ABSTRACTS FROM SCIENTIFIC PAPERS GRAVITY PROBE B RELATIVITY MISSION
Stanford University

1989

M. P. Reisenberger, et al., "A Possible Rescue of General Relativity in Di Herculis," Astronomical Journal 97, pp. 216-221, 1989.

Abstract:

The binary DI Her has attracted attention because its low observed rate of apsidal advance, dw/dt = 1.0° ± 0.3°/100yr, appears to contradict general relativity, which seems to require dw/dt = 4.3° ± 0.3°/100 yr. We present very tentative evidence in support of the hypothesis (advanced by Shakura) that the stars are rotating about axes highly inclined to the orbital axis. If the inclination of a component is > 54.7°, then its rotational distortion will slow the apsidal advance. From rather sparse data, we calculate dw/dt = 0.7° ± 2.0°/100 yr. Two measurements that could help settle the issue are proposed. Both could be done easily by an observer with access to a fairly large(>50 in.) telescope and a CCD spectrograph.

P. Axelrad, B. W. Parkinson, "Closed Loop Navigation and Guidance for Gravity Probe B Orbit Insertion," Journal of The Institute of Navigation, Vol. 36, No. 1, Spring 1989.

Abstract:

This paper addresses the problem of guiding the Gravity Probe B (GP-B) spacecraft from its location after initial insertion to a very precise low earth orbit. Specifically, the satellite orbit is required to be circular to within 0.001 eccentricity, polar to within 0.001 deg inclination, and aligned with the direction of the star Rigel to within 0.001 deg. Navigation data supplied by an on-board GPS receiver is used as feedback to a control algorithm designed to minimize the time to achieve the desired orbit. Translational control is provided by the proportional helium thrusters, which are used for drag-free and attitude control during the remainder of the science mission. Simulations of the guidance system are presented which give an indication of performance characteristics for several types of orbit injection errors.

This research is the first reported effort to use GPS as a sensor for a closed loop space guidance system.

B. W. Parkinson, P. Axelrad, "Closed Loop Orbit Trim Using GPS," 40th International Astronautical Congress Symposium on Astrodyanamics, Malaga, Spain, October 1989.

Abstract:

This paper describes an onboard closed-loop navigation and control system capable of executing extremely precise orbit maneuvers. It uses information from the Global Positioning System (GPS) and an onboard controller to perform orbit adjustments. As a result, the system *circumvents the need for extensive ground support*. The particular application considered is an orbit injection system for NASA's Gravity Probe B (GP-B) spacecraft. Eccentricity adjustments of 0.0004 to 0.005, and inclination and node changes of 0.001 to 0.01 deg. are demonstrated. The same technique can be adapted to other satellite missions.

C. W. F. Everitt, et al., "Gravity Probe B as a Geodesy Mission and Its Implications for TOPEX, April 1989.

Introduction:

Gravity Probe B (GP-B), a NASA Mission currently under development at Stanford University with support from Lockheed Missiles and Space Company, is designed to provide two extremely precise new tests of Einstein's general theory of relativity by means of observations on gyroscopes in Earth orbit. The experiment is to be flown in a polar orbiting drag-free satellite at an altitude between 600 and 650 km. The satellite will carry an onboard Global Positioning System (GPS) receiver for precise tracking. Launch is expected in 1995 or early 1996.

In 1987, following discussion between Smith and Everitt, we with other colleagues in the geodesy community came to the realization that Gravity Probe B could at very modest additional cost also provide new geodesy data of great importance in studies of geodynamics and also, more specifically, for improving the geoid to be applied in reducing the TOPEX (TOPographic Experiment) altimeter data. The TOPEX altimeter has a height measurement precision of 2 cm, and oceanographic applications are limited by satellite orbit and marine geoid accuracies. Gravity Probe B appears capable of making a major contribution to reducing these uncertainties by providing a significant improvement in the knowledge of the Earth's gravity field. The net result could well be a factor of five to ten improvement in the recovery of the medium to long wavelength components of the mean dynamic topography associated with the global circulation from TOPEX and even greater improvement in the determination of the geoid itself.

The contribution which GP-B can make to the knowledge of the Earth's gravity field is referred to as the "geodesy coexperiment." It has now been studied in some detail by two groups: D. E. Smith, O. L. Colombo and E. C. Pavlis at NASA Goddard Center, and by M. Tapley and J. V. Breakwell at Stanford University. A third independent study has been performed by W. G. Melbourne at JPL. We summarize here preliminary results of these investigations and indicate directions for future work.

A second co-experiment is being considered. External forces acting on the satellite are cancelled by the drag-free control system. The control effort is therefore a measure of the external forces. When corrected for radiation pressure and other modelable disturbances [*Moe et al., 1976*], it is a measure of atmospheric drag. The measurement can provide unprecedented spatial resolution of atmospheric drag. The measurement can provide unprecedented spatial resolution of atmospheric drag at this altitude. Preliminary discussion with Gerald Keating of NASA Langley Research Center suggests that adding mass spectrometers would help in resolving the direction of the relative wind and would provide compositional data for correlation with observed drag variations.

G. B. Green, P. Axelrad, "Space Applications of GPS," Institute of Navigation National Technical Meeting, San Mateo, CA, January 1989.

Abstract:

The country's space systems ground command and control network is rapidly becoming antiquated, and will not be able to handle the expansion of space traffic projected in the 21st century. There is a heavy reliance on vulnerable overseas ground locations which are not guaranteed. A cooperative satellite system architecture based on GPS would significantly alleviate the complexity of a future command and control structure. Specifically, if each satellite were to carry a GPS receiver as part of its telemetry tracking and command subsystem, all space vehicles could maintain accurte time, ephemeris, and attitude estimates. The commonalty of the system to all users would permit the operation of a time division multiple access system such that the ground monitoring function would be reduced to merely reviewing the telemetered data.

P. Wiktor, J-H. Chen, D. B. DeBra, "Optimal Thruster Configurations for the GP-B Spacecraft," Xth IFAC Symposium on Automatic Control in Aerospace, Tsukuba, Japan, July 17-21, 1989.

Abstract:

Thruster locations and control schemes which make the most efficient use of the available propellant of a constant flow propulsion system are investigated. A set of three necessary and sufficient conditions are established for a thruster system to be optimal in the sense of maximizing the smallest magnitude force which can be generated by the thrusters. Analytical expressions are derived for 'the envelope of least authority' which is defined as the smallest force magnitude vs. moment magnitude which can be generated by any given thruster system. Several thruster configurations are proposed for the GP-B spacecraft and their performance is compared with respect to their envelopes of least authority. The results are applicable to any system composed of thrusters which saturate at some finite value.

D. Bardas, M. A. Taber, et.al., "The Gravity Probe B Relativity Gyroscope Experiment: Preparations for the First Integrated Systems Test," Stanford University, January 1989.

Abstract:

The Gravity Probe B Relativity Gyroscope Experiment (GP-B) will provide a precise and controlled test of Einstein's General Theory of Relativity by observations of the precession of nearly perfect gyroscopes in Earth orbit. For gyroscopes in a 650 km polar orbit the theory predicts two orthogonal effects, known as the geodetic and frame-dragging precessions, with calculated rates of 6.6 arc-s/yr and 0.042 arc-s/yr respectively. The goal of the experiment is to measure the geodetic effect to better than 0.01% and the frame-dragging effect to better than 1%. This paper will summarize recent progress in gyroscope fabrication and testing along with preparation for the First Integrated Systems Test. Hardware for this test consists of full-sized components integrated into an experimental package which is a close prototype of that planned for the Science Mission spaceflight.

G. B. Green, C. W. F. Everitt, B. W. Parkinson and the Stanford University Gyroscope Team "The Flight Test Program of the 10^{-11} Degree/Hour Gyroscope," Fourteenth Biennial Guidance Test Symposium, Department of the Air Force, Headquarters 6585th Test Group (AFSC), Holloman Air Force Base, New Mexico, October, 1989.

Abstract:

Physicists and engineers at Stanford University have created a wide range of exotic technologies to build and conduct a flight test of the lowest drift gyroscope ever built. These gyroscopes provide an absolute (without calibration of the gyroscope) reference system stable to 10^{-11} degrees/hour total drift—a million times better than the typically good calibrated inertial navigation system grade gyroscope. The flight test program of these gyroscopes will probe the very foundations of inertial space.

1990

P. Axelrad, R. H.Vassar, B. W. Parkinson, "GP-B Orbit Modeling and Injection Requirements," AAS91-164, Winter of 1990.

Abstract:

Gravity Probe B (GP-B) is a NASA spacecraft mission to test two previously unverified aspects of Einstein's theory of General Relativity. The plan is to measure two tiny drifts, known as the geodetic and frame dragging drifts, as manifested in a nearly perfect gyroscope in orbit around the Earth. Our goal is to measure these drifts to an accuracy of 0.4 marcsec/yr as compared to the direction to a distant inertial reference. Of this error, approximately 0.1 marc/sec/yr is allocated to orbit induced drifts.

The ideal orbit for the GP-B spacecraft is circular, polar, and contains the line of sight to the guide star, Rigel. The drag compensation system employed to reduce the nongravitational disturbances acting on the science gyros governs the orbit motion during the course of the 18 month experiment. Thus, the orbit will be perturbed primarily by the non-central terms in the Earth's gravitational field, the Sun, and the Moon. An additional effect due to the precession of the equinoxes is also considered. These influences on the orbit are modeled and simulated in order to determine the initial orbit elements which will yield the smallest overall deviation from the ideal orbit. Injection error tolerances are derived to meet the desired Newtonian gyro drift rate of less than 0.1 marcsec/yr.

B. W. Parkinson, J. R. Crerie, "Phase-Lock Roll Control for Inertially-Pointing Spacecraft by Correlations of Star Intensity Profiles with a Stored Reference," 13th Annual AAS Guidance and Control Conference, Keystone, Colorado, February 3-7, 1990.

Abstract:

The spacecraft which houses the Stanford Relativity Gyroscope Experiment (GP-B) is designed to roll with a 10 minute period about its pointing axis. A precise measurement of roll phase is needed to demodulate the two relativity effects being measured by GP-B, and a steady roll rate is desired to effectively average disturbances to the experiment. Optimally, the spacecraft will be flown with no rotating machinery on board, so it is desired to control roll without the use of conventional rate gyros. A new technique has been devised to ***achieve highly accurate roll control without a rate gyro*** by employing one or more slit star sensors which rotate with the spacecraft, and correlate their output with a known reference to produce a measurement of roll offset.

The technique developed to control roll phase and ***rate mimics those used in pseudorandom noise telecommunication*** equipment. The algorithm regards the intensity pattern of the surrounding star field as pseudorandom noise which repeats itself every 360 degrees, and sets up a "phase-locked" loop to align the pattern with a stored reference pattern. Single-axis simulations confirm that such a device, when combined with a steady-state Kalman estimator, can control roll position to an accuracy of 25 arcsec RMS, and roll rate to an accuracy of 0.92 arcsec/sec RMS, even when the star sensor output and reference values are encoded with only one bit. This level of performance can be achieved using available thruster torques, and while staying within the mission-prescribed attitude acceleration limits. Algorithms for initial acquisition of roll phase have also been devised so that phase lock can be achieved within a fraction of the orbit period.

