STANFORD UNIVERSITY HANSEN EXPERIMENTAL PHYSICS LABORATORY
GRAVITY PROBE RELATIVITY MISSION- ABSTRACTS from THESES

ADACHI, KEIICHI ***NONLINEAR ON-ORBIT THRUSTER CALIBRATION*****, DEPARTMENT OF AERONAUTICS AND ASTRONOMY AUGUST, 1992,**

Abstract

The spacecraft used for the Gravity Probe B experiment, which will be launched around the turn of the century, uses a liquid helium cryogenic system. The test apparatus on the GP-B spacecraft is developed to check Einstein's general theory of relativity with extreme precision. The spacecraft requires an extremely accurate control system including ultralow flow rate helium thrusters which were especially developed and tested for GP-B. Since it is difficult to calibrate thruster force and moment for a spacecraft on the ground due to the weakness of the thruster force and the effect of impingement, the on-orbit calibration is an essential technology for the spacecraft.

The thruster calibration technique already developed is for linear thrusters. This thesis is concerned with nonlinear thruster calibration in which nonlinearity of the thruster curve and bias are treated. The alogrithm of the calibration is developed. It is an iterative calculation method that includes two ways of computing the overall force and moment vector using recursive least square fitting. Three kinds of simulations were done with the assumption of using a simple spacecraft and no noise. The basic characteristics of nonlinear thruster calibration are made clear in the single thruster calibration. Other characteristics and techniques were obtained in a one DOF, two-thruster calibration and in a two DOF, three-thruster calibration.

AXELRAD, Penina ***A CLOSED LOOP GPS BASED ORBIT TRIM SYSTEM FOR GRAVITY PROBE B*****, DEPARTMENT OF AERONAUTICS AND ASTRONOMY OCTOBER, 1990.**

Abstract:

This dissertation describes an onboard closed loop navigation and control system capable of executing extremely precise orbit maneuvers. In particular, a system to adjust the orbit of the Gravity Probe B (GP-B) spacecraft is developed and evaluated. this onboard system relies on the Global Positioning System (GPS) to provide navigation information directly to the vehicle, thus alleviating the need for extensive ground support.

GP-B is a NASA project designed to measure two relativistic effects on orbiting gyroscopes to an unprecedented accuracy. The exacting science goals of the mission place extremely stringent requirements on the spacecraft orbit. The ideal orbit is circular, polar, and contains the line of sight to a guide star which serves as a distant inertial reference. However, once the experiment begins, the spacecraft will be controlled by a drag compensation system, thus, the only opportunity to adjust the orbit is prior to the start of science data collection. In this research, we specify the target injection orbit based on orbit modeling over the entire 18 month mission, in order to best satisfy the ideal conditions on average. The perturbing effects of the geopotential, the Sun and the Moon gravity gradients, and other forces on the orbit are considered. Simulations show that the target inclination must be achieved to an accuracy on the order of 2 x 10-4 deg (25 m) to satisfy the experiment goals.

BAYT, Jr. R. L. ***PREDICTION OF END-CAP EFFECTS ON EQUILIBRIUM HELIUM BUBBLES IN THE GRAVITY PROBE B SPACECRAFT*****, Purdue University, August, 1995**

Abstract:

In the Gravity Probe B satellite, 2500 liters of liquid helium are used to remove heat from the experiment package, cooling it to 1.8 K. The helium tank is a cylinder with elliptical (2:1) end-caps. A circular center post housing the Relativity Experiment is located along the axis of the cylinder, which is also the spin axis of the spacecraft. The topology of the helium ullage bubble governs the location of the center of mass. The equilibrium state of the liquid, solid body rotation, possesses a radial acceleration field which causes the ullage bubble to rest upon the central post in an asymmetric manner. At high enough spin rates, the bubble wraps around the post and transitions to a torus. In this configuration, the center of mass is on the spin axis which prevents wobble of the spacecraft.

Experiments are performed to serve as a basis for comparison to numerical models of equilibrium bubble shapes. These models are developed using the Surface Evolver program for modeling free surfaces. The Surface Evolver program compared well with equilibrium interface shapes and wrapping spin rates found in the experiments. Further models were developed which examined the effect of an elliptical end-cap and center post dome on the bubble stability. Results show that at high spin rates and low bubble volumes, the bubble is more stable than the model without the end-caps. At larger bubble volumes and subsequently lower spin rates, the end-caps had very little effect. Methods for improving stability analysis are suggested.

BENCZE, WILLIAM J. ***GYROSCOPE SPIN AXIS DIRECTION CONTROL FOR THE GRAVITY PROBE B SATELLITE*, DECEMBER, 1996**

Abstract:

This dissertation describes a technique by which the orientation of the spin axis of an electrostatically suspended vacuum gyroscope (ESVG) can be controlled through the coordinated application of residual torques generated by the gyroscope's suspension system.

The Gravity Probe B Relativity Experiment (GP-B) is a joint NASA/Stanford University orbiting astrophysics experiment, now under development, to test two predictions of Einstein's theory of general relativity: the geodetic and frame-dragging effects, the second of which has never been experimentally observed. The relativistic sensors for this experiment are four identical, ultra-precise mechanical, electrostatically-suspended vacuum gyroscopes (ESVG) carefully isolated from Newtonian torques. General relativity predicts that the spin axes of these gyroscopes will precess with respect to a distant inertial reference frame at a rate of 6.6 arc-sec/year for the geodetic effect, and 42 marc-sec/year due to frame-dragging in the planned circular, polar orbit. To achieve the levels of measurement precision needed in this experiment, the orientation of the gyroscopes' spin axes must be aligned to within 10 arc-sec of the line-of-sight to a distant guide star.

Presented here is a technique by which the initial orientation of each gyroscope can be controlled through the use of residual torque's generated by the gyroscope can be controlled through the use of residual torques generated by the gyroscope's electrostatic suspension system. An analysis of the electrostatic torques acting on the gyroscope indicate that they depend on the rotor shape, which is nominally spherical but does not contain small manufacturing asphericities and a centrifugal bulge when spinning. One spinning, the torques are averaged by the rotation of the gyroscope, and are shown to take on a simple form: these *spin-averaged* torques cause the gyroscope to precess about the suspension electrode axes.

Orientation control torques are applied by introducing additional suspension voltages to the electrodes in combinations which do not exert a net force on the gyroscope, but do generate a torque. A control system is developed to use these voltages to drive the spin axis to a desired orientation in minimum-time using a bang-bang actuation scheme. Analysis shows that the spin-averaged torques may be modulated by the rotor's polhode motion. So, an identification technique was designed to measure the effective torque on the gyroscope at various points in the rotor's polhode cycle, and then use this information to ensure a minimum-time alignment trajectory.

Laboratory experiments confirmed the validity of the spin-averaged torque models and give a proof-of-principle of the effectiveness of the *bang-bang* spin axis orientation control system. Under active orientation control, the polhode modulations of the spin averaged torques were readily identified using the proposed identification technique. The net result of the laboratory tests is a confirmation that the spin axes of the gyroscope may be oriented using these techniques to the accuracy required for the GP-B experiment.

BERNATETS, VINCENT ***LONGITUDINAL CONTROL OF A MODEL AIRPLANE USING GPS SIGNALS*, SEPTEMBER, 1994**

Abstract:

The study reported here is a part of the design of an unmanned T12 airplane. The objective is to demonstrate a high bandwidth closed loop control using signals provided by the Global Positioning System. It deals with the control of the longitudinal motions and presents the results obtained by simulation

BLECKMANN, Michael ***A TEST OF COMPUTER CONTROLLED PROGRAMS FOR THE FABRICATION OF HIGH PRECISION QUARTZ SPHERES*, APRIL, 1993**

Abstract

Gravity Probe B is an experiment that employs the use of gyroscopes to test predictions of Einstein's general theory of relativity. This test measures the precession of gyroscopes, contained in an Earth satellite, in polar orbit. At the heart of each gyroscope is a spinning quartz sphere, coated with Niobium and electrically suspended in a housing. Einstein's theory predicts relativistic motions of the gyroscope that differ from Newtonian predictions by extremely small amounts. The observed motions of the gyroscope are so small that a near drift-free instrument is a minimum of requirement: Newtonian drift must be less than 10^{-11} degrees/hour. Any imbalance in the spinning rotor that may overwhelm the relativistic motions must be eliminated. The GP-B experiment aims to measure the motions to precision of 1 percent and better.

The gyroscope's rotor must therefore be manufactured to unprecedented precision. The target diameter is 37.99586 mm; perfect sphericity would be the ideal shape for the rotor, but since this, under circumstances can not

be produced yet, GP-B's polishing laboratory tries to get as close to it as possible: a sphericity should not exceed 25.4 nm, peak-to-valley. In the process a good surface finish helps to optimize the metal plating quality on the rotor.

The polishing process is the final stage in shaping the rotor in terms of sphericity and surface quality. Wilhelm Angele designed a machine to polish precision spheres in 1966. Since working with the initial design led to unsatisfactory results, a new design based on the old idea was created in 1991. While testing this new machine it became obvious that there are several details to be improved.

For the next generation of polishing machines, the motor speed and directional changes will be computer controlled. This will make it possible to control the orientation of the rotor and produce a new level of averaging of the polishing over the surface of the sphere. The purpose of this work project is to evaluate the effects that the various degrees of motorspeed and directional changes have on the polishing process.

BOL, Morris ***THE MEASUREMENT OF THE LONDON MOMENT,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MAY, 1965**

Abstract:

This dissertation presents the experimental verification of a prediction by F. London that a rotating superconductor produces a magnetic moment which depends only upon the state of rotation of the superconductor, and which is independent of the initial conditions. The predicted effects given by the equation:

$$H = \frac{2mc}{e} w$$

The result is derived from London's macroscopic equations, and is compared with zero resistance theory.

The experiment confirmed London's mercury sample 0.106" in diameter and ½" long. The mercury was contained in a beryllium-copper and aluminum container, to which was connected a 0.010" diameter tungsten wire coupled to a magnetically shielded, room-temperature drive motor. The magnetic moment was detected by means of a pair of pickup coils, vibrating about the end of the sample. The apparatus and method are described in detail.

An application of the London moment to detect the precession of a gyroscope predicted by Einstein's theory of General Relativity is described along with another technique employing the Mössbauer effect. A circuit for detecting small magnetic fields was developed and is described. This circuit may be used to measure the General Relativity precession of a gyro in conjunction with the London momenta

BRACKEN, Thomas. D. ***COMPARISON OF MICROWAVE INDUCED CONSTANT VOLTAGE STEPS IN WEAKLY COUPLED SUPERCONDUCTORS*****, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MARCH, 1971**

Abstract:

The Josephson voltage-frequency relationship $h\nu = 2eV$ relates the frequency ν of the ac supercurrent between two weakly coupled superconductors, when they are biased at a dc voltage V. If microwave radiation of frequency ν is incident on a weakly coupled structure, such as a thin film tunnel junction, constant voltage steps at $V = \frac{nh\nu}{2e}$ are induced in the dc current-voltage characteristic. These steps correspond to the zero beat between the applied fields and the ac super-currents. Absolute voltage measurements on these steps have yielded a value of 2e/h accurate to 2.2 ppm. The accuracy and reproducibility of these results have prompted a readjustment of the fundamental constants and a proposal to redefine the volt in terms of the Josephson relationship.

The purpose of the experiment described in this dissertation is to compare the value of 2e/h in different materials at the .001 ppm level by making a differential measurement of the corresponding voltage steps in two different junctions. Two Josephson junctions are biased on the same voltage step and their relative voltages compared using a sensitive cryogenic voltmeter. The voltmeter is a superconducting quantum interference device (SQUID) used as a null detector in a potentiometer. The maximum sensitivity of the voltmeter is $\pm 6 \times 10^{-14}$ volts. The limiting factor in the voltage comparison measurement is an uncertainty of $\pm 2.4 \times 10^{-13}$ volts introduced by opening and closing a mechanical switch. There is, however, a systematic error of up to 1.6×10^{-12} volts that is apparently due to motion of the switch.

The microwave radiation is provided by two phase locked X-band klystrons, whose difference frequency is stable to better than one part in 10^{12}. By varying the frequency of radiation incident on one junction it is possible to vary the step voltage and thus demonstrate a true null.

A lead junction and a shorted tin junction have been biased on the corresponding n = 15 step (V ≈ 300 μ V) and the voltages of the two compared. For one experimental run the upper limit that can be placed on any voltage difference between the two junctions is $\frac{D\mathrm{V}}{\mathrm{V}} = 1 \times 10^{-9}$. However, because of the spurious signal caused by motion of the switch, the upper limit on the voltage difference for several runs is $\frac{D\mathrm{V}}{\mathrm{V}} = 5 \times 10^{-9}$.

The resistance of the steps was measured in both samples by varying the current through the step and looking for a voltage change. The resistance of the n = 15 step of the lead junction was less than $10^{-8}\Omega$. The resistance of the corresponding step in the tin structure was less than $7 \times 10^{-11}\Omega$. In both cases the limit is set by the width of the step.

BULL, John S. ***PRECISE ATTITUDE CONTROL OF THE STANFORD RELATIVITY SATELLITE*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, MARCH, 1973**

Abstract:

The purpose of the Stanford Relativity Satellite is to measure the effect of general relativity more accurately than has ever been previously accomplished. This dissertation presents analytical and experimental phases of the attitude control system synthesis and analysis for the Stanford Relativity Satellite.

Einstein relativity theory predicts that the axis of a gyroscope in polar earth orbit will precess 6.9 arc-seconds per year in the orbit plane and 0.05 arc-seconds per year normal to the orbit plane. In order to record accurately the relativity effect, the relative motion is measured between an ultra low drift rate gyroscope (0.001arc-sec/yr) and a precisely controlled star tracker acting as an inertial reference frame. The satellite will contain four spherical quartz gyroscopes and a telescope in a low temperature environment provided by a liquid helium dewar. Overall satellite control will be provided through helium reaction jets utilizing helium boiloff from the dewar. Precise telescope pointing will be obtained through a fast cryogenic actuator pushing against the remainder of the satellite inertia.

The analytical design phase consisted of synthesizing linear constant gain control laws through (1) classical methods, (2) pole assignment techniques, and (3) quadratic synthesis of an optimal controller. In addition, a full state estimator is also synthesized through use of a quadratic performance index. The classical design depends on spectrally separated inner and outer control loops. The outer control loop presents the classical case of instability--a control separated from a sensor by a flexible coupling. Pole assignment techniques with less than full state feedback utilize natural system parameters to achieve desired pole locations. “Engenvector decomposition” of the Hamiltonian system is used to solve for the steady state Riccati control matrix and the steady state error covariance matrix for determining the constant optimal controller and estimator gains. A performance comparison of each of the control laws is made and advantages and disadvantages of each of the synthesis techniques is discussed. The optimal controller/estimator provided significant improvement in performance over controllers synthesized through classical methods and pole assignment techniques.

The experimental phase consisted of (1) hardware fabrication of an analog mechanization of the optimal controller/estimator and (2) designing, building, and testing of a continuous flow differential helium thrustor. Differential thrust is obtained (at Reynolds numbers less than 100) by differentially restricting the flow through two opposing nozzles. “Direct” measurement of the thrust is used to determine specific impulse and maximum thrust available. “Indirect” measurement of thrust gives better bandwidth and is used for dynamic thrustor testing. A closed loop attitude control simulation is conducted to verify analytical results in the presence of thrustor nonlinearities. Attitude control specifications were satisfied in the closed loop simulation.

CABRERA, Blas ***THE USE OF SUPERCONDUCTING SHIELDS FOR GENERATING ULTRA-LOW MAGNETIC FIELD REGIONS AND SEVERAL RELATED EXPERIMENTS*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MARCH, 1975**

Abstract:

Part I of this thesis describes a technique for producing ultra-low field regions. Lead foil (0.0025” thick and 99.9% pure) is used to construct cylindrical superconducting magnetic shields with bottom end caps (4” dia. x 33” long and 8” dia. x 56” long). We have obtained several shields with absolute fields below 10^{-8} gauss over 20” along their axes.

The shields are pleated, folded flat and then cooled through their transition (7° K) by “heat flushing,” i.e., moving the transition temperature from bottom to top in a slow and controlled manner. Cooling a shield inside of an outer previously heat flushed one produced our lowest fields when repeated 2 to 4 times. The magnetic fields

are measured using a Josephson double point contact magnetometer with a differential sensitivity of 10^{-9} gauss coupled to a flip coil for absolute calibration.

In Part II we describe the investigation of residual trapped flux in small superconducting shields and of remanentmagnetization in materials used in ultra-low field regions. The apparatus used for these measurements was placed inside an ultra-low field shield.

Using this same apparatus we also measured the magnetic charge of a series of samples with a single-pass technique. Schwinger has suggested that the theoretical quarks of Gell-Mann's model may be magnetically charged. An experiment here at Stanford and several others elsewhere that are designed to measure the fractional electric charge of the proposed quarks have had some tantalizing results (further definitive experiments are now in progress). Our apparatus will measure the magnetic charge of any sample appearing to have a fractional electric charge.

We have measured eleven samples (total mass 1.75 grams) and found the magnetic charge of all to be consistent with zero. The sensitivity is 1/50 g_o (g_o = hc/2e, the smallest magnetic charge allowed by the Dirac theory - although other theories predict larger values for the elementary magnetic charge). Our results are consistent with those from similar multipass experiments conducted by Alvarez et al.

CARINI, Paolo ***GRAVITOELECTROMAGNETISM: AN INTERFACE BETWEEN OUR SPACE PLUS TIME PERSPECTIVE OF THE PHYSICAL WORLD AND ITS SPACETIME DESCRIPTION IN GENERAL RELATIVITY DEPARTMENT OF PHYSICS,*** **AUGUST, 1995.**

Abstract:

Most physicists would probably agree about the elegance of the covariant spacetime formulation of Maxwell's theory but none can deny the utility of the concepts of electric and magnetic field. Our intuition about the physical world undoubtedly relates to space and time as two distinct entities, and spacetime fields are more easily interpreted through their spatial representatives. This is even more true of Einstein's theory of gravitation where all the effects of the gravitational field are encoded into the spacetime geometry itself. In this context it is the splitting of the curved spacetime into space plus time and the splitting of fully nonlinear general relativity which provide the interface between the theory and our intuition. Interestingly enough, this decomposition gives rise to a nonlinear analogy with flat spacetime electromagnetism, named for this reason "gravitoelectromagnetism," whose linearization leads to the more familiar linear analogy, but this nonlinear analogy is not well know at all.

However, gravitoelectromagnetism is not only this. In a broader sense it provides for the first time a single mathematical framework which permits the clarification of the interrelationships between the various spacetime splitting techniques which may be found in the literature and the comparison of the various ways of introducing spatial gravitational fields. The interminable literature and the lack of a common language in which to formulate a coherent approach to all the various pieces are two major difficulties that one who is interested in a deep understanding of this subject must overcome. Sometimes one finds different approaches mixed together in a single study making the physical interpretation of the results very difficult. At other times contrasting results are derived using different approaches but no clear explanation of the origin of these differences is provided. Finally there are problems which have been traditionally studied using only one approach but that may also be analyzed starting from a different one. Part of the goal of this work is to remove the obstacles which have limited our understanding in all of these situations.

Of course a language evolved enough to achieve this goal must be somewhat abstract and it necessarily involves some investment of time to become familiar with. In particular the transition from the abstract notation to a more practical one requires great attention and it is not always straightforward. For this reason several applications have been considered and some of the algebraic manipulation has been made explicit, making the presentation somewhat cumbersome at times.

The applications considered can be divided into two groups.

1. The first group includes some reformulations of solved problems in order to give them a correct or clearer interpretation or to provide alternative interpretations of the existing results. The study of the precession of the spin of a gyroscope, for example, provides a very simple geometrical interpretation of the "relative angular velocity" of the spin of the gyroscope as a derivative of the relative observer boost. The study of circular orbits in the rotating Minkowski, Kerr and Gödel spacetimes shows the gravitoelectric, gravitomagnetic and space curvature contributions to the spatial gravitational forces enter into the radial force balance equation. A consistent natural definition of centripetal acceleration permits the reformulation of the many articles on centrifugal forces in general relativity written by Abramowicz and his collaborators so that they can be reinterpreted in terms of a more traditional perspective on this topic. The analysis of the post-Newtonian limit of gravitoelectromagnetism helps clarify the confusing issue of the existence of a gravitational Thomas precession.

2. The second group consists of problems which have been solved here for the first time using the formalism of gravitoelectromagnetism. The transformation laws for the gravitoelectric and gravitomagnetic fields which exist in the literature only within various approximation schemes are given
here in there exact form. A complete formulation of the relative observer kinematics in general relativity leads to the most general relativistic addition of acceleration formula.

Hopefully this work will stimulate further investigations and will help facilitate communication among relativists who are familiar with only one piece or another of the larger picture.

CEVA, Juan C. ***REAL-TIME DYNAMICAL GPS EPHEMERIS PREDICTION FOR WAAS APPLICATIONS*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, SEPTEMBER, 1995**

Preface:

This thesis summarizes the work of two years of research at Stanford University as a research assistant in the Gravity Probe B Relativity Mission. The work was conducted at the Stanford University Wide-Area Differential GPS Laboratory and at the California Institute of Technology Jet Propulsion Laboratory.

During the last decades the field of satellite navigation has matured enormously. The Global Positioning System epitomizes the current stage of maturity of the field. The Federal Aviation Administration will augment the GPS system to provide precision landing and *en route* navigation capabilities to civilian planes.

The new navigation accuracy requirements demand the improvement of several aspects of the GPS system. Of major importance among these aspects is the improvements of the GPS ephemeris generation; first improving their accuracy, and second making them a real-time product.

