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Gravitational Experiments in Space: Gravity Probe B and STEP

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We describe two space based gravitational physics experiments, the Gravity Probe B Relativity Mission (GPB) and the Satellite Test of the Equivalence Principle (STEP). GP-B will perform precision tests of two independent predictions of general relativity, the geodetic effect and frame dragging. STEP will provide a precision test of a foundation of general relativity, the Equivalence Principle.

INTRODUCTION

Our present theory of gravity, Einstein's general relativity, is elegant, internally consistent and (so far) in agreement with observation. Yet, despite recent advances, the range of predictions tested and the precision to which experiments have tested the theory remain limited[1]. In addition, general relativity resists quantization, thwarting efforts to include the theory in a unified picture of the forces of nature. Nearly all attempts at unifying gravitation with the Standard Model result in a theory which differs from general relativity, and in particular, include additional vector or scalar couplings which potentially violate the Equivalence Principle[2,3].

Space offers the opportunity for new tests of general relativity with improved precision[4]. The use of drag compensation, first demonstrated in flight by the Discos instrument on the Triad mission[5], to reduce air drag, magnetic torque, and radiation pressure disturbances enables a uniquely quiet environment for experimentation, one not limited by seismic noise. In the following we describe two space based gravitational physics experiments, the Gravity Probe B Relativity Mission (GPB) and the Satellite Test of the Equivalence Principle (STEP). The experiments are at different stages in their life cycles. GP-B is scheduled to launch in April 2004. STEP is completing its technology development phase, building on many of the technologies advanced by GP-B.

GP-B

The Gravity Probe B Relativity Mission is a space based experiment developed at Stanford University with oversight by the Marshall Space Flight Center and funding from the NASA Office of Space Science. GP-B will test two predictions of

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general relativity, the geodetic and frame dragging effects, by measuring the precession of gyroscopes in a 642 km high orbit around the earth.

The relativistic precession of a gyroscope in a circular orbit around the earth is given by:

$$\overline{\Omega} = \left(\gamma + \frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R} \times \overline{v}\right) + \left(\gamma + 1 + \frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{\omega}_e \cdot \overline{R}\right) - \overline{\omega}_e\right]$$

where R is the position and v the orbital velocity of the gyroscope, I, M, and ω are the moment of inertia, mass and angular velocity of the earth, and G is the gravitational constant. For generality we include the PPN parameters γ and α_1; in general relativity $\gamma = 1$ and $\alpha_1 = 0$. The first term describes the geodetic precession, which arises from the curvature of spacetime due to the mass of the earth. General Relativity predicts that the spin direction of the gyroscope will change at the rate of 6.6 arcsec per year for a 642 km high, polar orbit. The second term, frame dragging or Lense-Thirring effect, represents the precession due to the dragging of the inertial frame by the rotation of the earth. General Relativity predicts the rate of precession of a low declination aligned gyroscope to be 0.042 arc sec per year (42 marcsec/yr). A polar orbit is chosen so the two precessions are orthogonal and can therefore be distinguished. Figure 1 depicts the direction of the two precessions.

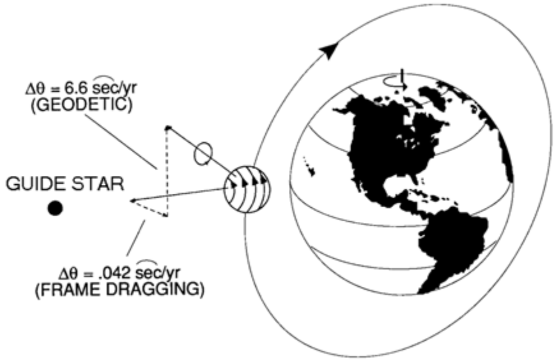

Figure 1. GP-B Concept.