C. W. F. Everitt, et al., "The Merits of Space and Cryogenic Operation in the Gravity Probe B Relativity Gyroscope Mission," The First William Fairbank Meeting, Rome, Italy, 1990.

Abstract: None

S. Buchman, Y, M. Xiao, L. Pollak, D. Kleppner, T. J. Greytak, "The Recombination of Atomic Hydrogen Below 1K," Physica B, Proceedings of the 19th International Conference on Low Temperature Physics LT-19 ed. David S. Betts, Brighton, Sussex, p. 745 August 1990.

Abstract:

We have conducted an NMR study of the hydrogen recombination process in the temperature range 0.2K – 0.6K. Starting with a gas of doubly polarized atomic hydrogen we produce molecular ortho hydrogen. The nuclear spin polarization is quickly lost after the recombination process. The time constant for the de-polarization is less than 0.1s, and the initial nuclear spin temperature of the solid is larger than 4K.

H. T. Chou, "A Robust Filter Configuration for DGPS Users," ION GPS-90, (ION Satellite Division 3rd International Technical Meeting), Colorado Springs, Colorado, September 1990.

Abstract:

This paper describes the implementation and performance of a robust filter configuration for Differential GPS users. The filter is set up to adaptively determine an error correction model while pseudo range corrections are being received from a DGPS reference station. In case the reference data link is lost, the model is used to predict the error corrections ahead. Hence, improved position accuracy over standard GPS can be maintained for a certain period of time after the loss of the correction signal from the reference station. Preliminary results of the filter implementation using actual GPS data are presented which demonstrate the efficacy of the configuration.

H. T. Chou, "An Anti-SA Filter for Non-differential GPS Users," ION GPS-90, (ION Satellite Division 3rd International Technical Meeting), Colorado Springs, Colorado, September 1990.

Abstract:

Selective availability induces large position errors for GPS users. In this paper, SA is modeled and the model parameters are identified by on-line system identification. Combining the results of identification with a Kalman Filter, an adaptive filtering algorithm is implemented. The effectiveness of this filter to alleviate the SA effects upon non-differential GPS users is justified by static test data.

B. W. Parkinson, P. Axelrad, "Techniques for Autonomous GPS Integrity Monitoring," AGARDograph No. 314, Advisory Group for Aerospace Research & Development, NATO Loughton, Essex, June 1990.

Summary:

The use of GPS for navigation critical applications such as aircraft non-precision approach or harbor and river crossings requires the navigation data to be both extremely accurate and extremely reliable. This paper outlines various approaches to GPS integrity checking, and describes a method for user autonomous satellite failure detection and isolation (D/I). The test statistic for the D/I algorithm is the range residual parameter based on six or more satellites in view. The nominal pseudo range measurement errors are modeled as normally distributed with mean in the range of –5m to +5m and standard deviation of 0.4m based on experiments conducted at Stanford. The theoretical statistical distribution of the range residual is given. Monte Carlo simulations present results of applying the algorithm to measurement sets containing a biased measurement. With a 100m biased measurement present successful detection is achieved 99.9% of the time, and successful detection and isolation is achieved 72.2% of the time. The user is always aware when isolation is not possible. User positioning errors resulting from application of the algorithm are always the same or better than the all in view solution.

C. Kee, B. W. Parkinson, P. Axelrad, "Wide Area Differential GPS", ION GPS-90 (ION SatelliteDivision 3rd International Technical Meeting), Colorado Springs, Colorado, September 1990.

Abstract:

The Global Positioning System (GPS) has proven to be an extremely accurate positioning sensor for a wide variety of applications. However in some situations, such as aircraft approach and landing, higher accuracy is required. Wide Area Differential GPS (WADGPS) is a system which could be used to meet such requirements. The WADGPS system is comprised of a master station, and local monitor stations distributed across the United States. The WADGPS system calculates and transmits a vector of error corrections to the users. This correction vector consists of parameters describing the three dimensional ephemeris errors, satellite clock offsets, and ionospheric time delay parameters. The master station gathers GPS measurements made at each of the local stations and estimates the errors using a combination of batch lease squares plus either nonlinear static estimation or Kalman filtering algorithm. The performance of a 15 station WADGPS network was investigated by simulation for users at sites across the U. S. The monitor stations were located at existing LORAN or VOR stations. Simulation results indicate that normal GPS positioning errors can potentially be reduced by more than 95% using WADGPS.

T. Walter, J. P. Turneaure, S. Buchman, C. W. F. Everitt, G. M. Keiser, "An Ultra High Vacuum Low Temperature Gyroscope Clock," Physica B, Proceedings of the 19th International Conference on Low Temperature Physics LT-19, ed. David S. Betts, Brighton, Sussex, P. 155 August 1990.

Abstract:

We propose to perform a nulll-gravitational redshift experiment by comparing a mechanical gyroscope clock with atomic clocks. The Gravity Probe B Relativity Gyroscope Experiment provides the opportunity for this co-experiment. The goal is to measure the effect to an accuracy of 0.01% of the gravitational redshift due to the eccentricity of the orbit of the earth about the sun. This corresponds to an integrated frequency measurement over one year of $\Delta v/v=3^{*}10^{-14}$. A major disturbance torque on the gyroscope is due to fluctuations in the molecular drag of the residual gas caused by temperature variations. We propose to use a low temperature bake-out technique in order to achieve the required vacuum of 10^{-17}torr.

C. E. Cohen, G. M. Keiser, B. W. Parkinson, "Tracking Gravity Probe B Gyroscope Polhode Motion," AIAA Guidance, Navigation and Control Conference, Portland, Oregon, August 20-22, 1990.

Abstract:

A freely spinning body undergoes the well-known polhode motion of its spin axis. For the state-of-the-art gyroscopes of the Relativity Gyroscope Experiment, this motion is particularly interesting, since its characteristics verify almost perfectly spherical *rotor has no markings*. This paper describes an unusual analysis technique that allows reconstruction of the polhode motion, relying on the *trapped magnetic flux* in the *superconducting rotor.*

D. Kalligas, "Do Cosmic Strings Violate the Equivalence Principle?" Proceedings from The First William Fairbank Meeting on Relativistic Gravitational Experiments in Space held at the University of Rome, Advanced Series in Astrophysics, and Cosmology, Vol. 7. September 10-14, 1990.

Abstract:

We examine the compatibility of cosmic strings with the equivalence principle. In particular, we look for mass dependent accelerations of particles moving in the field of a cosmic string, and also of cosmic strings moving in background gravitational fields. Contrary to recent suggestions, it appears that there should be no detectable violation of the equivalence principle.

J. M. Lockhart, R. L.Fagaly, L. W. Lombardo, B. Muhlfelder, "Magnetic Susceptibility of Instrument Materials Below 10K, Physica B. 165 & 166 (1990) 147-148.
Abstract:

Measurements were made of the magnetic susceptibility in the temperature range 2K – 10K of twenty-nine samples of materials and components used in the construction of cryogenic instruments. The use of SQUID-based superconducting susceptometers allowed high resolution. The data was fitted to a Curie law form and the values of the coefficients were determined. The remanent magnetization at 2Kof several of the samples was also measured.

M. Taber, et al., "Results from the First Integrated System Tests of the Gravity Probe B Experiment." The First William Fairbank Meeting, sponsored by ASI, ESA, ISSA, NASA, Rome, Italy, September 10-14, 1990.
Abstract:

The Gravity Probe B Relativity Gyroscope Experiment (GP-B) will provide a precise and controlled test of Einstein's General Theory of Relativity by observations of the precession of nearly perfect gyroscopes in Earth orbit. For gyroscopes in a 650 km polar orbit the theory predicts two orthogonal effects, known as the geodetic and frame-dragging precessions, with calculated rates of 6.6 arc-s/yr and 0.042 are-s/yr respectively. The goal of the experiment is to measure the geodetic effect to better than 0.01% and the frame dragging effect to better than 1%. This paper describes the First Integrated System Tests (FIST) which is the first attempt of the GP-B Program to design, build, integrate, and test hardware that is in many respects prototypical of the flight instrument. Results from the successful completion of the first two segments of FIST, which include the operation of two gyroscopes and a number of engineering tests, are summarized.

B. W. Parkinson, N. J. Kasdin "A Magnetic Attitude Control System for Precision Pointing of the Rolling GP-B Spacecraft," Acta Astronautica, Vol. 21, No. 6/7, pp. 477-486, January 23, 1990, Great Britain, Pergamon Press.
Abstract:

A new algorithm for magnetic attitude control of spinning spacecraft is presented. This algorithm requires real time measurements of the local magnetic field. A Kalman filter type estimator is derived that can obtain the local field by applying dither current to the magnetic rods. This eliminates the need for magnetometers, guaranteeing colocation of sensor and actuator and removing a number of failure modes. An example controller design is presented for the Gravity Probe B spacecraft pointing control. This controller achieves better than 20 milliarcsec pointing accuracy using the magnetic control algorithm without magnetometer measurements.

B. W. Parkinson, J. R. Crerie, "Phase-Lock Roll Control for Inertially-Pointing Spacecraft by Correlations of Star Intensity Profiles with a Stored Reference," 13th Annual AAS Guidance and Control Conference, Keystone, Colorado, February 3-7, 1990.
Abstract:

1991

C. W. F. Everitt, "Gravity Probe B: I. The Scientific Implications," Proceedings of the Sixth Marcel Grossmann Meeting on Relativity, Kyoto, Japan, eds. H. Sato and T. Nakamura, World Scientific, pp. 1632-1644, 1991*
Abstract:

This paper describes the two primary and four secondary experimental tests of general relativity expected to be performed by the Gravity Probe B relativity gyroscope mission and reviews recent discussions about the significance of the experiment.

D. Bardas, et al., "Gravity Probe: II Hardware Development; Progress Towards the Flight Instrument," presented at the Sixth Marcel Grossmann Meeting on Relativity, Kyoto, Japan, June 23-29, 1991.*
Abstract:

The Gravity Probe B Relativity Gyroscope Experiment (GP-B) will provide a precise and controlled test of Einstein's General Theory of Relativity by observations of the precession of nearly perfect gyroscopes in Earth orbit. For a 650 km polar orbit the two effects predicted by the theory, known as the geodetic and frame-dragging precessions, are orthogonal with calculated rates of 6.6 arc-s/yr and 0.042 arc-s/yr respectively. The goal of the experiment is to measure the geodetic effect to better than 0.01R and the frame-dragging effect to better than 1%. This paper summarizes progress towards development of the GP-B flight instrument, focusing primarily on the accomplishments of the last three years. It describes the First Integrated Systems Test (FIST), successfully completed in 1990, of a

partially prototypical instruments, as well as the development and flight of a Shuttle Test Unit (STU) which will test aspects of the gyro system performance in a low acceleration environment.

Y. M. Xiao, et al., "Gravity Probe B: III. The Precision Gyroscope," presented at the Sixth Marcel Grossman Meeting on Relativity, Kyoto, Japan, June 23-29, 1991.

Abstract

Gyroscopes with Newtonian drift rate less than 0.3 milli-arc-sec/year are under development for the GP-B experiment. This paper presents recent progress in the major areas of the gyro development, including rotor mass unbalance, rotor asphericity, rotor charge control and rotor spinup. All of these results are at or near the requirements of the GP-B experiment, which is expected to be launched in 1998.

G. B. Green, et al., "Calibration and Test of the World's Most Accurate Gyroscope," The ION National Technical Meeting, Phoenix, Arizona, January, 1991.