This thesis focuses on the GPS ephemeris prediction for the Wide-Area Augmentation System. The thesis intends not only to present the results of the research performed, but also intends to be a basic guideline on how to study and realize the GPS ephemeris production in real-time. Abundant bibliography has been provided to cover the aspects that could not be covered in the interest of conciseness or that simply required a deeper exposition. By doing so, it is hoped that the subject of (dynamical) orbit determination will be less obscured to those “cultures” that this author has found to be intimidated by such a technique. Chapter 1 introduces the fundamentals of the GPS system and differential techniques. Chapter 2 presents the concepts of wide-area differential GPS and wide-area augmentation systems. Chapter 3 provides the basic tools of orbital mechanics that are mecessary to deal with the orbit determination problem. The theory of orbit determination is covered in Chapter 4, where although general in its treatment, it focuses on GPS satellites. The tools presented in Chapters 3 and 4 have been used to produce the results presented in Chapter 5 where a summary of conclusions and suggestions for future work are given. Five appendices provide additional imformation or go into more detail on certain aspects of the GPS orbit determination problem. A few words about the notation are in order. Throughout this piece of work, vector quantities are denoted in bold face (e.g.,**r**), the only exception being when the vector is symbolized by a greek symbol, in that case the vector is denoted by an overhead arrow (e.g., $\vec{a}$). Matrices are denoted by underscoring the symbol of the quantitu (e.g., $\underline{A}$). Equations, tables and figures are numbered such that the first digit refers to the chapter number where they appear, and the second digit to the sequence of appearance in that chapter, such that Eq. 2.4 is the fourth equation of chapter two. During derivations, the equal signs bear an equation number underneath them to denote from what expression or expressions the current equality derives.

CHAO, Yi-Chung ***REAL TIME IMPLEMENTATION OF THE WIDE AREA AUGMENTATION SYSTEM FOR THE GLOBAL POSITIONING SYSTEM WITH AN EMPHASIS ON IONOSPHERIC MODELING*, DEPARTMENT OF AERONAUTICS AND ASTRONOMY JUNE 1997,**

Abstract:

The Global Positioning System (GPS) has demonstrated great potential to improve civilian aviation. However, before GPS can be used as a primary navigation system, the system’s integrity and accuracy must be enhanced to meet the safety standards set by the Federal Aviation Administration (FAA).

To meet these requirements, the FAA proposed and initiated the development of the Wide Area Augmentation System (WAAS) for GPS. WAAS augments GPS with a ground network of GPS receivers to deliver the Wide Area Differential GPS corrections and system integrity alerts, as well as adding an extra ranging signal from geosynchronous satellite to increase the continuity and time availability of the service. This augmentation will enable WAAS to be the primary navigation system for en route flight, terminal area approach, and non-precision approach, and can provide accurate vertical guidance for Category I precision approach.

This thesis presents the real-time WAAS implementation to meet the accuracy requirement of Category I precision approaches, especially includes algorithms for calibrating interfrequency biases, and for creating an ionospheric grid model. A feedback algorithm for generating the confidence level of the ionospheric correction shown in this thesis is proven to be useful. Furthermore, an integrity monitoring indicator using has been proposed for detecting local ionospheric disturbances, which may represent the most significant threat to WAAS in the coming solar maximum around the year 2000.

CHEN, Jeng-Heng ***HELIUM THRUSTER PROPULSION SYSTEM FOR PRECISE ATTITUDE CONTROL AND DRAG COMPENSATION OF THE GRAVITY PROBE B SATELLITE*****, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, DECEMBER, 1983**

Abstract:

This thesis is concerned with (1) the design and test of proportional helium thrustors, and (2) the optimal configuration of the thrustors for attitude control and drag compensation of the gravity probe-B spacecraft.

The propellant for the helium thrustors is the constant boiloff waste gas from cryogenic liquid helium. Differential thrust is obtained by movement of a spool located between two opposing nozzles thus differentially restricting the helium flow. The design procedure and test results of a high bandwidth, low power, good linear electromagnetic actuator for the spool movement are presented. Test of the thrustor in a vacuum chamber to evaluate its performance has also been done.

Two mathematical models are used to describe the helium flow through the thrustor under different flow conditions. The experimental data measured in the vacuum chamber and the computational results from the mathematical models are compared. The models agree with the experiment to 3% except near a Knudsen number $K_n = 1$ where errors of 10% are possible near the transition from one flow to the other. This model selection and verification for helium across the flow regime $K_n = 1$ is an original contribution to fundamental fluid mechanics. The performance of the helium thrustor at high flow rates (data which are not available from the experiment due to the limitation of the current pump capacity) is extrapolated from the mathematical modes.

CHOU, Hsing-Tung ***AN ADAPTIVE CORRECTION TECHNIQUE FOR DIFFERENTIAL GLOBAL POSITIONING SYSTEM,*** **DEPARTMENT OF AERONAUTICS AND ASTRONOMY, JUNE, 1991**

Abstract:

Accuracy and reliability are of the most important issues regarding the potential of the Global Positioning System (GPS) to become a sole means air navigation system. The purpose of this dissertation is to propose solutions to these two problems.

To improve the accuracy of the GPS, the Differential GPS (DGPS) concept is explored. The main ideas the existence of common errors between the reference station and users. Because of this commonality they can be eliminated by differential operations. Further, these common errors are major sources of error for GPS users. Thus, the removal of them can significantly improve the navigation accuracy of the GPS. There are many different differential concepts described in the GPS literature. The current research only investigates the pseudorange correction approach.

The success of the DGPS depends on the cooperation between the reference station and users. A DGPS reference station should transmit the proper correction messages with the shortest delay. Low pass filters, the Hatch/Eschenbach filter, and the Kalman filter are investigated as candidates to provide corrections. Based on static test data, the best one is chosen as the correction signal generator in this research.

Though user positions provided by “raw” DGPS are rather accurate, they are quite noisy for real time applications. Two filtering techniques are investigated to smooth these navigation solutions. The first technique is the Hatch/Eschenbach filter that makes use of carrier measurements to smooth pseudorange measurements. Using these smoothed measurements, clean navigation solutions can be obtained by the application of a least squares solver. The second technique is the Kalman filter that incorporate a *priori* knowledge of measurement error statistics and user dynamics with the current measurements to generate smoothed solutions. Measurement error statistics are obtained by analyzing the static test data. User dynamics are provided by modeling. Two models are constructed. One is for low dynamic or non-maneuvering users, the other is for high dynamic users.

To increase the DGPS reliability and alleviate the latency effect, an adaptive correction technique using the Recursive Least Squares Lattice Filter (RLSLF) is proposed. Under normal operating conditions, the RLSLF adaptively identifies the model parameters and order of the correction messages. If the correction messages from the reference station are delayed or interrupted, substitute correction signals are generated by using Δ-step predictor of the RLSLF. Using static test data with SA, the performance between this adaptive technique and the RTCM SC-104 correction were compared.

Several dynamic tests under different satellite geometry were dome to evaluate the performance of the DGPS implementation in the current research. All tests were performed on a straight road which was intentionally chosen to simulate a runway. From the test results, the statistics of horizontal, vertical, and absolute positioning error are calculated. The results should approximately reflect the performance of the current DGPS implementation operating in a real scenario.

Based on the results of the current research and the GPS 21 primary satellite constellation, a DGPS landing precision database is constructed. It provides the landing precision for various combinations of latitudes and evaluation mask angles. The information provided by this database is a projection of the DGPS landing precision under the full operational GPS.

CLARIDGE, David E. ***NINE GIGAHERTZ IMPEDANCE PROPERTIES OF POINT-CONTACT JOSEPHSON JUNCTIONS,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MARCH, 1976**

Abstract:

The complex rf impedance of tantalum point-contact Josephson junctions has been measured at a frequency of 8.9 Ghz. The impedance was measured as a function of the dc bias current I_0 for a range of values of the rf current amplitude I_{rf}. I_0 was typically varied in the range $0 \leq I_0 \leq 10\ I_m$ where I_m is the maximum zero-voltage current for the junction.

Measurements were made for various values of I_{rf} in the range $0.051\ I_m \leq I_{rf} \leq 10\ I_m$.

For dc bias-currents in the range $0 = I_0 = I_{mrf}$ (where I_{mrf} is the maximum zero-voltage current in the presence of I_{rf}), the real part of the normalized impedance r_{rf} increases monotonically while the imaginary part x_{rf} is inductive and decreases monotonically. As I_0 is increased, the impedance remains basically constant until the dc bias voltage nears the voltage of the first Josephson step (18.4 μV). Then rapid changes occur in the impedance. For small values of I_{rf} ($I_{rf} \ll I_m$) no further changes occur in the impedance as I_0 is increased. It should be noted that for small I_{rf} no step occurs on the I-V curve at

18.4 μV, but large changes in the impedance were still observed. For larger values of I_{rf}, structure occurs in the impedance for bias currents near or on one of the constant-voltage steps on the I-V curve. For $I_{rf} = 10\ I_m$ all structure disappears.

Auracher and Van Duzer have computed impedance curves based on the resistively-shunted-junction model for similar ranges of I_0 and I_{rf}. We have observed nearly all of the qualitative features of the theoretical curves. However, the observed structure is consistently smaller than the theoretical predictions, and we observed constant values of impedance between the constant-voltage steps. We also consistently observed “shoulders” on x_{rf} near the voltage steps. These were not predicted. Thus we conclude that the resistively-shunted-junction model provides a good but not complete explanation for the impedance behavior of tantalum point-contacts.

Impedance measurements can in principle provide an excellent measurement of the quasiparticle conductivity coefficient α. Attempts were made to measure α but inadequacies of the experimental apparatus prevented a meaningful measurement of this coefficient.

COBB, H. STEWART ***GPS PSEUDOLITES: THEORY, DESIGN, AND APPLICATIONS,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS SEPTEMBER 1997**

Abstract:

Pseudolites (ground-based pseudo-satellite transmitters) can initialize carrier-phase differential GPS (CDGPS) navigation systems in seconds to perform real-time dynamic positioning with 1σ errors as lows as 1 cm. Previous CDGPS systems were rarely used due to cumbersome initialization procedures requiring up to 30 minutes; initialization of the carrier-phase integer ambiguities via pseudolite removes these constraints. This work describes pseudolites optimized for this application which cost two orders of magnitude less than previous pseudolites.

Synchrolites (synchronized pseudolites), which derive their timing from individual Global Positioning System (GPS) satellites, are also described. Synchrolites can replace the CDGPS reference station and datalink, while simultaneously serving to initialize CDGPS navigation. A cluster of well-placed synchrolites could enable CDGPS navigation even if only one GPS satellite signal is available.

A prototype CDGPS system initialized by pseudolites and synchrolites was designed and tested. The goal of this system, known as the Integrity Beacon Landing System (IBLS), was to provide navigation accurate and reliable enough to land aircraft in bad weather. Flight test results for prototype pseudolite and synchrolite systems, including results from 110 fully automatic landings of a Boeing 737 airliner controlled by IBLS, are presented.

Existing pseudolite applications are described, including simulation of the GPS constellation for indoor navigation experiments. Synchrolite navigation algorithms are developed and analyzed. New applications for pseudolites and synchrolites are proposed. Theoretical and practical work on the near/far problem is presented.

COHEN, Clark E ***ATTIDUDE DETERMINATION USING GPS DEVELOPMENT OF AN ALL SOLID-STATE GUIDANCE, NAVIGATION, AND CONTROL SENSOR FOR AIR AND SPACE VEHICLES BASED ON THE GLOBAL POSITIONING SYSTEM,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, DECEMBER 1992**

Abstract:

The Global Positioning System (GPS) is poised to revolutionize aerospace Guidance, Navigation, and Control. While traditionally thought of as a navigation system, GPS *has now been demonstrated to be a formidable sensor for attitude determination* as well. In fact, GPS may now be considered a 10 state sensor, providing continuous real-time Position, Velocity, Time, and Attitude (PVTA) for all axes.

Attitude determination is derived from extremely precise (5mm, lσ) differential range measurements among multiple GPS antennas mounted on a flight vehicle. While physics does not set the ultimate achievable limits of performance, experimental testing is demonstrating pointing accuracies below 0.1 deg (1σ) with a usable bandwidth of several tens of Hz.

This dissertation describes the design and development of a new and unique GPS receiver with full PVTA capability. It chronicles the key innovations which have made this technology possible and addresses the fundamentals and performance of GPS-based attitude determination. A prototype receiver based on *antenna multiplexing* is presented which offers prospects of significantly reducing the size, weight, power, and cost of the hardware. Other conceptual designs are presented for achieving the highest possible performance. Methods of resolving the *cycle ambiguities* [1] of the GPS carrier based on motion are developed and tested in an effort to drive the performance of attitude determination as close as possible to perfection.

Maiden space flights of the new receiver are scheduled for launch into low Earth orbit. Test data is presented from extensive flights on a single-engine Piper Dakota that has been used to explore aircraft applications of attitude determination. Among these, attitude and precise position sensing using GPS can be applied to the estimation of the aircraft dynamic model in flight. The wealth of dynamic response data obtained through GPS can be used to estimate aircraft stability derivatives and, surprisingly, aeroelastic effects with millimeter-level clarity.

CORNELL, Eric **ULTRA LOW PRESSURE VAPOR PRESSURE MEASUREMENTS ON SURFACE-ADSORBED HELIUM-4, June 5, 1985. Senior Honors Thesis, Honors Advisor, C. W. Francis Everitt)**

Abstract: None

CRERIE, Jeffrey R. ***PHASE-LOCK ROLL CONTROL OF INERTIALLY POINTING SPACECRAFT,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, MARCH, 1993**

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. 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***. This is done 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 and disturbance torques are very large.

Because the system makes use of single-element photodiodes, current star-tracker technology is not optimized for this particular application. Thus, a hardware simulation was useful in demonstrating the capabilities of this simple, low-cost system, and was better in determining the noise characteristics of the combined sensor and

electronics. A laboratory-based hardware simulation was achieved by modelling the intensities of stars located within the relevant band on a NeXT graphics monitor and then animating this image at a rate governed by the plant dynamics model. This "scrolling star field" is imaged onto a high-speed, high-sensitivity silicon photodiode whose output undergoes a one-bit discretization before correlation with the stored reference. The correlation scheme, subsequent Kalman filtering, and updates to the dynamics model all occur within the Motorola DSP56001 Digital Signal Processor which comes installed on the NeXT computer. This hardware-in-the-loop test validates the theory previously described.

CUNNINGHAM, Charles E. ***APPLICATIONS OF A LASER-DRIVEN SUPERCONDUCTING SWITCH TO FUNDAMENTAL MEASUREMENTS AND TO LOW-FREQUENCY NOISE REDUCTION IN SQUID MEASUREMENTS*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, DECEMBER 1991**

Abstract:

A SQUID is used to study laser-switches, 10-40 nm thick niobium microbridges which are driven intot he normal state by laser pulses sent through a multimode optical fiber. Laser pulses induce a random change in the quantized flux state of the SQUID's input circuit. From the correlation between successive flux states, we have established that the laser-switch is able to follow 6 ns laser pulses. A technique based on flux quantization is used to measure precisely the inductance of superconducting circuit elements, as well as the magnetic penetration depth of niobium. Using a specially shielded toroidal solenoid, we have demonstrated that magnetic flux is quantized absolutely in superconducting circuits, refuting an assertion that fractional quanta of magnetic flux might exist. We observe that magnetic flux is trapped in the laser-switch occasionally if the laser's driving current is reduced to Zero, but never if the laser beam is interrupted mechanically. This observation is consistent with the hypothesis that flux is trapped when the laser-switch cools through its transition in the presence of a stable modal interference pattern produced by the fiber.

The noise energy spectrum of a SQUID is white at high frequencies and is 1/f (inversely proportional to frequency) at low frequencies; the limiting behaviors intersect at the 1/f knee. We have demonstrated two techniques which improve the signal to noise ratio in low-frequency SQUID measurements by modulating the signal at a frequency above the 1/f knee. In the first technique, a double-pole double-throw network of laser-switches is interposed between a pickup coil and the SQUID's input coil. For a modulated signal, the 1/f knee is reduced by more than an order of magnitude from the ummodulated 1/f knee with no loss in signal amplitude. In the second technique, the SQUID's input coil and a pickup coil are connected in series with a single laser-switch modulated inductor. The 1/f knee is reduced by more than two orders of magnitude, but with a factor of ~40 loss in signal amplitude due to incomplete inductance modulation.

DEAVER, Bascom S. ***EXPERIMENTAL EVIDENCE FOR QUANTIZED MAGNETIC FLUX IN SUPERCONDUCTING CYLINDERS*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYS8ICS JANUARY, 1962**

Abstract:

The experiment which is the subject of this dissertation was motivated by a prediction of Fritz London in 1948 that the magnetic flux trapped by a persistent current in a superconducting loop is quantized in units of hc/e. The experiment demonstrated the existence of quantized flux in hollow tin cylinders but in units of $hc/2e = 2.07 \times 10^{-7}$ gauss cm^2.

A brief resume of the London theory, particularly as it leads to the prediction of quantized flux, is presented. Also included are Onsager's comments on this prediction and his anticipation of the smaller unit.

Measurements were made on two hollow tin cylinders about one centimeter long and 13-microns inside diameter with wall thicknesses of 1.5 and 5 microns. These were fabricated by electroplating tin onto a one centimeter length of No. 56 copper wire.

To trap magnetic flux the cylinder was cooled below the superconducting transition temperature in the presence of a known applied axial field. The net flux in the cylinder was measured with the applied field on and after the field was turned off. The measurement was made by moving the cylinder up and down 100 times per second with an amplitude of one millimeter and observing the electrical pickup in two small coils, each of 10,000 turns, surrounding the ends of the cylinder.

The system was calibrated by cooling the cylinder below the transition temperature in zero field and observing the emf produced when the completely diamagnetic cylinder was vibrated in a known applied field. From the measured cross sectional area of the cylinder and the value of the applied field, the flux corresponding to this signal was calculated.

A total of about 250 data points are presented giving the following results:

1. The flux trapped in the cylinder both in the presence and absence of an applied magnetic field is not continuous but exhibits a step behavior, the first step occuring for Φ = hc/2e, within experimental error in the data. Considering all sources of error, the value of the trapped flux at the firststep is hc/2e ± 20%.
2. The data indicate additional steps at hc/e, 3hc/2e, and 2hc/e.
3. The ratios of the fields at which the steps occur are 1, 3, 5, and 7.
4. Since the time constant for the measuring apparatus was 22 seconds, the experiment gives only a large upper limit for the time involved in reaching the quantized values.

Theoretical explanations and interpretations which have appeared since the publication of these results are summarized and discussed. These have been based on both the Bose gas model and the Bardeen, Cooper, Schrieffer theory. All relate the appearance of the factor of two in the flux unit to the occurrence of pairs of electrons in a superconductor and consider these results as direct proof of their existence. The states of the cylinder with trapped flux are regarded as metastable with the momenta of the pairs correlatd over a macroscopic range (the circumference of the cylinder) and with the total angular momentum occurring in macroscopic units.

Finally some new experiments to explore more precisely the nature of the persistent current states are described.

de CORDOVA, S. S. F. ***ORIENTATION AND THREE-DIMENSIONAL MASS CENTER ESTIMATION IN A ROTATING DRAG-FREE SATELLITE,*** **CENTER FOR SYSTEMS RESEARCH, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, AUGUST, 1975**

Abstract

A drag-free satellite is controlled in translation so that it follows a proof mass in an internal cavity. The proof mass is in a drag free orbit because the main satellite shields it from all external forces.

Design conditions may result in the location of the proof mass being outside the mass center of the main satellite. When the satellite is spun about one axis so that the attraction forces it produces over the proof mass are averaged on the other two axes, the proof mass can be located, in general, on the spin axis, but possibly far away from the mass center.

In that case, attitude motions of the satellite are sensed by the proof mass. This coupling of a attitude and translation may lead to instability in the motion of the satellite when it is coupled with misalignments of the thrustors of the translation control system. The effect of the coupling between the attitude and translation controls are studied, and a boundary of stability is developed for the phenomenon.

Locating the proof mass on the spin axis far away from the mass center has the advantage of allowing estimation of the three-dimensional relative position of the mass center, proof mass, and pickoff null of the sensor. That estimation is important in order to avoid the “trapping” phenomenon and for correcting the drift of the pickoff null. Both “trapping” and drifting of the null tend to reduce the active life of a drag-free satellite. Two different solutions for the estimator are developed on a theoretical basis, and the results checked through analog computer and laboratory simulation. For the laboratory simulation, a 5 cm gap capacitive pickoff was made and attached to a 3-degree of-freedom spinning vehicle simulator. It is shown that the three-dimensional mass center position can be estimated when the proof mass is far enough from the mass center and some nutation is present.

The three-dimensional mass center estimation requires the previous knowledge of the vehicle attitude behavior, so the estimation of that behavior is also considered, using accelerometers as sensing devices. Several possibilities of building an estimator from measurements of the derivatives of the states are studied, and a general unified form for the estimators is given. The results are applied to estimating the attitude of a spinning satellite and checked through analog simulation.

DiDONNA, Brian ***SUSPENSION TORQUE PREDICTIONS FOR THE RELATIVITY GYROSCOPE EXPERIMENT, UNDERGRADUATE HONORS THESIS*****, DEPARTMENT OF PHYSICS, MAY 1994.**

Abstract:

The Gravity Probe B mission is an ultra-sensitive satellite test of General Relativity which relies on four precise gyroscopes in a near perfect earth orbit. In order to measure the effect of Earth’s gravity on the local inertial frame of the gyroscope, all other sources of gyroscope precession must be minimized so that non-relativistic drift be less than 0.3 milliarcsec/year. This paper analyses the torque on the rotors resulting from the action of the rotor suspension system. the equations for these torques are worked out to second order in rotor-suspension electrode capacitance as functions of rotor and electrode shapes and electrode voltages. Sensitive surface shape

measurements are taken of two finished rotors. A Talyrond 73 roundness measuring machine was used to measure the roundness of several great circles of the two rotors, then the single plane measurements were correlated to produce a complete surface measurement. Substitutions are made into the torque equations for rotor shape and expected mission electrode voltage levels in order to check current rotor fabrication technology and suspension system design against stated mission goals. It was found that the measured samples were slightly outside the design goal and torque levels are therefore too high to meet the above requirement on drift. Also, it is shown that a different suspension response algorithm which minimizes the sum of the squares of the electrode voltages could significantly improve gyroscope accuracy.

DeHOFF, Ronald L. ***MINIMUM THRUSTORS CONTROL OF A SPINNING DRAG-FREE SATELLITE, INCLUDING DESIGN OF A LARGE CAVITY SENSOR,*** **DECEMBER 1975**

Abstract:

A drag-free satellite is controlled in translation so that it follows a proof mass in an internal cavity. The proof mass follows a nearly gravity-only orbit because external surface forces do not act upon it. Forces which do tend to perturb the proof mass motion include vehicle self-gravity forces, thermal gradient forces, and electrostatic interactions. Increasing the internal cavity size reduces the magnitudes of these forces. Spinning the satellite attenuates the effects of these forces and allows a reduction in the number of required control thrustors.