Experiment System Overview

The small size of the relativity precessions requires that the experiment system have extreme measurement precision and that all sources of error be controlled. In order to achieve this requirement the experiment exploits the advantages of a near zero-g orbit in space and a near zero temperature in the experiment probe[6]. The experiment module consists of a helium dewar, which holds 2400 liters of superfluid helium, surrounding the experiment probe containing four gyroscopes, quartz block, and a star tracking telescope. The dewar is designed have an on orbit helium lifetime of greater than 16.5 months. The helium will be maintained at a temperature of 1.8K by means of a porous plug venting system. The boil off gas will be used by proportional thrusters to provide drag free control. The thrusters will keep the spacecraft centered around a gyroscope in free fall to produce residual accelerations at this gyroscope of less than 10^{-9} g ($g=9.8$ m/s^2). Three other gyroscopes are mounted within a rigid quartz block assembly. The quartz block provides precise positioning of the gyroscopes and the telescope, with cryogenic temperatures increasing mechanical stability. A series of windows provides an open line of sight out of the dewar. The star tracking telescope will be used to point the spacecraft towards a guide star, providing a distant inertial reference with which to compare the gyro spin direction. The spacecraft will roll about the line of sight to the guide star with a period of 1 to 3 minutes. This will average off axis accelerations (which contribute to Newtonian torques at the gyroscopes) to 10^{-12} g and will allow the gyroscope spin direction to be measured at roll frequency, avoiding the large noise at dc due to 1/f noise.

Gyroscopes and Gyroscope Readout

At the heart of the gravity probe B mission are the gyroscopes. The experimental precision dictates that the fundamental requirement for the Gravity Probe B mission is to orbit gyroscopes whose absolute Newtonian drift rates are less than 0.3 marcsec/yr and whose total inertial drift can be verified to an accuracy of better than 0.3 marcsec/yr. Figure 2 gives a schematic, exploded view of a gyroscope. The gyroscope is comprised of a rotor 3.8 cm in diameter which spins freely within the spherical cavity of a quartz housing. Newtonian torques on the gyroscope are minimized by the drag free satellite system and by controlling rotor sphericity and homogeneity. Rotors are fabricated from fused quartz with density inhomogeneity of less than 2 parts per million and are ground and lapped to achieve peak-to-valley asphericity of less than 25 nm. The rotors are coated with a 1.25 micron thick uniform layer of niobium which has a superconducting transition temperature of 9.2K. The niobium coating enables the rotor to be electrostatically suspended within the housing and provides a means for sensing the gyroscope spin direction, discussed below. The housing for the rotor, shown in two halves split by a parting plane, has 3 orthogonal pairs of electrodes used to suspend and sense the position the rotor. Once suspended, the rotors are spun-up by directing helium gas through the spin-up channel. The helium gas is then pumped away to high vacuum to eliminate residual gas damping of the rotor.

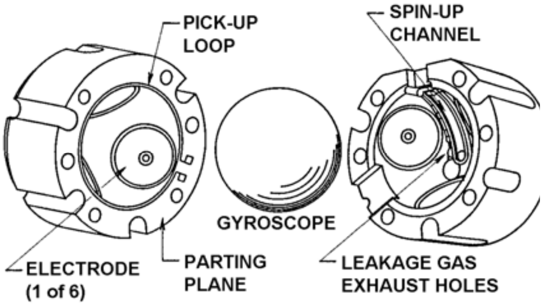

Figure 2. GP-B Gyroscope.

The housing electrodes also provide a means of sensing rotor charge. Since the rotors are freely floating, charge can accumulate due mainly to solar and South Atlantic Anomaly protons. A charge control system incorporates a UV fiber optic actuator that produces and controls photo electrons.

