Achievement of the Magnetic Environment Requirements for the Gravity Probe B Relativity Mission

J.C. Mester, D.O. Murray, and M.A. Taber, Stanford University
J. M. Lockhart, San Francisco State University and Stanford University

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 2×10^{-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 $\leq 9\times10^{-10}$ tesla

- Allocation: residual field in magnetic shield system, SIA and Probe remanent fields
- Verification: gyro trapped flux equivalent field $\leq 9\times10^{-10}$ tesla

Field Attenuation Factor shall be $\leq 2\times10^{-12}$ over the frequency band of 1.67 mHz to16.7 mHz referred to area of each gyro pickup loop

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

Magnetic Shield System

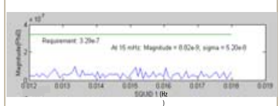
Series of Shields Provides Ultralow DC Fields and High Attenuation Of AC Fields

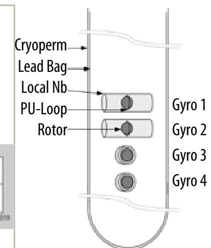
Cryoperm Shield	DC $\sim 3\times10^{-6}$ T, Attenuation: 2×10^{-1} Long., 1.5×10^{-2} Transverse
Lead Bag	DC $< 10^{-11}$ T, Attenuation: $< 10^{-8}$ Long., 3×10^{-7} Transverse
Local Nb Shield Rotor Self Shielding	} Attenuation: $< 10^{-5}$ Long ., $< 10^{-5}$ Transverse

AC Attenuation Ground Verification:

Field Applied at 15 mHz to Payload w/4meter Helmholtz System

Attenuation Factor $< 1\times10^{-12}$





Lead Bag: Expanded Superconducting Shield

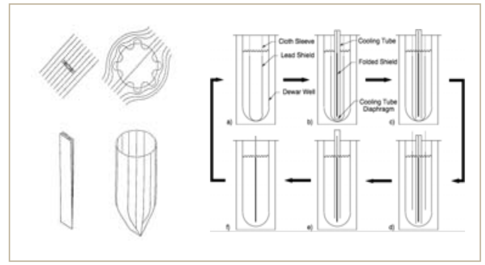
Folded lead foil cylinder inserted into dewar well, Cooled in controlled sequence

At transition to below Tc, ambient magnetic flux is trapped

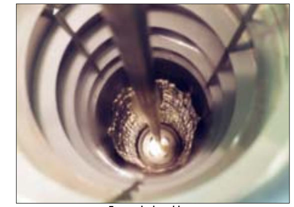
Lead cylinder is mechanically expanded, flux is conserved => B field decreases

2nd lead cylinder inserted and cooled inside first

Process iterated until desired field level achieved



Cooling tube w/ folded bag



Expanded ead bag

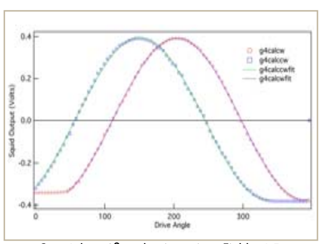
Lead bag removal

Final lead bag

Absolute Field Measurement

Rotating Coil Magnetometer measures absolute dc field vector vs. position

Measurement of 10 " lead bag shield before retainer installation:		3.5×10^{-12} tesla
Results after retainer installation at position of	Gyro 1:	1.9×10^{-11} tesla
	Gyro 2:	2.6×10^{-11} tesla
	Gyro 3:	8.7×10^{-11} tesla
	Gyro 4:	1.6×10^{-10} tesla



Gyro 4 data, 0°north orientation. Field ~1.5μgauss

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 Cryoscreener ($\leq$ 10cm diam parts in 10^{-11} T field)
- Cryotron SQUID Gradiometer (large parts, room temp)
- AMES Low Field (20' Helmholtz system-full probe test)

