

Proposal to
DEVELOP A ZERO-G, DRAG-FREE SATELLITE
and to
PERFORM A GYRO TEST OF GENERAL RELATIVITY IN A SATELLITE

Principal Investigators
Professor Robert H. Cannon, Jr.
Professor William M. Fairbank

Project Advisor
Professor Leonard I. Schiff

Submitted to the National Aeronautics and Space Administration
by the
Department of Aeronautics and Astronautics
and the
Department of Physics
Stanford University
November 1962

SUMMARY

Stanford University proposes to develop a small "zero-g" satellite which will follow a purely gravitational orbit by tracking an unsupported, shielded, internal proof mass. Stanford also proposes to continue and enlarge its long-term program to develop and perform, in a zero-g satellite, the Schiff gyro test of the General Theory of Relativity.

The zero-g satellite will have a number of uses in its own right. It will provide for the instantaneous measurement of atmospheric density and for more accurate measurements of the earth's gravitational field. It can provide for tests of inertial instruments in the complete absence of supporting forces. It will provide for early tests of crucial elements of the Schiff experiment apparatus. It may also make possible measurement of other gravitational effects. Finally, it can make possible orbital operations at very low altitude.

The Schiff experiment was conceived at Stanford in 1959 and the concept of performing it in an OAO satellite has been in continuous development here since, as has research in low temperature techniques for making it possible. This project was formally proposed to NASA in January 1961. Progress on this research has been documented periodically. It is hoped at this time to enlarge the research to include definite plans for satellite tests.

Planning of the zero-g satellite was begun at Stanford in June 1961, and results of a detailed feasibility study and error analysis were published in June 1962.

A zero-g satellite could be launched piggyback in either a NASA Thor-Agena or Air Force Discoverer shot, or could be launched by a Scout rocket, within three years from go-ahead.

I. INTRODUCTION

This proposal describes a research program at Stanford University which has two distinct but closely related parts. They are (1) to develop a specially-controlled satellite system to follow a purely gravitational orbit, and (2) to perform in a satellite the Schiff gyro experiment to test the General Theory of Relativity. (The second objective reiterates Stanford's earlier formal proposal to the NASA in January 1961, Ref. (4).)

The specially-controlled satellite system to be described here will be referred to as a "zero-g" or a "drag-free" satellite. * By this is meant an arrangement whereby a satellite is controlled so that its orbit is exactly that of a body under the action of gravity only, so that at some test point within the satellite a proof mass will be in free fall under the influence of the earth's gravitational force with no other forces being involved. This state of affairs is to be arranged for by sheltering the proof mass from all other significant forces (e.g., aerodynamic drag, electromagnetic forces, solar pressure, etc.), and then controlling the satellite shell (by gas jets) so that the shell never touches the proof mass. Such a satellite system can be used for a number of purposes, including the testing of instruments where it is advantageous to operate with no supporting forces, the measurement of instantaneous aerodynamic drag and thus of density distribution of the earth's atmosphere, studies of the earth's gravitational field, the control of particular satellite orbits, the measurement of relativity effects, a possible improved measurement of G, and others. Prospective applications of the satellite for various scientific and operational purposes are discussed in detail in Section IIA.

Use of the zero-g satellite to perform "ideal environment"*** tests of inertial instruments is of particular interest to Stanford in connection with the program, started here in 1959, to develop and perform the gyroscope test of the General Theory of Relativity proposed by Prof. Schiff in Ref. (1) and (2).

The experiment to test the General Theory of Relativity using a very accurate gyroscope was conceived at Stanford in the Autumn of 1959. Professor Schiff suggested at that time that if a sufficiently accurate gyroscope could be developed it could be used in an experiment to check the equations of motion in Einstein's General Theory of Relativity. The effect would be produced by the transport of the gyro through the earth's gravitational field. The magnitude of the effect in an earth-fixed laboratory is 0.4 arc seconds per year. Professor Schiff's suggestion was submitted for publication on February 8, 1960, Ref. (1). The same experiment was proposed independently (and unknown to Prof. Schiff) in an unpublished WSEG report in November 1959 by G. E. Pugh, Ref. (3).

Professor Fairbank proceeded to design such an experiment, using a superconducting gyro supported by a magnetic field. His original design included the Mössbauer readout scheme and the use of low temperatures to

* The project name SUZSIE is suggested (Stanford University Zero-G Satellite In-Orbit Experiments).

** Low temperature and zero magnetic field, for example, may also contribute to the "ideal" environment.

achieve dimensional stability and low-noise operation.

Professor Cannon suggested that the chances of success might be greatly enhanced by performing the experiment in an OAO satellite, where the effect would be somewhat larger and the supporting forces would be very greatly reduced, and from which precise astronomical comparison could be made. This concept was discussed with members of the Ames Research Center in the spring of 1961 at a meeting arranged by Mr. R. T. Jones. Stanford formally proposed to develop and perform this general relativity experiment in an OAO satellite in a proposal to NASA dated January 27, 1961, Ref. (4).

In June of 1961 Dr. Nancy Roman organized a meeting of relativity specialists to discuss possible relativity experiments in satellites. The conference was held at Stanford in June 1961, and the Schiff experiment was described at that time, Ref. (5), (6). The project has also been discussed periodically since with Dr. Roman and Mr. Jesse Mitchell.

During the conference the possibility of improving further the operation of the gyro by controlling the satellite so that no support forces on the gyro would be required occurred to Dr. Sherwin, of Aerospace Corporation, and to Mr. Lange of Stanford. This idea is also included in Pugh's report, Ref. (3). Calculations by Lange during the conference indicated the feasibility of such a scheme. Its potential value was also endorsed by Dr. Nordsieck, of General Motors, Santa Barbara. Design studies and error analysis were continued at Stanford during the subsequent year.

It was the general conclusion of the Stanford relativity meeting that the Schiff experiment was important and that the program to develop it should continue, Ref. (5), (6). In August 1961 Prof. Fairbank and M. Bol presented a paper (Ref. (7)), at the National Conference on Guidance, Control and Navigation of the American Rocket Society, in which they described conceptual planning and experimental research accomplished to that time on the Schiff experiment. In particular, experimental results on the use of the Mössbauer effect as a method of indicating the axis of rotation of the gyro were presented. Engineering design of the experiment in an OAO vehicle was reviewed by Prof. Cannon at an International Conference on Gyrodynamics at Celerina, Switzerland in August 1962, Ref. (8). Also pertinent to the development of the Schiff experiment was the discovery by Prof. Fairbank and B. S. Deaver that flux in superconducting material is quantized, Ref. (9). A summary status report on all of the research associated with this program which has been carried out since the original proposal to NASA is in preparation.

Design studies and error analysis on the zero-g, drag-free satellite have been pursued strongly at Stanford since June 1961, and their preliminary results were presented by B. Lange at the Joint National Summer Meeting of the Institute of the Aerospace Sciences and the American Rocket Society in June 1962, Ref. (10), and Mr. Lange has devoted full time to the problem as part of his doctoral research.

The research and design studies on the zero-g satellite and on certain engineering aspects of the gyro relativity experiment have been supported at Stanford since March 1961 by a basic studies grant from the NASA, under cognizance of the Office of Advanced Research and Technology. Work on the satellite program in the Physics Department has not yet required funding from NASA. The program has benefited from basic research in low temperature physics and superconductivity supported by the Air Force Office of Scientific Research, Department of the Army, Army Research Office, Durham, and the National Science Foundation, (This allied research is described in detail in Section III).

It was recognized early in the program that, in addition to its contribution to the gyro relativity experiment, the concept of a satellite tracking a proof mass so that the mass is unsupported, could make contributions to basic studies of inertial instrument behavior, as an engineering development tool. The Electronics and Control Branch of the Office of Advanced Research and Technology have encouraged development of this possibility.

It has also become evident, during the studies since 1961, that such a satellite could be useful for a number of other important scientific experiments, * so that interest has developed in building an early proof-mass satellite, not only as a forerunner of instrument test satellites and of the Schiff experiment, but as a research tool in its own right.

The work on a drag-free satellite has therefore been pursued steadily as a program, and discussions of the scientific potential of such a vehicle have been held with Dr. Robert Jastrow, Director of the Institute for Space Studies, Dr. William Hoffmann and Dr. H. C. Van de Hulst of Dr. Jastrow's group, Mr. William Kaula and Dr. John W. Townsend of the Goddard Space Flight Center, Mr. Jesse Mitchell of the NASA Office of Space Studies, and Dr. Ronald Smelt, Vice-President and Manager of the RIFT program at Lockheed and former manager of the Discoverer program. Discussions of the potential value in instrument experiments have been held over the last two years with Messrs. Jules Kantor, Raymond Bohling, Lawrence Gilcrest, Col. E. Gould, and Dr. Kelley and Dr. Bisplinghoff of the Office of Advanced Research and Technology.

Stanford has received enthusiastic offers of assistance in this program, both professional and material, from a number of aerospace and instrumentation firms, so that the availability of strong support in these areas is assured. Valuable technical discussions have already been held with research personnel at Jet Propulsion Laboratory, Autonetics, Space Technology Laboratories, Grumman, Lockheed MSD, Minneapolis Honeywell, General Electric, General Motors Research Laboratory, Linde Air Products and the University of Illinois.

*

Some of these are also suggested by Pugh in Ref. (3).

II. DESCRIPTION OF ZERO-G SATELLITE PROGRAM

A. APPLICATIONS OF A ZERO-G SATELLITE

Geophysical Measurements

The most obvious scientific application for this type of satellite is to use it to determine the distribution of the earth's atmospheric density by taking advantage of the fact that the satellite control system is at all times ejecting gas with a thrust exactly equal to the total of all non-gravitational forces acting on the satellite. Thus, by metering the gas flow (and knowing its specific impulse) one has a continuous measurement of total drag force. Then atmospheric density can be calculated with an accuracy limited only by knowledge of the other drag forces (e.g., magnetic and solar), and by the accuracy with which the "drag coefficient" is known. Relative variations of density with time and location can be assessed without knowing the drag coefficient. This application has been discussed at length with Dr. Van de Hulst and Dr. Hoffmann of the Institute for Space Studies. Dr. Van de Hulst noted that instantaneous measurements of atmospheric density to 1 per cent accuracy would be of considerable scientific value.* He also suggested that the measurement of the abrupt density change as the satellite passed through an auroral curtain, which could now be measured as a continuous profile, would be very interesting. The instantaneous readings would provide much more accurate information about the change in the shape of the earth's atmosphere with the time of day and, of course, by using a somewhat eccentric orbit the variation with altitude could also be measured on a continuous basis. The characteristics of the auroral curtain were discussed with Dr. Joseph W. Chamberlain of the Kitts Peak Observatory.