The gyroscope readout system must be capable of resolving changes in the rotor spin direction of less than 0.3 marcsec without producing interaction torques that could disturb that spin direction[7,8]. The low experimental operating temperature allows the properties of superconductivity to be exploited, both as the physical basis of the readout signal and in its detection. The readout signal is based on the magnetic field produced by the London moment of a rotating superconductor. When the superconducting niobium coated rotor is spun up, it develops a London magnetic moment aligned with its instantaneous spin axis. Interior to the gyro rotor, there is an effective uniform magnetic flux density of magnitude:

$$B_L = 1.14 \times 10^{-7}\, \omega_s \text{ Gauss}$$

where ω_s is the spin angular velocity. The London field is measured using a dc SQUID (or superconducting quantum interference device) magnetometer. On the parting plane between the two housing halves, there is a four turn superconducting loop that couples the London moment flux to the SQUID. The gyro spin axis is aligned close to the spacecraft roll axis, which lies in the parting plane, so the London moment produces a signal modulated at roll frequency. At a spin speed at 130 hertz, the London field will be just below 1×10^{-4} Gauss. Therefore, to resolve 0.3 marcsec changes in spin direction a field sensitivity of 1.5×10^{-13} Gauss is required. The noise performance of Gravity Probe B SQUID readout system meets this requirement with margin, as verified in full integrated systems testing.

Such low field levels also dictate the need for extensive magnetic shielding. Ultra low dc fields of less than 10^{-7} Gauss, required to minimize flux trapping in the rotor, are produced using the expanded superconducting lead shield technique[9]. This shield, coupled with extra internal superconducting shielding and an external Cryoperm shield yield ac (roll frequency) field attenuation at the gyroscopes of greater than 2×10^{12}.

Telescope and Guide Star Selection

It is necessary to measure the spin direction of the gyroscopes relative to a distant inertial reference frame, one not affected by the mass or spin of the earth. Therefore, a telescope is incorporated into the experiment module to track the position of a guide star. The star tracking telescope is of the folded Schmidt-Casagranian type with a 14.4 cm diameter aperture. It is constructed out of fused quartz and has an overall physical length of 50 cm. Two focused images are formed on the edge of roof prisms by splitting the incoming starlight with a beamsplitter. The edges of the roof prisms are perpendicular, providing two-axis readout. Each prism divides the star image into two partial images whose intensities are determined using cryogenic silicon photo detectors and cryogenic preamplifiers. The relative intensities of the prism-split images determine the direction of the line of sight to the guide star. Using this signal, the spacecraft attitude will be controlled to point in the direction of the guide star.

Cryogenic telescope tests have been performed using a ground based light source to act as a guide star. These tests have determined that the leading noise sources, photon counting noise and telescope readout electronics noise, are below system pointing requirements: less than 34 marcsec/√Hz.

An important factor in reaching design measurement accuracy is the selection of the guide star to provide an adequate inertial reference. Uncertainties in the proper motion of the guide star propagate directly as experimental error and therefore the guide star proper motion needs to be known to high precision. Review of candidate stars led to the selection of HR8703, which is of 5.69 optical magnitude and is radio bright. Observations by the Harvard Smithsonian Astronomical Observatory using VLBI have established sub 0.1 marcsec/yr proper motion uncertainties[10]. VLBI observations are continuing to further reduce these uncertainties.

GP-B Status

Payload and spacecraft elements underwent a series of testing and verification activities at the component and subsystem level. Integrated payload tests, conducted at Stanford University were completed in 2001. Payload-spacecraft integration took place at Lockheed Martin Sunnyvale. Prior to shipment to the Vandenberg, CA launch site the combined space vehicle completed a series of verification tests including acoustic and thermal vacuum tests. A late replacement of a dc/dc converter in a payload electronics box, prompted by reliability concerns, has recently been completed. Launch is scheduled for April 2004.

In parallel with space vehicle activities, a mission operations center (MOC) has been commissioned at Stanford. The MOC will provide command and control throughout mission lifetime. Wallops Island IONet will provide communication with ground stations at Svalbard, Norway and Poker Flat, Alaska.

Expected Performance

Integrated ground testing has yielded an expected on orbit performance that exceeds mission requirements by more than a factor of ten. Table 1 shows the requirements and expectation for the two relativity measurements based on 12 months of data taking out of a nominal 16.5 month mission lifetime. The improvement is primarily due to the performance of the SQUID based gyroscope readout system. At the expected performance level GP-B will provide the highest precision non null test of general relativity to date.