Nonmagnetic Fabrication Techniques

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

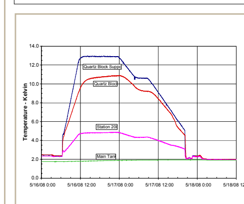
Large Cryoscreener

SQUID Gradiometer

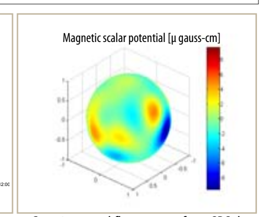
Material	Supplier	Remanent (emu)	Susceptibility (emu/g)
Structural Metals			
Al 6061	Alcoa, Reynolds	Š 4.0x10-7	7.0x10-7
Ti 99.6%, Grade 2	Goodfellow, TiCo	Š 2.5x10-7	3.1x10-6
Nb Type 1	Teledyne Wah Chang	Š 4.0x10-7	2.5x10-6
Copper 10100 99.99%	Sequoia Copper and Brass	Š 3.0x10-7	2.5x10-7
BeCu 25 C17200	Brush Wellman, NGK	Š 3.1x10-6	4x10-7
BeCu 125	Brush Wellman	1.7x10-7	1.5x10-7
binary BeCu	NGK Berylco	Š 1.9x10-7	2x10-8
binary BeCu	Ames Research Iowa St.	Š 9.7x10-8	4.3x10-8
BeCu 3HP	Brush Wellman	Š 6.5x10-7	8.3x10-8
Tl Cu unsc19900	Yamaha Metals	Š 3.0x10-7	3.7x10-7
Si Bronze	Sequoia Copper and Brass	0.3 - 2x10-4	-4.5x10-7
Phos Bronze C-51000	Copper and Brass Sales,	Š 2x10-5	Š 3.0x10-6
Phos Bronze Custom	Ames Research Iowa St.	1- 4.7x10-7	1x10-6-3x10-6
Molybdenum 99.97%	CSM Industries	Š 4.5x10-7	9.6x10-7
Structural Dielectrics			
Teflon	Dupont	Š 9.0x10-7	- 5.0x10-8
Delrin	Laird Plastics	Š 5x10-8	- 4.7x10-7
Kapton	Dupont	Š 2.0x10-7	1.6x10-7
Vespel	Dupont	Š 6.6x10-7	8x10-7
PEEK	E Jordon Brooks	Š 9.2x10-7	1x10-7
Sapphire	Saphikon Inc.	Š 7.4x10-8	-1.2x10-7
Quartz	Corning, Hereas Amersil	Š 1.5x10-7	-1.1x10-7
Wire and Ribbon			
Manganin .005"	Lakeshore Cryotronics	2.4x10-4	1.8x10-4
Phosphor Bronze	California Fine Wire	Š 2.5x10-6	
Copper 38 Gauge	Belden	4.0x10-7	- 3.7x10-8
Platinum-Tungsten	California Fine Wire	1.4x10-6	3.3x10-6
NbTi .005"/.010"	California Fine Wire	Š 1.8x10-6	2.0x10-6
Silver Ribbon .004"	California Fine Wire	1.5x10-8	2.7x10-8
Special			
Si Diode Therm	Lakeshore Cryotronics	1.0x10-6	
Ge Therm 1500B	Lakeshore Cryotronics	0.5 / 2x10-6	
Permalloy 55145-A2	Magnetics Corp.	2x10-6	
Indium 99.99%	Indium Corp. of America	3.0x10-7	7.8x10-8
Indium #150 Solder	Indium Corp. of America	7.0x10-8	2.3x10-7
PbSn 60-40 Solder	Kester	Š 7.0x10-8	2.5x10-8
Poly shrink tubing	Advanced Polymers Inc	Š 8.0x10-7	1.3x10-6
Trabond 2115 Epoxy	Tra-Con	Š 2.4x10-7	-3.5x10-7
Stycast 1266 Epoxy	Emerson & Cuming	Š 7x10-8	-4.6x10-7
Silver Epoxy 83-C	Emerson & Cuming	Š 2.3x10-6	8.8x10-7

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: 3.0×10^{-10} tesla
  - Gyro 2: 1.3×10^{-10} tesla
  - Gyro 3: 8.0×10^{-11} tesla
  - Gyro 4: 2.0×10^{-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, S5 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).

This research supported by NASA on contract NAS8-39225