Abstract: None

M. Tapley, et al., "Gradiometry Coexperiments to the Gravity Probe B and STEP Missions," Adv. Space Res. Vol. II, No. 6, pp. (6) 182-1991.

Abstract:

The Gravity Probe B spacecraft, designed to test predictions of general relativity, will fly in the mid 1990's. It will carry four electrostatically suspended gyroscopes in a cryogenic environment and will have a drag-free control system to minimize disturbances on the gyroscopes. The Stanford Test of Equivalence Principle (STEP) spacecraft, to fly later, will carry a set of test masses under very similar conditions. This paper explores the possibility of using differential measurements of the GP-B gyroscope suspension forces and the STEP test mass displacement readout to form single-axis gravity gradiometers. We show that the noise in the suspension systems is sufficiently small in the relevant frequency range, and that enough information is collected to compensate for the spacecraft's attitude motion. Finally, using Breakwell's "flat-earth" approximation, we compare these experiments to other geodesy experiments and predict the contribution they can make to the knowledge of the Earth's geopotential.

G. M. Gutt, et al., "An Ultralow Noise Amplifier for Superconductive Detectors," Third International Superconductive Electronics Conference, University of Strathclyde,Glasgow, Scotland June 25-27, 1991.

Abstract:

The design and construction of an ac-coupled, ultralow noise amplifier (equivalent input noise voltage E_n= 0.33 nV/$\sqrt{Hz}$, optimum source impedance 1kΩ at 100kHz) is presented. The amplifier employs nine Sony 2SK152-4 JFETs in parallel to yield the low noise result. Measurements were taken to characterize the amplifier's bandwidth, the additive voltage noise vs. frequency, and the current noise vs. frequency. SPICE modeling parameters for the JFETs used will also be discussed. Finally, we will review the performance of the amplifier in a flux-locked SQUID application.

J. P. Turneaure, J. Halbritter, H. A. Schwettman, "The Surface Impedance of Superconductors and Normal Conductors: The Mattis-Bardeen Theory," Journal of Superconductivity, Vol. 4, No. 5, 1991.

Abstract:

The contribution of the Mattis-Bardeen theory to the understanding of the surface impedance of superconductors and normal conductors is reviewed. The early theoretical and experimental studies of the surface impedance of conductors are sketched to provide the context in which the Mattis-Bardeen theory and, independently, the Abrikosov-Gor'kov-Khalatnikov theory were developed. the Mattis-Bardeen theory if described along with the methods for numerical calculation of the effects of anisotropy and strong coupling are briefly discussed. Theory is compared with representative measurements of the surface impedance, demonstrating excellent agreement in absolute magnitude and in the dependences on frequency, temperature, and material parameters.

Y. M. Xiao, G. M. Keiser, "Observations of Flux Motion in Niobium Films," IEE Transactions on Magnetics, Vol. 27, No. 2, March, 1991.

Abstract:

Magnetic field trapped in a superconducting sphere is examined at temperatures from 4.6 K to 5.5 K. The sphere is the rotor of a precision gyroscope, and is made of fused quartz and coated with a sputtered niobium film. The rotor diameter is 3.8 centimeters. The film thickness is 2.5 micrometers. The tests are carried out at ambient magnetic field

of about 1 milligauss. Unexpected instability of the trapped field is observed. The experimental results and possible explanations are presented.

C. Kee, B. W. Parkinson, P. Axelrad, "Wide Area Differential GPS," NAVIGATION, Journal of The Institute of Navigation, Vol. 38, No. 2, Summer 1991.

Abstract:

GPS has proven to be an extremely accurate positioning sensor for a wide variety of applications. However, in some situations, such as aircraft approach and landing, higher accuracy is required. Wide Area Differential GPS (WADGPS) is a system that could be used to meet such requirements. The WADGPS system comprises a master station, and local monitor stations distributed across the United States. The system calculates and transmits a vector of error corrections to users. This correction vector consists of parameters describing the three-dimensional ephemeris errors, satellite clock offsets, and ionospheric time delay parameters. The master station gathers GPS measurements made at each of the local stations, and estimates errors using a combination of nonlinear static estimation and batch least squares. The performance of a 15-station WADGPS network was investigated by simulation for users at sites across the United States. The monitor stations were located at existing Loran or VOR stations. Simulation results indicate that normal GPS positioning errors can potentially be reduced by more than 95 percent using WADGPS.

Y. M. Xiao, "Effects of Trapped Magnetic Flux on the GP-B Experiment, unpublished, July, 1991.

Abstract

Analytic formulars which describe the contribution of the trapped flux to the output of the magnetometry system are derived. The formulars reveal that the current readout system is adequate even there is significant flux trapped on the rotor; furthermore, if adequate filtering system or techniques to control the flux pattern could be developed, the trapped flux signal can significantly improve the readout accuracy and provide gyroscope dynamic information.

C. E. Cohen, B. W. Parkinson, "Mitigating Multipath Error in GPS Based Attitude Determination." Reprinted from Guidance and Control 1991,Vol. 74, Advances in Astronautical Sciences.

Abstract:

The Global Positioning System (GPS) offers the potential for significant cost savings in applications where inertial guidance has traditionally been the standard approach. Usually the velocity and position accuracies are the key selling points for GPS. Often overlooked is the capability of also using GPS to determine vehicle attitude.

Attitude is determined by differential measurements of GPS carrier phase between pairs of antennae. A major disturbance of phase measurements comes from unwanted reflections of the carrier (multipath). Reducing the causes or symptoms of multipath will enable differential phase receivers to achieve significantly higher accuracy. For example, with a 2 m antenna separation and a 2 Hz output rate, the method presented here has the capability to reduce the rms orientation error to less than one minute of arc with existing receivers.

A new calibration technique is described which models out multipath error emanating from the vehicle itself. The technique is readily applicable to flight vehicles (and perhaps certain classes of ground vehicles), where measurement errors due to multipath should be repeatable as a function of satellite direction relative to the vehicle body frame. Experimental results are presented to substantiate the accuracy improvements made possible by the technique.

E. T. Will, "Screening programme to select a resin for Gravity Probe B composites."Cryogenics 1991, Vol. 32. No.2.
Lockheed Palo Alto Research Laboratory, 3251 Hanover Street, Palo Alto, CA 94304, USA

The Gravity Probe B (GP-B) programme undertook a screening programme to select a possible replacement resin for the E-787 resin currently used in composite neck tubes and support struts. The goal was to find a resin with good cryogenic and structural properties, low helium permeation and an easily repeatable fabrication process. Cycom 92, SCI REZ 081 and RS-3 were selected for comparison with E-787. Identical composite tubes made from each resin and γ-alumina fibre (85% $A1_2O_3$, 15% SiO_2) were evaluated for cryogenic and structural performance and for processability. Cryogenic performance was evaluated by measuring low-temperature permeation and leaks to determine cryogenic strain behaviour. Structural performance was evaluated by comparing the resin-dominated shear strength of the composites. Processability was evaluated from fabrication comments and GP-B's own experience. SC1 REZ 081 was selected as the best overall resin with superior strength and cryogenic performance and consistent processability.
Keywords: composites; permeation; modulus

John G. Brisson, John C. Mester, IsaacF. Silvera, "Third sound of helium on a hydrogen substrate," Phys. Rev. B, Vol. 44, No. 22, December 1, 1991-II.

Abstract:

Measurements of third sound of thin helium films on molecular-hydrogen substrates have been made as a function of the measured helium thickness, both by a time-of-flight technique and in a third-sound resonator. Great care has been devoted to making uniform films of hydrogen, to determine reliable values of the helium-hydrogen van der Waals constant α and the thickness of the helium dead layer, Δ. Areal and gas-loading parameters have been measured to allow an absolute determination. We find a value of 21.3 K layer^3 for α and 2.0 for Δ. Comparisons are made to other values in the literature. Our value of the van der Waals constant is in good agreement with a complementary determination by Paalanen and Iye and by Cieslikowski *et al*., using electron mobility, but is much larger than a value reported by Mochel and a value calculated by Cheng *et al*. We also determine values for helium on copper; however, this determination depends on the literature value for the van der Waals parameter for helium on glass.

C. E. Cohen, G. M. Keiser, B. W. Parkinson, "Estimation of Gyroscope Polhode Motion Using Trapped Magnetic Flux." Reprinted from Journal of Guidance, Control and Dynamics, Vol. 15, Number 1, pp.152-158, January-February 1992.

A freely spinning body undergoes the well-known polhode motion of its spin axis. Applied to the cryogenic, electrostatically suspended spherical gyroscopes of the Gravity Probe B program, an unusual analysis technique is presented that allows reconstruction of the polhode motion, relying on the trapped magnetic flux in the

superconducting rotor. Cooled to a temperature below 9 K, the niobium rotor coating becomes a superconductor, trapping the ambient magnetic field. Fixed with respect to the rotor body frame, this trapped magnetic flux is used as a reference against which to track the path of the rotor spin axis. The field is modeled as a series expansion in spherical harmonics. Consideration of any higher-order moment of the magnetic field along with the dipole moment is sufficient to completely define the spin axis coordinates in the body frame.

Y. M. Xiao, S. Buchman, L. Pollack, K. Kleppner, T. J. Greytak, "Observation of Nonstatistical Ortho-para Ratoin Hydrogen Recombination at Low Temperatures, J.Chem. Phys. Vol. 96, March 1992.
No abstract

D. Kalligas, P. Wesson, C. W. F. Everitt, "Flat FRW Models with Variable G and L General Relativity and Gravitation," Vol. 24, No. 4, 1992.
Abstract:

We consider Einstein's equations with variable gravitational coupling *G* and cosmological term Λ. For a power-law time-dependence of *G*, the cosmological term varies in proportion to the inverse square of the time, provided the equation of state is not that of vacuum. There is then no dimensional constant associated with Λ. For a vacuum equation of state the model is compatible with classical inflation for a wide class of functions G (*t*) and Λ (*t*). For non-power-law behaviour of G (*t*), it is possible to have a scale factor that increases exponentially without a vacuum equation of state. For this case the energy density associated with Λ decreases exponentially, while at time zero it is equal with opposite sign to the regular energy density, so there is zero total energy initially.

Y. M. Xiao, W. Felson, C.H. Wu, G. M. Keiser, J. P. Turneaure, "Observation of the London Moment and Trapped Flux in Precision Gyroscopes," Proceedings of the Applied Supereconductivity Conference, Chicago, Ill, August 24-28, 1992.
Abstract:

Precision gyroscopes are under development for an experimental test of general relativity. The spherical gyroscopes are made of fused quartz and are sputter coated with a Nb film. The superconducting Nb film generates the London magnetic dipole moment proportional to the spin speed that is used to magnetically readout the direction of the gyro spin axis. Here, we report observations of the London moment of an operating gyroscope consistent with the expected magnitude and proportional to the spin speed. The magnetic flux trapped in the film interferes with the London-moment readout unless its magnitude is significantly smaller. Values of the dipole component of the equivalent trapped magnetic field as low as 1.5×10^{-11} T have been observed.

Y. Jafry, J. Vanden Beukel, "Ultralow Density Plume Measurements Using a Helium Mass Spectrometer," J. Vac. Sci, Technol. A, Vol. 10, No. 4 July/August 1992.