Effect	Requirement	Expectation
Frame Dragging	1.2%	0.1%
Geodetic	75 parts in 10^6	6 parts in 10^6

Table 1. Expected performance based on ground testing.

STEP

The Satellite Test of the Equivalence Principle is a program in development that will test the Equivalence Principle with a precision of better than five orders of magnitude beyond what has been achieved in ground tests. As formulated by Newton, the Equivalence Principle asserts the equivalence of gravitational mass m_g ($F = GMm_g/r^2$) and inertial mass m_i ($F = m_i a$). Generalized by Einstein, it is the foundation of general relativity. A consequence of the Equivalence Principle is the Universality of Free Fall: materials of different composition fall in a gravitational field with the same acceleration. Going back to Galeleo's Leaning Tower experiment, equivalence has been tested with improving precision. Present limits are placed at a few parts in 10^{13} by both ground based torsion balance experiments [11]and lunar laser ranging[12]. By exploiting the advantages of space, STEP will achieve a precision of 1 part in 10^{18}. A violation of equivalence would imply that general relativity is in error or that there is a new force of nature. A null result would constrain alternative or unified theories of gravitation.

STEP Collaboration

The concept for a cryogenic mission in space to test the Equivalence Principle was proposed by Worden and Everitt[13] following exchanges with Chapman and Hanson[14]. A ground based version, demonstrating key technologies and performing an

EP test at the 10^{-9} level, was build and operated in the 1980s with funding from the NASA PACE program and the National Science Foundation. STEP has grown into a international collaboration with mission and technology development funding from the NASA Office of Biological and Physical Sciences, ESA, and European national agencies including, CNES (France), DLR (Germany), ASI (Italy), and PPARC (UK). Participating institutions are listed in table 2.

Research Center Partners
Stanford University
University of Birmingham, UK
ESTEC
FCS Universität, Jena, Germany
Imperial College, London, UK
Institut des Hautes Études Scientifiques, Paris, Fr.
ONERA, Paris, France
PTB, Braunschweig, Germany
Rutherford Appleton Laboratory, UK
University of Strathclyde, UK
Universitá di Trento, Italy
ZARM, Universität Bremen, Bremen, Germany

Table 2. STEP Collaboration.

Mission Concept

STEP will compare the acceleration of four pairs of test masses in a 550 km high orbit about the earth. The free floating test mass pairs comprise differential accelerometers which are housed in a superfluid helium dewar enabling superconducting electronics and shielding and ultrahigh vacuum. As with Gravity Probe B, the helium boil off gas is used to power proportional thrusters to keep the satellite drag free using the test masses as reference. Within each differential accelerometer the test masses are constrained to move along one direction by means of a linear superconducting bearing. This constraint implies that any deviation from equivalence will produce a periodic differential acceleration at a well defined frequency. Measurements will be made with the satellite slowly rolling to modulate the EP signal; signal frequency equals orbit minus roll. The differential acceleration is measured using SQUID sensors. The differential accelerometers are designed such that the mass pairs form an outer test mass surrounding an inner test mass allowing their centers to be made coincident to minimize gravity gradient disturbances[15].

To minimize thermal variation the satellite will be in a sun synchronous orbit. Mission lifetime, determined by the boil-off of the liquid helium cryogen will be six months. Based on measured sensitivity of the SQUID detection system and a comprehensive error analysis[16] STEP will reach an expected precision of 1 part in 10^{18} in a measurement time of 20 orbits. This enables repeated tests (under varied conditions) during the mission lifetime to examine systematic effects.

Experiment Systems

STEP's key systems build on many of the technologies developed for GP-B including precision quartz manufacture, superconducting thin film patterning, SQUID detection systems, superconducting magnetic shielding, charge control, and helium proportional thrusters for drag free control. In the following we give a brief overview of STEP instrument features.