Dr. Ronald Smelt has suggested that using the drag-free technique to obtain exact plotting of the drag during perigee passage would contribute significantly to the important problem of predicting the reentry point of a satellite. (Because of the exponential variation of drag with altitude the drag as a function of time tends to be a series of moderately sharp impulses located at perigee.)

In addition, Dr. Smelt observed that the drag-free principle might be very useful in maintaining constant the major axis for vehicles like EGO where very high apogees are very sensitive to drag during perigee.

The possibility of using a satellite in a purely gravitational orbit to improve upon knowledge of the earth's gravitational field was discussed at length with W. Kaula and R. W. Bryant of the Goddard Space Flight Center. While the improvement over the existing knowledge of this field would not be as great as in the atmospheric studies, and would be limited by the accuracy of tracking techniques, the additional data obtainable from a satellite which followed a purely gravitational orbit at lower altitude might still be of considerable interest.

* The alternative of not thrusting, but instead measuring instantaneous satellite deceleration continuously, will probably be easy to incorporate into the zero-g satellite simply by "caging" the proof mass using its sensor signals. The system then becomes a precision, three-axis accelerometer. Provision for switching between zero-g mode and accelerometer mode can be included.

Professor Schiff has suggested that it may be possible, in the zero-g satellite, to make a much more accurate measurement of the value of the universal gravitational constant, G , than is now available. (At present G is known, from the Cavendish experiment, to about one part in 10^5 .) This would make basic knowledge of planetary masses correspondingly more precise.

Inertial Instrument Research

The provision of a low-g environment in a satellite as a means for carrying out advanced tests on inertial instruments is of course a very promising experimental technique. Nearly all of the mechanisms which limit the performance of current gyroscopes, for example, are related to the need for supporting the gyro against the force of gravity. Reducing this force by a factor of 10^5 or so should therefore reduce their effect by a corresponding factor, and allow attention to be focused on other possible mechanisms which may ultimately limit the performance of instruments even in a 1-g environment, and which will certainly be the key factors for operation in satellites and space vehicles.

But beyond this it is postulated that there is even more to be learned about the fundamentals of inertial instrument behavior in an environment where absolutely no support forces are involved, thus removing completely sources of error associated with the existence of a supporting mechanism.

It may be that there are experiments other than instrument experiments which could also be facilitated by the possibility of observing matter in a free-fall state over very long periods of time without having to apply to it any support forces of any sort. One thinks, for example, of studies of the behavior of liquids in such a state over long periods of time.

Relativity Experiments

The use of the zero-g satellite technique to perform the Schiff Relativity Experiment with an unsupported ball is described in some conceptual detail in Ref. (7) and (8). In particular, Fairbank's proposed use of the Mössbauer effect to read out the location of the spin axis of the unsupported gyro is described. A potentially much simpler electromagnetic method of readout is described in Section III of this proposal.

As is pointed out in Ref. (8), the Orbiting Astronomical Observatory is probably the ideal vehicle in which to do the Schiff experiment. The OAO in turn might be controlled as a ball-chasing satellite with little additional difficulty. Possible use of the OAO was discussed with the group at Ames Research Center, and with Mr. Jesse Mitchell at NASA headquarters in 1960, and continuing discussions, particularly with regard to attitude control, have been held with the attitude control groups at the Ames Research Center and at the Grumman Aircraft Company.

As described in Section III, it is planned to construct also a low-temperature environment, including a telescope, gyroscope and readout system. It may also be desirable to test this system in an early, small, zero-g satellite.

Two other relativity experiments have been suggested for which the purely gravitational orbit satellite might furnish required data. One is the so-called "gravitational clock" experiment for measuring any possible rate of change of the universal gravitational constant. In this experiment, suggested by Prof. Dicke of Princeton, Ref. (12), the satellite would be controlled to follow as low an orbit as possible with a purely gravitational path to within one part in 10^{11} , and variations in its orbit from the beginning of a year to the end of the year would be observed for deviations attributable to the change in the value of G over the year. This experiment has been discussed briefly with Prof. Dicke and at considerable length with Dr. Hoffmann, a co-author of Ref. (12). The other relativity measurement would involve noting the precession of the perigee of the satellite in an elliptical orbit and calculating the portion of it due to general relativity (after drag forces have been eliminated, and the effects of earth's harmonics have been accounted for). Both of these experiments seem extremely difficult to do.

Operational Uses

Finally, it is noted that the satellite proposed here could be operated for extended periods at altitudes so low that an ordinary satellite would re-enter due to atmospheric drag. Moreover, the satellite would continue to perform a purely gravitational orbit to a high degree of accuracy. (The operational limitations would be aerodynamic heating, and the amount of gas supply required in the satellite.) In addition to special scientific measurements possible from such a low altitude satellite, it is suggested that the technique might be used to simulate or rehearse the behavior of vehicles orbiting the moon, where there will be no atmosphere.

For example, rehearsals of the lunar landing module synchronous orbit technique might be held from an earth orbit, using the drag-free control technique to make the orbit resemble a drag-free orbit around the moon.

In this lunar landing scheme the LEM vehicle transfers from the Apollo lunar orbit to an inspection orbit with a very low perigee altitude by using thrust only normal to its velocity vector, so that the orbital period is unchanged. Then if the LEM crew elects not to land they will automatically rendezvous with the Apollo ship one orbital period later.

If this technique is rehearsed in an earth orbit, the use of a drag-free guidance scheme could enable the LEM rehearsal vehicle to transfer to an orbit with a lower perigee (limited only by heating and fuel requirements) than would be possible without drag cancellation. Then the effects of initial burn errors could be evaluated experimentally, without the necessity for drag correction, giving crew members a more realistic idea of what to expect in lunar orbit.

Finally, before proceeding to a detailed technical description of the system and of the development program, mention may be made of the possibility of carrying out pre-orbital tests of critical components and techniques in extended ballistic trajectory flights in the X-15 research vehicle. Mr. L. Green, Vice President, Research, North American Aviation, has indicated that his team would be very interested in performing such experiments, and that they would be quite feasible.

Dr. Townsend, of Goddard Space Flight Center, has suggested several possible methods of arranging for the satellite to be boosted into orbit, including piggyback launch on other NASA shots with the Thor Agena vehicle, piggyback launch with a Discoverer package, and launch by a Scout vehicle.

Stanford University feels that sufficient study of the engineering and scientific problems has now been completed to allow a program to be designed, with a first estimate of time and budgetary requirements.

B. DESCRIPTION OF SATELLITE SYSTEM

A conceptual drawing of the drag-free satellite is shown in Fig. 1.* The essential components are (1) the proof mass or "ball", (2) sensors for locating the ball, (3) external gas jets and, (4) a simple computer. In addition there will of course need to be hardware associated with the operation of the gas jets, telemetry, electromagnetic shielding, and possibly an amount of solid hydrogen for maintaining low-temperature operation. There may also be an auxiliary attitude control system in some cases. In others attitude may merely be monitored, by low-grade earth and solar sensors, but not controlled.

As Fig. 1 illustrates, the satellite and all of its parts are conceived of as being completely symmetrical. This is a very important concept because of the necessity for being able to calculate precisely the location of the zero self-gravity point between the ball and the rest of the satellite. (This necessity is discussed in detail in Appendix B and in Ref. (10).) It is also important to have the vehicle externally symmetrical to permit the best possible calculation of atmospheric density from drag measurements.

The proof mass or ball will be a solid or hollow metal sphere. It will be carefully centered in its cavity, and soft bottoming stops will be included for protection during high acceleration at launch.

The sensors shown in Fig. 1 are capacitive pickoffs, which would be the simplest to construct. However, it may be necessary to use an optical method of measurement in order to avoid disturbing capacitive forces between the pick-off and the ball and still have a signal which is sufficiently clean that it can be differentiated once for control purposes, and once more for indication of vehicle acceleration. Details of the pickoff selection are given in Appendix A.

The gas jets will be standard "off the shelf" low-thrust jets, such as are already in operation for attitude control of satellites. The jets are to be operated on-off, and will be on only a small per cent of the time, so that the

* It is estimated that the satellite will weigh between 50 and 100 pounds and have a diameter of about 28 inches.

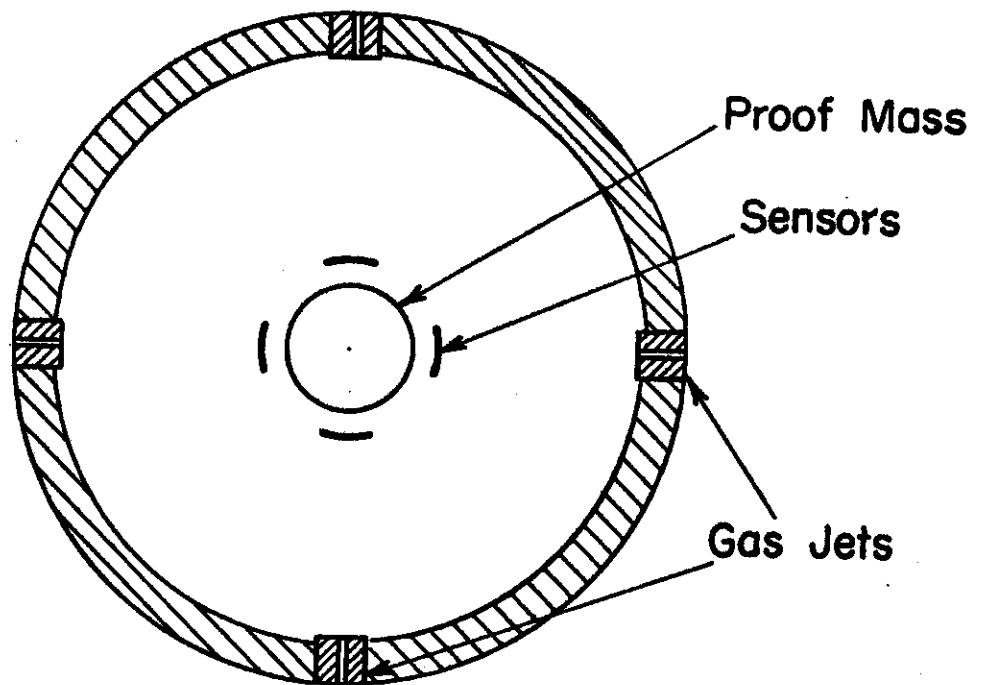


FIG.1 ELEMENTS OF DRAG-FREE
SATELLITE CONTROL SYSTEM

requirement for an extremely low-thrust device for operation at high altitudes is avoided.