Translational control can be accomplished with a minimum of two thrustors which produce opposing force components along the spin axis, and a component in the spin plane. The minimum thrustors control law is described which determines the proper algorithm for producing stable system motion. The stability limits are theoretically derived for operations with time delays. The effect of external forces on the stability and performance is discussed.

Sensing the position of the proof mass within a large cavity is a problem. A new optical sensor is proposed, using fluorescent reemission from the proof mass excited by a pulsed ultraviolet source. Orthogonally mounted, single axis sensors provide a three-dimensional position measurement of the proof mass position via a current imbalance proportional to the centroid of the light flux incident on the sensor strip. Frequency separation of the excited and excitant light flux allows three-axis operation using a single exciting source. Ultraviolet light energy is provided by a short xenon arc lamp producing large instantaneous light flux at a low duty cycle. This mode of operation yields a discrete measurement time history applicable to direct digital computer processing. The low duty cycle allows an extremely small average power consumption.

The control system was mechanized on a laboratory simulator demonstrate the performance of the minimum thrustors control law and the large cavity sensor. The effects of parameter variations and sensor nonlinearities are discussed.

DiESPOSTI, Ray S.. ***DATA REDUCTION SIMULATION FOR THE STANFORD RELATIVITY GYROSCOPE EXPERIMENT,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, JUNE, 1986**

Abstract:

The Stanford Relativity Gyroscope Experiment, also known as NASA Gravity Probe B, is a space experiment to test Einstein's General Theory of Relativity. The experiment consists of placing gyroscopes in low-earth-orbit and measuring the precessions of their spin axes as predicted by Einstein's theory. For a 650 km polar orbit, two precessions are predicted: a "geodetic" precession of 6.6 arcsec/year northward, due to the motion of the gyroscope about the earth, and a "motional" precession of 0.042 arcsec/year eastward, due to the coupling between the earth's rotation and the gyro's spin.

This thesis describes an all-digital data flow and data reduction simulation. A single gyroscope, with spin axis nominally along the direction of the star Rigel, is assumed to orbit the earth within a cryogenic satellite which rolls about the line-of-sight to Rigel.

The star serves as an inertial reference, and its direction with respect to the satellite is measured by a telescope. The gyro's spin axis direction, with respect to the satellite, is measured with a SQUID magnetometer. Subtraction of the telescope measurement from the gyro measurement gives of the gyro's spin axis with respect to the inertial reference. Relativistic precessions are measured by observing this "gyro minus telescope" data.

To perform the study, simulated gyro and telescope measurement data is generated by the "The Model" approach. The data is passed through a low-pass, pre-sampling filter to decrease the effects of aliasing and to attenuate undesirable high frequency components of the signal. Sampled data is processed by Kalman Filter algorithms. The Kalman Filter extracts optimal estimates of the relativistic precessions from the measurement data.

Computer simulation of a 14 -month mission has demonstrated that, with the assumptions used in this thesis, the geodetic effect can be estimated to an accuracy of approximately 0.04%, and the motional effect to an accuracy of approximately 3%. This research thus demonstrates the feasibility of data reduction for the mission.

DUHAMEL, Thiery. G. ***CONTRIBUTIONS TO THE ERROR ANALYSIS IN THE RELATIVITY GYROSCOPE EXPERIMENT*****, GUIDANCE AND CONTROL LABORATORY, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, APRIL, 1984**

Abstract:

In this thesis we examine various aspects of the error analysis in the Relativity Gyroscope Experiment. This experiment is designed to measure the relativistic precessions of a gyroscope in orbit around the Earth. For a polar orbit at altitude 500 km, there are two precessions: a “geodetic” precession in the northsouth direction, of magnitude 6.9 arcsec/year, due to the motion of the gyroscope around the Earth and a “motional” precession in the east-west direction, of magnitude 44 milliarcsec/year, due to frame-dragging by the rotating Earth. The design goal of the experiment is to measure the relativistic precessions with a precision of 1 milliarcsec/year.

Four electrostatically suspended superconducting spherical gyroscopes are onboard a cryogenic satellite. The direction of their spin axis is measured with SQUID magnetometers and compared to an inertial reference direction which is provided by a telescope pointed at the star Rigel.

We use a Kalman filter in its square root form to estimate the precision on the relativistic precessions at the end of one year. In order to reduce the computer time we used an analytical averaging technique.

We give a detailed examination of the aberration of starlight. We study the possibility of determination of the bending of starlight by the Sun by means of the Gyroscope experiment and show that it compares in precision with VLBI techniques.

We examine the dynamics of the gyroscope taking into account the effects of elastic distortion due to centrifugal force.

When the gyroscope rotors are cooled through their superconducting transition temperature, the ambient magnetic field is trapped in the rotor. We show how the trapped flux signal at spin frequency can be used to calibrate the scale factor of the SQUID magnetometers.

FELSON, WAYNE S. ***MAGNETIC DIPOLE ANDQUADROPLE READOUT FOR GROUND-BASED TESTING OF THE RELATIVITY GYROSCOPE UNDERGRADUATEHONORS THESIS*, DEPARTMENT OF PHYSICS, MARCH 1993.**

Abstract:

The Gravity Probe (GP-B) experiment is an ongoing project designed to test aspects of Einstein's general theory of relativity using ultra-precise gyroscopes in space. These spherical gyroscopes are electrostatically supported and have a thin superconducting coating. This thesis describes the use of trapped magnetic flux in the gyroscope as a readout method for ground-based testing. The magnetic field produced by the trapped flux can be expanded in terms of multipole moments. It will be shown that the dipole and quadrupole moments alone are sufficient to determine the full orientation of the gyroscope's spin axis in both the body and laboratory reference frames.

Experimental work investigating the feasibility of this readout method was performed at the GP-B Low-Field Facility. A set of three mutually orthogonal pickup loops attached to SQUID magnetometers were used to readout the motion of the trapped flux fields over time. Two of these loops were in the Helmholtz configuration, making them sensitive only to the magnetic dipole moment, while the third was designed to be sensitive only to the quadrupole.

While the full implementation of readout utilizing the quadrupole moment has not yet been successfully demonstrated, several important subgoals were achieved. In particular, the method of trapped flux dipole analysis was refined and used to reproduce the London moment signal to within a few percent accuracy.

FETEIH, Salah ***DYNAMICALLY TESTING OF GP-B ELECTROSTATICALLY LEVITATED SPHERICAL GYROSCOPES*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, SEPTEMBER 1989.**

Abstract:

This thesis describes the techniques used to test, verify, and assess the characteristics and performance of GP-B electrostatically-levitated, cryogenically-cooled spherical gyroscopes (designated 86-4 and 87R11c). These tests were conducted in ground-based testing facility and their results, in terms of mass unbalance and inertia ratios, were used to extrapolate the gyroscopes performance in Earth-orbit during the science mission.

Gravity Probe B (GP-B) is an ongoing joint project by Stanford, NASA, and Lockheed to test Einstein's general theory of relativity. The objective of the experiment is to detect and to measure the geodetic and frame-dragging effects exhibited by an Earth-orbiting spinning gyroscope. The general theory of relativity predicts that the first of these effects is 2.22 x 10^{-7} *deg/hr* and the second is 1.43 x 10-^{09} *deg/hr*.

Dynamic testing comprises levitating the gyroscope using electrostatic suspension and spinning it using a helium gas jet to the desired spin speed (1 - 5 *Hz*) in a low pressure, low magnetic field environment. A set of three orthogonal pick-up loops, each attached to a SQUID (Superconducting QUantum Interference Device) was used to detect the a.c. (spin frequency) and the d.c. components of the magnetic field trapped inside the gyroscope (known as the trapped flux).

The time histories of these signals is used to obtain the spin vector motion in the laboratory. this motion is used to estimate the mass unbalance and the inertial ratios of the gyroscope, and to obtain information on the coefficients of the gyroscope' higher harmonics in shape. Biases in the SQUIDs were calculated, and the spin vector trace inside the gyroscope is estimated.

This research develops techniques to reliably measure the time history of the spin vector in the lab using two or three pick-up loops, using the signature of the magnetic trapped flux inside the gyroscope. Also described is the technique used to estimate the gyroscope's characteristics using precession information in the lab and in the body. Spinning at 1 *Hz*, gyroscope 86-4 had a precession rate of 98 *deg/hr*, which represents a mass unbalance of 6.1 *mcm*. This mass unbalance would result in precession of 1 x 10^{-12} *deg/hr* or less than 0.03 $m\,\widehat{sec}$ */year* in orbit conditions. Therefore gyroscope 86-4 (based on mass unbalance estimated in the lab) is within science mission requirements in terms of precession due to Newtonian torques. This research also shows that we can estimate the coefficients of higher harmonics in shape of the gyroscope using the time rate of change of the spin vector in the lab. Decay of the trapped magnetic field was observed and recorded during this research, it was found to take place during the first few hours after levitating and spinning the gyroscope.

GARDNER, Robert D. ***INDUCTIVE SEARCH FOR MAGNETIC MONOPOLES WITH THREE-LOOP SUPERCONDUCTING DETECTOR AND DESIGN OF EIGHT-LOOP DETECTOR,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, JUNE, 1987**

Abstract:
Superconducting loops can be used to detect the passage of cosmic-ray magnetic monopoles by inductively coupling to the monopole field. A superconducting induction detector with three mutually orthogonal loops and 476 cm^2 sensing area averaged over solid angle was in operation at Stanford from 25 Jan. 1983 to 20 March 1986. It set a monopole flux limit of 4.4×10^{-12} cm^{-2} $_S$-1 sr^{-1} at 90% confidence limit, the best limit to date with a superconducting detector. This work describes the three-loop detector in detail, provides theoretical analysis of the detector response to a flux of magnetic monopoles, and describes results obtained from the detector. The detector response is found from Monte Carlos simulation of monopole trajectories to determine the locus of possible monopole signals. In addition, a larger detector has been constructed with eight loops laid in octagonal fashion around a cylinder and 1.5 m^2 sensing area averaged over solid angle, a factor of 30 larger than the three-loop detector. General design aspects of the eight-loop detector are discussed and a similar theoretical analysis of this detector is provided. The detectors are found to be very discriminating against spurious signals

GAZIT, RAN Y. ***AIRCRAFT SURVEILLANCE AND COLLISION AVOIDANCE USING GPS*****, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, AUGUST 1996**

Abstract:
Avoidance of in-flight collisions requires accurate and timely information on aircraft position and velocity. this information is obtained today by a ground-based surveillance system that is limited in accuracy, coverage and automation. A new concept for integrated navigation and surveillance suggests that every aircraft will periodically broadcast its position as determined by an on-board GPS receiver. The position reports will be received by Air Traffic Control ground facilities and will be used for aircraft tracking and conflict resolution.

The key to the successful application of this concept is a reliable data link architecture that will allow all aircraft within a specified detection range to exchange information at a required rate. In this research, the basic parameters and relationships that govern the data link channel capacity are identified, and bounds on the performance of several random-access and self-organized communication protocols are set.

Unique adaptive algorithms for aircraftt racking are designed and tested. The resulting tracking accuracy is shown to be superior to the performance of modern, multiple-model radar trackers. The improvement in tracking accuracy provides the means to reduce aircraft separation standards and to decrease the runway spacing required for independent parallel approaches, all without affecting the safety level.

Moreover, since each aircraft can receive the position reports of its neighbors, a highly accurate airborne collision avoidance system can be designed. The three-dimensional positioning information provided by GPS, coupled with new collision detection and avoidance algorithms can provide timely alarms with a low false alarm rate. This significantly improves the performance of the current airborne avoidance system.

GROMOV, Konstantin G. ***INVESTIGATION OF AGORITHMS FOR THE PRIMARY PROCESSING OF SIGNALS IN THE GPA/GLONASS INTEGRATED RECEIVER*****, SENIOR'S THESIS, V. I. U1 'yanov (Lenin) Institute of Electrical Engineering, Radio Engineering Faculty, Department ofRadio Systems, Saint Petersburg, 1992**

Abstract:
None (Translated version)

GUTT, GREGORY M. ***ENHANCEMENT, ANALYSIS AND VERIFICATION OF THE GRAVITY PROBE B SQUID READOUT SYSTEM,*** **DEPARTMENT OF ELECTRICAL ENGINEERING, AUGUST, 1997**

Abstract:
This dissertation discusses the analysis, development and testing of key parts of the gyroscope readout system for the Stanford Relativity Gyroscope Experiment, also known as Gravity Probe B (GP-B). The GP-B experiment is designed to accurately measure two physical phenomena that are predicted from Einstein's general theory of relativity: the frame-dragging effect and the geodetic effect. These two effects will be measured through the use of very accurate gyroscopes that are to be placed in a polar orbit at an altitude of 650 km about the earth. The geodetic effect is a consequence of a gyroscope moving through the distorted space-time generated by earth's mass. The frame-dragging effect is caused by the dragging of an inertial frame by a massive rotating body (the earth).

The general theory of relativity predicts that a gyroscope under these conditions will precess. In the GP-B specific case the expected precession rates are: $\approx 0.04\,\widehat{\sec}\,/year$ for the frame-dragging effect and $\approx 6.6\,\widehat{\sec}\,/year$ for the geodetic effect. The polar orbit of the GP-B experiment causes the precessions to be orthogonal to each other and therefore independently measurable. The goal of the experiment is to measure these two precession rates to an accuracy better than $0.5m\,\widehat{\sec}\,/year$.

To accomplish the measurement of these small precessions, a sophisticated detector system is needed to "read-out" the orientation of the gyroscope spin axis. The GP-B readout system utilizes a property of rotating superconductors known as the London momenta Each of the four GP-B gyroscopes is coated with a metal (niobium) which becomes superconductive when cooled below 9.2 K. A spinning body that is in the superconducting state produces a magnetic field (London moment) that is perfectly aligned with the spin axis of the body. The new challenge is to accurately measure the magnitude and direction of the magnetic field. For this purpose a Superconducting Quantum Interference Device (SQUID) is used. The SQUID is an extremely sensitive, nonlinear sensor that is responsive to magnetic flux. The readout system incorporates a superconducting pickup loop which surrounds the gyroscope and acts to couple the magnetic flux from the gyro's London moment to a SQUID. In this configuration the SQUID produces a voltage in response to the coupled flux. By analyzing the measured SQUID voltage based on the known coupling properties of the loop, the gyroscope orientation is computed.

Although SQUIDs are known to be ultra-quiet and accurate sensors, the requirements of the readout system are considerable. There are a number of environmental and systemic disturbances that can affect the performance of the SQUID readout system during the one year mission: electromagnetic interference (EMI), proton bombardment, temperature inducted drifts, noise and nonlinearities. Parts of the readout system were redesigned to better endure these phenomena. After physical construction of various portions of the readout hardware, experiments were performed to demonstrate that the error induced by these disturbances was acceptable. Hardware was tested under appropriately harsh conditions to show that the readout subsystems will work as expected.

Finally, an experiment was performed to test the entire integrated readout system from the pickup loops to the analog to digital converters. The goal was to show the strengths and weaknesses of the complete data chain. This test used an elaborate prototypical science mission test bed and simulated many of the essential aspects of a real mission. Simulated "truth" data were injected into the readout system at a rate of 2100 Hz for six days (3 gigabytes). The output of the readout system was simultaneously recorded and stored. Next, the data was analyzed using the baseline Kalman filter algorithm and compared against predicted results. The error between the measured signals and truth were within the expected range. The results of the collective experimental data set provide a promising indicator that the GP-B readout concept is sound and should be capable of measuring the general relativistic precessions to the required level of accuracy.

HAUPT, Gordon T. ***DEVELOPMENT AND EXPERIMENTAL VERIFICATION OF A NONLINEAR DATA REDUCTION ALGORITHM FOR THE GRAVITY PROBE BE RELATIVITY MISSION,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, MARCH, 1996**

Abstract:

This dissertation is a summary of recent work on the Niobium Bird project of the Gravity Probe B Relativity Mission (GP-B). The Niobium Bird is an integral part of the effort to develop a data reduction scheme for GP-B and provides a test bed for end-to-end verification of the mission. This verification is achieved by integrating prototypical readout hardware with numerical simulations and filtering algorithms to demonstrate that the required mission accuracy can be achieved.

The Gravity Probe B Relativity Mission will check previously unverified predictions of Einstein's General Theory of Relativity by measuring, over the course of a one-year experiment, the directional change of an Earth-orbiting gyroscopes' spin axis relative tothe distant inertial frame defined by the fixed stars. According to general relativity, the spin axis will undergo two orthogonal precessions of magnitude 6.6 and 0.04 arcseconds per year for a 650-km polar orbit. The readout system for measuring the direction of the spin axis will employ a SQUID (Superconducting Quantum Interference Device) magnetometer. A data reduction algorithm is used to estimate the relativistic drifts from the SQUID measurements. GP-B will measure these tiny drift angles to sub-milliarcsecond accuracy, a requirement which puts extreme constraints on the gyroscope and the readout system. Given these requirements, it is crucial that the gyroscope, readout system and data reduction 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 information is used to effect design changes in the gyroscopes, the readout system or the data reduction algorithm.

This thesis presents the latest results from the Niobium Bird. Improvements in the signal simulation include modeling of extraneous signals due to temperature variations and ambient magnetic field trapped on the surface of the gyroscopes. Upgrades to the readout hardware include seamless, high-speed data injection and acquisition capability, monitoring of environmental variables such as temperature and vibrations and ambient magnetic field trapped on the surface of the gyroscopes. Upgrades to the readout hardware include seamless, high-speed data injection and acquisition capability, monitoring of environmental variables such as temperature and vibrations, and characterization of system properties, including linearity and stability.

The measurements obtained by the SQUID readout system are a nonlinear function of the relativity parameters and other unknowns. This had led to the development and application of an optimal, recursive nonlinear least-squares estimation algorithm, which has been generalized for application to other nonlinear problems. The algorithm uses a state transformation to break the cost-function minimization into two steps, allowing the estimator to be both optimal and recursive. Examples are given in which significant improvement is shown over other common nonlinear estimation algorithms, such as the extended Kalman filter and iterated extended Kalman filter. The two-step estimator has been implemented in the Niobium Bird environment and has been used to demonstrate 0.2 milliarcseconds accuracy of the relativity estimates after one year. One-day experimental runs have helped confirm these simulation results.

HAURANI, Ammar ***VIBRATION TEST OF THE GRAVITY PROBE B GYROSCOPE*****, DEPARTMENT OF MECHANICAL ENGINEERING, OCTOBER, 1989**

INTRODUCTION:

Gravity Probe B is the relativity gyroscope experiment being developed by NASA and Stanford University to test two extraordinary, unverified predictions of Albert Einstein's general theory of relativity.

The experiment will check, very precisely, tiny changes in the directions of spin relative to a fixed star of four gyroscopes contained in an Earth satellite orbiting at 400-mile (650 km) altitude directly over the poles. So free are the gyroscopes from disturbance that they will provide an almost perfect space-time reference system. They will measure how space and time are warped by the presence of the Earth, and, more profoundly, how the Earth's rotation drags space-time around with it. These effects, though small for the Earth, have far reaching implications for the understanding of the Universe (see Ref #1).

The gyroscopes for Gravity Probe B have to provide a reference system stable to 1R-11 degrees/hour _ more than a million times better than the best inertial navigation gyroscopes. In inertial navigation many gyro disturbances can be quantified empirically and calibrated out. Not so in Gravity Probe B. Its gyroscopes have to be made stable to a level of 0.3 marsec/year and this must be on an absolute level.

Why, given the sophistication of modern gyroscope technology, is such a quest not absurd? In Gravity Probe B two factors_space and near zero temperature (see Ref #9)_ transform the problem. The gyroscopes are suspended spinning spheres made of solid fused quartz. Electrically suspended gyroscopes have long been among the best inertial navigation instruments but ordinarily their performance is limited by support forces. Space, enhanced by "drag-free control" (see Ref #10), allows the support to be reduced almost to 10E-11 g. Low temperature operation greatly improves the mechanical stability of the instrument and makes possible a very sensitive read out technique; and it also makes superconductive shielding of the gyroscopes against magnetic disturbances possible.

Conceptually, the Gravity Probe B instrument is simple. Its core is a block of fused quartz (a very stable glassy material), 21 inches long, bonded to a quartz telescope and containing within it four gyroscopes plus a drag-free proof mass. This gyro-telescope structure is kept at high vacuum within 9_foot (2.74 m)_long cigar_shaped chamber ("the probe"), which is inserted into a large dewar vessel filled initially with 400 gallons (1.514 liters) of superfluid helium. The dewar maintains the instrument at a temperature of 1.8 K above the absolute zero for two years. It is also the main structural element of the spacecraft.

Within the dewar, surrounding the probe, is a shield formed from superconducting lead foil which almost completely excludes the Earth's magnetic field. Thus, the gyroscopes operate (1) at low temperature (2) at low pressure (3) in low magnetic field (4) in the low gravity of space. These are four of seven "near zero" that have been identified as hallmarks of Gravity Probe B. The other three characterize the gyro rotor.

The satellite orbit is polar, circular, at 400-mile (650 km) altitude and coplanar with the line to the guide star, Rigel. The gyroscopes are aligned parallel to the telescope axis, two spinning clockwise and two counterclockwise, each gyroscope measuring both relativity effects (Frame dragging: Measuring the Rotation of space-time and the Geodetic Effect: Measuring the curvature of space-time).

Spheres of fused quartz, the size of ping-pong balls, each coated with a very thin, very uniform, chemically pure, mechanically *robust*, electrically stable layer of the metal niobium, the gyro rotors are a technological achievement. The conjoin Gravity Probe B's three remaining "near zeros" _extremes of homogeneity, mechanical sphericity, and electrical sphericity.

The gyro spin directions are referred via a quartz block to the telescope, and the telescope to the guide star. Truthful data demands a stable mechanical structure and a telescope capable, like the gyroscopes, of measuring angular changes to .1 milliarcsecond_a factor of 1,000 better than typical, very good, star-tracking telescopes.