Differential Accelerometer

Figure 3 depicts the STEP differential accelerometer. The differential accelerometer design uses precision quartz machining to provide the structures needed for test mass alignment, positioning and measurement. These structures include inner and outer bearing substrates, SQUID detection coil substrates, and capacitive positioning and sensing structures. A pressure activated caging system constrains the masses during launch: during science mode the test masses have no mechanical connection.

Test Masses

Central to the STEP mission are the test masses. The cylindrical symmetry allows the placement of one test mass inside the other to reduce gravity gradient effects, the dimensional constraint to produce a periodic signal, and convenient access for acceleration and displacement detection. Their belted design enables the masses to act gravitationally as spheres, that is, the design reduces

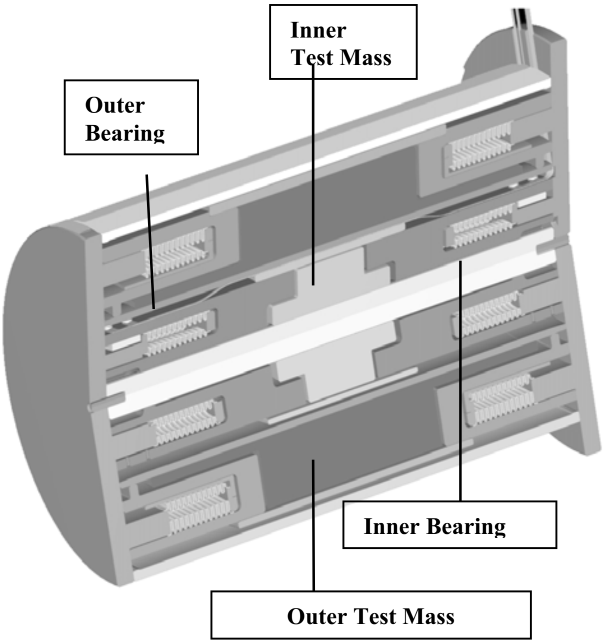

Figure 3. STEP Differential Accelerometer.

mass multipole moments, making the masses individually insensitive to gravity gradients[17]. The dimensions are selected to give 6th order insensitivity to gravity gradients. The STEP micron level machining tolerances and stringent density requirements place engineering constraints on the selection of test mass materials. The STEP collaboration has produced Be, Al, and Nb masses meeting these requirements. Analysis of the properties of several Pt alloys indicates that they can meet these requirements as well. The test masses are coated with a thin film of niobium that allows the use of superconducting bearings and SQUID acceleration detection.

To maximize the likelihood of detecting an EP violation, test mass materials should be 'as different from one another' as possible. While an optimal choice may depend on a particular violation model, Damour[18] has examined a general picture for new interactions that would couple to charges related to Lepton Number, Baryon Number, or electrostatic energy. Values for candidate masses are shown in table 3.

Material	Z	N	$\left(\frac{N+Z}{\mu}-1\right)10^3$	$\frac{N-Z}{\mu}$	$\frac{Z(Z-1)}{\mu(N+Z)^{1/3}}$
Be	4	5	-1.3518	0.11096	0.64013
Si	14	14.1	0.8257	0.00387	2.1313
Nb	41	52	1.0075	0.11840	3.8462
Pt	78	117.11	0.18295	0.20051	5.3081

Table 3. Lepton Number, Baryon Number and electrostatic energy values for candidate masses.

Superconducting Bearings

Each accelerometer contains an inner and outer superconducting bearing to constrain the motion of the test masses to one direction. The bearings are formed by patterning Nb thin films on quartz cylindrical substrates into meander circuits using a laser photo lithography process. Patterns are aligned to within 5 arc seconds of the cylinder axis. In operation persistent currents are injected into the bearing circuits to produce magnetic fields to repel the test masses along the radial direction.

Capacitive Sensing

Thin film electrodes are deposited on structures surrounding the test masses. These electrodes, with associated electronics serve multiple functions including: test mass position measurements in all degrees of freedom, initial test mass centering, cold damping of test mass motions, and test mass charge measurement.