Mechanization of the control system will depend upon whether an attitude control system is to be used or the vehicle is allowed to spin. In the latter case the computer may be slightly more complex to provide for "commutation." The control system design concept is discussed in detail in Appendix A.

For the first flight it is expected that the satellite will be used primarily to prove the control system concept and to make geophysical measurements. The only information to be telemetered from the satellite will then be ball location as measured by the sensors in Fig. 1, and, if the satellite is allowed the spin, a continuous indication of satellite orientation, e.g., from simple sun and earth sensors. In flights for testing inertial instrumentation,* precision attitude control of the vehicle and of the instruments relative to the vehicle will also be required. For many of these tests a standard star tracker, such as that to be used for coarse alignment of the OAO, should be adequate.

A preliminary evaluation of the expected performance of the satellite, based upon the above design, and upon assumed values for critical parameters, is given in Appendix B. It is concluded that the most critical disturbance will be gravitational attraction between the vehicle and the ball, and the precision with which the zero self-gravity point can be determined. It is estimated that the system can be so designed that the residual non-free-fall behavior of the vehicle will represent an equivalent force of 10^{-11} g's. Other effects considered have included forces due to stray electromagnetic and electrostatic fields, forces exerted by the sensing mechanism, the effect of gravity gradient forces, and the impingement of cosmic ray events.

C. DESCRIPTION OF SIMULATOR

Before the control system for a drag-free satellite is flown it will be tested on earth under conditions that are as similar as possible to those in flight.

Stanford proposes to develop a very low drag mechanical simulator with two horizontal translational and one rotational degrees of freedom for the vehicle and one vertical degree of freedom for the proof mass, giving an effective four-degree-of-freedom simulation.

Complete freedom to translate and rotate in the horizontal plane will be provided by "floating" the simulation apparatus on a gas film, created by very low-velocity gas jets emitting from the very flat bottom of the simulator against the very flat surface of the fixed base. (Low-accuracy versions of this technique are used by physics lecturers in "air pucks" to demonstrate Newton's laws of motion.)

* Such designation as SUZSIE-A (atmospheric measurement), SUZSIE-I (inertial instrument tests), etc., suggest themselves.

Drag in orbit may be simulated by tilting the table very slightly. Some scaling may be necessary, a drag acceleration of 5×10^{-6} g corresponding to a tilt of one second of arc.

The proof mass will be suspended from overhead on a stiff rod. Vertical motion of the ball can be interpreted as the fourth degree of freedom.

The simulator will be used in conjunction with an analog computer, which will include the dynamics of the other two degrees of freedom, as well as the motions of the rod. It will be necessary to make all connections to the vehicle via a low-power radio telemetry loop.

The complete position control system, including gas jets, ball sensing apparatus, computer, etc., will be mounted and operated in the simulator. The effects of various disturbances and failures can then be evaluated and the results of these tests will be used in the final control system design.

D. SATELLITE DEVELOPMENT PROGRAM

So far as Stanford University is concerned, the value of the scientific information gained from this program must be matched by its value to the academic program, for example in stimulating and supporting graduate students in their doctoral research. To this end, it will be Stanford's basic policy on this program to turn over to groups outside the university those parts of the program which, in our judgment, do not contribute to academic objectives and which should therefore more properly be the business of industrial development groups.

For example, the university will determine the control system design and develop its critical elements, including ball location sensors. But the design and construction of such items as the vehicle frame, computer and telemetry equipment, gas jets and valve system, attitude sensing elements, power supply, etc., as well as their packaging and assembly, will be turned over to a space vehicle development group outside the university with whom Stanford will collaborate closely. This division of activity is indicated in the budget, Section V.

Development of the satellite system can be divided into four major phases, as indicated in Fig. 2. These phases overlap to the maximum degree commensurate with an efficient development program.

In phase I a preliminary design of the control system will be made to determine its quantitative characteristics. This preliminary design will be strongly supported by analysis and computer simulation as required. When the preliminary design is completed, a detailed design of the control system logic and of critical hardware components will be carried out. A physical

simulation facility for testing vehicle-position control systems will be designed and constructed as part of Phase I, and physical testing of control models will be carried out continuously as the prototype and flight models evolve.

Phase II will have the task of determining experimental objectives and from these making preliminary specifications of the vehicle capabilities. Decisions will be made as to what physical quantities to measure, and from these the required orbit, lifetime and data sensing and transmission capability will be determined. The booster will also be selected. It is proposed that these determinations, as well as the choice of the major subcontractor, be made jointly by Stanford and NASA during Phase II.

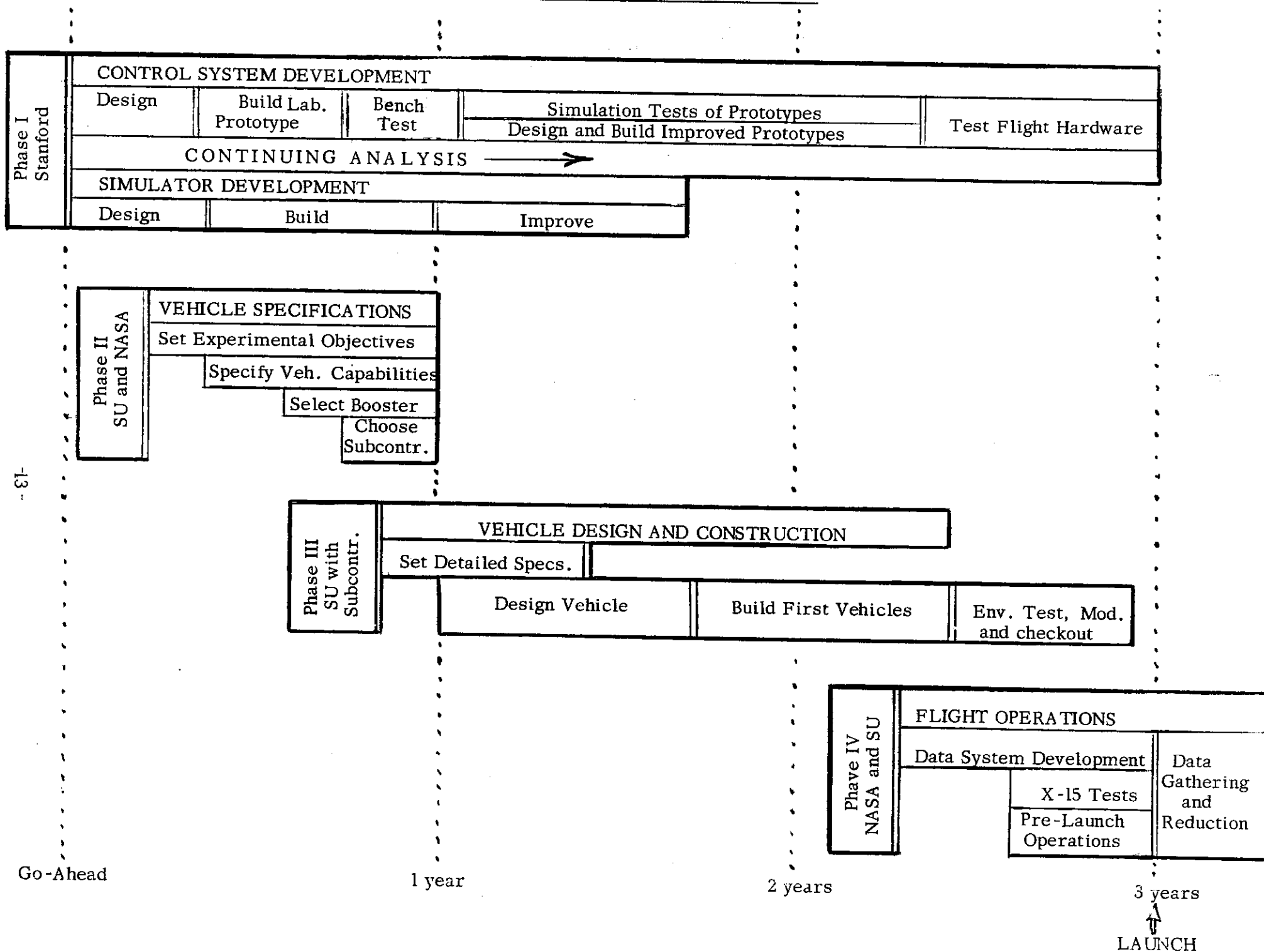
Phase III will begin with the choice of a contractor to build a vehicle and off-the-shelf items of flight hardware. A contractor may also build the flight version of the control system itself, although it is planned to develop the prototype model at Stanford. The determination of detailed vehicle system specs, design of the vehicle system, and construction and testing of the first vehicles would be carried out during Phase III, as shown in the chart. It is proposed that design of the vehicle and its equipment proceed on a joint basis, between Stanford and the contractor, with preparation of a prototype system and of a complete prototype vehicle the first task of Phase III.

The close ties enjoyed by members of the Stanford staff with a number of very experienced space vehicle development companies and laboratories and with makers of inertial instruments, as listed at the end of Section I (Introduction), will greatly facilitate the close collaboration which will be required between Stanford and the subcontractors involved in Phase III.

During Phase III exhaustive checkout of prototype and then flight systems will be made. The vehicle simulator developed in Phase I will be involved in checkout of the control system itself.

Phase IV is intended to include both the preparation for flight and the post-launch evaluation and use of data. It may be desirable to conduct short-term zero-g tests of the system in an X-15 aircraft prior to orbital operation. The orbital data of primary interest to Stanford will be that concerned with the performance of the control system. However, Stanford looks forward to participating closely with NASA specialists in the collection and evaluation of geophysical data.