Gravity Probe B and the Satellite Test of the Equivalence Principle are two proposed experiments in basic physics which will utilize *drag-free* satellites equipped with proportional helium thrusters. In order to calibrate the thrust systems for precise *aeronomic* measurements, it is necessary to model the effects of thruster plume impingement. Conventional plume models are invalid, owing to the high degree of rarefaction in the nozzles (Kn = 0.01-1.1). An experiment was devised to measure the plume angular mass flux distribution using a helium mass spectrometer. The results suggest that the plume shapes are unchanged with mass flows around the nominal, and are generally wider than for conventional spacecraft control jets. A narrowing effect was observed at very low mass flows, in qualitative agreement with Monte Carlo results from the literature. The continuum model for the plume was found to be surprisingly accurate at nominal mass flows, and the inverse-square law was demonstrated to be a valid description of the far-field radial density profile.

P. Zhou, S. Buchman, K. Davis, C. Gray, J. P. Turneaure, "Multilayer Ti-Cu Sputter Films for the Gravity Probe B Gyroscope Housings," Surface and Coatings Technology, 54/55) 548-551 1992.
Abstract:

Multilayer Ti-Cu films with three, five, and seven individual layers have been prepared by sputtering on fused quartz substrates. The multilayer films have been studied by electron field emission, X-ray diffraction, scanning electron microscopy (SEM), and X-ray photoelectron spectroscopy. Trilayer Ti-Cu-Ti electrode films exhibit reduced electron field emission. Ti-Cu-Ti trilayer films have been applied to the Gravity Probe B gyroscope housings. The thin

films have been deposited by sputtering onto the fused quartz housings to form suspension electrodes and lands. The gyroscopes have been successfully spun to 170 Hz.

C. H. Wu, "Modeling and Simulation of the AC Suspension System by Linear and Nonlinear Analysis, December 3, 1992, (unpublished)
Abstract:

The dynamics of the AC **current** modulated gyro suspension system is modeled with 1st order approximation of all the system nonlinearities. This model is then analyzed by both nonlinear and linear theories. Understandings and predictions of the system characteristics and behaviors are achieved through these analysis and finally verified by numerical simulation with a nonlinear model which includes the AC character of modulation. Analysis result also predicts the existence of 1 kHz oscillation under the condition of high rotor charge. Simulation results agree well to what had been observed in the lab. Limitation and extrapolation of analysis and simulation results are discussed, and consequently, guidelines for future design changes are derived. Finally, we pointed out that the recent study done by the LMSC needs fundamental corrections to their modeling and analysis.

M. R. Condron II, et al., "Noise Measurements on DC-SQUIDs with Varied Design," H. Koch and H. Lübbig, Springer-Verlag, Berlin, pp. .312-6, 1992.
Abstract:

We have fabricated and tested two types of SQUIDs. The first, a low inductance stripline device, was characterized using a commercial dc SQUID as a following amplifier. The second type was well coupled to a 0.16μH input coil and was characterized and flux-locked using an ultralow noise room temperature preamplifier. We present device characterization and noise data for both types of devices.

J. A. Lipa, D. H. Gwo, R. K. Kirschman, "Status of the Cryogenic Inertial Reference System for the Gravity Probe B Mission," Proceedings July 23-24, 1992, San Diego, CA, SPIE Vol. 1765 Cryogenic Optiala Systems and Instruments V/85 (1992.
Abstract:

We describe the status of the development and testing program for the inertial reference system for the Gravity Probe B gyroscopes. The gyroscope housings are attached to a cryogenic telescope with a 14 cm aperture that continuously points at a guide star. The star image is split to provide quadrant pointing information which is used to steer the spacecraft. This data is also combined with the gyro readout data to provide an absolute precession measurement. Motion of the guide star is independently checked by reference to background galaxies. Room temperature testing of a prototype telescope has been completed and preparations are being made for low temperature tests.

R. K. Kirschmann, S. V. Lemoff, J. A. Lipa, "Evaluation of GaAs FETs for Cryogenic Readout," Proceedings from Conference on Infrared Readout Electronics, Orlando, Florida, SPIE Vol. 1684, April 21-22, 1992.
Abstract:

Low-frequency, low-noise, low-power cryogenic electronics to read out photodetectors is being investigated for the star-tracking telescope of the Gravity Probe B spacecraft. We report our initial findings from evaluating more than 20 types of GaAs FETs, both commercial and non-commercial, for this application. Most exhibit useable dc characteristics at cryogenic temperatures, although gate leakage and hysteretic effects (presumably due to charge trapping) could be troublesome. Low-frequency noise (based primarily on grounded-gate measurements) at 4 K is "1/f-like", and for the quietest GaAs FETs appears to be at least as low as the lowest noise values reported for Si MOSFETs at 4 K. Further investigation is needed in several areas.

N. J. Kasdin "Discrete Frequency Disturbance Rejection in Multivariable Digital Controllers with Application to Gravity Probe B," presented at The 12th IFAC Symposium on Automatic Control in Aerospace, Ottobrunn, Germany, September 7-11, 1992.
Abstract:

The rejection of sinusoidal plant disturbances is a primary objective of closed loop control systems, particularly on spacecraft. In addition, all modern spacecraft use digital, or sampled data, controllers. This paper describes methods for analyzing the frequency response of sampled data controllers to plant disturbances at discrete frequencies. It then describes the proper method for performing direct signal LQR/LQG design with plant augmentation to exactly reject these disturbances. It is shown that the traditional method of mapping to the discrete domain the augmented continuous system does not result in a digital controller that cancels the disturbances. In fact, the disturbance model

must be mapped to digital separately with augmentation taking place in the discrete time problem. An example is presented to verify the technique.

Keywords. Digital control, Direct digital control, Disturbance rejection, Multivariable control systems, Optimal control, Sampled data systems.

G. M. Gutt, N. J. Kasdin, M. R. Condron II, B. Muhlfelder, J. M. Lockhart, M. W. Cromar, "A Method for Simulating a Flux-Locked dc SQUID," Paper EBC-2, 1992, Applied Superconductivity Conference, Chicago, IL. August 23-28, 1992. Being considered for the IEEE Transactions on Applied Superconductivity.
Abstract:

Many high precision experiments place severe requirements on the noise, linearity and slew rate of flux-locked dc SQUID systems (linearity requirement approaches 1 in 10^6 for Gravity Probe B). A computationally efficient and accurate method of simulating a dc SQUID's V-Φ and I-V characteristics has proven valuable in evaluating and improving various SQUID readout methods. The simulation of the SQUID is based on fitting of previously acquired data from either a real or a modeled device using the Fourier transform of the V-Φ curve. This method does not predict SQUID behavior, but rather is a way of replicating a known behavior efficiently with portability into various simulation programs such as SPICE. In this paper we discuss the methods used to simulate the SQUID and the flux-locking control electronics and present specific examples of this approach. Results include an estimate of the slew rate and linearity of a simple flux-locked loop using a characterized dc SQUID.

John C. Mester, Eric S. Meyer, Tito E. Huber, Meritt W. Reynolds, IsaacF. Silvera, Department of Physics, Lyman Laboratory, Harvard University, Cambridge MA 02138, "Measurements of Giant Cross Sections in Low Temperature ^{4} HE-^{4}HE Scattering", Journal of Low Temperature Physics, Vol. 89, Nos. 314, 1992.
We have studied binary collisions of ground state ^{4}He atoms at temperatures from 340 mK to 430 mK using an atomic beam apparatus built in a dilution refrigerator. Very large s-wave scattering cross sections between 120Å^2 - 250Å^2 have been observed. These are due to the proximity of a dimer state near the continuum of the interaction potential. Results show that the latest potential of Aziz et al. needs modification.

1993

M. A. Taber, D. O. Murray, J. M. Lockhart, D. J. Frank, D. Donegan, "Production of Ultralow Magnetic Fields for Gravity Probe B (GP-B) , Ad. Cryo. Eng., 39A 161, 1993.
Abstract:

The procedures for the production of a very low magnetic field of 10^{-11} tesla in a full scale prototype dewar have recently been completed. The GP-B Relativity Gyroscope Experiment will provide a controlled test of Einstein's General Theory of Relativity by making observations of the precession of nearly perfect gyroscopes in Earth orbit. The gyroscopes consist of highly spherical and homogeneous fused silica rotors which are coated with a thin superconductor and operated at a temperature 2 K. Readout of gyro precession is accomplished by measuring the orientation of the magnetic dipole moment (London moment) which is generated by the spinning superconductor and is aligned with the spin axis. The GP-B experiment requires an ambient field of = 2 x 10^{-11} gauss) in order to minimize trapped flux in the rotors and thereby insure the proper operation of the SQUID-based gyroscope magnetic readout. The process to reach the required low field level is by iterative expansion of superconducting lead foil shields. The methods developed to effect the lead shield expansions and to accurately measure the low field are presented along with the final results.

S. Buchman, T. Quinn, G. M. Keiser, D. Gill, "Gravity Probe B Gyroscope Charge Control Using Field Emission Cathodes," J. Vac.Sci. Technol. B11 (2) March/April 1993.

We propose and test a method for controlling the charging of the Gravity Probe B (GP-B) electrostatically suspended gyroscopes using electrons generated by field emission cathodes. The GP-B Gyroscope Experiment is designed to measure for the first time the geodetic and the frame-dragging effects predicted by Einstein's general theory of relativity. The expected accuracy of ~0.3 marsec/yr (10^{-11} deg/h) will allow for a 0.01% measurement of the geodetic effect and a 1% measurement of the frame-dragging effect. Gyroscope charging is caused by cosmic radiation, by field emission, and by the separation of dissimilar metals. The expected charging rate for the gyroscopes is ~1 n/yr and consequently above the 50 pC limit dictated by disturbing torque considerations. The present charge control technique is based on ultraviolet photoemission of electrons from both the gyroscope and an auxiliary electrode. Experiments have shown this method to be effective at room temperature in ground testing, and calculations indicate that it is

suitable for charge control in orbit. As an alternative we demonstrate the use of Spindt-type field emission cathodes for the control of the positive charges demonstrate the use of Spindt-type field emission cathodes for the control of the positive charges on the gyroscopes, by using a 10 000 tip emitter array produced by SRI International. The device requirements are (a) stable and reliable operation over two years at 2 K and 1.5 x 10^{-9} Pa, (b) average power dissipation in the device of less than 50 μW, (c) peak emission current of 1-100 pA, (d) dimensions less than 2 mm, (e) magnetization less than 10^{-8} G, (f) electric field at the gyroscope less than 10^4 V/m. The control of negative charges on the gyroscope is achievable by operating in a regime in which the secondary electron emission coefficient is greater than unity.

R. K. Kirschman, J. A. Lipa, "Further Evaluation of GaAsFETs for Cryogenic Readout," Proceedings from Conference on Infrared Detectors and Instrumentation SPIE Vol. 1946, pp. 350-364, April 12-16, 1993.
Abstract:

Low-frequency, low-noise, low-power cryogenic electronics to read out photodetectors is being investigated for the star-tracking telescope of the Gravity Probe B spacecraft. We report additional results in evaluating low-frequency "1/f" noise of commercial and non-commercial GaAs field-effect transistors (FETSs) at room and liquid-helium temperatures. No correlation was found between noise at these two temperatures. For our dc biasing conditions, the lowest-noise non-commercial GaAs FETs give a typical value of $K_f (\equiv A_f$ x gate area) $\approx 2 \times 10^{-22}$ $V^2 \bullet m^2$; this corresponds to a noise voltage of ≈ 80 nV/Hz $^{1/2}$ at 1 Hz for a gate area of 3 x 10^4 μm^2, only a factor of ≈ 3 higher than the best Si JFETs of comparable gate area operated at their optimum temperature. RTSs (random telegraph signals) were observed for many GaAs MESFETs at 4 K, for gate areas up to ≈5000 $\mu m^{2.}$ We also examined low-frequency "1/f" noise in relation to FET materials, processing, and pinch-off voltage but the results were inconclusive.