SQUID Sensing

Perpendicular to the bearing axis the accelerometer contains superconducting loop circuits coupled to SQUID magnetometers. By trapping small currents in these circuits a weak restoring force is produced along the sensitive axis of the accelerometer. Accelerations experienced by the test masses will produce displacements of mass positions, which can be sensitively detected by the SQUIDs. With the circuit design as shown in figure 4, one can measure the common mode acceleration with one SQUID (used for the drag free control reference) and differential mode acceleration (the Equivalence Principle violating signal) with a second SQUID. Ground testing, using SQUIDs developed for GP-B, has confirmed differential acceleration sensitivities of better than 10^{-18} g.

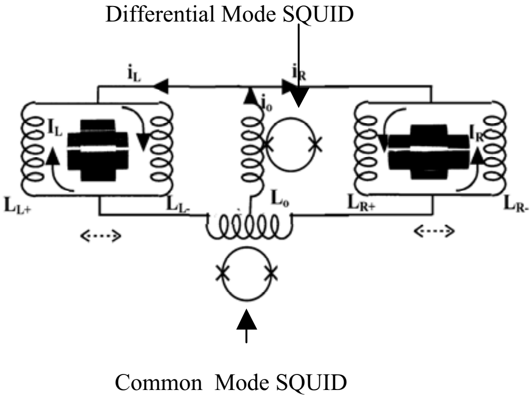

Figure 4. Step accelerometer SQUID sensing.

Dewar and Aerogel Confinement

STEP's four differential accelerometers are supported by a ridged quartz block structure housed in a 200 liter superfluid helium dewar. The dewar supports the operation of the superconducting instrumentation and magnetic shielding, reduces the thermal noise of the test masses, and provides the source of boil-off gas for the drag free control proportional thrusters. A possible disturbance due to the motion of the liquid helium is mitigated by use of Aerogel, which completely fills the helium reservoir. Ground testing has confirmed that Aerogel constrains superfluid helium even against 1 g accelerations and cryogenic shake tests have verified the integrity to survive launch loads[18].

STEP Status

Following the endorsement of scientific peer review panels and after successful completion of NASA OBPR Science Concepts Review and Requirements Definition Reviews, STEP has pursued paths to become a flight program.

STEP was selected for a Phase A study within the NASA OSS SMEX 8/9 program. The mission was not selected for flight since the review panel concluded that STEP's complex technology did not fit within SMEX constraints. However, the Phase A concept study report has provided a mature mission design. Further, ESA funded a suite of activities to support the initial proposal response to SMEX AO: 99-OS-05 and the preparation of the SMEX Concept Study Report. These included:

1. An Industrial Study awarded to ASTRIUM UK to develop the concept for low cost spacecraft to meet the STEP requirements,
2. A Payload Feasibility Study awarded to European STEP science team institutions to create a comprehensive review of European payload contributions, and
3. A joint JPL Team X/ESTEC CDF (Concurrent Design Facility) review to verify STEP space vehicle and mission implementation designs.

The industrial efforts yielded the production of the STEP Service Module Study Final Report (April 2000) detailing a spacecraft design based on ASTRIUM's low cost LEOSTAR bus. Two follow on studies, a STEP Pre-Phase B Service Module Study (April 2002) which included updated modal, thermal, and data handling analyses and STEP Pre-Phase B SM/PL Interface Design Document (IDD) (March 2002) detailing payload-spacecraft interface issues have resulted in a mature STEP spacecraft design. The Payload Feasibility Study Final Report (July 2002) details the European payload contributions including cost and schedule estimates. The Team X /CDF review culminated with the STEP Service Module JPL/CDF Joint Exercise Summary (June 2001) which confirmed STEP's mission requirements, technical requirements and mass and power budgets.

NASA has awarded the US STEP team FY03 funding as part of a two year proposal to finalize technology development. This places STEP in prime position to successfully compete for a flight program opportunity and to make important contributions to fundamental physics.

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