FIG. 2. SCHEDULE FOR FIRST ZERO-G SATELLITE



III. DESCRIPTION OF PROGRAM

TO PERFORM THE SCHIFF EXPERIMENT IN A SATELLITE

A. PROPOSED RESEARCH

As its share of this research effort the Department of Physics, with Professor W. M. Fairbank as principal investigator, proposes to design and construct with the cooperation of industry a low temperature environment, capable of being flown in a satellite, which will contain a few pounds of solid hydrogen and liquid helium sufficient to keep the inner space within 4°K of the absolute zero for one year. In this low temperature environment an attempt will be made by techniques described later in this section to include an inside working volume with exactly zero magnetic field, completely shielded by a superconducting shell containing no trapped flux. Inside this volume will be placed a superconducting sphere whose position can be sensed and whose axis of spin can be read. An attempt will be made to include a sufficiently simple and sensitive read-out to perform the Schiff experiment in a satellite.

It is an objective of this proposal to incorporate in a zero g satellite this low temperature environment, containing a magnetically field-free region and an unsupported superconducting spinning ball, and to demonstrate the performance of this gyro, using a star-tracker reference.

Eventually it is planned to include in the low temperature environment an approximately 5-inch telescope hopefully capable of observing a fixed star to better than 0.1 second of arc. It is expected that the cooperation of industry would be obtained in the construction of the telescope, the making of the superconducting ball, and the construction of the low temperature environment.

Two new and novel methods of read-out are being explored by us in the Department of Physics at Stanford under research with AFOSR. One makes use of the Mössbauer effect and a spinning cylinder co-moving with the gyroscope. The other utilizes superconducting circuits, developed at Stanford for the detection of quantized flux, to measure directly the spin axis as indicated theoretically by the London moment.

The latter method, if it should prove successful, is particularly appealing for use in a zero-g, zero-magnetic-field satellite due to its inherent simplicity, as will be discussed below.

B. BACKGROUND

Advantages of Low Temperature

It has been our opinion since the original conception of the Schiff experiment that a helium temperature environment offered unique advantages for performing the Schiff experiment to the desirable accuracy of a few hundredths of a second of arc per year. At these temperatures the coefficient of expansion of materials approaches zero, eliminating errors due to small changes in temperature. It is for this reason that we would expect to

include the telescope in the hydrogen-cooled dewar. The creep of a spinning ball is minimized and almost perfect vacuum can be obtained around a spinning ball, and He^4 gas can be introduced and removed merely by changing the temperature of a He^3 refrigerated surface. Thus if there are no electromagnetic losses, a spinning ball could easily be made to spin a year without appreciably slowing down due to gaseous drag. Superconductivity offers a possibility of a perfect magnetic shield as will be discussed below, and will aid in the attainment of a nearly-perfect, zero-g gyroscope.

A spinning, superconducting ball in zero magnetic field theoretically offers a unique method of read-out as will be explained later.

It is our feeling that the experimental demonstration of a flyable liquid helium temperature region will be a contribution to space physics.

Simplicity of Low Temperature Flight Package.

It is estimated that a very simple flight package, insulated with Linde Company super-insulation and containing only a few pounds of solid hydrogen and liquid helium, could be flown for a year in a zero-g satellite. We have discussed this problem with the Linde Company and it is expected that a flyable experimental package of less than 2 feet O.D. could be constructed. We propose to construct this package in cooperation with such an industrial company. Provisions for paying for construction and aid in design of such a flyable dewar are included in the budget of this proposal.

Experimental Significance of Quantized Flux

In 1961, Deaver and Fairbank*, and independently Doll and Nabauer, demonstrated that flux in a superconducting loop is quantized in integral units of $hc/2e = 2 \times 10^{-7}$ gauss cm^2 . This has the immediate experimental consequence that any flux passing through a superconducting shield must be quantized in these units. Thus, theoretically, if a superconducting spherical shell could be cooled down in an external field of less than one-half a flux unit, no trapped flux could pass through the superconducting shield. Thus, in principle, the region inside the superconducting sphere would be completely shielded from all external magnetic flux. Leads could be passed in and out of such a region through open-ended superconducting cylinders.

In the process of detecting quantized flux, a superconducting circuit has been developed which has the sensitivity to detect less than 0.01 unit of flux. In particular, it should be possible to detect less than half a flux unit passing through an arbitrarily large cross-section area. Thus if a superconducting sphere, surrounded by such a detector, is cooled down inside an outer superconducting shield of higher transition temperature, it should be possible to detect the balance of the field inside the outer superconducting shield until less than half a flux unit is passing through the inside spherical shell. If the inside spherical shell is then cooled down below its transition temperature, it is expected that no trapped flux will remain inside the sphere.

It is an objective of this research to build into the proposed low temperature dewar the necessary shields and detection equipment to provide and verify this

* Reference 9.

zero magnetic field region. Such a region offers interesting new possibilities for physics research. All the research in connection with superconducting gyroscopes of which we are aware has been bothered by trapped flux. In addition, trapped flux has appeared as a problem in the design of superconducting accelerators, with which we are also concerned. If a magnetic field-free region can be obtained, it appears to us that many of the problems with superconducting gyroscopes will disappear, and in particular that one can design an experiment combining completely magnetic field-free regions with a zero g satellite to perform in a very elegant way the Schiff experiment. We are at the present time attempting to obtain such a magnetic field-free region.

The Mössbauer Method of Read-Out

Bol and Fairbank have demonstrated with two wheels on a glass-blowing lathe that the Mössbauer effect can be used to detect the direction of the spin axis of a spherical gyroscope with respect to a co-moving spinning cylinder. From these experiments, it is estimated that the axis of the gyroscope can in principle be determined with respect to the axis of the cylinder to 0.01 second of arc. This method is being investigated as part of our basic research program under support by the AFOSR. The possibility of including this read-out in the satellite experiment will be investigated.

The London Moment Read-Out

The London equations predict that the superconducting electrons in the penetration layer of a spinning superconducting sphere will lag behind the lattice, resulting in a surface current which produces inside the sphere, even in the presence of zero external magnetic field, a constant magnetic field parallel to the spin axis of the sphere equal to

$$\frac{2 mc}{e} \omega = 10^{-7} \omega \text{ gauss.}$$

We are at the present time performing experiments under the sponsorship of the AFOSR designed to demonstrate the existence of this moment. Although this moment is very small, it offers the possibility of a particularly simple method of read-out for a spinning superconducting ball in a zero-magnetic-field, zero-g satellite. When combined with the superconducting circuits which we have developed for the measurement of quantized flux, we calculate that it may eventually be possible to read the spin axis of a superconducting ball by means of the London moment to a sufficient accuracy to perform the Schiff experiment.

As we currently envision it, the general relativity experiment in a zero-g satellite would consist of a 5-inch telescope* cooled to liquid hydrogen temperatures. If the London moment method of readout proves feasible, the back of the telescope lens would be connected to a quartz block. The quartz block would contain the superconducting gyroscope inside a spherical copper shell. Detection coils would be evaporated on three right-angle, optically flat surfaces built into the quartz block. Each coil would encompass an equator of the ball and be connected to a

* A very bright star, such as Sirius, can be used as a reference, so that the light-gathering capability of a large telescope should not be required.

a detection circuit. A signal from two of the three coils would give the complete information as to the direction of the axis of the ball with respect to the telescope lens. Thus the relativity experiment would consist of comparing a photoelectric signal made by the image of the star from the telescope with the output signals from the detection coils which yield the orientation of the spin axis of the gyroscope. This detection system has the unique advantage that it requires no marking of the ball and measures the spin axis of the ball independent of how it wanders.

Other Methods of Readout

It may turn out to be preferable to use some other method of readout, such as an optical readout, in this experiment and we plan to keep abreast of developments in other laboratories. We will use a different readout method in performing the Schiff experiment if one is developed which is sufficiently accurate, reliable, and is deemed preferable.

C. SUMMARY

We plan to continue under separate support the basic studies in low temperature physics which will make possible, we feel, the relativity experiment. In addition we specifically propose here to carry out the necessary research to prove the feasibility of the above described experiment, and to develop and perform the experiment in a satellite. Hopefully, this research will enable us (1) to fly a refrigerated region in space, kept cold by solid hydrogen and possibly also by liquid helium; (2) to include in the low temperature region a superconducting ball whose position is sensed magnetically and whose axis of spin is determined by the observation of the magnetic field produced by the London moment; and (3) to compare the direction of this axis of spin with a telescope.

The low temperature environment may very well make more feasible the zero g experiment. Insofar as this may be compatible with the zero g experiment, we propose to include low temperature refrigeration in with the first or second zero g satellite. Our ultimate objective is to perform the Schiff experiment itself in a zero-g satellite. (The satellite may be one developed at Stanford or it may be a version of the OAO.)

We have made this proposal to develop low temperature techniques to perform the Schiff experiment because we believe this environment and the properties of superconductors offer unique advantages to the performance of the experiment to the desired accuracy. It is the purpose of this proposal to carry these ideas far enough to make actual practical tests. This proposal is not meant to preclude the possibility that other developments may prove that some other method is ultimately preferable. However, we regard this as the most promising at the present time.

IV. PERSONNEL AND FACILITIES

PRINCIPAL INVESTIGATORS

(Publications are listed in Appendix C.)

Robert H. Cannon, Jr., -- Associate Professor of Aeronautics and Astronautics

Education

B.S. Mechanical Engineering	1944	University of Rochester
Sc. D. " "	1950	MIT

Experience

Radar Officer	U.S. Navy	'44-46
Hydrofoil Development ("Highpockets" and other Navy craft)	Baker Manufacturing Co.	Summers '47-50
Instructor	MIT	'49-50
Missile Guidance	Bendix Aviation Research Lab.	'50-51
Supervisor, Autopilot Systems Development (F86D, F100, VTOL)	Autonetics Division North Am. Aviation	'50-54
Research Specialist and Systems Engineer, Inertial Navigation Instruments and Systems	Autonetics Division North Am. Aviation	'54-57
Lecturer and Visiting Assistant Professor	UCLA	'55-57
Assoc. Professor of Mechanical Engineering	MIT	'57-59
Assoc. Professor of Aeronautics and Astronautics, and Electrical Engineering	Stanford University	'59---
Consultant, Inertial Guidance and Satellite Attitude Control	Lockheed Missiles and Space Company Space Technology Labs. Space and Information Systems Div., North American Aviation Stanford Research Institute	

William M. Fairbank -- Professor of Physics

Education

B. A.	1939	Whitman
M. S.	1947	Yale University
Ph. D.	1948	Yale University

Experience

Teaching Fellow	University of Washington	'40-42
Staff Member	MIT Radiation Lab.	'42-45
Sheffield Fellow	Yale University	'45-46
Research Assistant in Low Temperature	Yale University	'46-47
Assistant Professor of Physics	Amherst College	'47-52
Associate Professor of Physics	Duke University	'52-58
Professor of Physics	Duke University	'58-59
Professor of Physics	Stanford University	'59---

Special Awards

1961 California Scientist of the Year, awarded by the California Museum of Science and Industry.

1963 Oliver E. Buckley Solid-State Physics Prize, awarded by the American Physical Society.

Professor of Instrumentation

An inertial instrument specialist of the highest caliber, with a record of contributions to satellite instrumentation and control, will be added to the faculty in Aeronautics and Astronautics during the spring of 1963. (Negotiations have not yet proceeded to where the man's name can be given.)