M. B. Tapley, C. W. F. Everitt, "Co-Co-Experiments in Gravitational Physics with GP-B and STEP," Adv. Space Res. Vol. 13, No. 7, pp. (7) 77-(7) 80, printed in Great Britain.
Abstract:

We show that the Gravity Probe B (GP-B) and the Satellite Test of the Equivalence Principle (STEP) missions, with their disturbance-free orbits and precise tracking, will facilitate determination of at least two effects of post-Newtonian gravitation. First, for Einstein's classical test of general relativity, the advance of periapse of an orbit, the GP-B determination will be 3 parts in 1000. Second, for the eccentricity of objects orbiting the Earth as it orbits the sun, the GP-B determination will be 200 times more sensitive than lunar laser ranging measurements and at least 5 times more sensitive than Lageos due to GP-B's lower orbit. Nordtvedt shows that the annual variation in the eccentricity of such an orbit is zero only if general relativity is correct in its choice of parameters in the Parameterized Post-Newtonian generalized formulation of metric theories of gravitation. This test will discriminate between relativity and other theories at a level of 6 parts in 10^4. The perigee advance test also provides the most sensitive available test of the exotic β parameter associated in competing theories of gravitation with the second moment of the Earth's gravitational self-energy.

J. Zhu, J. Mester, J. Lockhart, J. P. Turneaure, "Critical States in 2D Disk-shaped Type-II Superconductors in Periodic External Magnetic Field, Physica C212 216-222, (1993).

Following the procedure of Mikheenko and Kzuovlev, we present analytical solutions of field and current patterns in thin film disk-shaped type-II superconductors in perpendicular time-varying periodic external magnetic fields. We also calculate the magnetic moment and effective susceptibility. The analysis is carried out within the framework of the critical state model assuming a constant critical current. Our results are compared to that of Mikheenko and Kuzovlev; and we discuss the discrepancies.

J. C. Mester, Eric S. Meyer, Meritt W.Reynolds, Tito E. Huber, Zuyu Zhao, Barry Freedman, Jinha Kim, and Isaac F.Sislvera, Lynman Laboratory of Physics, Harvard University, Cambridge, MA , "Cold Collisions of Ground State ^{4}He: Giant S-WaveScattering Cross Sections", Physical Review Letters, Vol. 71, No. 9 Agusut 30, 1993.

We have measured integral elastic cross sections for ground state ^{4}He-^{4}He scattering at collision energies from 1.35 to 0.5 K using a novel atomic beam apparatus built into a dilution refrigerator. Scattering is almost *s* wave, and is predicted to be enormous due to a possibly bound state near the continuum. The effective integral cross section ranges from 200 to 1000 $Å^2$ as collision energy is reduced in our experiment. These cross sections are in agreement with the values predicted using the latest analytical potential of Aziz and Slaman.

Eric S. Meyer, John C. Mester, IsaacF. Silvera, "Comment on "The weakest bond: Experimental observation of helium dimer," (J. Chem. Phys. 98, 3564 (1993).
No abstract

Eric S. Meyer, John C. Mester, Isaac F. Silvera, "Novel Technique for Producing Ultracold ^{4}He Beams," Ohys. Rev. Ltrs. Vol. 70, No. 7, February 15, 1993.

We have developed a technique for producing ultracold beams of ground state ^{4}He atoms by evaporation from a film at subkelvin temperature in a dilution refrigerator. Our analysis shows that we have cooled atoms to below 700 μK. This new technique has great promise for determining the He-He interaction potential to high precision and searching for ^{4}He dimer formation. It might also be used to study quantum reflection off surfaces and to search for Bose-Einstein condensation in a dilute gas of ^{4}He.

PACS numbers: 34.40.+n, 34.20.Gj, 67.40,-w

H. Uematsu, B. W. Parkinson, J. M. Lockhart, B. Muhlfelder, "The Gravity Probe B 'Niobium Bird' Experiment Verifying the Data Reduction Scheme for Estimating the Relativistic Precession of Earth-Orbiting Gyroscopes," Spaceflight Mechanics, Vol. 82, Advances in the Astronautical Sciences, 1993.

Gravity Probe B (GP-B) is a relativity gyroscope experiment begun at Stanford University in 1960 and supported by NASA since 1963. This experiment will check, for the first time, the relativistic precession of an Earth-orbiting gyroscope that was predicted by Einstein's General Theory of Relativity, to an accuracy of 1 milliarcsecond per year or better. A drag-free satellite will carry four gyroscopes in a polar orbit to observe their relativistic precession. The primary sensor for measuring the direction of gyroscope spin axis is the SQUID (superconducting quantum interference device) magnetometer. The data reduction scheme designed for the GP-B program processes the signal from the SQUID magnetometer and estimates the relativistic precession rates. We formulated the data reduction scheme and designed the Niobium bird experiment to verify the performance of the data reduction scheme experimentally with an actual SQUID magnetometer within the test loop. This paper reports the results from the first phase of the Niobium bird experiment sensor, and addresses the issues they raised. The first phase resulted in a large, temperature-dependent bias drift in the SQUID electronics, which showed the need to implement a temperature-insensitive design and a temperature regulation scheme.

S. Buchman, B. Muhlfelder, J. Lockhart, "Testing Einstein with Superconductors," Superconductor Industry, pp.12-17, Winter 1993.

The launch of Gravity Probe B in 1998 will put the unique properties of superconductors to work in new capacity: testing the predictions of Einstein's theory of relativity.

1994

R. W. Brumley, S. Buchman, Y. M. Xiao, "Trapped Flux Reduction in a Spherical Niobium Shell at 1 mG," Physica B 194-196, 1793-1794, 1994.
Abstract:

We have developed a method to reduce flux trapped in a superconducting spherical shell. A normal spot on the shell sweeps flux lines until they close in on themselves. Using this technique the dipole moment corresponding to a trapped field of 1 mG has been reduced to about 6% of its original level.

Peter J. Wiktor, "Minimum Control Authority Plot: A Tool for Designing Thruster Systems," Journal of Guidance, Control, and Dynamics, Vol. 17, No. 5 September-October 1994.
Abstract:

A new performance measure for thruster systems called the minimum control authority is defined. It is one of the most important performance measures since it corresponds to the worst case output of the thruster system. Various thruster system designs can easily be evaluated based on this performance measure. Several techniques are derived to calculate the minimum control authority as a function of the thruster configuration, the way in which the thrusters are controlled, and the physical mechanism that limits the thrusters' out puts. A technique to generate a plot of the worst case moment vs force-generating capability of a thruster system is also derived. This so-called minimum control authority plot can be used to evaluate the worst case output of various thruster system designs against each other and against the worst case disturbance forces they have to overcome. To illustrate the concept and demonstrate its usefulness, the minimum control authority plot is applied to evaluate various thruster system designs for the Gravity Probe B (GP-B) spacecraft. The baseline thruster for GP-B was selected based on the minimum control authority plot. Although the focus of this article is on thruster systems, the techniques developed are applicable in general to any system of actuators of any type, for example, the primary flight control effectors of highly maneuverable aircraft.

J. C. Mester, C. W. F. Everitt, B. W. Parkinson, J. P. Turneaure, Hansen Experimental Physics Laboratory, Stanford, California, "Gravity Probe B: Status and Flight Plans," *Proceedings of the Symposium on the Early Universe*, Madras, India (Dec. 1994).
Abstract:

The Gravity Probe B Relativity Gyroscope Experiment will test two independent predictions of the General Theory of Relativity by measuring the precession rates of gyroscopes in a 650 km high polar orbit about the earth. The goal is to measure the geodetic effect to a precision to 2 parts in 10^5 and the frame-dragging effect to a precision of 3 parts in 10^3. This paper presents the status of the program and progress toward science mission launch.

John Mester, Eric Meyer, Tito Huber, Meritt Reynolds, Isaac Silvera, Dept. of Physics, Harvard University, "Low Temperature Scattering of Helium and Hydrogen," Physica B 194-196 (1994) 887-888.
Abstract:

We investigate two body interactions of ^{4}He and atomic H in the low energy limit. H-^{4}He and ^{4}He-^{4} He integral scattering cross sections are determined from the attenuation of beams of ^{4}He atoms through target gases of H and ^{4}He at temperatures below 400 mK. We analyze the results within the Quantum Corresponding States framework. Implications for scattering isotopic species of He and H are discussed.

H. P. Jin, P. Wiktor D. B. DeBra, "An Optimal Thruster Configuration Design and Evaluation for Quick STEP," Reprints, 13thIEAC Symposium, Automatic Control in Aerospace-Aerospace Control, 1994.
Abstract:

A technique to calculate the margin of safety of a multi-thruster system is defined. This technique is based on normalizing the thruster configuration matrix by the expected disturbance environment. An technique based on maximizing the margin of safety is outlined yielding an optimal configuration of a set of thrusters. The technique

assumes a fixed number of thrusters, some geometrical constraints, a specific thruster controller and a specific thruster limit. Two thruster controllers are presented for one-sided thruster systems. A nonlinear pseudoinverse controller based on a modified Newton Raphson iteration is shown to have higher control authority than one based on a biased pseudoinverse controller. These controllers as well as the thruster configuration optimization technique are applied to the design of a thruster system for the Quick STEP (Quick Satellite Test of Equivalence Principle) spacecraft.
Key Words: Actuator Configuration, Controllers, Optimization, System Evaluation, Redundancy.

Y. Xiao, S. Buchman, G. M. Keiser, B. Muhlfelder, J. P. Turneaure, C. H. Wu, "Magnetic Flux Distribution on a Spherical Superconducting Shell," Physica B, Physica B 194-196 65-66, North-Holland, (1994).

We report measurements of flux distributions on superconducting spherical shells in an ambient magnetic field of 0.2±0.1μG. The aim of these experiments is to minimize the number of flux lines trapped in the superconducting shells, a important requirement for the Gravity Probe B gyroscopes.

C. R. Lages and Rodney H. Torii, "Network Model of Cryogenic Phase Separators," Cryogenics, Vol. 34,ICEC Supplement, 1994.

We have studied a simple network model for porous plug phase separators by comparing the flow of helium through a straight capillary to that of a capillary which branches into two capillaries of different diameters. For helium flow above a critical value, the straight capillary model has shown that in order to maintain phase equilibrium the liquid-vapor interface retreats into the capillary. This result is consistent with previous single capillary models. Branch points (nodes) were added to the straight capillary in two ways. The first configuration connects five capillaries to form an H (two nodes). The H-shape configuration proved to be intractable. The second configuration consists of three capillaries connected to form a Y (single node). In this case, we have been able to find solutions which satisfy conditions of steady-state equilibrium.

