

# ACHIEVEMENT OF THE MAGNETIC ENVIRONMENT REQUIREMENTS FOR THE GRAVITY PROBE B RELATIVITY MISSION



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## Abstract

The proper function of the Gravity Probe B gyro readout system necessitated the most stringent magnetic environment requirements of any NASA flight program. We describe the generation of an ultralow magnetic field of  $< 10^{-11}$  tesla in the flight Dewar, a non-magnetic materials, fabrication, and assembly regimen to minimize remanent fields in the vicinity of the science gyros, and a magnetic shield system that attenuated external magnetic field variation by a factor of  $2 \times 10^{-12}$ . Techniques for requirement verification were developed that including the creation of specialized magnetic measurement facilities. On-orbit gyro trapped flux and readout data confirm the achievement of the fundamental magnetic requirements.

## GP-B Magnetics Requirements

Steady State Field at the position of the science gyroscopes shall be  $\leq 9 \times 10^{-10}$  tesla

- Allocation: residual field in magnetic shield system, SIA and Probe remanent fields
- Verification: gyro trapped flux equivalent field  $\leq 9 \times 10^{-10}$  tesla

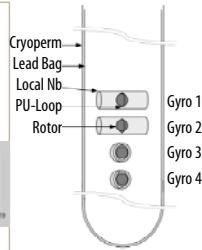
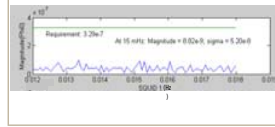
Field Attenuation Factor shall be  $\leq 2 \times 10^{-12}$  over the frequency band of 1.67 mHz to 16.7 mHz referred to area of each gyro pickup loop

- Allocation: cryoperm shield, lead bag, local shield, and rotor self shielding

## Magnetic Shield System

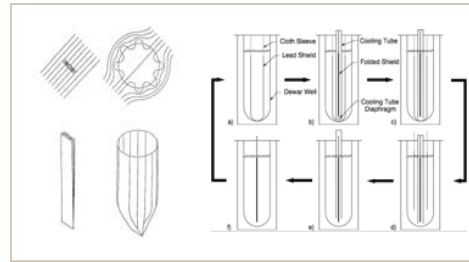
Series of Shields Provides Ultralow DC Fields and High Attenuation Of AC Fields  
Cryoperm Shield DC  $\sim 3 \times 10^{-6}$  T, Attenuation:  $2 \times 10^{-1}$  Long.,  $1.5 \times 10^{-2}$  Transverse  
Lead Bag DC  $< 10^{-11}$  T, Attenuation:  $< 10^{-8}$  Long.,  $3 \times 10^{-7}$  Transverse  
Local Nb Shield  
Rotor Self Shielding } Attenuation:  $< 10^{-5}$  Long.,  $< 10^{-5}$  Transverse

AC Attenuation Ground Verification:  
Field Applied at 15 mHz to Payload  
w/4meter Helmholtz System  
Attenuation Factor  $< 1 \times 10^{-12}$



## Lead Bag: Expanded Superconducting Shield

Folded lead foil cylinder inserted into dewar well, Cooled in controlled sequence  
At transition to below  $T_c$ , ambient magnetic flux is trapped  
Lead cylinder is mechanically expanded, flux is conserved  $\Rightarrow$  B field decreases  
2nd lead cylinder inserted and cooled inside first  
Process iterated until desired field level achieved



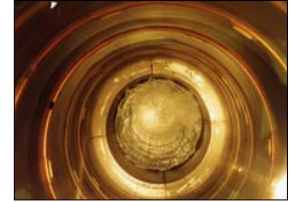
Cooling tube w/ folded bag



Expanded lead bag



Lead bag removal



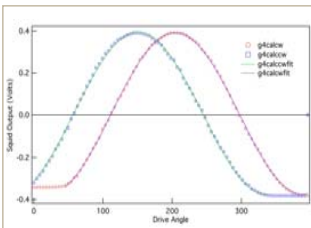
Final lead bag

## Absolute Field Measurement

Rotating Coil Magnetometer measures absolute dc field vector vs. position

Measurement of  $10^{-10}$  tesla lead bag shield before retainer installation:  $3.5 \times 10^{-12}$  tesla  
Results after retainer installation at position of Gyro 1:  $1.9 \times 10^{-11}$  tesla

Gyro 2:  $2.6 \times 10^{-11}$  tesla  
Gyro 3:  $8.7 \times 10^{-11}$  tesla  
Gyro 4:  $1.6 \times 10^{-10}$  tesla



Gyro 4 data, 0° north orientation. Field  $\sim 1.5 \mu\text{gauss}$



Rotating Coil Magnetometer

## Materials and Parts Control

### Requirements Scale With Proximity To Gyros

#### Properties Controlled

- Remanent Moment
- Magnetic Susceptibility
- Unwanted Superconductivity (Trapped Flux Fields)
- Electrical Conductivity (Johnson Noise Currents)

#### Screening Facilities

- QD MPMS Susceptometer (small parts and coupons)
- Large Crysoscreener ( $\leq 10$ cm diam parts in  $10^{-11}$  T field)
- Cryotron SQUID Gradiometer (large parts, room temp)
- AMES Low Field (20' Helmholtz system-full probe test)