LEONARD I. SCHIFF

Professor of Physics and Executive Head, Department of Physics
Stanford University

Education

- 1933 B.E., Physics, Ohio State University
- 1934 M.Sc., Ohio State University
- 1937 Ph.D., Massachusetts Institute of Technology
- 1937-38 National Research Council Fellow, University of California and California Institute of Technology

Experience

- 1937 (summer) Research physicist at General Electric Company
 - 1938-40 Research associate, physics, University of California and California Institute of Technology
 - 1940-42 Instructor, physics, Univ. of Pennsylvania
 - 1942-44 Assistant professor of physics, University of Pennsylvania
 - 1944-47 Associate professor of physics, University of Pennsylvania
 - 1942-45 Acting chairman, Department of Physics, University of Pennsylvania
 - 1945-46 Staff member, Los Alamos Scientific Laboratory
 - Part-time research physicist with the National Defense Research Committee at Columbia Univ. (1941-45) and at the Univ. of California (1943-44); and with the Navy anti-submarine warfare operations research group (1943-45); February 1952 visiting professor, Iowa State College and Institute for Atomic Research; April 1955 Stewart Lecturer, University of Missouri
 - 1956-57 Visiting professor of physics and Guggenheim Fellow, University of Paris
 - 1955- Chairman Physics Advisory Committee Air Force Office of Scientific Res.
- At Stanford
- 1947-48 Associate Professor of physics
 - 1948- Professor of physics and executive head, Department of Physics

Societies

American Physical Society (elected fellow 1940 councilor, 1953-57); American Association for the Advancement of Science (elected fellow, 1940); Federation of American Scientists (member Administrative Committee 1945-46 and 1947-48, council delegate 1950-53); California Academy of Sciences (elected fellow, 1952); National Academy of Sciences (elected 1957)

Editorial

- 1943-45 Associate editor of Review of Scientific Instruments
- 1945-47 Associate editor of The Physical Review
- 1951-54 Associate editor of Reviews of Modern Physics
- 1950-56 Member, Editorial Board of Physics Today
- 1952- Member, Editorial Committee of Annual Review of Nuclear Science (associate editor, 1953-57; co-editor, 1959)
- 1954- Consulting editor, International Series in Pure and Applied Physics, McGraw-Hill Book Co.
- 1960- Associate editor of Journal of Mathematical Physics

Publications

About 70 research papers and 20 non-research papers, and the following books:
Quantum Mechanics (McGraw-Hill, 1949 and 1955), Italian, Russian, and Japanese translations published; co-author of Our Atomic World (U. of New Mexico Press 1946.)

Recipient of Lamme gold medal, Ohio State University, 1959

Personal data: Born: March 29, 1915, Fall River, Massachusetts
(News and Publications, Stanford 1960-65)

RESEARCH STAFF

Dr. Francis Everitt -- Post-doctoral Research Associate

Education

B.S.	1955	A.R.C.S., London
Ph.D.	1959	D.I.C., London

Experience

Researcher	Physikalische-Technische-Bundesanstalt, Braunschweig, West Germany	'54
Research Associate	Imperial College, London	'58-60
Research Associate and Instructor	University of Pennsylvania	'60-62
Research Associate	Stanford University	'62---

Design Engineer

A first-class designer with experience in designing inertial and electronic instruments for satellites will be added to the full-time staff of the project.

Graduate Students

A major share of work on the project at Stanford will be carried by third-year graduate students.

CONSULTANTS

The following members of the Stanford University faculty are very interested in this project and have offered to contribute their consultation to it.

Dr. Ronald Smelt, Vice-President, General Manager of the RIFT program, former manager of the Discoverer Satellite program, Lockheed Missiles and Space Company.

Dr. John Spreiter, Chief, Theoretical Studies Br., Ames Research Center, NASA.

Dr. Howard Seifert, Professor of Aeronautics and Astronautics, Editor of Space Technology, Wiley 1959 and Ballistic and Space Vehicle Systems, Wiley, '61, and former president of the American Rocket Society.

The combined Guidance and Control and Systems Theory Laboratories at Stanford comprise some nine professors and 65 graduate students engaged in various theoretical and experimental aspects of automatic control. The key professors whose council would be directly available to this project include Prof. G. F. Franklin, a leader in control theory, particularly sampled data and random aspects, Prof. I. Flügge-Lotz, pioneer in contactor control systems research, and Prof. B. Widrow, who is engaged in significant research in adaptive control techniques.

Prof. W. A. Little, of the Physics Department, is also engaged in low temperature physics research and has a personal interest in this program. (Prof. Little made the presentation of the Stanford experiment to the NASA relativity conference.)

In addition to the above people who are directly interested in our project, a large research group with experience in microwave techniques and electron and solid state devices at Stanford will be very helpful in our development of electronic instrumentation, while the Stanford Radio Science group have extensive telemetering and data reduction experience and facilities which will be helpful to this project.

Close cooperation is enjoyed with people at Ames Research Center, with Dr. John Harding at the Jet Propulsion Laboratories and with people participating heavily in satellite programs at Lockheed Missiles and Space Co., Space Technology Laboratories, and with the OAO group at Grumman Aircraft Engineering Company. Helpful and encouraging meetings have also been held with members of the staff at the Institute for Space Studies, and the Goddard Space Flight Center.

FACILITIES

The following digital computing facilities are available:

Stanford Computation Center:

Burroughs 220

Burroughs B-5000 to be delivered by June, 1963

IBM 650

IBM 7090

Systems Lab

IBM 1620 with hybrid connection to 20 amplifier analog machine

A precision machine shop is available in connection with the tube laboratory of the SEL.

Low Temperature Laboratories

A complete low temperature physics laboratory exists at Stanford and auxiliary equipment is available from other experiments. The principal investigator, W.M. Fairbank, is directing related low temperature research involving especially

quantized flux, the London moment, the rotating superconductor, trapped flux, and other aspects of superconductivity which will contribute directly to the development and execution of the proposed experiments. In particular, under sponsorship of the AFOSR, basic research is being carried out with the direct purpose of studying the properties of rotating superconductors, superconducting gyroscopes, novel methods of detection, such as the Mössbauer effect, with the ultimate objective of solving the basic problems related to the Schiff experiment. This research will continue in parallel with the present proposal to build a flyable low temperature environment for the Schiff experiment. Professor W.A. Little is directing a related research effort on superconductivity and other low temperature problems and will be available for consultation on the project.

Proposal Budget Pages 24 and 26 Omitted

The vehicle itself, together with its flight hardware, is to be designed and built by a subcontractor, with Stanford's collaboration. The subcontractor's costs for design and construction are to be added to this budget by NASA, as suggested to Prof. Cannon by Dr. Townsend of Goddard Space Flight Center.

Proposal Budget Pages 24 and 26 Omitted

REFERENCES

1. Schiff, L. I., "Possible New Experimental Test of General Relativity," Phys. Rev. Lett., 4, 215-217, March 1, 1960. Submitted February 8, 1960.
2. Schiff, L. I., "Motion of a Gyroscope According to Einstein's Theory of Gravitation," Proc. Nat'l Academy of Sciences, 46, 871 (1960).
3. Pugh, G. E., "Proposal for a Satellite Test of the Coriolis Prediction of General Relativity," WSEG Research Memo No. 111, November 1959.
4. Fairbank, W. M. and Schiff, L. I., "Proposal for an Experimental Test of General Relativity," submitted to NASA, Office of Space Flight Programs, Attn: Dr. Abe Silverstein, January 27, 1961.
5. Proceedings, Conference on Experimental Tests of Theories of Relativity, Stanford University, July 20-21, 1961.
6. Schiff, L. I., "A Report on the NASA Conference on Experimental Tests of Theories of Relativity," Physics Today, 14, No. 11, 42 (1961).
7. Fairbank, W. M., and Bol. M., "Check of General Relativity Using a Superconducting Gyroscope," presented at ARS National Meeting on Guidance, Control and Navigation, Stanford University, August 1961.
8. Cannon, R. H., Jr., "Requirements and Design for a Special Gyro for Measuring General Relativity Effects from an Astronomical Satellite," invited for presentation at the International Union of Theoretical and Applied Mechanics, Celerina, Switzerland, August 1962.
9. Deaver, B. S., and Fairbank, W. M., "Experimental Evidence for Quantized Flux in Superconducting Cylinders," Phys. Rev. Lett., 7, 43, 1961.
10. Lange, B. O., "Feasibility Study for a Purely Gravitational Orbit Satellite," presented at the IAS National Summer Meeting, Los Angeles, California, June 19-22, 1962, IAS Paper No. 62-111.
11. Lange, B. O., "Application of Contactor Control in a Rotating Reference Frame," to be submitted to the ASME for publication.
12. Dicke, R. H., Hoffmann, W. F., Krotkov, R., "Tracking and Orbit Requirements for Experiment to Detect Variations in Gravitational Constant," Proceedings of the Second International Space Science Symposium, Florence, April 10-14, 1961.

APPENDIX A

CONTROL CONSIDERATIONS FOR DRAG-FREE SATELLITES

Control Techniques

In order to have a drag-free satellite it is necessary to sense the position and velocity of the proof mass or ball with respect to the satellite and to chase it with the satellite. The control system may be classified as either linear or "on-off," and may be used with three-axis attitude control of the satellite or with a spinning satellite. Sensors may use optics or capacitive pickoffs.