Eric S. Meyer, Zuyu Zhao, John C. Mester, Isaac F. Silvera, "Nonlocal distribution of the recombination energy in spin-polarized atomic hydrogen," Phys. Rev. B, Vol. 50, No. 13, October 1, 1994-I
Abstract:

One of the important but little studied characteristics of spin-polarized hydrogen is the enormous energy release due to surface recombination into molecular H_2. We have studied the relaxation and distribution of this energy throughout a sample. A phenomenological parameter, *F*, defined as the fraction of total recombination energy released locally at the point of recombination has been measured. Our upper bound of $F<0.04$ demonstrates that very little energy is directly coupled to the surface at this point.

Zuyu Zhao, Eric S. Meyer, Barry Freedman, Jinha Kim, John C. Mester, Isaac F. Silvera, "Surface Recombination in Spin-Polarized Hydrogen: Where Does the Heat Go? Physica B 194-196 (1994) 917-918.

The recombination of two hydrogen atoms to the molecular state is the most energetic chemical reaction per unit mass known. The heat released from such recombination has so far made it impossible to cool a gas of spin-polarized hydrogen (H↓) into the regime of quantum degeneracy. To better understand this problem, we have studied 2nd-order surface recombination in an adsorbed gas of H↓ from the standpoint of heat distribution. We have measured an upper bound on the fraction F of the total recombination energy which is deposited locally on the surface at the point of recombination.

J. M. De Freitas, M. A. Player, "Optical Homogeneity of Gyroscope Blanks for the Gravity Probe B Experiment," presented at the Applied Optics and Opto-electronic Conference, University of York, UK, September 5-8, 1994.
Abstract:

The Gravity Probe B is a relativity gyroscope experiment being developed by NASA and Stanford University to test the prediction of the general theory of relativity by observing the extent of precession of the gyroscope in orbit around the Earth. The rotor of the proposed gyroscope will be made of vitreous silica. This paper describes the measurement of the optical homogeneity (or mass density distribution) of used quartz cubes of side 50mm. The

variations in refractive index Δn, across the faces of the cubes are measured with a unique scanning interferometer, and are of the order of $\Delta n = 3 \times 10^{-6}$ with a precision better than 10^{-7}. achieved through orthogonal polynomial fitting of the optical path difference surfaces. First and second order moments of the density variations are calculated from three orthogonal projections.

1995

H. Dougherty, D. Hegel, J. Kierschenbaum, J. Vanden Buekel, W. Reeve, N. J. Kasdin, "Relativity Mission Spacecraft Control Systems," Control Eng. Practice, Vol. 3 No. 8. pp.1119-1123, 1995
Abstract:

The attitude and translation control system described in this paper provides precision pointing and drag-free control to accomplish a scientific mission. The unique proportional helium thruster, which uses helium boil off from the payload, controls thrust using pressure feedback to meet the high-accuracy requirements for force knowledge. The attitude control law torque commands are combined with the translation control law force commands through a distribution matrix to determine individual thruster commands. The Global Positioning System (GPS) is used to determine position and velocity.

Key Words. Actuators, aerospace control, attitude control, closed-loop systems, control applications, control system design, conventional control, satellite control.

S. Buchman, T. Quinn, G. M. Keiser, D. Gill and T. J. Sumner, "Charge Measurement and Control for the Gravity Probe Gyroscopes," Rev. Sci Instruments, Vol. 66, No. 1 Part 1, January 1995.
Abstract:

We describe a technique based on photoemisison for controlling the charge of the Gravity Probe B electrostatically suspended gyroscopes, and three methods for measuring this charge. Charging is caused by cosmic radiation in orbit and by enhanced field emission in ground testing. Errors induced by disturbing torques require the potential of the gyroscope to be smaller than 15 mV
(15 pC) during the space experiment. The disturbing drift rate produced by measuring the controlling the charge in orbit is small than 10^{-13} degrees/hr, as compared with the 10^{-11} degrees/hr systematic drift rate of the gyroscope.

The principal charge measurement method is based on the determination of the control effort needed to balance a force modulation applied to the suspension electrodes. This technique is insensitive to pick-up from the suspension system and to gyroscope miscentering, and is independent of the gyroscope acceleration. We demonstrate that the force modulation method is suitable for charge monitoring in orbit with an accuracy equal to or better than 4 mV.

N. J. Kasdin, "A Runga-Kutta Algorithm for the Numerical Integration of Stochastic Differential Equations," The Journal of Guidance, Control, and Dynamics, Vol. 18, Number 1, pp. 114-120, January-February 1995.
Abstract:

This paper presents a new Runge-Kutta (RK) algorithm for the numerical integration of stochastic differential equations. These equations occur frequently as a description of many mechanical, aerospace, and electrical systems. They also form the basis of modern control design using the linear quadratic regulator/Gaussian (LQR/LQG) method. It is convenient, and common practice, to numerically simulate these equations to generate sample random processes that approximate a solution of the system (often called Monte Carlo simulations). It is shown in the paper that the standard deterministic solution techniques are inaccurate and can result in sample sequences with covariances not representative of the correct solution of the original differential equation. A new set of coefficients is derived for a RK-type solution to these equations. Examples are presented to show the improvement in mean-square performance.

G. T. Haupt, G.Gutt, J. M. Lockhart, N. J. Kasdin, G. M. Keiser, B. W. Parkinson, "The Stanford Relativity Mission, "Niobium Bird." Verification of the Science Mission by Experimental Application of a New Nonlinear Estimation Algorithm," 18th Annual AAS Guidance and Control Conference, Keystone, Colorado, February 1-5, 1995.
Abstract:

The Stanford Relativity Mission is one of NASA's most challenging experiments. It will check previously untested aspects of Einstein's General Theory of Relativity by measuring, over the course of a one year experiment, the directional change of an Earth-orbiting gyroscope's spin axis relative inertial space as defined by the fixed stars. According to general relativity, the spin axis undergoes two orthogonal precessions of magnitude 6.6 and 0.04 arcseconds per year for a polar 650 km orbit. These tiny angles will be measured to sub-milliarcsecond accuracy, a

requirement which puts extreme constraints on the gyroscopes and the readout system used to measure the spin axis direction. Given these requirements, it is crucial that the gyroscope readout system and datar eduction performance be verified to the fullest extent possible on the ground before the mission is flown.

Analogous to the "Iron Birds" of the aircraft industry, the Niobium Bird is intended to provide precisely this end-to-end verification. The Niobium Bird (the name refers to the extensive use of niobium in the experiment) is a hardware-in-the-loop simulation, integrating computer simulation of the science signal with prototypical readout hardware. A data reduction scheme uses the experimental data to obtain estimates of the relativistic drifts, which are then compared with the simulation parameters to determine the accuracy of the system. This paper presents the latest results from the Niobium Bird, including improvements in the signal modeling, hardware upgrades and application of a new nonlinear least squares estimation scheme developed specifically for the Relativity Mission. The improved simulations have achieved 0.12 milliarcsecond errors in the relativistic estimates, providing verification of the science mission's ability to meet its accuracy requirements.

N. J. Kasdin, "Discrete Simulation of Colored Noise and Stochastic Processes and 1/fxx Power Law Noise Generation," The Proceedings of the IEEE, Vol 83, No. 5 May 1995.
Abstract:

This paper discusses techniques for generating digital sequences of noise which simulate processes with certain known properties or describing equations. Part I of the paper presents a review of stochastic processes and spectral estimation (with some new results) and a tutorial on simulating continuous noise processes with a known autospectral density or autocorrelation function. In defining these techniques for computer generating sequences, it also defines the necessary accuracy criteria. These methods are compared to some of the common techniques for noise generation and the problems, or advantages, of each are discussed. Finally, Part I presents results on simulating stochastic differential equations. A Runge-Kutta (RK) method is presented for numerically solving these equations.

Part II of the paper discusses power law, or $1/f^{\alpha}$, noises. Such noise processes occur frequently in nature and, in many cases, which nonintegral values for α. A review of 1/f noises in devices and systems is followed by a discussion of the most common continuous 1/f noise models. The paper then presents a *new digital model* for power law noises. This model allows for very accurate and efficient computer generation of $1/f^{\alpha}$ noises for any α. Many of the statistical properties of this model are discussed and compared to the previous continuous models. Lastly, a number of approximate techniques for generating power law noises are presented for rapid or real time simulation.

J. Zhu, J. Lockhart, J. P. Turneaure, "Field-dependent Critical Currents in Thin Nb Superconducting Disks," Physica C, Vol. 241, pp. 17-24, 1995.
Abstract:

Magnetic hysteresis loops were measured on thin Nb superconducting disks using a SQUID-based technique; field-dependent critical currents have been observed in thin superconducting disks at low magnetic flux trapping densities (=4G). Such phenomena were found to exist over a wide rangeof temperatures below the transition temperature. The observed field-dependent critical current densities are attributed to long rangeinteractions between trapped vortices in a superconducting film whose thickness is much less than or comparable to the penetration depth. In the framework of Kim's critical statemodel, we developed a numerical method to calculate the field-dependent critical currents by fitting the measured magnetic hysteresis loop. Our experimental data were adequately explained by Kim's critical statemodel. Shielding currents and magnetic field patterns in thin superconducting disks were calculated.

D. Kalligas, P. S. Wesson, C. W. F. Everitt "The Classical Tests in Kaluza-Klein Gravity," The Astrophysical Journal, Vol. 439, No. 2, Part 1, February 1, 1995.
Abstract:

The possible existence of extra dimensions to spacetime can be tested astrophysically using Kaluza-Klein theory, which is a natural extension of Einstein's general relativity. In the simplest version of the theory, there is a standard class of five-dimensional solutions that are analogous to the four-dimensional Schwarzschild solution. However, even a small departure of the extra dimension from flatness affects the first or dominant part of the potential, making it possible to test for the existence of an extra dimension. Data from the solar system indicate that in our region of space the terms due to the fifth dimension are small (=0.1%) compared to those due to the usual four dimensions of spacetime. However, the parameters of Kaluza-Klein theory are not universal constants and can vary from place to place depending on local physics. Hence other astrophysical systems may serve as better laboratories for investigating

the possible existence of extra dimensions. *Subject headings*: cosmology: theory — gravitation — relativity — solar system: general

V. B. Johri, D. Kalligas, G. P.Singh, C. W. F. Everitt, "Gravitational Energy in the Expanding Universe," General Relativity and Gravitation, Vol. 27, No. 3, pp. 313-318, 1995.
Abstract:

The role of gravitational energy in the evolution of the universe is examined. In co-moving coordinates, calculation of the Landau-Lifshitz pseudotensor for FRW models reveals that: (i) the total energy of a spatially closed universe irrespective of the equation of state of the cosmic fluid is zero at all times, (ii) the total energy enclosed within any finite volume of the spatially flat universe is zero at all times, (iii) during inflation of the vacuum energy driving the accelerated expansion and ultimately responsible for the creation of matter (radiation) in the universe, is drawn from the energy of the gravitational field. In a similar fashion, certain cosmological models which abandon adiabaticity by allowing for particle creation, use the gravitational energy directly as an energy source.

