layer Shield
Press Fit End
Welded End
distance from center (cm)
Internal Field (nT)
@ 60,000 nT Applied
60
50
40
30
20
10
20
15
10
5
5
10
15
20

QUESTIONS AND ANSWERS

DR. ROBERT VESSOT, Smithsonian Astrophysical Observatory:

We measured three sets of shields using the maser as its own magnetometer, and we found that out of three, one set was very much worse than the others by a factor of almost two. We strongly suspect that part of the acceptance procedure, if you are going to build masers, is to measure each individual magnetic shield before you put it into the assembly. It is very likely that there is some lack of control in the annealing process, or perhaps in the metallurgy, which I doubt.

The other thing is that I heard you mention that the shielding had to be over the whole cavity. I take it you meant over the bulb, which is much smaller than the cavity.

MR. WOLF:

I realize it's not over the entire cavity, but also it is not a point function at the center of the cavity either.

DR. VESSOT:

No, it is in a region of 7-inch diameter above the geometric center of the array.

MR. WOLF:

We did not do an off-axis measurement. As you can see by the configuration of the shields and the configuration of the magnetometer, it was impossible to do off-axis measurements. All we could do was measure the axial asymmetry.

DR. VESSOT:

I agree with you. More work is certainly needed on magnetic shields if you are expecting 60,000 nanotesla variations.

MR. WOLF:

About the quality of shields: Are you saying that we should measure each individual layer of the four-layer system as opposed to the four nested layers as they are?

DR. VESSOT:

Yes.