Even in space, weak forces must be applied to keep the rotors centered in their housings. Levitation is electrical with voltages applied to three pairs of saucer-shaped electrodes inside the spherical cavities, and the rotor stays centered to a few millionths of an inch while spinning at 10,000 rpm_twice the speed of a sports car engine. To lift the rotor on Earth takes 1,000 volts. In space only a fraction of a volt is needed. This reduction is crucial to the enormous improvement in gyro performance required and obtained in Gravity Probe B (see Ref #1).

During the launch phase, the rotors are not suspended thus are free to rattle inside the housings under the effect of vibrations. Damage to the rotor or the housing subject to vibrations, can deteriorate the quality of the gyroscopes, necessary for the adequate functioning of the Gravity Probe B experiment.

The purpose of our research is to study the effect of the random vibrations experience by the gyroscopes during the launching phase. As mentioned in the introduction, the rotors are not suspended in their housings until reaching the orbital altitude of 400 miles (650 km). Until then, they are a free to rattle thus facing possible damage. Our objectives are:

1-Evaluate the vibration loads on the gyroscope using the existing information

` 2-Develop the theory necessary for the understanding of the dynamics of the rotor inside the housing subject to vibrations. The stresses developed at the impact surfaces of the rotor and the housing are to be studied.

3.-Design and set up an experiment with an actual gyroscope subject to vibrations, to study the motion of the rotor and the resistance of the hosing and of the rotor to damage.

4. -Correlate the results of steps 2 and 3.

HEBARD, Arthur F ***SEARCH FOR FRACTIONAL CHARGE USING LOW TEMPERATURE TECHNIQUES*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, DECEMBER, 1970**

Abstract:

The purpose of the experiment described in this dissertation is to search for fractionally charged particles called quarks. The symmetries of high energy physics would be greatly simplified if quarks with charge ± 1/3 and ± 2/3 the charge of an electron exist as the basic building blocks of all the known mesons and baryons. The proton, for example, would be made from two + 2/3 quarks and one - 1/3 quark.

The central assumption of the experiment is that cosmic rays have been bombarding the earth since time began with sufficient energy to create free quarks which will combine with matter to form long-lived fractionally charged entities. A low temperature apparatus is described which is capable of detecting electric charge smaller than that of an electron on a superconducting niobium sphere with a mass of 7×10^{-5} gm. A quark on the niobium sphere would be observable as an irreducible fractional charge and the probability of finding one is proportional to the mass of the sphere. For comparison, the mass of the niobium sphere is more than 10^6 times the mass of a typical Millikan Oil Drop. parallel capacitor plates with an oscillation period of 1.5 seconds and a Q in the range of 1500-3000. A square wave electric field is applied at the resonant frequency and the amplitude change, as recorded by a SQUID magnetometer, is a direct measure of the electric charge on the sphere. Separate positron (Na-22) and electron (T1-204) radioactive sources are used for charge control.

Preliminary results obtained for a single sphere indicate a non-zero residual charge of magnitude -.37 ± .03. This value of approximate magnitude -1/3 does not necessarily imply the reality of quarks because of the fact that there might exist spurious charge forces which are caused by the apparatus. Such a force might arise for example if the induced electric dipole moment on the sphere, which is proportional to the electric field, interacts with a fixed field gradient, caused by a surface dipole layer on the capacitor plates, to give a force linear in the electric field and hence indistinguishable from the charge force.

Before this result can be taken as evidence for a quark, the sensitivity of this apparent residual charge to different experimental conditions will be investigated and the results checked by measurements on other spheres which must have charge intercepts of one -1/3, + 1/3 and zero.

HESS, George B. ***MEASUREMENTS OF ANGULAR MOMENTUM IN SUPERFLUID HELIUM,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, APRIL, 1967**

INTRODUCTION:

A constraint on the vorticity of the superfluid component appears to play an essential role in the two-fluid model of liquid helium II. Landau's (1941) theory predicted that the superfluid is incapable of rotation, and a similar conclusion was implicit in the phenomenological theory of F. London (1938a, b; 1939) and Tisza (1938, 1947), based on analogy to Bose-Einstein condensation. Contrary to this, a number of experimental studies found no measurable difference between superfluid rotating in equilibrium and classical rigid rotation (Table 1).

These experimental results were later understood on the basis of the quantized vortex model of Onsager (1949) and Feynman (1955). They proposed that the circulation around an arbitrary path in the superfluid need not be zero, but must be a multiple of h/m, where h is Planck's constant and m is the mass of a helium atom. Vorticity is permitted, but is confined to vortex line singularities, each of circulation h/m. In a large scale rotation experiment with many vortex lines present, classical fluid rotation may be approximated on the average, and the deviations on a small scale are not readily observable. In order to show gross deviations from classical rotation, the container must have radius and angular velocity sufficiently small that almost only a few vortices may be present in equilibrium.

H. London (1947) proposed an experiment to test whether superfluidity in helium results from a constraint against vorticity I thermodynamic equilibrium or is a metastable phenomenon resulting from weakness of interactions. This experiment consists in setting a cylindrical container of liquid helium I into slow uniform rotation about its axis. While the container continues to rotate, the helium is slowly cooled to a temperature well below the λ-point. If superfluidity is simply due to the absence of interactions, the angular momentum of the helium should be unchanged on cooling. On the other hand, if the superfluid state is the thermodynamic equilibrium state, the superfluid which is created during the cooling can have no angular momentum, and the excess angular momentum must be transferred to the container.

The angular velocity must be sufficiently small that it is not energetically favorable to form even none vortex in the superfluid. Specifically, as H. London predicted before the vortex model, the maximum angular velocity must be of order $\tilde{n}/mR^2$, where R is the radius of the container. Consequently, the predicted angular momentum transfer is rather small:Δ L= (constant) $M(\rho_{s/}\rho)(\tilde{n}/m)$, where M is the mass of helium and the constant turns out to be about 10.

Experiments of this type have been carried out previously only at angular velocities much too large, relative to the diameter of the container, to avoid occurrence of hundreds of vortices and with sensitivity too low to detect a deviation from classical angular momentum.

The work reported here is a realization of London's experiment. A Beams magnetic suspension is used as a frictionless bearing to support a container of liquid helium in essentially free rotation, so that angular momentum transfer from the helium can be observed as a change in the period of rotation. Measurements extend down to angular velocities at which no vortices are expected. The overall sensitivity is about 0.1 of the classical angular momentum at the predicted critical angular velocity for the occurrence of the first vortex in equilibrium. A few additional runs have been made in which the container is cooled through the λ-point at rest and then set into rotation, in order to study the reversibility of this superfluid state.

JACOBS, Mark W. ***The Metric of Our Universe: Its Form and Observational Effects,*** **DEPARTMENT OF PHYSICS, August 1995.**

Abstract:

To understand astronomical observations of objects at large distances, it is essential to have a model of the cosmological spacetime metric. The Universe on average seems well-described by the uniform-density FLRW models, but with metric perturbations possible on all scales. The first part of the thesis is devoted to a method for solving the gravitational field equations for these perturbations. It gives an expression in terms of pseudo-Newtonian gravitational potential, which is valid for an almost arbitrary range of matter-density fluctuation

amplitudes. The matter-density field is assumed to be known, and the metric perturbations are assumed to be scalar-type, that is, with no "gravitomagnetic" (vector or gravitational-wave (tensor) components. The application of the expression for the potential is illustrated by simple calculations of deflection and redshift for a light ray passing an isolated, static mass-point, and compared to the corresponding Newtonian (or thin-lens) calculations. Fractional changes to the deflection are essentially insignificant; however for high emitter redshifts the correction to the Newtonian redshift perturbation can be on the order of 10%, both perturbation values being about 1 : 10^6 of the unperturbed value due to the cosmological expansion.

Finally, on a separate topic, the second part of the thesis deals with the geodesic motion of test particles in Gödel's universe, and its similarity to the motion of charged particles in a uniform magnetic field.

JAFRY, Yusuf R. ***AERONOMY COEXPERIMENTS ON DRAG-FREE SATELLITES WITH PROPORTIONAL THRUSTERS: GP-B AND STEP,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS MARCH 1992.**

Abstract:

GP-B (Gravity Probe B) and STEP (SatelliteTest of the Equivalence Principle) are two proposed space experiments in basic physics, scheduled for launch around the end of the decade. Both will utilize *drag-free* spacecraft in ≈ 600 km polar, orbits around the earth. By monitoring the activity of the drag-free compensators, it will be possible to obtain in situ drag measurements from which variations in atmospheric density and winds can be observed with unprecedented resolution (≈ 80 km, spatially; ≈ 10 seconds, temporally). With the inclusion of additional instrumentation such as neutral mass spectrometers and energy analyzers, it will be possible to distinguish the effects of the various species; thus significantly enhancing the aeronomic contribution of the drag data. This complementary drag/composition data will represent the first comprehensive in situ investigation of the properties of the upper-thermosphere/lower-exosphere and should lead to a fuller understanding of the dynamics of this essentially unexplored region.

The pioneering flight of Triad in 1972 has successfully demonstrated that a drag-free satellite (DFS) can furnish useful aeronomic data. High resolution in situ density measurements at 850 km were obtained for the first time. GP-B will be the first DFS to use proportional thrusters (Triad had on-off control), and STEP is likely to inherit the technology. The drag information will be contained in *both* the motion of the spacecraft about the drag-free proof-mass, and the thruster activity.

A new *minimum variance smoother* has been developed to *deconvolve* the *net* forces from the proof-mass sensor measurements. The smoother is an adaptation of an existing algorithm, which has been tailored to cater for *completely unknown inputs*. The smoother is demonstrated to be accurate and robust in comparison with simpler Kalman filter techniques.

After the deconvolution process, the thrust force must be subtracted from the net force to yield the estimate of the drag. Hence, the accuracy of the drag measurements will ultimately depend on the accuracy of the thruster calibration and on stability of the scale-factors and biases. Assuming that *closed-loop* thrusters are used, then the errors associated with the calibration of each thruster can be substantially reduced, and perhaps the largest remaining source of uncertainty will be associated with impingement of the thruster plumes on the spacecraft surfaces. It is thus desirable to model these effects.

Conventionally, plume calculations are performed based on the assumption of continuum viscous flow in the nozzle. However, owing to the low thrust levels, the flow through the GP-B nozzles will be highly rarefied, rendering the continuum model invalid. An experimental procedure was devised to characterize the plume structure. A mass spectrometer, modified from a commercially available helium leak detector, was used to measure the mass flux distribution. The instrument was mounted on a robotic cradle inside a vacuum chamber, allowing measurements to be performed over a range of angles from the plume centerline, and over a range of distances downstream from the nozzle exit. The observed plume shapes were found to be essentially unchanged with mass flow - except for a slight narrowing at very low mass flows. The experimental results were compared with Boyd's DSMC (Direct Simulation Monte Carlo) solutions pertaining to the nozzle geometries and flow conditions used in the experiments. For the assumption of diffuse interaction with the nozzle walls, the numerical results were found to be in excellent agreement with the experimental results at nominal flow rates. The experimental data are valuable because there is no other data pertaining to the far-field plumes of such highly-rarefied nozzle flows. From the results of the plume study, for the planned location of the thrusters, it is concluded that the impingement effects will not be significantly detrimental to the aeronomy coexperiments.

JHIN, Philip ***CONTROL OF A SPINNING DRAG-FREE SATELLITE TO REDUCE TRAJECTORY ERRORS DUE TO MASS ATTRACTION,*** **AUGUST 1970**

Abstract

The Quick STEP (Satellite Test of the Equivalence Principle) mission seeks to improve the testing of the equivalence of inertial and gravitational mass by six orders of magnitude over present measurements. The Quick STEP payload comprises four Equivalence Principle (EP) differential accelerometers at different locations in the spacecraft. The purpose of the translation control system is to minimize disturbances on the drag free EP accelerometer to perform the best EP experiment, while the purpose of the attitude control system is to minimize disturbances on the non drag free accelerometers and perform valuable EP experiments with them as well.

The translation controller estimates the disturbance at the EP frequency and uses feed forward to cancel its effect, thus realizing the quietest environment for the drag free accelerometer in its axial direction; while in the radial direction, a virtual proof mass concept was used to minimize the attitude motion disturbance.

The attitude controller design consists of two parts. The first part determines the optimal reference orientation by minimizing the total specific force on the non drag free accelerometers. The second part controls the spacecraft attitude to follow the optimal reference input. We have designed a new type of estimator, which uses the combined information from the star tracker measurements, accelerometer measurements and GPS measurements to estimate the necessary states for the attitude control. Unlike a conventional Kalman filter, this estimator does not use control force in its time update process. This method is applicable to a class of control systems which consists of a fast controller, a slow estimator and nonwhite process noise.

A new concept of safety margin to quantify the performance of a thruster configuration is introduced. This concept can be used to evaluate thruster configurations and design optimal thruster configuration. A new thruster controller for one-sided thruster systems is developed, which is based on the linear pseudo-inverse controller for two-sided thruster systems. This controller is applicable to any one-sided actuator system, including the one sided thruster system used in the Quick STEP spacecraft.

JIN, Haiping ***TRANSLATION AND ATTITUDE CONTROL FOR THE QUICK STEP SATELLITE,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, AUGUST 1996**

Abstract

The Quick STEP (Satellite Test of the Equivalence Principle) mission seeks to improve the testing of the equivalence of inertial and gravitational mass by six orders of magnitude over present measurements. The Quick STEP payload comprises four Equivalence Principle (EP) differential accelerometers at different locations in the spacecraft. The purpose of the translation control system is to minimize disturbances on the drag free EP accelerometer to perform the best EP experiment, while the purpose of the attitude control system is to minimize disturbances on the non drag free accelerometers and perform valuable EP experiments with them as well.

The translation controller estimates the disturbance at the EP frequency and uses feed forward to cancel its effect, thus realizing the quietest environment for the drag free accelerometer in its axial direction; while in the radial direction, a virtual proof mass concept was used to minimize the attitude motion disturbance.

The attitude controller design consists of two parts. The first part determines the optimal reference orientation by minimizing the total specific force on the non drag free accelerometers. The second part controls the spacecraft attitude to follow the optimal reference input. We have designed a new type of estimator, which uses the combined information from the star tracker measurements, accelerometer measurements and GPS measurements to estimate the necessary states for the attitude control. Unlike a conventional Kalman filter, this estimator does not use control force in its time update process. This method is applicable to a class of control systems which consists of a fast controller, a slow estimator and nonwhite process noise.

A new concept of safety margin to quantify the performance of a thruster configuration is introduced. This concept can be used to evaluate thruster configurations and design optimal thruster configuration. A new thruster controller for one-sided thruster systems is developed, which is based on the linear pseudo-inverse controller for two-sided thruster systems. This controller is applicable to any one-sided actuator system, including the one sided thruster system used in the Quick STEP spacecraft.

KALLIGAS, Dimitri G. ***OBSERVATIONAL CONSTRAINTS ON SCALAR-TENSOR THEORIES OF GRAVITATION AND THE PRESENCE OF EXTRA DIMENSIONS,*** **DEPARTMENT OF APPLIED PHYSICS, NOVEMBER, 1995**

Abstract:

If the primary goal of this thesis were to be represented as an attempt to answer a single question, then this question would have to be: *"What can we further learn, if anything, about the exact nature of the gravitational interaction by increasing the accuracy of the classical solar system tests?"*

The demonstration (Damour & Nordtvedt, 1993) that scalar-tensor (ST) theories of gravitation generically converge to Einstein's pure tensor theory with the evolution of the Universe, and the possible persistence of this property in string theory (Damour & Polyakov 1994), have provided a renewed interest and strong motivation for trying to increase the accuracy of the solar system tests.

To help identify at what level deviations due to a "scalar-graviton" are expected, we derive the constraints that nucleosynthesis imposes on scalar-tensor theories and compare with solar system constraints. Since scalar-tensor theories have a free function $a(f)$ which specifies the scalar field coupling to matter, comparing them to observation requires an ansatz for $a(f)$ and in this way hampers the generality of the derived limits. We try to confront this problem by using a Taylor expansion for $a(f)$ for all times between today and the nucelosynthesis era, thus allowing for any well-behaved function $a(f)$. We explicitly give the graphical representation of the permitted-forbidden ranges of the Taylor coefficients of $a(f)$ according to both the nucleosynthesis and solar system constraints, demonstrating in this way the necessary accuracy for detection. The evolution of f is found to be small enough to validate the use of the Taylor series representation, and for attractor ST-theories nucelosynthesis typically places stronger limits on $1 \quad \gamma_{PPN}$ than solar system tests. The latter property, however, depends on the total density of the universe in a way which enables us to draw the surprising conclusion that within this class of scalar-tensor theories a measurement of a nonzero $1 \quad g_{PPN}$ in our solar system will indicate an upper limit on the amount of dark matter in the universe.

Deviations due to scalar-tensor theories, if detected, may also have ramifications regarding the presence of extra dimensions to spacetime (the latter being abundantly employed in Grand Unification attempts such as Superstrings, Super Gravity and Kaluza-Klein theories). However, the dimensionality of spacetime problem can also be addressed within Einstein's general relativity by extending it to higher than four dimensions. As far as the solar systems tests are concerned, we need to try to classify and examine the properties of all possible higher-dimensional one-body problem solutions, looking particularly for any distinctive features. As a first step in this direction we consider the one-body problem in the simplest case of one extra dimension with three-dimensional spherical symmetry and no dependence on the extra dimension in the metric, and derive the predictions for the classical tests. It turns out that there are stable orbits and that - apart from the obvious solution with a flat extra dimension - there is a whole family of solutions parametrized by the degree to which the extra dimension departs from flatness. In fact, such a departure will affect the dominant potential (associated with g_8 term) and will alter the classical tests. We find that the predicted changes in our solar system allow for $\gamma_{PPN} > 1$, which can be used as a leading indicator for the presence of the extra dimensions, although to conclude upon their presence we also need to examine other astrophysical systems, and eventually devise a "super-PPN" framework which encompass $(4 + N)$-gravity.

KASDIN, N. Jeremy ***PRECISION POINTING CONTROL OF THE SPINNING GRAVITY PROBE B SPACECRAFT*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, MARCH, 1991**

Abstract:

This dissertation describes the design and analysis of a very precise satellite pointing control system. Specifically, attitude control for the Gravity Probe B (GP-B) spacecraft is considered. An on-board telescope is used to point the satellite at a guide star to better than 20 milliarcsec rms. This will be the most precisely pointed spinning satellite ever flown. In addition, sensor noise and acceleration constraints unique to GP-B make the design particularly challenging.

Gravity Probe B is a NASA satellite experiment to verify two previously untested predictions of Einstein's General Theory of Relativity: that a local inertial direction in a polar orbit about the spinning Earth will rotate with respect to the universe's inertial (fixed) frame in two orthogonal directions by the amounts 6.6 arcsec/yr and 42 milliarcsec/yr (known as the geodetic and frame-dragging effects). The GP-B flight will orbit nearly perfect gyroscopes to measure these two effects. By comparing the gyroscope spin axes with an inertial reference provided by the telescope being pointed at the guide star, the relativistic drifts can be detected. Because of the small size of the drifts being measured and limitations in the telescope response, very precise pointing control is required.

In addition to the pointing requirement, constraints are placed on satellite acceleration. Because the rotors must be supported against residual forces by an electrostatic suspension, large satellite accelerations couple into the rotor's out-of-roundness to produce torques and Newtonian drifts. This thesis analyzes this effect and determines limits on allowable accelerations induced by the pointing controller.

Following the dynamic modeling and torque analysis, a new digital LQR/LQG controller is designed for attitude control. This controller employs a unique penalty function to handle the acceleration requirements and a notch to reduce errors at the spin frequency due to inertially fixed disturbances. A new digital algorithm is presented for designing discrete estimators with disturbance rejection.

Finally, satellite performance is hampered by fact that the telescope is occulted by the Earth for half of each orbit. As a result, the science gyroscopes must be used for attitude control. Unfortunately, the readout system for the gyroscopes is corrupted by 1/f noise, a common problem in electronic devices. In this thesis, a new discrete model for 1/f noise is derived and used for both design of an occultation controller and generation of noise sequences for simulation.

KEE, Changdon ***WIDE AREA DIFFERENTIAL GPS (WADGPS*****), DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, DECEMBER 1993**

Abstract:

The Global Positioning System (GPS) has proven to be an extremely accurate positioning sensor. A Stand-alone civilian user enjoys an accuracy of 100 meters, which is adequate, for a wide variety of applications. However in some situations, such as aircraft precision approaches and taxi-way guidance, higher accuracy is required.

Conventional Differential GPS (DGPS) usually has an accuracy to 2 to 5 meters within 100 kilometers of the stationary calibration receiver, even with the expected levels of induced Selective Availability (SA) errors. To implement DGPS on a large scale, the total number of monitor stations needed to cover the United States Continent to this accuracy would exceed 500. Wide Area Differential GPS (WADGPS) is a system that can limit the number of necessary monitor stations to 15 while achieving the same accuracy. WADGPS can reduce the installation cost and the operational cost of the system dramatically. The WADGPS system comprises a master station and monitor stations distributed across the United States. It calculates and transmits a vector of error corrections to the users preferably via satellite. This correction vector consists of parameters describing the three dimensional ephemeris errors, the satellite clock offsets including SA, and optionally the ionospheric time delay.

The performance of a 15-station WADGPS network was investigated by simulation for users at sites across the United States, and the results indicated that normal GPS positioning errors can potentially be reduced to about one meter using WADGPS.

Experimental results from field tests using six monitor stations with a 1600km minimum baseline from a dual frequency user showed a submeter positioning accuracy, provided the data link had no time delay. These results strongly support the potentital of WADGPS to give high positioning accuracy at a cost substantially lower than that of conventional DGPS.

KLINGER, David L. ***ERROR MODELING OF PRECISION ORIENTATION SENSORS IN A FIXED BASE SIMULATION,*** **CENTER FOR SYSTEMS RESEARCH, GUIDANCE AND CONTROL LABORATORYM, JULY, 1974**

Abstract:

Models of noise and dynamic characteristics of a gyro and autocollimator for very small signal levels are presented. Measurements have been evaluated using spectral techniques for identifying noise from base motion. The techniques have been developed to enable the sensors for a relativity experiment to be evaluated in spite of the fact their accuracy will exceed any reference standards available.