S. Buchman, J. P. Turneaure, J. A. Lipa, "Prospects for an Improved Superconducting Cavity Stabilized Oscillator Clock," presented at the Dark Matter in Cosmology, Clocks and Tests of Fundamental Laws Conference, Cedex, France.
Abstract:

Superconducting Cavity Stabilized Oscillators (SCSO) have produced the most stable clocks to date for integration times between 10^2 and 10^3 seconds, achieving an Allen variance of $3x10^{-16}$. The principal contributors to cavity frequency variations are: a) acceleration effects due to gravity and vibrations b) temperature variations, and c) variations in the energy stored in the cavity. We discuss the prospects for improvements in all these areas, for both ground and space based SCSO's. Improvements of at least one order of magnitude should be achievable on the ground, while space offers the opportunity for a 10^{-18} clock for the range around 10^3-10^4 seconds integration time. We also show that calculations of cosmic radiation effects indicate that the frequency variations induced by heating and trapped flux generation, annihilation and motion are smaller than 10^{-18}. Finally we discuss some of the possible ground and space based applications of an improved SCSO clock. These include the measurement (in conjunction with hydrogen masers) of the dependence of fundamental constants on the gravitational potential, gravitational redshift measurements, measurements of the anisotropy of the velocity of light, and the potential for gravity wave detection.

S. Buchman, et al., "A Low Temperature Gyroscope Clock for Gravitational Redshift Experiment."
Abstract:

We describe a test of Local Position Invariance to be performed by comparing mechanical and atomic clocks in a null gravitational redshift experiment. This experiment will be placed in a 650 km polar orbit as a co-experiment of the Relativity Mission (also known as Gravity Probe B, GP-B). The mechanical clocks are provided by the rotation of the GP-B high precision orbiting gyroscopes, while the atomic clocks are Earth based and referenced to the satellite by GPS. The goal is to measure the gyroscope clock frequencies to an accuracy of 0.01% of the gravitational redshift due to the eccentricity of the orbit of the Earth about the Sun. This corresponds to an integrated frequency measurement over one year of $\Delta/\nu = 3x10^{-14}$. We present an analysis of the main torques which disturb the gyroscope clocks. The dominant torque is due to fluctuations in the molecular drag of the residual gas (caused by temperature variations), and is minimized by using a low temperature bake-out technique in order to achieve the required vacuum of 10^{-14} Pa. We compare results of ground based (flight prototypical) gyroscope clock experiments with the numerical simulations of the major disturbance torques. Effects due to cosmic radiation, precession, polhoding, and the readout system are also discussed.

P. Zhou et al., "Multilayer Films of TiC, Ti and Cu for the Gravity Probe B Relativity Mission Gyroscopes," presented at ICMCTF-95, San Diego, California, April 24-28, 1995, Surface & Coatings Technology 76-77 516-520 (1995).
Abstract:

Single component and multilayer films of TiC, Ti and Cu have been produced by sputtering on fused quartz substrates and have been investigated for suitability as electrodes for the electrostatically suspended gyroscopes of Gravity Probe B. The main requirements for these films are low electron field emission in fields of 3×10^7 V/m, low film stress, and good thermal and electrical conductivity in the temperature range 2 K - 400 K. The films have been studied using x-ray diffraction, scanning electron microscopy (SEM), Auger electron spectroscopy (AES), Rutherford back scattering spectrometry (RBS), and four-point resistivity techniques. SEM measurements indicate that the TiC

films have very smooth surfaces and that multilayer films of TiC, Ti andCu have reduced roughness as compared to the Ti-Cu multilayer films. Seven layer 2.6 μm thick Ti-Cu films have been successfully used in the Gravity Probe B gyroscopes, meeting all requirements. Multilayer films of TiC, Ti and Cu are presently being tested with the expectation that they will further improve gyroscope performance.

C. R. Lages, R. H. Torii and D. B. DeBra, "Evaporation of Superfluid Helium in a Capillary," Cryogenics Vol. 35, No. 1, 1995.

Abstract:

The steady-state evaporation of superfluid helium at a liquid-vapour interface near the exit of a cylindrical capillary is considered. In order to maintain phase equilibrium, as the evaporation rate increases the liquid-vapor interface will retreat into the capillary. Due to the very large density difference between the liquid and vapour, the retreat of the interface into the capillary produces a sharp change in mass flow. A simple capillary model has been applied to flow in porous plug phase separators by considering parallel capillaries of equal length but with a distribution of diameters. In this case it is found that the change in mass flow is consistent with what has been observed for an increasing pressure drop across a porous plug. this suggests that the equilibrium flow states occur as the liquid-vapour interface retreats into a porous plug in response to incremental increases in the pressure drop across the plug.

D. Kalligas, P. S. Wesson, C.W. F. Everitt, "Bianchi Type I Cosmological Models with Variable *G* and Δ A Comment," Reprinted from General Relativity and Gravitation, Vol. 27, No. 6, 1995.

Abstract:

We treat in an alternate way a problem recently considered by Beesham [1]. We find that anisotropic Bianchi I inflationary cosmologies with variable gravitational and cosmological "constants" admit de Sitter expansion at least for late times.

J. M. DeFreitas, M. A. Player, "Ultrahigh Precision Measurements of Optical Heterogeneity of High Quality Fused Silica," Applied Physics Letter 66 (26) June 26, 1995.

Abstract:

We present ultrahigh precision measurements of the optical heterogeneity of high quality fused silica at the index level. The measurements were made with a unique scanning heterodyne interferometer developed as part of the Gravity Probe B Program. Striae of refractive indexvariation (optical path difference smaller than 5 nm) are celarly visible on an extended heterogeneity background of around. Both striae and extended heterogeneities are repeatable to within a few parts in 108. These results show the nature and extent of the heterogeneities of high quality vitreous silica. 1995 American Institute of Physics.

J. M. DeFretias, M. A. Player, "Polarization Effects in Heterodyne Interferometry," Journal of Modern Optics, Vol. 42, No. 9, 1875-1899, 1995.

Abstract:

A detailed analysis of the polarization effects which lead to nonlinearity in the non-ideal optical heterodyne interferometer is presented. Extensive use is made of the coherency matrix representation by settingup a 'cross-coherency matrix' representation. A generalized treatmentof periodic phase errors (nonlinearity) is then presented. Individual contributions to the nonlinearity have been characterized as either 'independent' or 'dependent' phase errors. In the single-pass plane-mirror heterodyne system, to which the approach is applied, phase errors for rotational misalignment of the nominally orthogonal linearly polarized input states, beam splitter leakage, non-orthogonality, ellipticity and the effect of misaligned polarizer-mixer are explicitly considered. The latter effect is found to produce nonlinearity only when in combination with any one of the first three and is therefore a dependent phase error. The nonlinearity arising from eiiipticity is identical with that from rotational misalignment except that it has an offset. Rotational misalignment and ellipticity produce nonlinearity at the second harmonic and are second order for practical set-ups. It is also found that cominations of positive (anticlockwise) and negative (clockwise) angular misalingments of the azmuth of the states, non-orthogonality and misorientations of the polarizer-mixer, all relative to the polarizing beam splitter axes, lead to different peak-to-peak nonlinearities in the given system.

G. Haupt, N. Kasdin, G. Keiser, and B. Parkinson, "An Optimal Recursive Iterative Algorithm for Discrete Nonlinear Least-Squares Estimation," AIAA Guidance, Navigation, andControl Conference, August 7-10, 1995 AIAA-95-3218.

Abstract:

The estimation algorithm developed in this paper offers an alternative to standard recursive nonlinear estimators such as the extended Kalman filter and the iterated extended Kalman filter. The algorithm, which is developed from a quadratic cost function basis, splits the problem of cost function minimization into a linear first step and a nonlinear second step by defining new first-step states that are nonlinear combinations of the unknown states. Estimates of the first-step states are obtained by minimizing the first-step cost function using a Kalman filter formulation. Estimates of the unknown, or second-step, states are obtained by minimizing the second-step cost function using an iterative Gauss-Newton algorithm. The two-step estimator is shown to be optimal for static problems in which the time variation of the measurement equation can be separated from the unknowns. This method is then generalized by approximating the nonlinearity as a perturbation of the dynamic update, while keeping the measurement cost function the same. In contrast, the extended Kalman filter and the iterated extended Kalman filter are shown to linearize the measurement cost function, resulting in suboptimal estimates. Two example applications confirm these analytical results.

A. S. Silbergleit, *A. F. Ioffe Physical-Technical Institute, Russian Acadmey of Sciences,* "Nonlinear Motions Against the Newtonian Uniform Expansion Background: The Case of the Unperturbed Density," J. Math. Phys. 36 (2), February 1995. © 1995 American Institute of Physics.

Abstract:

A class of nonlinear perturbations of the Newtonian uniform expansion background is studied, for which only the velocity field is assumed to be perturbed. The general closed form solution to the corresponding equations of motion is found, and several particular families of solutions are analyzed. All the flows of this class are proved to be essentially rotational. A major part of liquid particles constituting the flows have a nonuser angular momentum and move along parabolas, the rest move along straight lines. The analysis is carried out by means of both the Euler and Lagrange variables. *© 1995 American Institute of Physics*

L. A. Bakaleinikov, A. S. Silbergleit, "On the Applicability of the Approximate Poincaré Mapping to theAnalysis of Dynamics Induced by ODE Systems II. Proximity of Coordinate Partial Derivatives of Poincaré Mappings," Physica D 83 (1995) 342-354.

Abstract:

The uniform closeness of coordinates partial derivatives of the approximate and exact Poincaré maps for ODE systems with hyperbolic fixed point possessing the homoclinic orbit connecting this point to itself is studied. The conditions of the uniform bound existence for the difference between these derivatives in the domain of uniform closeness of the approximate and exact Poincaré maps are found. It is shown that partial derivatives for the systems with more than one unstable direction are generally not uniformly close.

L. A. Bakaleinikov, A. Silbergleit, "On the Applicability of the Approximate Poincaré Mapping to the Analysis of Dynamics Induced by ODE Systems I. Proximity of Mappings," Physica D 83 (1995) 326-341.

Abstract:

The closeness of the approximate (R^L) and the exact (R) Poincaré mappings for ODE systems with a hyperbolic critical point possessing a homoclinic orbit, is studied. The mappings are shown to be not uniformly close in their whole domain. The existence of the uniform estimate in a general case is provided by the restriction of mappings R, R^L to some subset. The images of mappings R^L and R occur to be uniformly close in the whole domain only for particular cases of 2-dimensional systems, systems with a single unstable direction at the equilibrium point and systems with two unstable directions corresponding to a complex conjugate pair of eigenvalues.

1996

C. W. F. Everitt, "Fritz London," (A Scientific Biography KOSTAS GAVROGLU. Cambridge University Press, New York, xxiv, 299 pp).Science Magazine, Vol. 272, pp. 1273-1274, May 31, 1996.

R. Brumley, S. Buchman, J. Mester, "Measurements of the Thermal Emissivity of a Superconducting Niobium Film," Proceedings of the 21st International Conference on Low Temperature Physics Prague, August 8-14, 1996, Czechoslovak Journal of Physics, Vol 46 (1996), Suppl S5.

Abstract:

The radiative exchange of heat between a superconducting Nb film at 4.2 K and a Ti film at 4.2 -11 K has been measured. A Nb-coated quartz sphere was used as a bolometer to measure total heat absorbed, from which an effective emissivity was derived. Under these conditions the effective emissivity of the Nb film is about 3%.