A linear control system has certain inherent theoretical and practical disadvantages. Theoretically it uses more fuel than the optimum control, and practically it is very difficult to build linear gas jets (especially where the nominal thrust level is of the order of 10^{-6} pounds). If "on-off" or contactor control is used a drag-free satellite may be constructed with "off-the-shelf" cold gas control jets.

If the vehicle is assumed to have perfect three-axis attitude control to a reference frame which does not rotate in inertial space, the approximate equations of motion can be shown to be (Ref. (10)) :

$$m_B \ddot{\vec{r}}_C = - \frac{m_B}{m_S} (\vec{F}_C + \vec{F}_D)$$

This is equivalent to three uncoupled equations of the form

$$m_B \ddot{x} = f_C + f_D$$

f_D is approximately periodic with the satellite's orbital period, but is assumed constant over one limit cycle. f_C is approximately 10^2 to 10^4 times as large as f_D .

It is shown in Ref. (10) that, because of f_D , limit cycles at the origin do not waste gas if the control is so designed that the jets always act in a direction opposite to f_D . Thus, under this condition the total impulse required can be no greater than $\sqrt{3} F_D T_L$. (The $\sqrt{3}$ arises as the worst case where F_D is not aligned with any of the three control axes.) For a 300-mile circular orbit the mass of control gas needed would be about 1/100 the mass of the vehicle. A linear switching scheme with a dead-band at the origin which would achieve this is described in Ref. (10).

LIST OF SYMBOLS FOR APPENDICES A AND B

m_S	mass of the satellite
m_B	mass of the proof mass or "ball"
\vec{r}_c	position vector of the ball in the satellite
\vec{F}_C	control force applied to the satellite
\vec{F}_D	drag force applied to the satellite
x	x component of \vec{r}_c
f_c	x component of $-\left(\frac{m_B}{m_S}\right)\vec{F}_C$
f_D	x component of $-\left(\frac{m_B}{m_S}\right)\vec{F}_D$
T_L	lifetime of the satellite in orbit
g	earth's gravity (assumed to be 32 ft/sec^2)
ϵ_o	permittivity of free space (8.85 pf/meter)
E_n	electric field normal to the surface of the ball
r	radius of inner cavity containing the ball
w	weight of the ball on earth
a	disturbing acceleration of the ball
q	charge on the ball
E	average electric field at the ball
m_{HB}	magnetic moment induced in the ball
m_{HS}	magnetic moment of the satellite
χ_m	magnetic susceptibility of the ball
μ_o	permeability of free space ($4\pi \times 10^{-7}$ henry/ meter)
H	magnetic field at the ball
B_e	magnetic induction of the earth
V_o	orbital velocity of the satellite
P	total power in irradiating light flux shining on the ball
c	speed of light (assumed to be $3 \times 10^8 \text{ m/sec}$)
V	voltage between capacitive pickoff and ball
v	volume of the ball
A	area of the ball
Z_o	departure of ball from drag free orbit due to acceleration errors
e	eccentricity of orbit
m	mass of the ball
e/m	charge to mass ratio of the electron

R	radius of the ball
I	moment of inertia of the ball
ω_o	mean angular rate of the satellite in orbit
ω_s	spin angular velocity of the ball
ω_D	gyroscope drift rate
ϵ	a parameter used to estimate the magnitude of effects which depend on a lack of spherical symmetry (assumed to be 10^{-5})
σ	electrical conductivity of the ball
B	magnetic induction at the ball
ρ_m	the mass density of the ball

The attitude control system and the position control system can interact due to forces from the attitude jets and due to thrust vector misalignment of the position jets. These interactions may increase the amount of gas necessary over the requirements of attitude control alone plus positions control alone. However, this type of control will probably be necessary for experiments with very precise gyroscopes. The problem can be minimized by careful design. The situation can also be improved by operating the precision gyroscope experiments in orbits of about 500 miles, where the impulse requirements are relatively low.

An alternative to three-axis attitude control is to spin the satellite. This requires that the position jets be commutated at the spin rate, which is reasonable, since commercial gas valves are available with on and off times of the order of 10 milliseconds. Spinning simplifies the attitude control problem and, in addition, all perturbing forces on the ball tend to average except along the spin axis. Perturbing forces which act normal to the orbit plane do not change the shape or size of the orbit, but only the inclination. (The change in inclination corresponds to a position change of less than 10 feet per year for an acceleration of 10^{-9} g and eccentricities of 0.01.) Thus, if the spin axis is controlled to point normal to the orbit plane the effect of perturbing forces is reduced.

The computer associated with the position control of a spinning satellite will be more complicated than for a non-spinning vehicle, but the overall complexity may be less because of the simpler attitude control. A number of position control schemes for spinning vehicles are under study at Stanford. The most complicated system is to measure the spin rate, compute the position and velocity of the proof mass with respect to a non-rotating reference, and fire the jets accordingly. This system has the advantage that no attitude control whatsoever is required, but it is also not possible to point the spin vector normal to the orbit plane.

Current thinking at Stanford favors a simpler spinning system. In this scheme the vehicle is given a preferred spin axis and a passive damping mechanism. The preferred spin axis is controlled to point normal to the orbit plane using either magnetic moments or gas jets. The control error signal and spin rate are read from the output of a horizon sensor fixed in the spinning vehicle. This uncouples the axis parallel to the spin axis and reduces the control of the other two axes to only fourth order. The details of the commutating control of this plant will be described in a forthcoming paper, Ref. (11).

To summarize, the techniques of contactor control can be mechanized to control drag-free satellites with present-day hardware, and it will not be necessary to await the development of very low thrust throtttable engines such as ion propulsion units. The limit cycles associated with undamped contactor control will not waste control gas because there is a minimum amount of gas usage necessary to counteract drag.

Sensors

There are two possible ways to sense the position of the ball with respect to the satellite: capacitive pickoffs and optical viewing.

The ultimate choice between these two systems will be dictated by the tradeoff between the disturbing force on the ball and the signal-to-noise ratio of the position signal, which must be differentiated once to give rate and (hopefully) twice to give acceleration measurements between pulses, which are independent of the jet thrust levels.

The capacitive pickoff is inherently simpler than a photomultiplier system but it may cause excessive forces on the ball. These forces can arise from two mechanisms :

- (1) The sensing electric field of the pickoff exerts a pressure $\frac{\epsilon_0 E_n^2}{2}$
- (2) The very close proximity of the sensing plates makes the ball much more sensitive to image charge which goes as $(\frac{x}{r})^3$ (Ref. (10)).

The capacitive pickoff is the logical choice for a sensor if these two effects are not too large.

If a photomultiplier is used the ball can be placed in the center of a large spherical cavity which is the ideal geometry to reduce gravitational and electric disturbances. Reference (10) describes a position sensing system using a photomultiplier and a cross shaped beam of light. This system can give a signal-to-noise ratio of 10^4 with a disturbing acceleration of 10^{-16} g. The minimum position displacement which can be detected depends on the size of the beam, the signal-to-noise ratio, and the ball's diffraction image; but it is probably of the order of 1 micron for a beam 1.1 times the diameter of the ball. By chopping the light source (e.g., with a vibrating reed chopper) it is possible to use a single light source and to time share the output from a single photomultiplier tube.

If the ball were to be lost by the fine position sensor, its position could be determined grossly in the cavity using a light source and two lateral photoeffect detectors.

APPENDIX B

PERFORMANCE EVALUATION FOR DRAG-FREE SATELLITE

There are several sources of force which can make the proof mass follow an orbit different from that caused by external gravitational forces only. These are :

- (1) Gravitational attraction of the vehicle on the ball (vehicle gravity).
- (2) Electromagnetic forces due to stray and induced charge and magnetic moment on the ball.
- (3) Forces due to sensing the position of the ball. These could be optical radiation pressure or electric attraction from capacitive pickoffs.

The relative magnitudes of these forces are discussed in Ref. (10). In that paper it was assumed that the charge on the ball could be neutralized to about six electrons, or to a corresponding potential of one microvolt. This is still an important unknown. However, before electromagnetic forces become comparable to gravitational forces the charge on the ball would have to be around 10^6 electrons or about 0.1 volts.

Below is a summary of the magnitudes of various disturbing forces. For the assumptions behind these numbers consult Ref. (10).

If the mass of the ball is 10 gms then $w = 10^4$ dynes

Source of Disturbance	Formula	Key Magnitudes	Typical Values (acceleration in g's)
Vehicle Gravity	$\frac{a}{g} \approx 10^{-10} \left(\frac{x}{r} \right)$	$\frac{x}{r} = .1$	10^{-12}
Stray Field in Cavity	$\left\{ \begin{array}{l} \frac{a}{g} = \frac{qE}{w} \end{array} \right.$	$q = 10^{-18}$ coul $E = 1$ volt/meter	10^{-17}
		$q = 10^{-12}$ coul $E = 1$ volt/meter	10^{-11}
Image Attraction of Spherical Cavity for Charged Ball with Zero Stray Field	$\left\{ \begin{array}{l} \frac{a}{q} = \frac{q^2}{w4\pi\epsilon_0 r^2} \left(\frac{x}{r} \right)^3 \end{array} \right.$	$q = 10^{-18}$ coul	10^{-26}
		$\frac{x}{r} = 0.1$	
		$q = 10^{-12}$ coul $\frac{x}{r} = 0.1$	10^{-14}

Source of Disturbance	Formula	Key Magnitudes	Typical Values (acceleration) in g's)
Induced Magnetic Moment	$\begin{cases} F = (m_{HB} \cdot V) H \\ \frac{a}{g} = \frac{3\chi_m m_{HS}^2}{4\pi^2 \mu_o r^7 \rho_m g} \end{cases}$	$\chi_m = 10^{-5}$ $m_{HS} = 1 \text{ amp m}^2$	10^{-20}
Force due to Motion through the Earth's Magnetic Field	$\frac{a}{g} = \frac{q v_o B_e}{w}$	$q = 10^{-18} \text{ coul}$ $q = 10^{-12} \text{ coul}$	10^{-17} 10^{-11}
Radiation Pressure from optical sensor	$\frac{a}{g} = \frac{P}{wc}$	$P = 10^{-9} \text{ watts}$	10^{-16}
Electric force from capacitive pickoff	$\frac{a}{g} = \frac{\epsilon_o V^2}{w r^2} \left(\frac{x}{r} \right) A$	$V = 10^{-3} \text{ volts}$ $A = 10^{-6} \text{ meters}$ $r = 10^{-3} \text{ meter}$ $x = 10^{-4} \text{ meter}$	10^{-15}

For a two hundred and fifty mile orbit a/g due to drag is about 10^{-6} . In the neighborhood of 250 miles this changes roughly one order of magnitude for every 100 miles of altitude. Thus, discounting the effect of solar radiatiol pressure, it appears that for high orbits the shield contributes greater perturbation than atmospheric drag. This is not necessarily the case for two reasons: (1) the average disturbing force is nominally in a fixed direction in space, while drag always opposes satellite velocity, (2) if spin is used the average force can always be normal to the orbit plane where the effects of the perturbing forces are much less. The distance the satellite will move out of the orbit plane due to a normal acceleration is given by

$$Z_o = \frac{e at}{\omega_o}$$

Thus the effects on the orbit of the perturbing forces are not very great. At low altitudes, where the drag acceleration is much larger, the improvement due to drag shielding is correspondingly greater.