Conventional tests of gyroscopes, telescopes, and other precise orientation sensors normally rely on more accurate standards to provide a reference. These standards are used in an absolute sense, in that all errors are attributed to the instruments being tested, including those of the calibration equipment. When the precision of the instruments under test surpasses that of available laboratory calibration equipment, different methods are needed. This situation exists in a test of general relativity theory being developed at Stanford University.

The experiment is constructed to measure the precession, due to relativistic effects, of an extremely precise earth-orbiting gyroscope. The design goal for non-relativistic gyro drift is 0.001 arcsec per year. A telescope, used to maintain the experiment satellite in an inertially fixed orientation, has similar extreme precision. A laboratory test is desired which accounts for environmental effects, especially gravity, and isolates inherent sensor errors.

Developing appropriate test methods using the actual relativity sensors was impractical due to the expense and unavailability of prototypes. Consequently, an analogous, though less accurate fixed base simulator was developed. This simulator was used in developing methods of instrument error modeling and performance evaluation applicable to the relativity experiment sensors and other precision pointing instruments.

Two Atlas missile gyros, integrated into a Minuteman I guidance assembly, and two specially designed autocollimators serve as analogs to the relativity experiment sensors. A three-axis Minuteman I stable platform provides a movable mount for the sensors. The sensors are used to stabilize the platform with less than 1 arcsec jitter. The noise equivalent angle of the primary auto collimator is 0.1 arcsec.

A spectral approach is used in analyzing the fixed base simulator signals and developing error models for the sensors. A review of spectral theory and practical considerations in computing spectral functions introduces a discussion of experimental results. Comparisons are made of gyro and autocollimator spectra taken with the instruments both resting on quiet test beds and serving as feedback sensors in platform stabilization loops. Coherency between signals is used to indicate mutual instrument error sources and to provide confidence in the estimation of system transfer functions.

Analysis of autocollimator spectra uncovered the presence of a platform gimbal resonance. The source of resonance was isolated to gimbal bearing elastic restraint properties most apparent at very small levels of motion ($<$ 100 μrad). A model of these properties which include both elastic and coulomb friction characteristics is discussed, and a describing function developed.

KNIGHT, Larry V. ***SLOW GROUND STATE ELECTRONS AND THE ANOMALOUS MAGNETIC MOMENT OF THE FREE ELECTRON, LOW TEMPERATURE PHYSICS GROUP DEPARTMENT OF PHYSICS, NO DATE***

Abstract: None

LANGE, Benjamin ***THE CONTROL AND USE OF DRAG-FREE SATELLITES, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS,* JUNE 1964**

Abstract:

A scientific earth satellite which is guided in a drag-free orbit by a shielded, free-falling proof-mass has been proposed by a number of investigators. The outer satellite, which completely encloses the proof-mass, has a jet-activated translation-control system that causes it to pursue the proof-mass such that the two never touch. This thesis examines the feasibility and some of the applications of this scheme.

The complete system equations of motion are derived, and the various special cases which apply for different missions and types of attitude control are delineated. In addition, a set of linear equations for both translation and libration of a satellite in orbit are derived. These represent a combined version of the linear form of Hill's Lunar Equations and Lagrange's Libration Equations.

The control and guidance system is analyzed with respect to system performance and gas usage requirements, and an exact solution of the fuel consumption integrals is presented in closed form for a linear pressure-scale-model of the atmosphere.

A linear-feedback control-synthesis method is developed for a class of even-ordered dynamical plants which possess a property that is defined as "frequency symmetry." This method allows a simple linear-feedback law to be computed which is stable for all positive values of the control gain so that it is useful for the synthesis of contactor control systems.

The principal trajectory errors which are due to vehicle gravity, stray electric and magnetic fields, and sensor forces are investigated. It is found that drag and solar radiation pressure forces may be effectively reduced by three to five orders of magnitude for 100 to 500 statute mile orbits, and that the deviation from a purely-gravitational orbit may be made as small as one meter per year. Such a satellite may be used to make precise measurements in geodesy and aeronomy.

Finally, if a spherical proof-mass is spun as a gyroscope, its random drift rate would be very small because all the drift-producing torques which are associated with the support forces are eliminated. The sources of gyroscope drift which are not associated with support forces are analyzed, and it is found that the random drift would probably be less than 0.1 second of arc per year. Such a gyroscope could be used to measure the effects which would ultimately limit the performance of the best terrestrial or satellite-borne gyroscopes, and it might also be good enough to perform the experiment proposed by G. E. Pugh and L. I. Schiff to test general relativity.

LAWRENCE, David G. AIRCRAFT LANDING USING GPS DEVELOPMENT AND EVALUATION OF A REAL TIME SYSTEM FOR KINEMATIC POSITIONING USING THE GLOBAL POSITIONING SYSTEM, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, SEPTEMBER 1996

Abstract:

The advent of the Global Positioning System (GPS) is revolutionizing the field of navigation. Commercial aviation has been particularly influenced by this worldwide navigation system. From ground vehicle guidance to aircraft landing applications, GPS has the potential to impact many areas of aviation. GPS is already being used for non-precision approach guidance; current research focuses on its application to more critical regimes of flight. To this end, the following contributions were made:

1) Development of algorithms and a flexible software architecture capable of providing real-time position solutions accurate to the centimeter level with high integrity. This architecture was used to demonstrate 110 automatic landings of a Boeing 737.
2) Assessment of the navigation performance provided by two GPS-based landing systems developed at Stanford, the Integrity Beacon Landing System, and the Wide Area Augmentation System.
3) Preliminary evaluation of proposed enhancements to traditional techniques for GPS positioning, specifically, dual antenna positioning and pseudolite augmentation.
4) Introduction of a new concept for positioning using airport pseudolites.

The results of this research are promising, showing that GPS-based systems can potentially meet even the stringent requirements of a Category III (zero visibility) landing system. Although technical and logistical hurdles still exist, it is likely that GPS will soon provide aircraft guidance in all phases of flight, including automatic landing, roll-out and taxi.

LEE, Kou-Nan WIDE DYNAMIC RANGE HELIUM THRUSTER DESIGN FOR THE RELATIVITY GYROSCOPE SATELLITE, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, JUNE, 1992

Abstract:

The Relativity Gyroscope Satellite, Gravity Probe B (GP-B) Program, uses helium thrusters for attitude control and drag compensation. These thrusters use gas which is generated in cooling the experiment as the propellant. The current differential proportional thruster design for helium flow near the nominal flow rate has been developed by Bull (1973) and Chen (1983). Using a differential restrictor to modulate the flow, its maximum flow rate is twice the nominal flow rate.

There is a possibility that GP-B may need a thruster having a much wider flow dynamic range than the current design. A dual mode wide dynamic range helium thruster has been developed with a flow dynamic range one to two orders of magnitude wider than the previous design. It has a restrictor and an annular nozzle formed by a plug inside a circular opening. At low flow rates, fine modulation can be achieved by changing the restricted gap (valve opening) with the nozzle throat area kept constant. At higher flow rates, the thruster gives rapidly increasing throat area as the valve opens with almost no restrictor effect. At a nominal helium flow rate, the Reynolds number is as low as 1 with this design.

Tests have been performed to verify the wide dynamic range performance and to understand the properties of the annular nozzle. A mathematical model of the thruster has been developed to match the experimental thruster performance and to provide a basis for future design. By choosing the geometry of the annular nozzle and restrictor, one can design the thruster with desired performance characteristics.

LIGHTSEY, Glenn E. DEVELOPMENT AND FLIGHT DEMONSTRATION OF A GPS RECEIVER FOR SPACE, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, FEBRUARY, 1997

Abstract:

Although the Global Positioning System (GPS) was principally designed for terrestrial applications, it offers significant benefits to spacecraft users as well. A single low cost GPS receiver can provide a lot of critical spacecraft sensing functions, including orbit determination, attitude and attitude rate measurement, as well as precision timing. A spacecraft that employs this consolidation of information can obtain significant cost, power, mass, and reliability improvements over existing systems that offer comparable performance. In order to achieve this capability, however, GPS receiver algorithms designed for the terrestrial environment must be rewritten to function properly in space. The objective of this research is to discover and develop these necessary modifications to an existing terrestrial GPS receiver and demonstrate the new operational capability of this receiver through on-orbit experiments.

This dissertation documents several of the most important innovations that were accomplished to provide autonomous and reliable GPS receiver operation in space. For example, carrier phase integer resolution was enhanced for marginally observable measurements using a new singular value decomposition (SVD) algorithm. This approach shortens the initialization time needed to obtain real-time attitude solutions and improves the overall integrity of the solutions. The ability to perform attitude determination on nonaligned antenna arrays was enabled by the characterization of a Right Handed Circular Polarization effect on the differential carrier phase measurements. Several other effects, such as antenna phase pattern modeling, on-orbit receiver calibration, nonaligned antenna arrays, and orbit propagation were also discussed in the context of the spacecraft measurement environment.

The new receiver capability is demonstrated through analysis of dynamic simulation and flight results from the RADCAL, REX II, and GANE spacecraft. Real-time on-orbit GPS-based attitude determination of better than 0.2 degrees rms is demonstrated using a 1.5 x 3 m antenna array the GANE experiment. Future applications and experiments are also described.

LOCKHART, James M. ***EXPERIMENTAL EVIDENCE FOR A TEMPERATURE-DEPENDENT SURFACE SHIELDING EFFECT INSIDE A COPPER TUBE,*** **LOW TEMPERATURE PHYSICS GROUP DEPARTMENT OF PHYSICS, AUGUST, 1976**

Abstract:

The temperature dependence of the ambient axial electric field inside a vertical copper tube has been investigated. A vertical metal tube subject to the gravitational field of the Earth is expected to have spatial variations in the electrostatic potential along its axis because of contact potential differences between adjacent crystals in the metal and because of the gravitationally induced rearrangement of the metallic electrons and ions. The result of a previous measurement by Witteborn and Fairbank (WF) of the ambient axial electric field inside a copper tube at 4.2°K is roughly four orders of magnitude too small to be consistent with the predictions of the theory of Dessler et al. and the results of several room temperature measurements. Schiff, among others, pointed out that the WF result would be consistent with the other results if a shielding effect involving electrons on the inside surface of the tube were to exist at 4.2°K but not at room temperature. In this work the electron time-of-flight method of WF was used to measure the ambient axial electric field inside a copper tube at temperatures ranging from 4.2°K to 300°K.

The relevant literature on theoretical and experimental studies of patch effect fields and strain-induced fields (particularly gravitationally-induced fields) in and near the surface of metals is reviewed. Some ways in which the discrepancy between the WF result and the other results could be resolved are mentioned.

The slow electron time-of-flight method which was used to study the ambient field is discussed and the versions of the apparatus used at 300°K, 77°K, and 4.2°K are described. A drift tube heater and temperature monitor system is described which allows the 4.2°K version of the apparatus to be used over the range 4.2°K-11°K. The manner in which ambient fields are measured is discussed in detail, as is the effect of the delayed emission of electrons from electrostatic and magnetic potential traps.

Room temperature results are presented which indicate an ambient electric field inside the tube of more than 10^{-6} V/m. This value is essentially consistent with the room temperature measurements of strain-induced fields made by other workers. Data taken at 77°K is presented; it is quite similar to the room temperature data. Data from experiments at 4.2°K is described and it is shown that this data implies an ambient field in the tube at 4.2°K which is several orders of magnitude smaller than the ambient field found at 300°K and 77°K.

Ambient field studies made with drift tube temperatures of 4.2°K, 4.3°K, 4.4°K, 6.3°K, 9°K, and 11°K are then described. The 4.2°K measurements in this series were made with the drift tube heating system in place; they yielded an ambient field measurement consistent with the earlier measurement at 4.2°K and with the WF result. The ambient field at 4.3°K was found to be roughly 3×10^{-8} V/m, while at 4.4°K the field was about 3×10^{-7} V/m. For the three higher values of temperature the ambient field was in the range $(3.5\text{-}8) \times 10^{-7}$ V/m. This last range of values is consistent with the ambient field expected from the gravitationally induced distortion of the lattice of the copper tube. It is suggested that the observed temperature dependence of the ambient field in the tube is a manifestation of the presence of a surface shielding effect in the tube which is functional only at temperatures below approximately 6°K.

Sources of error are discussed and various consistency checks which were performed on the results are described. Finally, some possible physical mechanisms which could produce a temperature dependent surface

LOHEZ, Dominique ***LINEAR KALMAN FILTER FORMULATION OF THE NONLINEAR DATA REDUCTION PROBLEM FOR THE STANFORD RELATIVITY GYROSCOPE EXPERIMENT,END-OF-STUDY PROJECT Ecole Nationale Supérieure de l'Aéronautique et de l'Espace,* AUGUST, 1993**

Abstract:
L. I. Schiff predicted, using Einstein's general theory of relativity, that the spin axis of a gyroscope orbiting the earth would precess. The objective of the GP-B experiment is to estimate this precession rate to a precision better than 0.5 milliarcsecond per year.

This experiment will use four superconducting electrically suspended spinning gyroscopes. Their spin-axis directions will be measured by Superconducting QUantum Interference Device (SQUD) magnetometers, and then will be compared to a remote inertial frame defined by the direction to a guide star. The resulting electric signal will be nonlinear.

One technique we can use in the data reduction problem is to build an extended Kalman filter to estimate the drift rates directly. But this requires a good basic knowledge of the actual values we want to estimate, or else, we can get biased final estimates. Another one consists of using a two-step filtering algorithm and referring to the spectral separation principle. We assume the slowly varying terms to be constant over an orbit duration, then we redefine the state vector and introduce combinations of these slowly varying parameters in order to get a linear measurement equation. In the first step, we perform a least square fit of the measurements every orbital period, and get estimates of the combinations. Then we extract the terms of interest using nonlinear operations. In the second step, we consider the outputs of the first-step filter as pseudo-measurements in order to estimate the slowly-varying parameters.

In our study, we made a comparison of both methods, analysed their respective advantages and disadvantages, investigated the effect of the initial misalignments on the final estimation accuracies and suggested further possible investigations.

MICHELSON, Peter F. ***PROPERTIES OF SUPERCONDUCTING WEAK LINKS*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, DECEMBER, 1979**

Abstract:
Josephson junctions(tunnel junctions, point-contacts and microbridges) are useful in a wide variety of applications such as the precision measurement of voltage and magnetic field. In recent years there has been increased interest in the high frequency (10 Ghz - 1000 Ghz) application of these devices. Most of these applications have been theoretically discussed in terms of a simple model of the junction known as the resistively-shunted junction model. Predictions of this model are reviewed along with a discussion of phenomena predicted by the microscopic tunnelling theory and relaxation models based on time-dependent Ginzburg-Landaul theory. Particular attention is focused on the phase-dependent conductivity: the so called $\cos\phi$ conductance. The discrepancy between theory and experiment in this regard is discussed and suggestions are made about how this discrepancy may be resolved.

Microwave reflection measurements on a point-contact in a microwave resonator are described. The data are consistent with a resistively-shunted junction model including a phase-dependent conductance with a negative sign. The d.c. I-V characteristics have also been measured at finite voltage and certain features of these characteristics are discussed.

MONTOGMERY, PAUL Y. ***CARRIER DIFFERENTIAL GPS AS A SENSOR FOR AUTOMATIC CONTROL*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, JUNE, 1996**

Abstract:

This thesis is about the use of the Global Positioning System (GPS) as a sensor for automatic control. To control a vehicle outdoors in an uncontrolled (non-laboratory) environment, information on orientation and position is needed. Automotive or agricultural vehicles, aircraft and ships are possible mobile examples. Cranes or derricks are possible machine examples. To achieve control, the ability to sense position and orientation accurately, robustly and reliably is paramount. The vehicle investigated here is a small, highly maneuverable, autonomous aircraft. Having three degrees of position and three degrees of orientation freedom, it provides a challenging and suitably general platform on which to demonstrate the concept.

The thesis describes the construction, modeling, hardware and algorithms that were employed to make the autonomous aircraft pictured on the previous page fly a predetermined trajectory (from takeoff to landing) without any form of inertial instrumentation or human intervention. To the knowledge of the author, this is also the *first* time such capability has been demonstrated.

MOSKOWITZ, Bruce E. ***OBSERVATIONS ON THE STANFORD 4800 KG GRAVITY WAVE DETECTOR WITH A COSMIC RAY MONITOR,*** **LOW TEMPERATURE PHYSICS GROUP DEPARTMENT OF PHYSICS, DECEMBER, 1985**

Abstract:

Gravitational radiation was first predicted in 1916 by A. Einstein as a consequence of the theory of general relativity. The resonant acoustic detector, invented in 1960 by J. Weber, promises the best chance at present of direct observation of gravitational radiation. The group at Stanford University has constructed a 4800 kg cryogenic detector which is the most sensitive detector successfully operated to date.

In this dissertation data are presented from the 1985 run of 36.8 days aggregate collection time. Over the full bandwidth of approximately 13 Hz, the optimum detector noise temperature was found to be 8 mK when the system was operated at 4.3 K. An actual filter was implemented over a 5 Hz bandwidth which yielded the filtered noise temperature as low as 15 mK and as high as 30 mK.

The rate of events whose signal temperature exceeded 0.6 K was found to be about an order of magnitude higher than that for a similar run in 1981, partly due to greater general activity in the laboratory.

A preliminary coincidence experiment was conducted between the Stanford detector and a room temperature detector in Guangzhou, China, whose noise temperature was 3 K. In a total of 9.38 days of simultaneous data collection the number of coincidences observed was entirely consistent with random statistics. Varying the coincidence window width or the systematic timing delay in the data did not affect this result.

In the second half of this dissertation, the effect of cosmic rays or gravity wave bar detector is considered. A one-dimensional thermoacoustic model is used to predict the size of the signal. Measurable effects are restricted to rarer events which may easily be vetoed as gravity wave candidates.

A plastic scintillator cosmic ray shower monitor has been assembled and operated in coincidence with the Stanford 4800 kg detector. Energies of showers were calibrated against minimally-ionizing muon background. In a 261 hour run, five events were observed which were expected on the basis of the thermoacoustic model to give signals of strength greater than 3 mK. The gravity wave data following 1142 extensive air showers with density > 1 particle/m^2 were found to be buried deeply in the detector noise level of 19 - 26 mK.

NAKAGAWA, Wataru ***LOW -TEMPERATURE CHARACTERIZATION OF AVALANCHE PHOTODIODE (APD) IN GAIN MODE, UNDERGRADUATE HONORS THESIS,*** **DEPARTMENT OF PHYSIC/GRAVITY PROBE B RELATIVITY MISSION JUNE 06, 1996.**

Abstract:

We characterized the performance of a silicon avalanche photodiode (APD) in the gain mode at near liquid nitrogen temperatures. We developed a method for determining the optimum operating bias voltage for the detector for temperatures ranging from 85-120 Kelvin, and observed the sensitivity of detector performance to slight variations in bias voltage and temperature. Finally, we demonstrated the potential for the device to detect photons at a rate of approximately 10^5 per second, and suggested a method for determining the absolute quantum efficiency of the device.

Ndili, Awele N. ***ROBUST GPS SUTONOMOUS SIGNAL QUALITY MONITORING***, **DEPARTMENT OF MECHANICAL ENGINEERING , AUGUST 1998**

Abstract:
The Global Positioning System (GPS), introduced by the U. S. Department of Defense in 1973, provides world-wide navigation capabilities to both military and commercial users. It achieves this purpose through a constellation of 24 satellites in global orbit, each emitting a low-power radio-frequency signal for ranging. GPS receivers receive these transmitted signals and computer position from range measurements made to four or more visible satellites. An end user with a GPS receiver can determine their location anywhere on the globe to within 30 meters.

GPS has become very popular in recent years, finding a wide range of applications, including aircraft navigation, marine oceanic, coastal and inland-waterway navigation, search and rescue, agriculture, surveying, space borne attitude and position determination, and vehicle navigation. Each application places demands on GPS for various levels of accuracy, integrity, system availability, and continuity of service. For example, aircraft Category I precision approach requires a 5m vertical accuracy, achieved 99.9% of the time.

Radio frequency interference (RFI), which results from many sources such as TV/FM harmonics, radar or Mobile Satellite Systems (MSS), presents a challenge in the use of GPS, by posing a threat to the accuracy, integrity and availability of the GPS navigation solution. This threat is a result of the low power levels of received GPS satellite signals relative to RFI. With increasing interference, GPS accuracy degrades, with a resulting loss in integrity. At high enough RFI power levels, the GPS receiver loses lock, resulting in system unavailability and a loss of continuity of service. This presents a severe problem to GPS users, especially for integrity-critical applications such as aircraft high-precision approach and auto-land, where an integrity breach could result in loss of life.

In order to use GPS for integrity-sensitive applications, it is therefore necessary to monitor the quality of the received signal, with the objective of promptly detecting the presence of RFI, and thus provide a timely warning of the degradation of system accuracy, thereby boosting the integrity of GPS. This presents a challenge, since the myriad kinds of RFI effect the GPS receiver in different ways. In addition, there are other forms of interference, such as physical blockage and attenuation, which though not being of the radio frequency type, nonetheless contribute to the integrity threat. What is required then, is a *robust* method of detecting GPS accuracy degradation which is effective regardless of the origin of the threat.

This dissertation presents a new method of robust signal quality monitoring for GPS. Algorithms for receiver autonomous interference detection and integrity monitoring are presented. Candidate test statistics are derived from fundamental receiver measurements of in-phase and quadrature correlation outputs, and the gain of the Active Gain Controller (AGC). Performance of selected test statistics is evaluated in the presence of RFI: broadband interference, pulsed and non-pulsed interference, coherent CW at different frequencies; and non-RFI: GPS signal fading due to physical blockage and multipath. Results are presented which verify the effectiveness of the methods proposed.

The benefits of pseudolites in reducing service outages due to interference are demonstrated. Pseudolites also enhance the geometry of the GPS constellation, improving overall system accuracy. Designs for pseudolites signals, to reduce the near-far problem associated with pseudolites use, are also presented.

