

Applications of Superconductivity to Space-Based Gravitational Experiments

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Techniques based on superconductivity are crucial in providing the means of achieving the high accuracy and low noise required by experimental tests of gravitational theories. We discuss applications of superconductivity to two space-based experiments: the Gravity Probe B Relativity Mission (GP-B), and the Satellite Test of the Equivalence Principle (STEP). Superconducting shields attenuate the dc magnetic field to less than 10^{-11} T and provide an ac shielding factor in excess of 10^{12} . The readout of the GP-B gyroscopes is based on the London magnetic dipole generated by a rotating superconductor and detected with state-of-the-art dc SQUIDs, which are also used in STEP.

1. INTRODUCTION

Low temperature techniques have been widely used in high precision experiments due to their advantages in reducing thermal and mechanical disturbances, and the opportunity to utilize the low temperature phenomena of superconductivity and superfluidity. Gravitational experiments have reached the stage at which both low temperature technology and ultra low gravity space environments are needed to meet the requirements for measurement precision.

General Relativity predicts the geodetic and frame dragging effects to be 6.6 arcsec/yr and 0.033 arcsec/yr in a 650 km polar orbit [1]. The GP-B experiment [2] will measure these effects with an accuracy of at least 0.3 marcsec/yr, by determining the precession of the local frame, given by gyroscopes, with respect to the fixed frame of the stars, given by a telescope pointed to HR5110. Figure 1 shows the GP-B experimental concept.

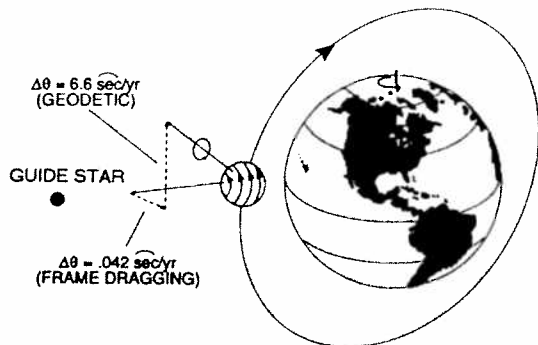


Figure 1. GP-B experimental concept

STEP [3] is designed to improve the measurement of the Equivalence Principle from the present accuracy of

10^{-12} to about 10^{-17} . This cryogenic experiment uses differential accelerometers (with test masses of different materials) placed in a drag free satellite. Figure 2 shows the STEP experimental concept. The position of the test masses is sensed with SQUID magnetometers with 10^{-2} Å precision, while magnetic shielding is provided by superconducting enclosures; both adaptations of GP-B developed techniques. Radial suspension for the test masses is provided by superconducting magnetic bearings.

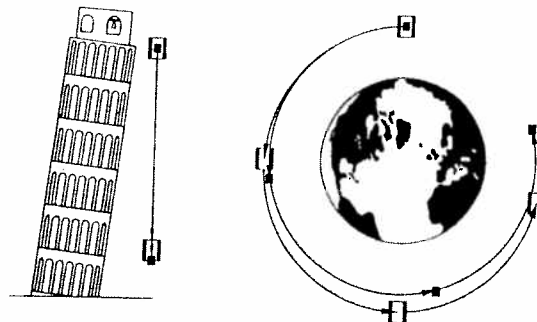


Figure 2. STEP experimental concept

2. MAGNETIC SHIELDING

The London moment [4] based readout requires shielding from external ac magnetic fields by 10^{12} . A dc field of less than 10^{-11} T is needed to insure low trapped flux in the gyroscopes. This level of shielding is achieved by using a system of superconducting magnetic shields, in conjunction with controlling the magnetic properties of the probe materials. A ferromagnetic shield provides a 10^{-6} T magnetic field region within which the main field reduction is achieved by the expansions of superconducting lead foil

cylinders. The foil cylinder, folded to minimize the cross-sectional area, is cooled through its superconducting transition temperature. Cooling rates are controlled in order to minimize thermal gradient induced currents. Once the lead cylinder is superconducting, it is mechanically unfolded to its maximum diameter. This operation reduces the magnetic flux in the cylinder by roughly the ratio of the folded to the expanded cross-sectional areas, a factor of about 20 in practice. Figure 3 represents schematically the expansion process. This process is repeated with additional lead cylinders being expanded one at a time inside the reduced field produced by the previous expansions. The lowest magnetic field values achieved are about 5×10^{-12} T; with further reduction prevented by thermoelectric effects in the lead foil.