Saps Buchman, Francis Everitt, Brad Parkinson, John Turneaure, Mac Keiser, Mike Taber, Doron Bardas, Jim Lockhart, Barry Muhlfelder, John Mester, Yueming Xiao, GregoryGutt, Dale Gill, Robert Brumley and Brian DiDonna, "Experimental techniques for gyroscope performance enhancement for the Gravity Probe B relativity mission," Class. Quantum Grav. 13 (1996) A185-A191, 1996.

Abstract: The Gravity Probe B relativity mission experiment is designed to measure the frame dragging and geodetic relativistic precessions in a 650 km polar orbit. We describe some of the advanced experimental techniques used to achieve the required gyroscope accuracy of between 0.05 and 0.3 marsec yr $^{-1}$. The subjects discussed are: (i) the development of high-precision gyroscopes with drift rates of less than 0.02 marcsec yr^{-1}, (ii) a low-temperature bake-out procedure resulting in a helium pressure of less than 3 x 10^{-12} Pa at 2.5 K, (iii) a read-out system using DC SQUID magnetometers with a noise figure of 5 x 10^{-29} J Hz-1 at 5 mHz and (iv) AC and DC magnetic shielding techniques which produce an AC attenuation factor in excess of 10^{13} and a residual DC field of less than 10^{-7} G.

N. Jeremy Kasdin, Christian Gauthier, "Gravity Gradient Gyroscope Drifts in the NASA Relativity Mission/Gravity Probe A Experiment," The Journal of the Astronautical Sciences, Vol. 44, pp. 129-147, No. 2, April-June 1996.

Abstract:

This paper examines the torques and resulting drift of the Relativity Mission or Gravity Probe B (GP-B) gyroscopes due to gravity gradient forces. Drifts are examined for both forces transmitted through the gyroscope suspension and torques due to the gravity gradient derived considering a nonspherical Earth (J_2 oblateness only) and a slightly eccentric orbit. The effects of the Sun and Moon on the gyroscopes are also discussed. The resulting drift rates for various guide star candidates is presented.

S. Buchman, M. Taber, J. Lockhart, B. Muhlfelder, C. W.F. Everitt, J. P. Turneaure, B. Parkinson, "Applications of Superconductivity to Space-Based Gravitational Experiments."

Abstract:

Techniques based on superconductivity are crucial in providing the means of achieving the high accuracy andl ow 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 SatelliteTest 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 1012.. The readout of the GP-B gyroscopes is based on the London magnetic dipole generated by a rotating superconductor and detected with state-0f-the art dc SQUIDs. which are also used in STEP.

Y. Jafry, T. J. Sumner, S. Buchman, "Electrostatic charging of space-borne test bodies used in precision experiments," Class. Quantum Grav. 13 Ap7-A106, 1996.

Abstract:

Space-borne physics experiments involving the measurement of small motions of test bodies are likely to be limited by disturbance forces. Of particular concern are forces arising from electrostatic charging of the test body due to interactions with particle radiation. Estimates of charging rates have been computed using Monte Carlo particle-transport codes in combination with semi-empirical particle flux models. Results are presented for the STEP and LISA geometries, and are extrapolated for GP-B. The consequences of the charging are assessed for each experiment, and a method for alleviating the problem is discussed which uses the photo emission technique already in the hardware development phase for GP-B.

Matthew C. Sullivan, John Mester, James Lockhart, "Superconducting Thin-Film Absolute Field Magnetometer," Proceedings of the 21st International Conference on Low Temperature Physics Prague, August 8-14, 1996, Czechoslovak Journal of Physics, Vol. 46 (1996), Suppl. S5.

Abstract:

We report on the design of an obsolute field magnetometer being developed to measure the ultra-low magnetic fields (<10-7 Gauss) produced for the Gravity Probe B Relativity Mission. The hysteretic behavior of fluxon motion in thin-film Niobium is used to devise a superconducting thin-film fluxgate magnetometer. Comparisons with

conventional fluxgate and SQUID systems will be discussed. (Research supported by NASA, contract number NAS8-39225).

A. S. Silbergleit, G. M. Keiser, "Eddy Currents from Moving Point Sources of Magnetic Field in the Gravity Probe B Experiment," submitted and accepted by "Technical Physics, to be published 1997.
Abstract:

Two boundary value problems in plane geometry which model the field and current distribution produced by moving sources of magnetic field (fluxons) in surrounding normal metals are solved analytically. In the first case a fluxon moves with a constant velocity in a superconducting plane separated by a gap from a half-space with a finite electrical conductivity. In the second case the half-space is replaced by a thin layer whose conductivity is high. The methods used are some perturbation techniques, Fourier integral transform and the Parceval identity. the latter is exploited for obtaining the expression of dissipated power that is needed for some estimates important for the Gravity Probe B project within which this study has been originated.

J. C. Mester and J. M. Lockhart, "Remanent Magnetization of Instrument Materials for Low Magnetic Field Applications," Proceedings of the 21st International Conference on LowTemperature Physics Prague, August 8-14, 1996.
Abstract:

We report remanent magnetization and magnetic susceptibility measurements made on materials used in the construction of cryogenic instruments. SQUID based magnetometers were used to make the measurements over a range of background fields form 10-2 to 10-7 Gauss. Although the materials tested are generally regarded as non-magnetic, some samples have sufficiently high magnetization values, or values which vary with foundry lot and heat, that use in low field or magnetically sensitive applications is contraindicated.

E. V. Galaktionov, A. S. Zil'bergleit, Yu. A. Polovko, É. A. Tropp, "On the types of quasistationary states of a coupled spin system of optically oriented electrons and nuclei in semiconductors," Tech. Phys. 41 (3) March 1996, © 1996 American Institute of Physics.
Abstract:

A study is made of the quasistationary states (states for which several components of the solution are constant while the rest vary in time) of a system which models the dynamics of a coupled spin system of optically oriented electrons and nuclei in semiconductors. Restrictions on the parameters of the system are found which ensure the existence of two types of quasistationary states: periodic states with two constant components, and states with a complex structure having one constant component. © 1996 American Institute of Physics. [S1063-7842(96)00203-9]

1997

Mark T. Sullivan, et al. "Detector mount system for thermal isolation," SPIE-
The International Society for Optical Engineering, Volume 3132, 31 July - 1 August 1997
Abstract:

This paper describes the design, fabrication, and testing of a low-temperature detector mount system which provides thermal isolation between detector electronics, operating at 80 kelvins, and a quartz telescope at 2.5 kelvins. The detector will be used to acquire and track the guide star for the Gravity Probe B Relativity Mission. The detector mount makes use of the use of a beamsplitting optic. The entire package mounts to a quartz post through a semi-kinematic mount. Design consideration is given to electromagnetic interference and low-remanent magnetic moment. The detector mounts use a flex cable for electrical connections, as well as thermal grounding. The principal benefit of this design is the ability to operate relatively warm pre-amplifier electronics in a low-temperature environment with minimal disruption to a cryogenic system. Test results have shown this detector mount capable of dissipating less than 2 milliwatts with an 80 K temperature differential.
Keywords: low-temperature, detector, thermal conductivity, polyimide, flex circuit, kinematic, telescope, Gravity Probe B.

P. Zhou, S. Buchman, C. Gray, J. Turneaure, "Stress and Its Effect on Surface Morphology in Multi-Layer Ti-Cu Films," Materials Research Society Mat. Res. Soc. Symp. Proc. Vol 441 1997.
Abstract:

We have characterized the stress and its effects on surface morphology for multi-layer thin films of about 3μm total thickness, consisting of three or seven layers of Ti and Cu. These films constitute the electrostatic suspension electrodes for the gyroscope housings of the Relativity Mission Gravity Probe B. Full understanding of surface morphology is critical for meeting the complex requirements of this application.

The residual stresses have been measured using a laser curvature technique, while the surface morphology was studied by scanning electron microscopy (SEM). We find that the surface morphology depends strongly on the stress, which evolves with the Ti-Cu multi-layer period. Average stress and the resulting surface roughness decrease for thinner Cu layers (increased total number of layers). Seven layer Ti-Cu films with low stress and very smooth surface have been successfully used for the electrodes of the gyroscope housings.

S. Buchman, Y. Jafry, "Cosmic Radiation Issues for Gravitational Experiments in Space," Proceedings of the XXXIInd Rencontres de Moriond,Very High Energy Phenomena in the Universe, Series: Moriond Workshop, January 18-25, 1997.
Abstract:

We discuss the disturbances caused by cosmic radiation on the test masses used for gravitational experiments in space. Experiments being considered are Gravity Probe B (GP-B), the Space Test of the Equivalence Principle (STEP), and the Laser Interferometer Space Antenna (LISA). the main disturbance effects are: charge deposition by particles stopping in the test masses, torque and momentum transfer, heating caused by energy deposition, and trapped flux motion in superconducting films. Charging is the main disturbance, requiring active compensation in order to meet the goals of gravitational experiments. The GP-B charge measurement and control system is completed, and has demonstrated the capability to limit the charge of gyroscopes to less than 10 pC. Non-contact charge measurement methods include the force modulation of the position or feedback control effort of the test masses, and charge evaluation using data from particle detectors. These charge measurement and compensation techniques are applicable to STEP and LISA. All other disturbances caused by cosmic radiation on the drag free test masses of these experiments are shown to be either small or manageable with appropriate experimental techniques.

P. Zhou, S. Buchman, C. Gray, J. Turneaure, "Stress and Its Effect on Surface Morphology in Multi-Layer Ti-Cu Films," Mat. Res. Soc. Symp. Proc. Vol. 441 Materials Research Society, Dec. 1997.
Abstract:
We have characterized the stress and its effects on surface morphology for multi-layer thin films of about 3μm total thickness, consisting of three or seven layers of Ti and Cu. These films constitute the electrostatic suspension electrodes for the gyroscope housings of the Relativity Mission Gravity Probe B. Full understanding of surface morphology is critical for meeting the complex requirements of this application.

The residual stresses have been measured using a laser curvature technique, while the surface morphology was studied by scanning electron microscopy (SEM). We find that the surface morphology depends strongly on the stress, which evolves with the Ti-Cu multi-layer period. Average stress and the resulting surface roughness decrease for thinner Cu layers (increased total number of layers). Seven layer Ti-Cu films with low stress and very smooth surface have been successfully used for the electrodes of the gyroscope housings.

1998

Saps Buchman, William Bencze, Robert Brumley, Bruce Clarke, G. M. Keiser, "The Design and Testinf of the Gravity Probe B Suspension and Charge Control Systems," W. W. Hansen Experimental Physics Laboratory, Stanford University, ©1998 The American Institute of Physics 1-56396-848-7/98.
Abstract:

The Relativity Mission Gravity Probe B (GP-B), is designed to verify two rotational effects predicted by gravitational theory. The GP-B gyroscopes (which also double as drag free sensors are suspended electrostatically, their position is determined by capacitative sensing, and their charge is controlled using electrons generated by ultraviolet photo emission. The main suspension system is digitally controlled, with an analog backup system. Its functional range is $10 m/s^2$ to 10^{-7} m/s^2. The suspension system design is optimized to be compatible with gyroscope Newtonian drift rates of less than 0.1 marcsec/year (3×10^{-12} deg/hr), as well as being compatible with the functioning of an ultra low noise dc SQUID magnetometer. Testing of the suspension and charge management systems is performed

on the ground using flight gyroscopes, as well as a gyroscope simulator designed to verify performance over the entire functional range. We describe the design and performance of the suspension, charge management, and gyroscope simulator systems.