High Precision Gyroscopes

Zero-g satellites offer the opportunity of constructing very low drift gyroscopes because the rotor need not be supported. In the absence of support torques, the gyroscope can still be torqued by :

- (1) Gravity gradient torques from the earth and from the satellite itself.
- (2) Electromagnetic torques.
 - (a) Eddy current torques.
 - (b) Circulating currents due to spinning excess charges.
 - (c) Asymmetric excess charges.
 - (d) The Barnett effect.
 - (e) Induced magnetic moments.
 - (f) Asymmetric electric moments.
- (3) Optical radiation pressure torques.

A brief estimate of these torques is reported in Ref. (10). The most difficult effects to calculate are the electromagnetic, because they depend in many cases on the total accumulated charge on the gyro rotor. Below is a very rough order-of-magnitude estimate of each of these effects. Some of the electromagnetic torques are quoted per excess electron. The exact calculation of some of these quantities is being carried out at Stanford at this time.

$$m = 330 \text{ gm} \qquad R = 2 \text{ cm}$$

$$I = 53 \times 10^{-6} \text{ kg meters}^2$$

$$\omega_s = 10^3 \text{ rad/sec}$$

$$\xi = 10^{-5} \qquad 1 \text{ sec arc/yr} \approx \frac{1}{2} \times 10^{-12} \text{ rad/sec}$$

Source of Torque	Formula	Key Magnitudes	Typical Values of ω_D (rad/sec)
Gravity Gradient	$\omega_D = \frac{3}{2} \frac{\epsilon \omega_o^2}{\omega_s}$	$\omega_o = 1.2 \times 10^{-3}$ r/sec	4.5×10^{-14} rad/sec
Eddy Currents	$\omega_D \approx \frac{\sigma B^2 \epsilon}{\rho_m}$	$\frac{1}{\sigma} = 0.1$ ohm meter $B = 2 \times 10^{-5}$ weber/m ²	10^{-17} rad/sec
Circulating Currents due to Spinning Excess Charge	$\omega_D \approx \frac{R^2 q B}{2 I}$	$q = 1.6 \times 10^{-19}$ coul	$10^{-23} \frac{\text{rad}}{\text{sec electron}}$
Asymmetric Excess Charges	$\omega_D \approx \epsilon \left(\frac{a}{g}\right) \times 10^4$ rad/sec	$\frac{a}{g} = 10^{-19}$ / electron	$10^{-20} \frac{\text{rad}}{\text{sec electron}^2}$
Barnett Effect	$\omega_D \approx \frac{5}{2} \frac{\chi_m v H}{R^2 \rho_m e/m}$	$\chi_m = 10^{-5}$ $R = 2$ cm $\rho = 10$ gm/cm	10^{-15} rad/sec
Induced Mag- netic Moments	$\omega_D \approx \left(\frac{a}{g}\right) \times 10^4$ rad/sec	$\frac{a}{g} = 10^{-20}$	10^{-21} rad/sec
Asymmetric Electric Moments	$\omega_D \approx \frac{\epsilon \epsilon_o E_n^2}{\rho_m R^2 \omega_s}$	$E_n = 0.1$ v/m $\rho_m = 10$ gm/cm ³ $R = 2$ cm	2.5×10^{-16} rad/sec

It appears that by careful design (which may include discharging the ball at periodic intervals) that gyroscopes with drift rates limited by gravity gradient torques can be constructed. These instruments would drift at a rate in the neighborhood of 0.1 sec arc/year and would help to spotlight the physical effects which may well limit the performance of future generations of precision gyroscopes.

APPENDIX C. PUBLICATIONS OF PRINCIPAL INVESTIGATORS

ROBERT H. CANNON, JR.

1. "Performance of Hydrofoil Systems," Sc.D. Thesis, M.I.T., June 1950.
2. "Final Engineering Report, Flight and Fire Control System E-7," EM-622 North American Aviation, Inc., 5, April 1954, pp. 63-139. (Contract AF 33(038-20921).
3. "Automatic Control of High-Performance Aircraft," Jnl. Inst. Nav., vol. 4, No. 5, March 1955.
4. "Stable Platforms for High-Performance Aircraft" (with D.P. Chandler) given by Cannon at IAS Annual Summer Meeting, 19 June 1957, Aero. Engr. Rev., vol. 16, No. 12, December 1957.
5. "Platform Stabilization," (with D.P. Chandler) given by Chandler at IRE-sponsored National Convention on Military Electronics, 18 June 1957. Published in Convention Proceedings.
6. "Rectification Drift in Single-Axis Gyroscopes," Jnl. of Appl. Mech., vol. 25, No. 3, September 1958, p. 357.
7. "Vibration Analysis by the Root Locus Method," Proceedings Third U.S. National Congress of Applied Mechanics.
8. "Root Locus Analysis of Structural Coupling in Control Systems," Jnl. of Appl. Mech., vol. 26, No. 2, June 1959, p. 205.
9. Articles on Guidance Systems, Inertial Guidance, Navigation, Control, Missile Guidance, Fire Control Systems, Autopilots, Navigation Instruments, Gyrocompass, Gyroscope, and Schuler Pendulum contributed to Encyclopedia of Science and Technology, McGraw-Hill, 1960.
10. "Methods for the Control of Satellites and Space Vehicles," vol. II, Sect. V, WADD Report 60-643, edited by Roberson, 31 July 1960.
11. "Gyrocompass Alignment of Inertial Guidance Systems," Jnl. Aerospace Sciences, vol. 28, No. 11, November 1961.
12. "Some Basic Response Relations for Reaction-Wheel Attitude-Control Systems," ARS Jnl., vol. 32, No. 1, January 1962.
13. "Gyroscopic Coupling in Space Vehicle Attitude Control Systems," given at Joint Automatic Control Conference, 1961, ASME Jnl. of Basic Engineering, vol. 84, Series D, No. 1, March 1962.

14. "Momentum Vector Considerations in Wheel-Jet Satellite Control System Design," (with D.B. DeBra) given at ARS National Conference on Guidance, Control and Navigation, Stanford University, 1961; Progress in Astronautics and Rocketry, vol. 8, Ed. by Roberson and Farrior, Academic Press, 1962.
15. "First National Conference on Guidance, Control, and Navigation," (with J.S. Farrior), Astronautics, November 1961.
16. "Requirements and Design for a Special Gyro for Measuring General Relativity Effects," invited for presentation at International Union of Theoretical and Applied Mechanics, Celerina, Switzerland, August 1962.
17. "Basic Response Relations for Attitude Control Systems Using Gyros," submitted to International Federation of Automatic Control for presentation at Basil, Switzerland, 1963.

WILLIAM M. FAIRBANK

1. "Second Sound in Liquid Helium II," (with C.T. Lane, H.A. Fairbank), Phys. Rev., 71, 600 (1947).
2. "Second Sound in Liquid Helium II," (with C.T. Lane, H.A. Fairbank, H. Schultz), Phys. Rev., 70, 475 (1947).
3. "The Thermophone as a Source of Sound in Liquid Helium and Liquid Hydrogen," (with H.A. Fairbank, C.T. Lane), J. Acous. Soc. Am., 19, 475 (1947).
4. "Conversion of Ordinary Sound into Second Sound," (with H.A. Fairbank, C.T. Lane), Phys. Rev., 72, 645 (1947).
5. "High-Frequency Surface Resistivity of Tin in the Normal and Superconducting States," Phys. Rev., 76, 1106 (1949).
6. "The Rapid Separation of He^3 from He^4 by the 'Heat Flush Method'," (with T. Soller, A.D. Crowell), Phys. Rev., 91, 1058 (1953).
7. "Temperature Dependence of the Nuclear Susceptibility of He^3 between 1.2° and 4.2°K ," (with W.B. Ard, H.G. Dehmelt, W. Gordy, S. R. Williams), Phys. Rev., 92, 208 (1953).
8. "Fermi-Dirac Degeneracy in Liquid He^3 below 1°K ," (with W.B. Ard, G.K. Walters), Phys. Rev., 95, 566 (1954).
9. "Superconductivity of Millimeter Wave Frequencies," (with C.S. Blevins, W. Gordy), Phys. Rev., 100, 1215 (1955).
10. "The Amplitude Dependence of the Velocity of Second Sound," (with A. J. Dessler), Phys. Rev., 104, 6 (1956).