NEUHAUSER, Barbara Jo ***I. CONSTRUCTION OF AN ULTRALOW TEMPERATURE LABORATORY, II. THERMAL RELAXATION IN SUPERFLUID HELIUM-3*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, \ AUGUST 1985**

Abstract:
The first part of this thesis describes the construction of an ultralow temperature laboratory capable of reaching temperatures below 0.002 K. Continuous refrigeration to 0.012 K is provided by a cold plate/dilution refrigerator system. Single-cycle cooling to 0.002 K is accomplished by adiabatic demagnetization of cerous magnesium nitrate (CMN), a paramagnetic salt. Thermometry is done by measuring the resistance of carbon and germanium sensors, the magnetic susceptibility of lanthanum-diluted CMN, and the anisotropy of gamma radiation from a cobalt-60 nuclear orientation thermometer. Systems have been developed to allow precise control of the temperature and pressure of the liquid helium-3 sample. Certain innovative features of the ultralow temperature cell also are discussed.

The second part of this thesis describes measurements of thermal relaxation of liquid helium-3 in the ultralow temperature cell following sudden magnetic cooling of the CMN refrigerant. Analysis of the transient response of a thermal model of the cell indicates that the ratio of the time constants immediately below and above the superfluid-to-normal transition temperature provides a close estimate of the ratio of the corresponding helium-3 heat capacities, at least in the superfluid A-phase. This ratio is important because it characterizes strong coupling effects. The thermal relaxation data also reveals that the onset of hydrodynamic heat flow differs markedly in the two superfluid phases. This fact is used to identify the polycritical point on the phase diagram.

PAIK, Ho Jung ***ANALYSIS AND DEVELOPMENT OF A VERY SENSITIVE LOW TEMPERATURE GRAVITATIONAL RADIATION DETECTOR, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS,*** **NOVEMBER 1974**

Abstract:

This dissertation consists of two parts: Theory of Gravitational Radiation Detectors (Part I) and Development of a Very Sensitive Cryogenic Detector of Gravitational Radiation (Part II).

Part I begins with an analysis of the interaction of gravitational radiation pulses with three-dimensional elastic bodies. The Pochhammer-Chree solution is used to calculate the cross-section of a cylindrical mass-quadrupole antenna to second order accuracy in the radius-to-length ratio. This correction is shown to be about 2% for a typical Weber-type detector. A mathematical analysis of the Brownian motion of a single and coupled harmonic oscillators is carried out. The limitations imposed on the detectability of gravitational radiation signals by the combination of the wideband noise coming from diverse sources in the electronics and the narrowband noise from the antenna are carefully studied to obtain the functional dependence of the detection sensitivity on the values of various detector parameters.

This detector theory is then applied to existing Weber-type room temperature detectors with piezoelectric crystal pickup to compare their theoretical sensitivities with actual achieved sensitivities. Also, an analysis is presented of two particular types of cryogenic detectors; one with an inductance-modulated rf tank circuit as sensor and the other with a superconducting tunable-diaphragm transducer. It is shown that the sensitivity of the first type depends critically on the extent to which one can reduce the frequency fluctuations of the rf oscillator. In the second type of the cryogenic detector, which has been developed by the author and others, one takes advantage of a high mechanical Q of niobium at low temperatures to achieve a high transducer coupling without lowering the Q of the antenna. A circular niobium diaphragm clamped at its edge to one end-face of the antenna acts as an accelerometer. The displacement of the diaphragm modulates the persistent current in the superconducting coils located adjacent to its surfaces and in turn the ac current generated in this process is detected with a very low-noise SQUID magnetometer. When a resonant-diaphragm detector of mass 5000 kg is cooled to 3×10^{-3}°K, its time of 0.35 sec which is an improvement by a factor of 10^6 to 10^7 over present room temperature detectors. This will enable one to look for signals coming from extragalactic sources.

Part II is essentially the experimental confirmation of the transducer theory developed in Part I. The transducer coupling as a function of persistent current has been verified and possible dissipation mechanisms in the superconducting tunable-diaphragm transducer have been investigated. The Q of a typical niobium diaphragm decreases from 5×10^6 to 7×10^4 as its coupling with current increases from 0 to 0.9. A better electromagnetic shielding will improve the situation. The decrements of niobium diaphragms have been also measured as functions of temperature and pressure. Also reported is the work done to develop a high-sensitivity toroidal SQUID with a tight input coil coupling. The achieved sensitivity is better than $3 \times 10^{-5}\ \phi_0/\sqrt{\text{Hz}}$ with effective SQUID inductance of 6×10^{-11} H where ϕ_0 is the flux quantum. The preliminary test of the transducer on a prototype gravitational radiation detector of mass 700 kg is discussed in the concluding part of this dissertation. This prototype detector, which will be cooled to 2°K, is expected to have a gravitational radiation flux sensitivity of 1.3×10^2 erg/cm^{2}Hz with an optimum integration time of 0.04 sec. With this prototype detector, it is hoped that the theoretically predicted events in our galaxy will already be detected with a good signal-to-noise ratio.

O'CONNOR, Michael L. *CARRIER-PHASE DIFFERENTIAL GPS FOR AUTOMATIC CONTROL OF LAND VEHICLES*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, DECEMBER 1997,

Abstract

Real-time centimeter-level navigation has countless potential applications in land vehicles, including precisetopographic field mapping, runway snowplowing in bad weather, and land mine detection and avoidance. Perhaps the most obvious and immediate need for accurate, robust land vehicle sensing is in the guidance and control ofagricultural vehicles.Accurate guidance and automatic control of farm vehicles offers many potential advantages; however, previousattempts to automate these vehicles have been unsuccessful due to sensor limitations. With the recent developmentof real-time carrier-phase differential GPS (CDGPS), a single inexpensive GPS receiver can measure a vehicle'sposition to within a few centimeters and orientation to fractions of a degree. This ability to provide accurate real-time measurements of multiple vehicle states makes CDGPS ideal for automatic control of vehicles.This work describes the theoretical and experimental work behind the first successfully demonstrated automaticcontrol system for land vehicles based on CDGPS. An extension of pseudolite-based CDGPS initializationmethods was explored for land vehicles and demonstrated experimentally. Original land vehicle dynamic modelswere developed and identified using this innovative sensor. After initial automatic control testing using a YamahaFleetmaster golf cart, a centimeter-level, fully autonomous row guidance capability was demonstrated on a JohnDeere 7800 farm tractor.

OHSHIMA, Yoshimi *ANALYSIS AND TESTING OF GYROSCOPE PERFORMANCE FOR THE GRAVITY PROBE B RELATIVITY MISSION,* DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, AUGUST 2000.

Abstract

This dissertation describes the analysis and experimental testing of the performance of electrostatically suspended vacuum gyroscopes (ESVG) designed for the Gravity Probe B Relativity Experiment (GP-B).

The GP-B mission is a satellite-based gyroscope experiment currently under joint development by NASA and Stanford University. It is designed to test two predictions of Einstein's General Theory of Relativity: the geodetic effect and the frame-dragging effect. They are predicted to be 6.6 and 0.042 arc-sec/year, respectively, for a planned circular polar orbit. The primary goal of the GP-B mission is to measure the geodetic effect to better than 0.01%, and the frame-dragging effect to better than 1%. In order to achieve this goal, the non-relativistic drift rate of the gyroscope must be less than 0.3 milli-arc-sec/year.

Presented is the analysis of the part of the Newtonian torque on the gyroscope rotor that is due to the electrostatic support, estimation of the science-mission drift rate, and experimental validation of the theoretical torque modeling. The analysis of the electrostatic torque indicates that the torque depends on both the close-to-perfect rotor shape with very minor manufacturing asphericity, and the voltage applied to the electrodes. To estimate the science-mission drift rate, we used the measured asphericity of an existing rotor that was below flight quality. Throughout the analysis, the estimated drift rate of the gyroscope induced by the non-relativistic effect was less than the maximum allowed drift rate of 0.3 milli-arc-sec/year for this effect. This result is gratifying because the actual flight rotors will exhibit a much lower non-relativistic drift rate. In the laboratory, parameters that characterize the electrostatic torque were measured by changing the voltages applied to the electrodes and the position of the gyroscope rotor in its housing cavity. The results match well with the theoretical expectations, confirming the validity of the theoretical approach regarding the electrostatic torque on the rotor.

As a conclusion, the gyroscopes developed for the GP-B science mission can be trusted to satisfy the mission requirement.

PEREZ, Christopher A. ***OBSERVATIONAL SIGNATURES OF ROTATING BLACK HOLES*, DEPARTMENT OF PHYSICS AND CENTER FOR SPACE SCIENCE AND ASTROPHYSICS, DECEMBER 1993**

Abstract:
Accretion disks provide an excellent medium for studying the strong-field structure of rotating black holes. We examine two potentially observable relativistic effects. In the first part, we explore the effects of the gravitational field of a rotating black hole on the propagation of light from the accretion disk. In the second part, we investigate adiabatic oscillations trapped near the inner edge of the accretion disk.

To obtain an accurate depiction of an accretion disk at the image plane, we solve the photon orbit equations analytically in the Kerr metric to determine the point of origin on a thin accretion disk of a photon which intersects a specified point on the image plane. We employ simple models for the spectral intensity emitted by the disk. Using this solution, we generate grayscale computer images of intensity of accretion disks with various angles of inclination around black holes of different angular momenta to see the effects of frame-dragging and other relativistic effects on the light propagation. For the observational relevance of these effects, we also obtain light curves produced by gravitational lensing by much smaller intervening masses passing in front of our model accretion disk (acting as a gravitational microscope to reveal the structure of the disk).

We extend our studies by examining trapped adiabatic oscillations in accretion disks around Kerr black holes. We analyze the normal modes of oscillations (which are analogous to the *p*- and *g*-modes of stars) within thin accretion disks which are terminated by an innermost stable orbit. We develop a general formalism for investigating the adiabatic oscillations of arbitrary unperturbed disk models. We obtain the lowest eigenfrequencies and eigenfunctions of various modes. Each of these modes will be obtained for various angular momenta of the black hole. These trapped modes do no exist in Newtonian gravity, and thus provide a probe of the strong-field structure of rotating black holes. Our predictions are related to past and future observations which could detect modulation in the X-rays from stellar mass black holes and in the optical and UV from supermassive AGN black holes.

PIERCE, John M. ***THE MICROWAVE SURFACE RESISTANCE OF SUPERCONDUCTING LEAD, TRAPPED MAGNETIC FLUX, AND A NEW MAGNETOMETER USING SUPERCONDUCTIVITY,* LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, JUNE 1967**

Abstract:
An investigation has been made into the causes of the residual surface resistance which is always observed in superconductors at microwave frequencies. the initial impetus for this work was provided by the prospect of constructing a linear accelerator using a superconducting rf structure. To make a superconducting accelerator attractive it was necessary to make surfaces with residual loss two orders of magnitude less than had previously been observed. This was achieved in 1964, when we observed a Q of 5 x 10^9 in a TE_{011} mode cavity operating at 2856 Mhz. This great improvement is attributed partially to methods of applying the electroplated lead surface, and partially to the fact that magnetic flux trapped through the surface was reduced. The cavity was cooled in a very low magnetic field (< 5 milligauss).

We also measured the effects of high rf magnetic fields on the surface, and found no degradation of the Q for fields up to 300 gauss.

A superconducting linear accelerator is now under construction.

Recently, we have done experiments which shed further light on the effects of trapped flux on the surface resistance. These experiments were done with a cavity in which the Q's of three modes could be measured after

the cavity was cooled in very low field and in various applied magnetic fields. The results of cooling the cavity in an applied field can be explained by assuming that a fraction ($H_{applied}/H_{critical}$) of the cavity is maintained normal by trapped flux. These normal regions "hide" down in depressions on the surface. The fact that the frequency dependence of the loss due to trapped flux in $\omega^{2/3}$ supports this hypothesis.

Further, the residual loss which is still observed even in the very best surfaces we have made, even when they are cooled in a very low magnetic field, is still due largely to trapped flux. But this trapped flux is produced by thermoelectric currents generated when the cavity is cooled; it is not from an external field. By cooling very slowly in a low field we have recently achieved a residual Q of 5×10^{10} in a cavity resonant at 12.2 Ghz in the TE_{013} mode.

A new and extremely sensitive magnetometer has been developed which uses unique properties of superconductivity. Calculations and measurements indicate that this magnetometer can detect a field change of 3×10^{-10} gauss in a loop with 1 cm radius. For this to be possible, however, region in space must be provided in which the magnetic field is less than 1 milligauss and fluctuates in time less than the above. This has not been possible due to the same thermoelectric problems in superconducting shields as limit the residual Q of cavities. With the explanation of these effects, however, the way is now open to make nearly perfect shields as well as nearly perfect microwave cavities.

The magnetometer uses a superconducting loop in which a field change is translated into a persistent current. Linking the loop is a cylinder of superconductor which can be switched alternately between the normal and superconducting states at a frequency of 150 KHz. Since the magnetic flux linking a superconducting cylinder is quantized, inductive impulses are given to the loop, and a large oscillation is built up which is proportional to the persistent current. The result is an output power equivalent to spinning the sensing loop at a frequency ~ 10^7 Hz. This accounts for the great sensitivity.

PERVAN, Boris S. ***NAVIGATION INTEGRITY FOR AIRCRAFT PRECISION LANDING USING THE GLOBAL POSITIONING SYSTEM*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, MARCH, 1996**

Abstract:

The great potential benefit offered to commercial aviation by the Global Positioning System (GPS) lies in the possibility of inexpensive, seamless navigation from takeoff to touchdown. While this goal is highly motivating, significant technical challenges have existed, the most difficult of which have been associated with navigation during zero-visibility (Category III) precision landing. The severe requirements for accuracy, integrity, continuity, and availability have demanded a new level of GPS navigation system performance. For example, the integrity requirement of 'one undetected navigation failure in a billion approaches' has often been perceived as unattainable using GPS. In response, the central focus of this research has been to establish the viability of high-integrity satellite-based navigation for the precision landing of aircraft.

This dissertation demonstrates that highly precise GPS carrier phase measurements from spacecraft and ground-based pseudolites can provide the basis for high navigation integrity. It is shown that the considerable accuracy margin offered by carrier phase provides leverage for autonomous integrity monitoring aboard the aircraft in the sense that extremely tight fault detection thresholds may be set without incurring high false alarm rates. Furthermore, when placed under the approach path, pseudolites provide the means for real-time cycle ambiguity resolution and ensure the availability of redundant measurements for autonomous integrity monitoring.

Prototype algorithms for airborne kinematic carrier phase processing, including high-speed algorithms for the first high-integrity real-time cycle ambiguity resolution, were developed, implemented and tested. Algorithm performance was verified through an extensive battery of flight tests culminating in 110 successful automatic landings of a United Airlines Boeing 737-300. In addition, the framework of Receiver Autonomous Integrity Monitoring (RAIM) was adapted for application to both cycle ambiguity resolution and kinematic positioning and for the detection of the wide range of navigation system failure scenarios. Navigation integrity and its parametric interrelationship with accuracy, continuity, and availability were quantitatively assessed through analysis, simulation, and flight test.

PULLEN, Samuel P. ***PROBABILISTIC ENGINEERING DESIGN OPTIMIZATION: APPLICATIONS TO SPACECRAFTAND NAVIGATION SYSTEMS*****, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, JUNE, 1996,**

Abstract:

In addition to designing engineering systems for optimal performance, developing systems that are robust to possible failures and/or non-ideal operating conditions is of great importance. In modern engineering practice, this is normally accomplished by incorporating conservative performance margins such that projected “worst-case” outcomes can be accommodated. In aerospace, safety or robustness considerations often dominate the design process, but this can lead to over-designed systems, lengthy development programs, and expensive final products.

Provided that decision makers accept the unavoidable possibility of failure, a superior approach based on *system uncertainty* and *user utility* modeling exists. System performance uncertainty, including unknown parameters and possible unit failures, is modeled using the best available information. The user’s utility function, of arbitrary mathematical form, expresses the relative “goodness” of all possible outcomes. Once the axioms of decision theory are met, a maximum-utility search among the design space determines the optimal solution. Because these problems do not conform to standard mathematical assumptions, there is no guarantee of finding the best possible answer, but modern computer search techniques now provide the capability to converge toward the global optimum in reasonable time. As with traditional systems engineering, the optimal decision process is *iterative*, since the computer search results are reviewed by designers who can further develop their risk and utility models.

The approach has been successfully applied to several system design tasks in this thesis. A tutorial aircraft landing control problem is used to illustrate the basic procedure and to demonstrate the safety improvements that are possible when controllers are designed with system failure modes in mind. Applications to spacecraft design are then developed. New models for spacecraft reliability prediction have been combined with mission utility functions to predict the overall mission reliability of the *Gravity Probe B* (GP-B) spacecraft and to find improved redundancy architectures for space vehicles.

Uncertainty-based optimization has also been demonstrated to significantly improve the process of *Receiver Autonomous Integrity Monitoring* (RAIM) for Global Positioning System (GPS) navigation users. Similar uncertainty models applied to augmented Differential GPS (DGPS) systems can predict overall performance and integrity for large regions of users. Combining these with top-level objective models allows augmented GPS architectures to be optimized iteratively, as the latest experimental data *updates* the risk model and motivates additional system improvements.

QIN, Xinhua ***DATA REDUCTION ANALYSIS FOR THE STANFORD RELATIVITY GYROSCOPE EXPERIMENT,***
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, AUGUST, 1991

Abstract:

This thesis discusses the data reduction simulation and error analysis for the Stanford Relativity Gyroscope Experiment. This experiment is designed to test the Einstein’s general theory of relativity. Two untested relativistic effects are predicted for a gyroscope moving in a 650 km polar orbit around the earth: *a geodetic* effect and a *frame-dragging* effect. The geodetic effect has a magnitude of 6.602 arcsec/year in the north-south direction. It is due to the orbital motion of a gyroscope in a curved space-time around the earth. The *frame-dragging* effect has a magnitude of 0.042 arcsec/year in the east-west direction. It is due to the dragging of the “inertial” frame by the massive rotating earth. The goal of this experiment is to detect these two effects to better than 0.5 marcsec/year.

Four superconducting electrically suspended gyroscopes are placed in a cryogenic dewar carried by a drag-free spacecraft. The directions of their spin axes are measured by SQUID (Superconducting QUantum Interference Device) magnetometers and compared to a remote inertial frame, which is provided by pointing a telescope toward a guide star Rigel.

A Kalman filter is used to perform the data reduction simulation and error analysis. A two-step Kalman filtering algorithm is developed based on the spectral separation principle. Slowly varying terms are treated as time-invariant in the first step filter. This filter is restarted for every orbital period. The second step filter uses the outputs from the first step filter as pseudo-measurements to estimate the slowly varying terms. This algorithm has the advantages of clearer insight into the data reduction process, intermediate data for dynamical modeling, better numerical performance, and less computation time.

A data reduction simulation is performed with realistic spacecraft roll dynamics. The sensitivity to spacecraft roll angle error is investigated. Studies show that data reduction can be successfully performed with only one roll angle measurement as well as one roll rate correction per roll period. Studies also show that spacecraft roll control error starts to have significant influence on the experiment accuracy when its RMS (Root Mean Square) value is bigger than 100 arcsec.

The initial gyro spin axis alignment has a significant effect on the experiment accuracy. Studies show that, for a one-year mission, the optimal initial gyro alignment is close to the apparent line of sight to the guide star. This analysis is the basis for a newly established fundamental experiment requirement.

Data reduction algorithms with a low resolution analog-to-digital converter (12-bit) are also studied. These include a data integration filter and a S-Δ analog-to-digital converter. These algorithms are tested by simulations.

REISENBERGER, Michael P. ***ON THE THEORETICAL SIGNIFICANCE OF EQUIVALENCE PRINCIPLE TESTS*****, DEPARTMENT OF PHYSICS , AUGUST, 1994**

Abstract:

A conjecture, due originally to Schiff and amplified by Thorne, Lee and Lightmann states that the universality of free fall of test bodies is only possible if the underlying field theory of matter is universally coupled, that is, if gravity influences matter only by modifying the metric and connection that enter the matter field Lagrangian.

To check this conjecture I have investigated the constraints on the matter field Lagrangian imposed by IFP2, the requirement that test bodies not only follow universal world lines, but that these world lines are geodesics of a metric. The (classical) motion of stable bound states of a quantum field theory of matter coupled to a classical background metric and, weakly, to an arbitrary collection of non-metric classical background "gravitational fields" was found. The necessary and sufficient condition for these bound states (= test bodies) to obey IFP2 turns out to be that the currents that couple to the non-metric gravitational fields integrate to zero over those bound states.

An attempt was then made to find all solutions to this requirement, i.e. all couplings to non-metric gravity allowed by IFP2. The condition is too difficult to solve in its original quantum form. Therefore, classical field theory was considered instead, with bound solutions which are static in their rest frames playing the role of test bodies.

In a 1 + 1 dimensional toy model all couplings allowed by IFP2 were found. In 3 + 1 dimensions many specific types of allowed couplings to non-metric gravity were found, showing that IFP2 does not imply universal coupling and *a fortiori* that Schiff's conjecture is not strictly correct. On the other hand, almost all the counter-example theories seem very unreasonable as physical theories. A possibly realistic coupling to an anitsymmetric tensor gravitational field was found, but it may be trivial as a counter-example to Schiff's conjecture.

In the process of carrying out the analysis of Schiff's conjecture the test body limit has been made mathematically precise and several clearly defined versions of the "Equivalence Principle," of different strengths, have been identified, some of which have apparently not been defined explicitly in the literature.

The energy conservation arguments of Dicke and Haugan in support Schiff's conjecture have been recast in a Lagrangian formalism and extended, and an improved derivation of Ni's results in the X g framework is given.

Finally, an efficient method for calculating the motion of test bodies from a Lagrangian field theory of matter in a nearly metric gravitational field is derived.

REHSTEINER, Fritz H. STATIC AND DYNAMIC PROPERTIES OF HYDROSTATIC THRUST GAS BEARINGS WITH CURVED SURFACES,CENTER FOR SYSTEMS RESEARCH, *Guidance and Control Laboratory,* MARCH, 1968

Abstract:

The influence of plate curvature on the static and dynamic (stability) properties of hydrostatic (externally pressurized), orifice-regulated thrust gas bearings is investigated. Explicit theoretical and experimental results are presented for circular bearings with gap profiles bounded by a parabola and a straight line.