#### Non-magnetic Fabrication Techniques

- Nonmagnetic Tooling for Machining and Assembly
- Nonmagnetic Cutting and Lubrication Fluids
- Chemical Surface Etching
- Specialized Plating Protocols



Large Crysoscreener

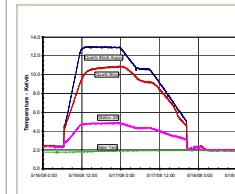


SQUID Gradiometer

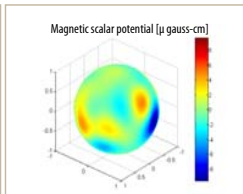
Material	Supplier	Remanent (mT)	Permeability (Cr/emu)
<b>Structural Metals</b>			
Al 6061	Alco, Reynolds	5.42e-7	3.20e-7
Al 99.99, Grade 2	Goodfellow, TGA	5.23e-7	3.10e-7
Al 7075-T6	Hobasite Metal Company	5.40e-7	2.50e-7
Copper 99.99999%	Special Copper and Brass	5.23e-7	3.20e-7
Al 62-017200	Bush-Whitman, NCA	5.33e-7	4.01e-7
Al 6101	HighPurity	1.70e-7	3.00e-7
Alloy 6061	Allen Research Metals	5.23e-7	3.00e-7
Alloy 6061	Bush-Whitman	5.93e-7	4.30e-7
Al 6061	Allen Research Metals	5.63e-7	4.30e-7
Al Cu alloy 9990	Yamaha Metals	5.30e-7	3.30e-7
Al Bronze	Sheepskin Copper and Brass	0.51-20e-4	4.50e-7
Al Bronze C51000	Copper and Brass Sales	5.20e-7	5.20e-6
Plus Bronze C51000	Allen Research Metals	1.43e-7	1.01e-6
Aluminum 99.99%	CMV Industries	5.45e-7	3.10e-7
<b>Structural Alloys</b>			
Titanium	Dupont	5.90e-7	5.00e-7
Inconel	Johns-Manville	5.20e-7	4.70e-7
Kapton	Dupont	5.20e-7	1.60e-7
Nepel	Dupont	5.60e-7	8.0e-7
FR-4	Si Industries	5.20e-7	3.0e-7
Suphite	Suphite Inc.	5.70e-7	1.20e-7
Quartz	Quartz America	5.10e-7	3.10e-7
<b>Wire and Ribbon</b>			
Aluminum 99.99%	Johnson Cryogenics	2.40e-7	1.30e-7
Phosphor Bronze	California Fine Wire	5.20e-7	2.30e-7
Copper B Gauge	Belden	4.0e-7	3.70e-7
Phosphor-Tungsten	California Fine Wire	1.80e-7	3.30e-7
Al 100/100	California Fine Wire	5.30e-7	2.00e-7
Silver Ribbon 200A	California Fine Wire	1.50e-7	2.30e-7
<b>Special</b>			
Al Oxide-Therm	Johnson Cryogenics	1.00e-6	
Al Therm 1000B	Johnson Cryogenics	0.51-20e-4	
Phosphor 010-02	Magnum Corp.	3.0e-7	
Inconel 99.99%	Magnum Corp. of America	1.0e-7	7.80e-7
Inconel 710-0300	Magnum Corp.	7.0e-7	2.30e-7
FR-40-40 solder	Magnum	5.70e-7	2.00e-7
Polyimide Kapton	Advanced Polymers Inc.	5.80e-7	1.30e-6
Indium 2713 Epoxy	Tec-Con	5.20e-7	3.20e-7
Epoxy 1045 Epoxy	Electron 8 Gaming	5.20e-7	4.80e-7
Silver Epoxy 81-C	Electron 8 Gaming	5.20e-7	4.80e-7

## On-orbit Verification

- SQUID Readout System on-orbit data verification for both AC and DC requirements
- Low frequency data (roll and orbital): Caged gyro test - low earth field interference
- High frequency data (spin harmonics): Trapped flux (uniform field equivalent)
  - Gyro 1:  $3.0 \times 10^{-10}$  tesla
  - Gyro 2:  $1.3 \times 10^{-10}$  tesla
  - Gyro 3:  $8.0 \times 10^{-11}$  tesla
  - Gyro 4:  $2.0 \times 10^{-11}$  tesla
- Trapped flux values measured after on-orbit flux flush operation



Flux Flush Operation 5/15/2004



Gyro 1 trapped flux contour from SRS data.

## References

- 1) J. Mester, et al. *Ultralow Magnetic Fields and Gravity Probe B Gyroscope Readout. Advances in Space Research*; (2000); vol.25, no.6, p.1185-8
- 2) J. Mester and J. M. Lockhart, *Remanent Magnetization of Instrument Materials for Low Magnetic Field Applications. Proceedings of the LT21, Czechoslovak Journal of Physics*, 46, 55 2751 (1996).
- 3) B. Cabrera, Ph.D. Thesis, Stanford (1975).
- 4) M.A. Taber et al. *Production of Ultralow Magnetic Fields for Gravity Probe B. Advances in Cryo. Eng. 39A*, 161-170 (1993).
- 5) M.A. Taber et al. *Gravity Probe B Payload Verification And Test Program. Advances in Space Research*, Volume 32, Issue 7, October 2003, Pages 1417-1420
- 6) B. Olding, Honors Thesis, Stanford (1998).