11. "Phase Separation in Liquid He^3 - He^4 Solutions," (with G. K. Walters), *Phys. Rev.*, 103, 262 (1956).
12. "Nuclear Resonance in Liquid He^3 under Pressure," (with G. K. Walters) *Phys. Rev.*, 103, 263 (1956).
13. "Nuclear Alignment in Liquid He^3 below 1°K ," Proc. of the International Conference on Low Temperature Physics, Paris, 14 (1955).
14. "Liquid Helium Bubble Chamber," (with E. Harth, M. Blevens, G. Slaughter), *ibid.*, 371.
15. "Helium Heat Rectifiers and a Simple Magnetic Refrigerator," (with C. D. Fulton, C. F. Hwang, J. M. Vilas), Proc. of the Cryogenic Engineering Conference, 330 (1956).
16. "A Liquid Helium Bubble Chamber," (with M. E. Blevins, M. M. Block, M. J. Buckingham, E. M. Harth, and C. G. Slaughter), *ibid.*, 330.
17. "Liquid Helium Bubble Chambers," (with E. M. Harth, M. M. Block, M. J. Buckingham, C. G. Slaughter, and M. E. Blevins), *CERN Symposium*, 2, 22 (1956).
18. "Helium Thermal Rectifiers for Magnetic Cooling," (with C. F. Fulton, J. M. Vilas, and V. L. Kenyon), Symposium on Liquid and Solid He^3 , Ohio State University, 135, 1957.
19. "Nuclear Resonance Experiments in Liquid He^3 ," (with G. K. Walters), *ibid.*, 205.
20. "Nuclear Resonance Experiments in Solid He^3 ," (with G. K. Walters), *ibid.*, 220.
21. "Nuclear Resonance Experiments in He^3 - He^4 Solutions," (with G. K. Walters), *ibid.*, 226.
22. "Specific Heat of Liquid He^4 near the Lambda Point," (with M. J. Buckingham and C. F. Kellers), Proceedings of the Fifth International Conference on Low Temperature Physics and Chemistry, University of Wisconsin, 50, 1958.
23. "Helium Thermal Rectifiers," (with C. D. Fulton, J. M. Vilas, and V. L. Kenyon), *ibid.*, 221.
24. "Nuclear Resonance Experiments in He^3 ," (with G. K. Walters), (invited talk), *ibid.*, 86.
25. "Nuclear Alignment in Liquid and Solid He^3 ," (with G. K. Walters) *Nuovo cimento* 9, 297 (1958).

26. "A Liquid Helium Bubble Chamber," (with J. Leitner, M. M. Block and E. M. Harth), Supplement au Bulletin de l'Institut International de Froid, Commission I, Delft, 1958, Annexe 1958-1, 45, 1958.
27. "Nuclear Spin Relaxation in Solid He³," (with J. M. Goodkind), Phys. Rev. Letters, 4, 458 (1960).
28. "Nuclear Resonance in Solid He³," Helium Three, edited by John G. Daunt, Ohio State University, 47, 1960.
29. "Nuclear Spin Relaxation in Solid He³," (with J. M. Goodkind), *ibid.*, 53.
30. "Nuclear Resonance in Solid He³," (with E. Dwight Adams and Horst Meyer), *ibid.*, 57.
31. "Liquid and Solid He³," Proceedings of the VII International Conference on Low Temperature Physics, University of Toronto.
32. "Nuclear Susceptibility of Solid He³," (with Horst Meyer, E. Dwight Adams), *ibid.*, 620.
33. "Nuclear Spin Relaxation in Solid He³," (with J. M. Goodkind), *ibid.*, 625.
34. "Isothermal Flow of Superfluid Helium in 1.1 mm Capillary" (with J. N. Kidder), *ibid.*, 560.
35. "The Nature of the Lambda Transition in Liquid Helium" (with M. J. Buckingham), Progress in Low Temperature Physics, vol. III, Amsterdam, 1961), Chapter III.
36. "Experimental Evidence for Quantized Flux in Superconducting Cylinders," (with Bascom S. Beaver, Jr.), Phys. Rev. Letters, 7, 43 (1961).
37. "Check of General Relativity Using a Superconducting Gyroscope," (with M. Bol), presented at ARS National Meeting on Guidance, Control and Navigation, Stanford University, August 1961.
38. "High Power Superconducting Cavities for Accelerators," (with J. M. Pierce and P. B. Wilson), Eighth International Congress on Low Temperature Physics, Queen Mary College, University of London (1962).
39. "Low Temperature Susceptibility of He³," (with D. H. Cohen, J. M. Goodkind, and E. D. Adams) *ibid.*, 137.
40. "Quantized Magnetic Flux in Superconducting Cylinders," (with Bascom S. Beaver, Jr.), *ibid.*, 238.
41. "Critical Velocities and Boundary Interactions in the Isothermal Flow of Superfluid Helium," (with J. N. Kidder), Phys. Rev., 127, 987 (1962).

Addendum to
PROPOSAL TO DEVELOP A ZERO-G, DRAG-FREE SATELLITE
and to
PERFORM A GYRO TEST OF GENERAL RELATIVITY IN A SATELLITE

Addendum to Section II D:

ZERO-G SATELLITE DEVELOPMENT PROGRAM

This addendum is written to modify the original proposal in accordance with NASA's request that additional time be included at the beginning of the schedule in which to carry out more deliberate feasibility studies and laboratory experiments before beginning the development of flight hardware and of the vehicle itself.

While we subscribe to the philosophy of a more deliberate program of preliminary analysis and laboratory experimental work at the start of the program, before the commitment of funds to vehicle development, we believe at the same time that once flight plans have been decided upon the vehicle development should proceed as rapidly as possible. This is reflected in the attached revised schedule for the first zero-g satellite, which should be compared with Fig. 2 of the original proposal.

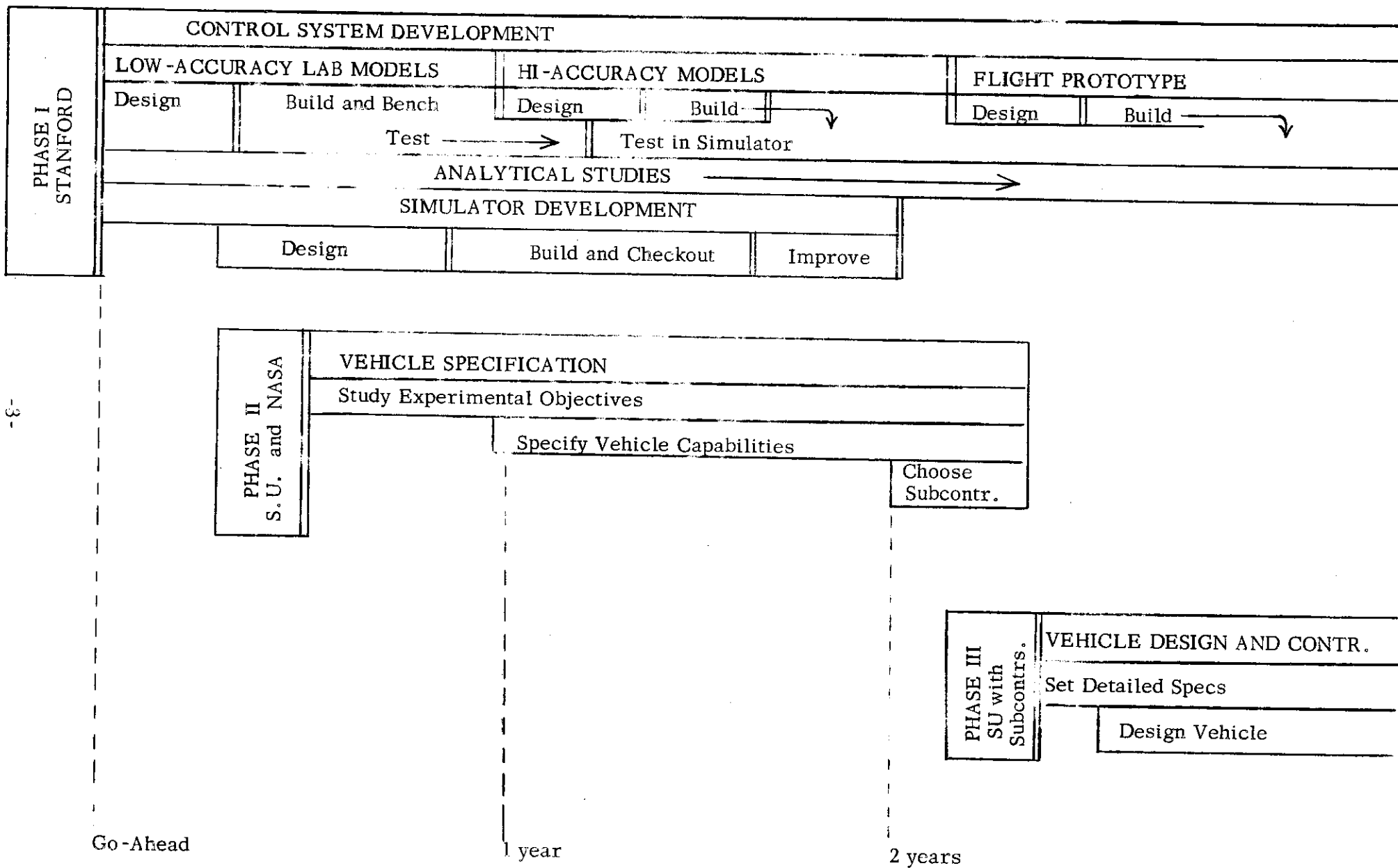
In the revised schedule the times for analytical studies, laboratory experiments, and the study of experimental objectives for the zero-g satellite are all extended to twice their original length. In Phase I the design of a prototype control system is preceded by the design and testing of two laboratory models over a period of two years. In particular, the first year will be spent developing models of low accuracy which will not require the precision design and fabrication of later models.

Development of a physical simulator in which to test control system concepts and, eventually, flight prototype hardware has been greatly slowed down compared with the original schedule.

The philosophy in the new Phase I schedule has been to delay the requirements for (1) a professional instrument designer, (2) the expense of precision machining, and (3) the purchase of measurement and computing equipment for linear-motion simulator experiments until the start of the second year. Expenditures for these items would begin early in the second year. It is emphasized that to delay these expenditures for longer than one year will rapidly bring the whole program to a standstill, since extreme accuracy is the very essence of the whole program and the feasibility of performing the proposed experiments simply cannot be established without the capability to develop and test laboratory model control systems of very high accuracy.

In the revised schedule the start of Phase III is delayed until the early part of the third year of the program -- 18 months later than in the original schedule. From that point on the schedule would proceed just as in the original schedule, with the launch date for the first vehicle 4-1/2 years after go-ahead.

At the outset of the program the major effort will be concentrated on establishing which problem areas will be crucial to the success of the program, and the analytical studies during the first two years will be concentrated on the solution of these problems. This analytical effort, together with the results of experimental work in Phase I and the studies of flight objectives in Phase II, will form the basis for establishing the feasibility of the proposed zero-g satellite experiments.



Addendum Budget Pages 4-6 Omitted