The main part of the theory is based on classical lubrication theory in which fluid inertia is neglected. Bearings with parallel and with inclined plate axes are considered in the chapter on "statics." A first chapter on dynamics is based on the lumped-parameter model. Particularly the motion of a bearing that is asymptotically unstable is investigated by approximate analytical methods. A second chapter deals with asymptotic stability according to a distributed-parameter model. Results of a fairly extensive numerical study are presented.

The thermal problem of a narrow channel whose width is varying periodically with time and which is filled with a viscous gas, and first-order effects of fluid inertial are considered in the Appendix. The possibility of "thermal damping" of bearing vibrations is revealed. However, the effect on bearing-dynamic stability is usually insignificant.

The theory is tested by means of a freely floating test vehicle that can be equipped with bottom plates of different curvature. While the data from static measurements agree with theory to within the measuring accuracy throughout, major discrepancies are observed in the dynamic stability tests. An attempt is made to explain them.

Bearings employing concave plates are far superior to flat-plate bearings as far as load-carrying capacity and static stiffness are concerned. This is particularly true when the load approaches the “closure” value at which the plates touch. However, dynamic stability allowed loads may be bad enough to jeopardize the gain in static performance.

ROSE, Karl R. ***SUPERCONDUCTING ORDER PARAMETER MEASUREMENTS,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MARCH, 1971**

Preface:(Acknowledgement parts omitted)

This experiment was conducted to investigate the properties of superconducting thin films in the neighborhood of the current and thermal transitions. The density of “superconducting charge carriers” in the region of interest was observed by measuring the charge carrier limited reactive conductivity. The two fluid model of superconductivity predicts that this conductivity is proportional to the superconducting electron density or what is called the order parameter. This conductivity for filamentary samples is the same as that observed for an inductance. This kinetic inductance was measured by a resonance technique. A tuned circuit excited at power levels of 10^{-15} watts controlled an oscillator by using a sensitive phase-locked technique. The sensitivity was sufficient to observe a 0.1% change in the zero degree order parameter.

The data show that the two fluid model and the Landau-Ginsburg theory are adequate representations of the superconducting state. The reactive conductivity shows the $1 - (T/T_c)^4$ dependence at low temperatures and the correct limiting form, $1 - T/T_c$, near the transition. However, a deviation in the direction of a larger conductivity, and hence order parameter, is observed very close to T_c. This effect is attributed to fluctuations.

At temperatures sufficiently close to the transition, the superconducting condensation energy becomes comparable to thermal energies. Using the Ginsburg criterion, a simple model is proposed which explains the effect quite well. This criterion assumes that the spatial range of a fluctuation is the temperature dependent coherence length. The data and model show an average order parameter which is larger than that calculated from Landau-Ginsburg in the usual fashion. The net observable effect takes the singularity out of the temperature dependent penetration depth which varies inversely to the square root of the order parameter.

The order parameter was also measured as a function of current. The data agreed well with the Landau-Ginsburg theory which predicts a small decrease in the order parameter when a current is flowing. The size of the effect is an excellent measure of the true depairing current density. The critical current density measured in this fashion agrees well with B.C.S. calculations.

ROSS, Graham ***DYNAMICS OF SUPERFLUID HELIUM IN LOW GRAVITY*****, DEPARTMENT OF MECHANICAL ENGINEERING , JULY, 1994**

Abstract:

The subject of this dissertation is the development of a computational fluid dynamics (CFD) simulation that models the unique characteristics of heliumII. The simulation is based on the commercial CFD code FLOW-3D.

The code implements Landau’s “two fluid” model of heliumII, which postulates a “super fluid” component (which has zero viscosity and zero entropy) and a “normal fluid” component (which has the properties of heliumI). The superfluid and normal fluid are completely interpenetrating but have individual velocity fields as well as separate sets of equations for momentum and continuity. Under certain conditions, a current of the superfluid will flow indefinitely, similar to the phenomenon of persistent electrical currents in superconducting metal rings.

The modeling of the interaction between the two fluids is controlled by experimentally-based critical velocity thresholds and the Gorter-Mellink mutual friction model in the bulk liquid. A method of coupling the two fluids at the free surface and calculating the motion of the free surface has been developed based on extrapolation of observations of reversible changes in angular momentum by experimenters in the field.

The computer model is compared to closed-form solutions and to experimental 1-g HeII slosh measurements gathered as part of this research. Predictions of HeII behavior in low-g conditions are calculated and the results of the single-fluid model are compared to the two-fluid model. The impulse response of HeII using the two-fluid model is very different from the fluid motion calculated from a single-fluid model.

SEELIG, Jonathan ***HIGH EFFICIENCY, HIGH INTERNAL GAIN SINGLE PHOTON COUNTING USING AVALANCHE PHOTODIODES*****, HONORS THESIS, DEPARTMENTOF PHYSICS, December, 1994.**

Abstract:

Using a monochromatic light source and a commercially available small area avalanche photodiodes at near cryogenic temperatures, we have detected single photon events and calibrated the quantum efficiency of these detectors. The highest calibrated efficiency was 90%. We believe this to be the highest quantum efficiency single photon event detection in the visible spectrum. The time profile of our pulses showed a 1/e decay time of 16 microseconds yielding an effective bandwidth or pulse resolution rate of 10 kHz. We have also determined a breakdown voltage vs. temperature relation for these particular APDs and demonstrated the coldest known operation conditions for such devices.

SELZER, Peter M. ***A STUDY OF THERMALLY GENERATED MAGNETIC FIELDS IN AN ANISOTROPIC CRYSTAL AT LOW TEMPERATURES*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MAY, 1974**

Abstract:

The purpose of the experiment described in this dissertation is to study static circulating electric currents which are produced when a temperature gradient is applied to an anisotropic metallic single crystal. These circulating currents produce magnetic fields which may be detected with a sensitive magnetometer, using low-temperature techniques.

The theory of these thermoelectric eddy currents is reviewed for both the normal and superconducting state, and a cryogenic apparatus for their measurement on a single crystal of tin is described.

The results indicate that, above the superconducting transition temperature, circulating currents and, consequently, magnetic fields arise which are proportional to the temperature gradient and agree with the qualitative behavior predicted by the theory.

In the superconducting regime magnetic fields are also detected, but they agree neither in temperature dependence nor in magnitude with the theoretical prediction. Several explanations are offered for the source of these magnetic fields other than circulating currents within the crystal.

The results in the superconducting state suggest that the theoretical predictions have overestimated the magnitude of the circulating current and the concomitant magnetic field by a significant amount.

SHAW, Gerald L. ***MODELING A CRYOGENIC He^3 NUCLEAR GYRO*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, GUIDANCE AND CONTROL LABORATORY AND THE DEPARTMENT OF PHYSICS, DECEMBER, 1980**

Abstract:

Over the last two decades, several nonconventional gyro schemes have been proposed. Directed primarily at eliminating the bearing problems in conventional mechanical gyros, it was anticipated that either better performance could be achieved or performance comparable to conventional gyros could be achieved at a lower cost. No attempt is made here to compare or contrast all of these various schemes, but rather to look at certain aspects of a particular device, a cryogenic He^3 nuclear gyro, and to provide models for estimating its performance.

The nuclear gyro is highly dependent upon the stability and homogeneity of the magnetic field environment. A combination of low temperature physics technologies makes such a device practical. By generating the applied field with superconducting coils the stability of this field is guaranteed by the inherent stability of the persistent super environment is provided by enclosing the device within a superconducting shield.

Nevertheless, even in an ideal magnetic field environment, the nuclear gyro is subject to various rectification mechanisms. Of particular interest is the role kinematic rectification plays in this device. Rectification mechanisms are discussed, and mathematical models derived for calculating the methods of kinematic rectification drift. An experiment designed to measure and distinguish the kinematic rectification effects are discussed.

The effects of thermal gradients and accelerations in the presence of an inhomogeneous magnetic field are also discussed, and models derived from which their magnitudes are calculated.

TABER, Michael A. ***I. SPIN-LATTICE RELAXATION OF DILUTE SOLUTIONS OF POLARIZED He^3 IN LIQUID He^4 IN LOW MAGNETIC FIELDS AT 4 K.***
***II. AN ANALYSIS OF A PROPOSED CRYOGENIC He^3 NUCLEAR GYROSCOPE AND ITS APPLICATION TO A NUCLEAR ELECTRIC-DIPOLE MOMENT EXPERIMENT*, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, AUGUST 1978**

Abstract:

Measurements were made of the spin-lattice nuclear relaxation time of 0.07% solutions of polarized helium-3 in liquid helium-4 at 4 K by use of an rf-biased SQUID (Superconducting Quantum Interference Device) magnetometer in magnetic fields ranging between 30 microGauss and 3 milliGauss. After the effect of magnetic-gradient-induced relaxation was subtracted by extrapolation to large magnetic fields, it was found that the relaxation time was 40 hours in a 1 cm-diameter Pyrex cell. When the sample cell was prefilled with an amount of hydrogen estimated to be equivalent to uniform wall coating of 30 molecular layers thickness, the extrapolated relaxation time increased to 5 days. It is estimated that this result was dominated by intrinsic relaxation due to helium-3 dipole interactions in the bulk of the sample.

As a potential application, the performance of a proposed cryogenic nuclear gyroscope utilizing a helium-4 — polarized helium-3 gas mixture with SQUID magnetometer readout in zero magnetic field is theoretically analyzed. The possibility of using a modified version of this device based on a polarized helium-3 — superfluid helium-4 mixture for the purpose of an experimental search for an electric-dipole moment in the helium-3 nucleus is also discussed.

TAPLEY, Mark B. ***A GEODETIC GRAVITATION GRADIOMETER COEXPERIMENT TO GRAVITY PROBE B*****, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, AUGUST, 1993**

Abstract:

Geodesy is the science of measuring the gravitational field of and positions on the Earth. Estimation of the gravitational field via gravitation gradiometry, the measurement of variations in the direction and magnitude of gravitation with respect to position, is this dissertation's focus.

Gravity Probe B (GP-B) is a Stanford satellite experiment in gravitational physics. GP-B will measure the precession the rotating Earth causes on the space-time around it by observing the precessions of four gyroscopes in a circular polar, drag-free orbit at 650km altitude. The gyroscopes are nearly perfect niobium-coated spheres of quartz, operating at 1.8 K to permit observations with extremely low thermal noise. The permissible gyroscope drift rate is less than 10^{-11} degrees/hour, so the torques on the gyros must be tiny. A drag-free control system, by canceling accelerations caused by nongravitational forces, minimizes the support forces and hence torques.

We explore the feasibility of using the residual suspension forces centering the GP-B gyros as gradiometer signals for geodesy. The objective of this work is a statistical prediction of the formal uncertainty in an estimate of the Earth's gravitation field using data from GP-B. We perform an instrument analysis and apply two mathematical techniques to predict uncertainty. One is an analytical approach using a flat-Earth approximation to predict geopotential information quality as a function of spatial wavelength. The second estimates the covariance matrix arising in a least-squares estimate of a spherical harmonic representation of the geopotential using GP-B gradiometer data.

The results show that the GP-B data set can be used to create a consistent estimate of the geopotential up to spherical harmonic degrees and order 60. The formal uncertainties of all coefficients between degrees 5 and 50 are better by factors of up to 30 than uncertainties in current satellite-only estimates and up to 7 than uncertainties in estimates such as GEM-T3 [Lerch 1992] which include surface data. The primary conclusion resulting from this study is that the gravitation gradiometer geodesy coexperiment to GP-B is both feasible and attractive.

TEAGUE, E. Harrison ***FLEXIBLE STRUCTURE ESTIMATION AND CONTROL USING THE GLOBAL POSITIONING SYSTEM,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS May, 1997**

Abstract:

This dissertation describes the development of a new sensing system for real-time measurement and control of flexible structure motions using the Global Positioning System (GPS). The sensor uses measurements of the carrier phase of the GPS signal at several antennas to estimate the deformation and orientation of a structure on which the antennas are mounted. Its distributed nature, plus its superior DC performance, make the GPS based sensor a powerful source of information for large structure vibration control. Also, the GPS sensor is unique in that it provides information for vibration estimation *and* bias-less structure orientation estimation simultaneously.

Realization of this GPS sensor has brought to light some new challenges. Previous work has demonstrated the applicability of GPS carrier sensing for vehicle attitude determination, and a principle challenge of this work has been resolution of the *cycle ambiguities*[1] inherent in the phase measurements. The most successful techniques have used attitude motion of the vehicle *(the structure)* over time, plus the assumption that the structure is nearly rigid, to provide observability of the unknown cycle parameters. But, as this thesis will show, the previous techniques do not work for structures with significant structural flexibility, and a central focus of this research has

been to develop algorithms that can take flexibility into account. A new solution to the cycle ambiguity problem is presented that combines measurements taken during structural motion with a model of the platform dynamics to initialize the unknown cycle ambiguities.

Real-time signal processing algorithms were developed, implemented, and tested on an experimental large flexible structure in the laboratory that was designed to exhibit flexible motions detectable by current GPS receivers (approximately 1 cm sensitivity in a 0-10 Hz bandwidth). The 8 meter long, 180 kg test structure is suspended from above and emulates the motions of a large, flexible, orbiting platform, moving with low frequencies and large structural deflections. This test structure is outfitted with an array of GPS antennas for motion sensing, and an array of compressed air thrusters for control actuation. The GPS sensor provides better than 0.5° rotational accuracy, determined by comparing with on-board gyroscopes. Several automatic control experiments were performed by closing feedback loops from the GPS measurements to the thruster commands. Automatic vibration damping tests showed the ability to reduce free structure vibrations to sub-centimeter/sub-degrees levels (as measured by GPS) with approximately 5 second settling times. Also, tests of the closed loop system response to impulsive disturbances showed rejection of such disturbances with negligible overshoot. Finally, a 35° rigid-body slew maneuver was performed showing simultaneous rigid body orientation and elastic vibration control. Vibration motion was maintained within sub-centimeter/sub-degree levels throughout the 30 second slew.

This work represents an exciting advancement in the field of GPS sensing. It is significant because it shows the potential for GPS as a high precision large-array real-time sensor. It also marks the first demonstration of real-time flexible platform vibration control using GPS as the only source of motion information.

---

[1]Because carrier waves are identical cycle to cycle, the number of full cycles in the measurement is ambiguous at the time of initial signal lock.

TASHKER, Michael G. ***INTEGRAL CONTROL OF A SPINNING DRAG-FREE SATELLITE,*** **CENTER FOR SYSTEMS RESEARCH, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, GUIDANCE AND CONTROL LABORATORY, APRIL, 1974**

Abstract:

A drag-free satellite is controlled in translation so that it follows a proof mass in an internal cavity. The proof mass is in a drag-free orbit only under the influence of gravitational forces because it is shielded from all external forces by the surrounding satellite. In typical drag-free satellite designs, the largest force that perturbs the proof mass from following an orbit solely under the influence of gravity is the mass attraction of the surrounding satellite for the proof mass. Spinning the satellite is desirable because it attenuates the effect of this disturbing force and simplifies the attitude control.

The gradient of the mass attraction force coupled with the offset of the proof mass from the center of spin of the satellite produces a force that is not attenuated by spin. Reduction of this force without knowledge of the mass attraction properties of the satellite can be accomplished by the application of integral control. Drag, which is assumed constant in an orbital frame, is oscillatory in the spinning satellite frame of reference. The classical theory of integral control is extended to the reduction of errors in the presence of nonconstant forces that can be modelled by differential equations. The performance of systems with integral control and estimators to generate missing states is studied.

A spinning body possesses symmetry that enables its behavior to be described by differential equations of lower order with explicit complex terms. The techniques of complex symmetry are applied to the synthesis of a control system for the spinning drag-free satellite. Classical synthesis and analysis techniques are extended to complex symmetric systems. These include the complex symmetric root locus, Bode plot, polar plot and Nyquist criterion, and root square locus for optimal control.

The control system was mechanized on a laboratory simulator in order to demonstrate the performance of the system with integral control. The effects of parameter variation and system nonlinearities are reported. As a result of these experiments, an engineering judgment is made on the feasibility of such a control system for a flight vehicle, including selection of control mechanization.

TATE, Janet ***A PRECISE DETERMINATION OF THE MASS OF A COOPER PAIR OF ELECTRONS IN SUPERCONDUCTING NIOBIUM,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, OCTOBER, 1987**

Abstract:

We have used a superconducting, thin-film niobium ring deposited on the equator of a precision quartz hemispherical rotor to measure the ratio of Planck's constant to the mass of a Cooper pair of electrons, h/m^*. We attained a precision of 5 ppm (statistical) and an accuracy of 30 ppm (systematic) for a combined, root sum of squares error of 30 ppm.

As a result of two macroscopic quantum phenomena - flux quantization and the London moment, the flux through a rotating, superconducting ring is a multivalued function of its rotation frequency. The flux goes to zero at certain equally spaced frequencies. The ratio h/m^* is proportional to this frequency spacing. It is also proportional to the cross sectional area of the niobium ring. The frequency spacing is measured by spinning the quartz hemisphere here in a precision helium gas bearing at 6 K, and using a SQUID magnetometer to monitor the flux through the niobium rings as a function of rotation rate. The area of the ring is obtained by measuring two perpendicular equatorial diameters of the quartz rotor at 6 K. This measurement is interferometric, using a continuously tunable dye laser whose frequency is referred to precisely calibrated, Doppler-free absorption lines in molecular tellurium and iodine. The roundness of the quartz rotor is determined at room temperature.

Using the values for Planck's constant and the rest mass of the electron, m_e, recommended in the most recent fundamental constants revision, we find that the mass measured in this experiment is larger than twice the free electron mass by 84±30 ppm. Our result disagrees with theoretical predictions that this experiment would observe a mass which is smaller than twice the free electron mass by 8 ppm.

UEMATSU, Hirohiko ***THE GRAVITY PROBE B NIOBIUM BIRD EXPERIMENT: EXPERIMENTAL VERIFICATION OF A DATA REDUCTION SCHEME WITH A PROTOTYPICAL DC SQUID READOUT SYSTEM*, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, OCTOBER, 1993**

Abstract:

This dissertation describes the concept and the latest results from the niobium bird experiment, which is an integrated, end-to-end test environment for the data reduction scheme and the readout system designed for the Gravity Probe B program (GP-B).

The Gravity Probe B program is a relativity gyroscope experiment begun at Stanford University in 1960 and supported by NASA since 1963. This experiment, for the first time, will check 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 the 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. I reformulated the two-step Kalman filters, originally developed by J. V. Breakwell and X. Qin, and designed the niobium bird experiment to verify the performance of the data reduction scheme experimentally with SQUID readout hardware within the test loop.

The niobium bird experiment comprised three major components: a truth model, Kalman filters, and a SQUID readout system. The truth model simulated the science signal, which was injected into the SQUID readout system. The SQUID output was then fed into the two-step Kalman filters as a measurement, and the true values and the estimates by the filters were compared to evaluate the filter performance. I also evaluated the performance of the readout hardware in terms of the stability and the signal-to-noise ratio, including the SQUID magnetometer, the lowpass filter, and the A-to-D converter.

The latest results from the niobium bird experiment showed that the temperature-dependent bias drift in a commercially available dc SQUID was too large to achieve the required estimation accuracy. I used a commercially available dc SQUID manufactured by Quantum Design, Inc., which showed a strong correlation between the readout bias and the temperature of the SQUID controller with a cross-correlation coefficient of 0.968 or a temperature coefficient of about 1 arcsecond per Kelvin. This correlation, with a lack of temperature regulation, yielded a large bias drift in the SQUID magnetometer which was about tweny times larger than what I assumed in the simulation. For the GP-B science mission, the bias drift in the SQUID readout can be reduced to meet the requirement by implementing a temperature regulation system and designing a SQUID controller with a smaller temperature coefficient.

I also examined by the effect of the gyroscope's polhode motion in the presence of the trapped flux, the effect of a faster roll period, and the effect of the telescope pointing error on the data reduction by simulations. I modeled the trapped flux signal by modulation of a SQUID scale factor. Even though the model I used may not represent the actual effects accurately, the simulation showed that the trapped flux signal can be spectrally separated by using a faster polhode period.

VASSAR, Richard ***ERROR ANALYSIS FOR THE STANFORD RELATIVITY GYROSCOPE EXPERIMENT,*** **DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS GUIDANCE AND CONTROL LABORABOTY AND THE DEPARTMENT OF PHYSICS, MARCH, 1982**

Abstract:

This thesis discusses an error analysis performed for the Stanford Relativity Gyroscope Experiment. The experiment is designed to measure any relativistic precession of a gyroscope carried in an earth-orbiting satellite to an accuracy of ±1 milliarcsec/yr. Einstein's General Theory of Relativity predicts two precessions: A "geodetic" precession due to the orbital motion of the gyroscope about the earth (6.9 arcsec/yr) and a "motional" precession due to the interaction of the earth's rotation with the spinning gyro (0.44 arcsec/yr).

There are four superconducting electrically suspended spherical gyroscopes on the satellite. The direction of their spin axes is measured by means of SQUID magnetometers and compared with an inertial reference. The plan is to use the star Rigel as the "inertial" reference. Its direction is measured using a telescope on the satellite.

The error in determining the relativistic precessions was calculated using a Kalman filter covariance analysis with a realistic error model. An averaging technique was used to reduce the amount of computer time needed to perform the covariance analysis by a factor of ~ 1000.

Studies show that a slightly off-polar orbit is better than a polar orbit for determining the "motional" precession, i.e., depending on the a priori uncertainty in Rigel's proper motion either a 70 deg orbit or 86.25 deg orbit is best for determining the motional precession. SQUID magnetometer noise turns out to be the dominant measurement error source. Depending on its magnitude, the a priori proper motion uncertainty may be the dominant error source in the experiment. If Rigel's proper motion is known exactly, the motional precession can be measured to an accuracy of 0.52 milliarcsec/yr in an 86.25 deg. orbit.