The ferromagnetic shield and lead foil superconducting cylinder provide an ac shielding factor of about 10^9 , while a superconducting cylinder surrounding the gyroscope increases the shielding factor to 10^{12} . Finally, the superconducting gyroscope rotor shields the readout loop from external fields by an additional factor of 10. The ac attenuation of the shielding scheme has been measured [5] to be 2×10^{11} , without the rotor and in a position of the lead foil shield for which the attenuation is only 10^8 . The attenuation of the nominal system is conservatively calculated to be in excess of 10^{13} .

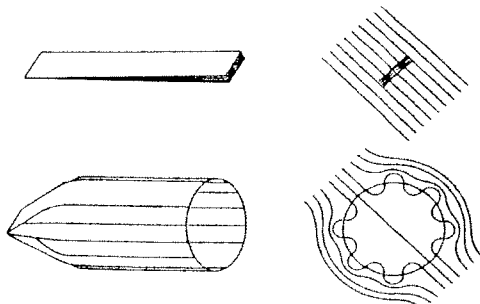


Figure 3. Lead cylinder expansion.

3. THE LONDON MOMENT READOUT

The London moment is the effect by which a rotating superconductor produces throughout its volume a magnetic field B_L aligned with the spin axis ω_s . For a sphere of radius r the resulting magnetic dipole moment M_L ($T \cdot \text{cm}^3$) is:

$$M_L = \frac{r^3 B_L}{2} = -\frac{mc}{e} r^3 \omega_s = -5.69 \times 10^{-12} r^3 \omega_s$$

where m and e are the mass and the charge of the electron, and c the speed of light.

The angular momentum is the conserved quantity which represents the orientation of the local frame of reference, while the instantaneous spin axis cones around it. For a force free gyroscope with a small fractional difference in the principal moments of inertia $\Delta I/I$, the coning angle and frequency are given by $\Delta I/I$ and the spin speed ω_s respectively.[6] For the GP-B gyroscopes $\Delta I/I \leq 5 \times 10^{-6}$, causing the coning angle to be smaller than 1 arcsec, and to average to the level of 1 marcsec in less than 5 seconds. Thus the London magnetic dipole represents the angular momentum direction, independent of polhoding.

Figure 4 is a schematic of the London moment readout concept. Experiments conducted at GP-B [7] have demonstrated that the London moment is the ground state of a superconducting rotating sphere. The same magnetic dipole is achieved independently of the thermal history of the process, that is cooling through the superconducting transition followed by spinning, or cooling after spinning. At the 5 mHz detection frequency, the noise performance of the read-out in a fully prototypical experimental system is about 5×10^{-29} J/Hz. This is equivalent to a resolution of 1 marcsec for an integration time of four hours, or about 20% better than the GP-B requirements.

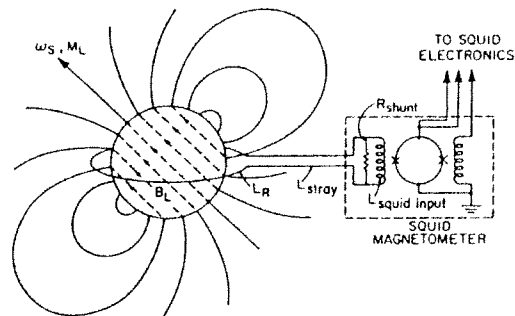


Figure 4. London moment readout system schematic.

ACKNOWLEDGMENTS

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