WALTER, Todd ***A GYROSCOPE CLOCK FOR A NULL GRAVITATIONAL REDSHIFT EXPERIMENT,*** **DEPARTMENT OF APPLIED PHYSICS, DECEMBER, 1993**

Abstract:

This dissertation describes the analysis and experimental testing of the frequency stability of electrostatically-levitated, superconducting gyroscopes. The tests were conducted on the ground at cryogenic temperatures using a magnetic readout of the gyroscope rotor's spin phase. By achieving fractional frequency stabilities on the order of 3×10^{-11} over one year or better it would be possible to perform a test of Local Position Invariance (LPI). LPI states that in local freely falling frames, the outcome of any nongravitational test is independent of where and when in the universe it is performed. This means that all clocks, independent of the physical principle on which they are based, should exhibit the same gravitational redshift. The experiment proposed in this thesis is intended to compare a gyroscope clock to an atomic clock as they both experience the same time-varying gravitational potential. There is expected to be no difference between the two types of clocks, therefore this is a null gravitational redshift experiment.

While the gyroscope clock is unique as a laboratory instrument, it is a familiar natural phenomenon. The Earth itself is spherical rotating-body clock that was the first clock used by mankind and it still serves as the reference for all of our time scales. More recently, neutron stars with short rotation periods and high frequency stabilities have been observed. These millisecond pulsars have long-term frequency stabilities rivaling today's best atomic standards.

A unique opportunity to perform a gravitational redshift experiment exists in the Gravity Probe B (GPB) program. GPB is a satellite experiment whose purpose is to test two predictions of Einstein's General Theory of Relativity: the geodetic and frame-dragging effects. These effects will be measured by monitoring the precession rates of nearly perfect gyroscopes against the inertial stars. Navigation of the satellite is aided by means of the Global Positioning System (GPS). Thus GPB already has in place nearly all of the essential elements for the proposed clock experiment. These include nearly disturbance-free gyroscopes whose pointing and spin phase can be referenced to the inertial frame of the fixed stars and onboard access to Earth-bound atomic clocks through GPS. The varying gravitational potential is provided by the eccentricity of the Earth's orbit about the Sun. *Therefore with very little change to GPB, the clock experiment can be performed using the same gyroscopes.*

I have performed additional analysis to verify that the disturbance levels have been sufficiently reduced so as to maintain the desired frequency stability. Possible sources of disturbance to the spin frequency of the gyroscope include background gas, cosmic rays, thermal variations and interactions with the support system. Small differences in the principal moments of inertia lead to a motion of the spin axis with respect to the body frame.

This motion is known as polhode motion and will lead to periodic variations in the measured frequency. Reliable analytic models for the effects of gas damping, polhoding and precession due to the mass unbalance moment have been developed. I have verified these models by means of testing conducted on the ground and achieved stabilities on the order of 10^{-7}. By extrapolating to the Science Mission conditions, we can determine a theoretical level of frequency stability. Provided that the pressure is lowered below 10^{-17} torr and the temperature is modeled to *1* mK the resulting instability level induced by these three effects would be below the $3x10^{-14}$ level. In addition to the expected effects, a previously unmodelled torque has been observed. While the physical cause of the torque is still unknown, its magnitude is highly correlated with the square of the potential difference of the rotor with respect to electrical ground. To reach a level below $3x10^{-14}$, the empirical model suggests that the potential would have to be reduced to ~ 10 mV and modeled to *1* mV. Neither of th ese requirements places unreasonable limitations for the Science Mission. To reduce the effects of thermal variations on the frequency instability, new rotors are being made and tested that are constructed from single crystal silicon rather than fused quartz. These rotors show much promise for the clock experiment.

WATERS, C. A. ***MICROWAVE SURFACE IMPEDANCE STUDIES ON COPPER AT LOW TEMPERATURE,*** **DEPARTMENT OF PHYSICS, LOW TEMPERATURE PHYSICS GROUP, DECEMBER, 1979**

Abstract:

The variation of surface impedance has been measured as a function of temperature in resonant microwave cavities made of copper and aluminum. This work was motivated by the discovery by Lockhart, Witteborn and Fairbank of a temperature-dependent shielding of the ambient electric field inside a copper tube. In their experiments, the field at 4.2 Kelvin was observed to be about one ten-thousandth of its value at 300 Kelvin, with most of this reduction occurring between 4.5 and 4.2 Kelvin. This shielding is believed to involve electrons either within the layer of copper oxide at the metal surface, or outside the surface but bound to it. It was expected that the electronic behavior responsible for the shielding might produce measurable changes in the microwave surface impedance of the metal.

We have made measurements of the surface resistance and reactance by means of the related cavity parameters of quality factor (Q) and resonant frequency respectively. The range of temperature investigated was from 1.6 to 14.0 Kelvin. Changes in resonant frequency with temperature were measured with an accuracy of about one Hertz at a frequency of 9.120 megahertz, which corresponds to a fractional change in surface reactance of 10^{-5}. Fractional changes in surface resistance were measured with about 5×10^{-4} accuracy.

The cavities were cylindrical, and were usually driven in the transverse electric 011 normal mode. A number of circular endplates and cylindrical bodies made of copper or aluminum were assembled in various combinations to form cavities. In one all-copper cavity the frequency, as a function of temperature, has shown a discontinuous change of slope at 3.48 ± 0.04 Kelvin. Although the shape of this function was influenced by various experimental factors, the temperature of the slope discontinuity was repeatable, and was not affected by adsorbed gas contamination on the cavity walls, or by the substitution of aluminum endplates for copper on one or both ends. It does, however, vary with an applied static axial magnetic field in a manner consistent with the parabolic critical-field relationship of a Type I superconductor. Below the critical temperature strong magnetic hysteresis effects were observed. A fractional decrease in Q of 0.002 accompanied the frequency slope discontinuity, and was similarly affected by the magnetic field. In certain runs a similar anomaly occurred at 7.12 ± 0.03 Kelvin.

An entirely different cavity with an aluminum body and simple copper endplate showed a slope discontinuity at 6.06 Kelvin and this was repeated when this copper endplate was tested on a copper cavity body.

Certain all-copper and ali-aluminum cavities had smooth frequency curves, and these agreed well with corresponding data on the thermal expansion of these materials.

Careful examination of the data and experimental procedure indicates that these effects are not instrumental artifacts, or the result of contamination by ordinary superconducting material. The spin glass transition was considered as an explanation and rejected. We plan to reach a full understanding of these effects through further experiments.

WIKTOR, Peter J. ***THE DESIGN OF A PROPULSION SYSTEM USING VENT GAS FROM A LIQUID HELIUM CRYOGENIC SYSTEM*****, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, JUNE, 1992**

Abstract:

Two spacecraft, Gravity Probe B (GP-B) and the Satellite Test of the Equivalence Principle (STEP), incorporating on-board liquid helium cryogenic systems are scheduled to fly around the turn of the century. Effective propulsion systems can be implemented for these spacecraft by directing the helium gas which boils off from the cryogenic systems in specific directions through a set of thrusters. Due to extensive development and testing work at Stanford and elsewhere, the ultralow flow rate helium thrusters for such a propulsion system are now considered proven technology. This thesis is concerned with implementing the thrusters into an effective overall propulsion system. Our primary concern is maximizing the forcing capability or control authority of the propulsion system. A worst case analysis of the thruster system is performed. Various techniques are derived to calculate the worst case output or minimum control authority of the thruster system. The techniques are general and apply to any parallel configuration of actuators. They are used in this thesis to design a propulsion system for GP-B which maximizes the minimum control authority and to study redundancy of the GP-B thruster system under a worst case thruster failure. A general thruster controller is derived for a liquid helium propulsion system which can generate desired output forces and at the same time vent the required helium gas needed to cool the cryogenic system. We show how the helium gas vent rate can be controlled to maintain a stable liquid helium supply temperature and pressure. An on-orbit thruster calibration scheme is developed to make sure the correct output force is generated. Using a nonlinear simulation of the spacecraft dynamics, the calibration scheme is shown to calibrate the 108 parameters needed to describe the outputs of a set of 18 thrusters to better than 1% accuracy. Finally an on-orbit mass trim control system is derived to reduce the centrifugal force and moment disturbances on the propulsion system due to mass property offsets.

WILKINS, Daniel C. ***TOPICS IN SPINNING BODIES IN GENERAL RELATIVITY,*** **DEPARTMENT OF PHYSICS, AUGUST, 1972**

Abstract:

This thesis divides into four parts.

In the first part, we treat the dynamics of a spinning particle. The mathematically exact theory, due primarily to A. Papapetrou, is reviewed. Following L. I. Schiff, we allow also for a non-gravitational constraining force. We point out that because of the freedom of choice of the local comoving frames, the motion of the spin vector relative to them is quite arbitrary, and therefore without meaning unless the orientations of the local frames are somehow specified. This encourages one to look for frame-independent effects. The precession of the spin vector relative to a telescope trained on a star is such an effect.

Under the weak-field, slow-motion approximation and with a particular choice of local frames, we obtain a simple formula for the spin precession. The spin-equation of L. I. Schiff in the exterior region of a rotating sphere is recovered. It is shown to hold in the weak-field vacuum region of any stationary source (even a collapsed object). The precession of the spin relative to a comoving telescope is shown explicitly to be frame-independent. An analogy with electromagnetism, already well-known for the motion of non-spinning particles, is extended to the equation of motion of the spin. The extension is only possible because of our particular choice of local frames.

The second part of the thesis is a study of the bound orbits of a (non-spinning) particle in the gravitational field of a collapsed rotating body without charge, i. e., a Kerr black hole. I review the main features of black hole physics. B. Carter has given the separated equations of motion. Use of effective potentials enables us to give necessary conditions for binding. To enhance the effects of rotation, the most rapidly rotating black hole is considered. For simplicity, we specialize to orbits of constant radius (“spherical” orbits). The set of stable spherical orbits is described. From the relations between the periods for motion in latitude and longitude, it follows that all orbits are dragged in the sense of the black holes rotation. As the radius of an orbit approaches that of the black hole, the amount of dragging increases without limit. Consequently, a particle in orbit near a rotating collapsed body will describe a helix-like path.

Next we study the two-body problem by means of two exact solutions (due to Israel-Wilson and Perjés) of the Einstein-Maxwell equations. One system examined consists of two charged black holes; the other consists of two equal charged particles with equal but opposite angular momenta. Both systems are in equilibrium. The hope of seeing black hole formation prompts one to bring together the particles of either system by reducing the parameter of separation. The two black holes coalesce to a new black hole, but the corresponding physical process would take an infinite time as seen by a distant observer in the asymptotically flat background. The two spinning particles do not coalesce to a black hole; rather, the result is an axially symmetric static solution without horizons, and which depends on the initial angular momenta. Further work is needed to explain this unexpected outcome.

Two arguments, one concerning the Israel-Wilson-Perjés solutions and one concerning black holes, both point to the existence of a gravitational spin-spin force. Returning to the Papapetrou equations, we find the spin-force on a test particle in the weak-field, slow-motion approximation. This force is somewhat different from the analogous force on a magnetic dipole in classical electromagnetism.

WILSON, Edward G. ***LOCAL AND NONLOCAL EFFECTS IN THE PENETRATION OF MAGNETIC FIELDS INTO SUPERCONDUCTING THIN FILM CYLINDERS,*** **LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, JUNE 1976**

Abstract

We have measured the temperature dependence of magnetic field penetration into superconducting tin films, some of which may be fitted with a local theory, and others of which show distinctly nonlocal effects. The Pippard and BCS theories provide (very similar) generalization of the London local relationship between the supercurrent J and the vector potential A in a superconductor. In the nonlocal theories J(r) is proportional to a weighted average of A within a volume roughly equal to ξ^3, centered at r. The coherence length ξ is shortened by a non-infinite mean free path ℓ, following the relation $1/\xi = 1/\xi_0 + 1/\ell$. As long as ξ exceeds the London penetration depth λ_L, the penetration of a magnetic field into the superconductor exhibits nonlocal effects that cannot be matched by a local theory. For $\xi < \lambda_L$ however, the Pippard theory becomes approximately local, and it reduces for $\xi << \lambda_L$ to a London-type theory with an effective $\lambda = \lambda_L \sqrt{1+x_0/\ell}$. We consider tin, for which ξ_0 = 2,300 Å and λ_L = 340 Å. In a pure bulk sample tin should be highly nonlocal, showing effects dramatically different from the London theory, including a depth at which the penetrating field is zero, and at greater depths a small field opposite in sign to the outside field. Sommerhalder and Thomas showed that the nonlocal theories predict similar effects for a hollow cylinder, and Dragneid and Sommerhalder reported observing a reversed field inside one of thirty thin film Sn cylinders. The magnitude of the reported reversed field is at least 300 times greater than predicted by the theory, however, and no detailed comparison with the theory was presented.

We have vacuum deposited fifteen Sn film cylinders of thicknesses between 6000 Å and 12,000 Å onto quartz substrates. The interior penetration resulting from an axial external dc field is measured with a 30 MHz SQUID magnetometer as a function of temperature. The background field is reduced to 5 x 10^{-5} g with two concentric μ-metal shields and then held fixed by a superconducting lead shield. The remanent field is not visible because the applied field and magnetometer are zeroed before each measurement, so we measure the change in internal field (ΔH_i) due to an applied exterrnal field (ΔH_a).

Although pure bulk tin should always be nonlocal in behavior, evaporated films have shortened ℓ and thus $\xi < \xi_0$ because of impurities introduced during evaporation, and because of crystalline imperfections in the deposited film. Nonetheless, we have observed two films whose magnetic field penetration behavior is well modelled by the nonlocal theory, and is poorly modelled by the local theory. We thus believe that we have for the first time unambiguously demonstrated the effects of the nonlocal averaging over the coherence length n magnetic field penetration into superconductors.

We have not found reversed fields inside any of our superconducting tin cylinders, and we have discovered a mechanism which could explain the implausibly large field reversal reported by Drangeid and Sommerhalder. We observed a spurious field reversal effect which was very probably due to the motion of flux pinned in the tin film, and experimental details in the report by Drangeid and Sommerhalder suggest the likelihood of pinned flux in the film when they saw field reversal. However, we certainly do not conclude that field reversal does not exist; the difficulties of obtaining thin films with sufficiently longmean free paths and sufficiently small pinhole leakages are quite sufficient to explain an absence of experimental verification of this effect.

WITTEBORN, Fred C. ***FREE FALL EXPERIMENTS WITH NEGATIVE IONS AND ELECTRONS*****, LOW TEMPERATURE PHYSICS GROUP, DEPARTMENT OF PHYSICS, MAY, 1965**

Abstract: None

WORDEN, Paul W. Jr. ***A CRYOGENIC TEST OF THE EQUIVALENCE PRINCIPLE,*** **HIGH ENERGY PHYSICS LABORATORY, W. W. HANSEN LABORATORIES OF PHYSICS, MARCH, 1976**

Abstract:

The weak equivalence principle is the hypothesis that the ratio of inertial and passive gravitational mass is the same for all bodies. A greatly improved test of this principle is possible in an orbiting satellite. The most

promising experiments for an orbital test are adaptations of the Galilean free-fall experiment and the Eötvös balance. Sensitivity to gravity gradient noises, both from the earth and from the spacecraft, defines a limit to the sensitivity in each case. This limit is generally much worse for an Eötvös balance than for a properly designed free-fall experiment. The difference is related to the difficulty of making a balance sufficiently isoinertial. Cryogenic technology is desirable to take full advantage of the potential sensitivity, but tides in the liquid helium refrigerant may produce a gravity gradient that seriously degrades the ultimate sensitivity. The Eötvös balance appears to have a limiting sensitivity to relative difference of rate of fall of about 2 X 10^{-14} in orbit. The free fall experiment is limited by helium tide to about 10^{-15}; if the tide can be controlled or eliminated the limit may approach 10^{-18}. Other limitations to equivalence principle experiments are discussed.

An experimental test of some of the concepts involved in the orbital free-fall experiment is continuing. The experiment consists in comparing the motions of test masses levitated in a superconducting magnetic bearing, and is itself a sensitive test of the equivalence principle. At present the levitation magnets, position monitors and control coils have been tested and major noise sources identified. A measure of the equivalence principle of about 10^{-5} has been made with one test mass and the earth as test bodies. Differential measurements are postponed, pending modifications to the apparatus and development of a system for digitizing data. The experiment and preliminary results are described.

WU, Chang-Huei ***DC ELECTROSTATIC GYRO SUSPENSION SYSTEM FOR THE GRAVITY PROBE B EXPERIMENT*****, DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS, DECEMBER, 1993**

Abstract:

The Gravity Probe B experiment is a satellite-based experiment primarily designed to test two aspects of Einstein's General Theory of Relativity by observing the spin axis drift o near-perfect gyroscopes in a 650-km circular polar orbit. The goal of this experiment is to measure the drift angles to an accuracy of 0.3 milli-arcsec after one year in orbit. As a result, electrostically suspended free-spinning gyroscopes operating at a very low temperature became the final choice for their ultra-low Newtonian torque-induced drift rate.

The Conventional AC current-driven suspension system faces two fundamental difficulties for ground gyro testing. Field emission causes rotor charging and arcing with an imperfect electrode or rotor surfaces because the electric field intensity needed to support a solid rotor in the 1-g field is more than 10^7 V/m. The system not only becomes unstable at a high rotor charge, which can be more than 500 volts, but may also lose control in case of arcing. Both the high voltage AC suspension signal and the high frequency (1 Mhz) signal for rotor position sensing interfere with the superconducting SQUID magnetometer for spin axis readout through inductive coupling. These problems were resolved by using DC voltage to generate a suspension force and a low frequency position sensor. In addition to the Input/Output linearization algorithm developed to remove the system nonlinearity for global stability and dynamic performance, we also minimized the electric field intensity to reduce rotor charging. Experimental results verified the desired global stability and satisfactory dynamic performance. The problem of rotor charging is virtually eliminated. More importantly, the DC system is compatible with the SQUID readout system in the Science Mission configuration. Consequently, experiments in low magnetic field at a sub-micro-gauss level for SQUID design verification and trapped flux distribution study were finally realizable in ground environment.

The second part of the research focused on design issues for the Science Mission in a micro-g environment. The unique requirement of the GP-B experiment is to minimize suspension-induced torque and subsequent spin axis drift. A nonlinear control law which employs stiffened spring and stiffened damping coefficients was developed to achieve both low RMS noise in steady-state operation and quick response for situations like a micrometeoroid impact. Rotor voltage measurement and in-flight sensor bias correction schemes were developed to ensure system stability and absolute centering accuracy. Simulation results verified the system performances and confirmed that a suspension-system-induced rotor spin axis drift lower than 0.1 milliarcsec/year can be reached.

YANSOUNI, Pierre A. ***DATA PROCESSING FOR PICKOFF PARAMETER IDENTIFICATION, CENTER FORSYSTEMS RESEARCH, GUIDANCE AND CONTROL LABORATORY,*** **JULY, 1970**

Abstract:

This research is a study of the feasibility of measuring the null shift of the nonlinear sensor in a drag-free satellite, using only its output signal. The null location is important because it represents the average position of

the proof-mass center which, in the ideal configuration, should be superposed to the center of mass and center of geometry disturbing forces. In addition, the null shift could become large enough to allow the proof mass to hit the walls of the enclosing cavity and, thus, could impair completely the functioning of the entire system.

The relative motions between the proof mass and main body of the satellite are parabolic functions of time, which are distorted by the nonlinear characteristic of the pickoff in a manner that is proportional to the null shift. In principle, therefore, the shape of the motions implies the null location. An analytical model is selected for the characteristic, and its parameters are adapted to minimize the square of the error between its output and the actual measurements.

Because the model is parametrically nonlinear, the minimum-seeking technique is a linearized first-order gradient method applied iteratively. Numerical difficulties, resulting from a “near singularity” of the least square fit (caused by the equivalence, at first order, of some of the parameters), required the use of a weighting technique carefully controlled for efficiency. Some rescaling and change of variables were necessary to obtain a more equal distribution of the gradient components with respect to each of the parameters.

A major difficulty developed with the presence of a secondary minimum whose relative amplitude, with respect to the minimum corresponding to the actual set of parameters, varies randomly depending on the particular sample of the noise contained in the measurements. To distinguish between these two minima, it was necessary to analyze the residuals so as to identify patterns that are specific to each minimum. Identification of these patterns is possible by employing cross-correlation techniques.

The results are evaluated in terms of the covariance of the estimated values of the null shift, as a function of both the noise power and the amplitude of the null shift.

A number of numerical simulations were performed on a simplified one-dimensional model. The estimation procedure also was applied to the experimental data obtained from the two-dimensional air-cushion simulator of the drag-free satellite.

ZHU, Jun ***CRITICAL STATES IN TYPE-II THIN FILM SUPERCONDUCTORS, DEPARTMENT OF APPLIED PHYSICS,1994***

Abstract:

This thesis describes our theoretical and experimental research on the subject of the critical state model in disk-shaped *type*-II thin film superconductors with magnetic fields applied perpendicular to the film.

The theoretical work included analytically solving the critical state equation for a thin superconducting disk in a time-varying periodic external field assuming a constant critical current density. In the framework of Kim’s critical state model, we have developed a numerical method and have solved the critical state equation for field-dependent critical current densities. The numerical results coincide with the analytic solutions in the limit of constant critical currents.

The experimental work included design and construction of the cryogenic probe as well as the measurements performed. We describe the details of the low temperature probe. Using a SQUID-based technique and the probe, we conducted magnetization measurements, studied temperature gradient effects on trapped flux, and made flux creep measurements in dc sputtered Nb, epitaxial Nb and rf sputtered NbN thin films. A great deal of effort was devoted to investigating the dc sputtered Nb films deposited by the Gravity Probe B (GP-B) loop coating system at Stanford since Nb is the superconducting coating of the gyroscope rotor designed for the General Relativity (GR) test. We investigated the thickness dependence of the critical current of superconducting polycrystalline Nb films. In addition, an epitaxial Nb thin film and a dc sputtered NbN thin film were used to explore a greater range of parameters. Critical currents were extracted from the magnetic hysteresis loops by applying the analytical solutions and the numerical method that we developed. Good agreement was obtained between the measured data and the theoretical fits. We discuss our analytical and numerical model, and analyze the agreement and deviations between the experimental results and the fit. Current densities and field profiles were calculated for thin superconducting disks. Experimental research was also conducted on the temperature gradient induced flux motion and the temperature gradient induced field expulsion in thin superconducting films. Thermally activated flux creep was observed and recorded for the first time in thin superconducting disks in an axial magnetic field. The thermal activation energy was deduced.

Throughout this thesis, we emphasize the important points that we experienced during the Ph.D. research; we hope that it will be valuable help for others.