General Disclaimer

One or more of the Following Statements may affect this Document

JUN 1976
RECEIVED
NASA STI FACILITY
INPUT BRANCH

High-Energy Physics Laboratory
W. W. Hansen Laboratories of Physics
STANFORD UNIVERSITY
STANFORD, CALIFORNIA

ANNUAL REPORT FOR THE YEAR 1974 TO 1975

On a Program to

PERFORM A GYRO TEST OF

GENERAL RELATIVITY IN A SATELLITE

AND DEVELOP ASSOCIATED CONTROL TECHNOLOGY

Co- Principal Investigators

W. M. Fairbank, C. W. F. Everitt, D. B. DeBra

Contributors to Report

J. T. Anderson, B. Cabrera, R. R. Clappier,

J. A. Lipa, B. Nesbit, F. J. van Kann,

R. A. Van Patten, P. W. Worden, Jr.

TABLE OF CONTENTS

A. INTRODUCTION

The period November 1974 to October 1975 has seen extraordinary

progress in the Stanford Gyro Relativity program. During the first

half of the reporting period we continued gyro developments in the

main laboratory dewar, concentrating on the operation of a three

axis gyro readout and on improvements to the methods of cancelling

trapped fields in the rotor. In March 1975 these efforts culminated

in the first successful observations of the London moment in the

spinning gyro rotor. We continued work in the laboratory dewar

unitl August 1974 by which time we had accumulated nearly 1,000

hours of gyro testing at liquid helium temperatures at spin speeds

up to 36 Hz.

The London moment observations in March 1975 marked the end of one

phase of the gyroscope development. The painful work described in

last year's Annual Report and in section B below made it abundantly

clear that the field cancellation techniques available for the main

laboratory dewar simply were not good enough. With great labour we

reached fields down to 1.3×10^{-5} gauss; a precise gyro readout needs

fields approaching 10^{-7} gauss or less. Early this year, in fulfilment

of the experiment plan outlines in our July 1973 Request for Continua-

tion we began construction of a Second Gyro Test Facility, which we

initially intended to be a quick turn-around facility for developing

quartz gyro housings. In March, shortly after observing the London

moment, it dawned on us that the right next step in the program would be to modify the function of this facility by incorporating into it an ultra-low field magnetic shield of the "expanding balloon" type, to allow the gyro to be cooled in a field below 10^{-7} gauss. This change of plan, while conceptually simple, has led to radical changes in our thinking and organization. Following a review meeting at NASA Headquarters on March 19, 20, 1975, attended by H. D. Calahan, R. Decher, C. W. F. Everitt, W. M. Fairbank, M. McDonald, R. A. Potter, N. Roman, A. L. Schardt, and others, we formulated a new goal for the laboratory research at Stanford during the next 12 to 18 months, namely, to operate a gyroscope in the new ultra-low field facility with readout resolution approaching 1 arc-second. Details are given in section E .

The London moment work and the development of the new ultra-low field facility have provided the main thrusts of our research this year, but we have done other tasks as follows

1. sputtering work
2. magnetometry
3. construction and installation of the North Star simulator
4. analysis of torques on the gyro, especially in inclined orbits
5. equivalence principle accelerometer
6. analysis of a twin-satellite test of relativity.

In addition to the laboratory experiment we have continued work with NASA and Ball Brothers Research Corporation on the flight program. In November 1974 we submitted to NASA a proposal in

response to AO #6, for Delta or Shuttle launch of a preliminary
relativity experiment with accuracy approaching 0.01 arc-sec/year.
In March 1975 NASA George C. Marshall Space Flight Center issued to
Ball Brothers Research Corporation a modification to Contract
NAS 8-29848 in order to provide cost trade-offs and a Phase A
Study of various possible two-flight programs for the Gyro
Relativity experiment. The Study was completed in October 1975.
The best program appears to be one based on two Shuttle Missions,
the first to be launched early in 1980 on Shuttle 10 with an
accuracy goal of 0.02 arc-sec/year, in a 57° inclined orbit and
the second to be launched about 18 months later in a polar orbit
with a goal of 0.001 arc-sec/year. The overall cost of the program
was estimated at $25 M.

There have been several personnel changes at Stanford during the
current reporting period. One, totally unforeseen, was the tragic
death of John R. Nikirk on March 22, 1975 about two weeks after
the first London Moment observations in which he had played a crucial
part. We have prepared a memoir of John, which reviews his work at
Stanford and which may also serve as a historical retrospective of
some of the work that led up to our observation of the London Moment.
Copies are available along with this report. In January 1975 Dr. B.
Cabrera, who has been responsible for the development at Stanford of
ultra-low magnetic field techniques (See Section D) joined the group
full time. In September 1975 Mr. B. Nesbit joined the group as an
Aeronautics Department graduate student in succession to Dr. D.
Klinger, who left us last year. He is working on ball-coating and
measurement techniques.

B. GYRO OPERATIONS AND OBSERVATION OF THE LONDON MOMENT

In last year's Annual Report we described three methods for detecting
the London moment in a gyro limited by short running time and
appreciable quantities of trapped flux in the rotor. Briefly these were:

1. unbalancing the rotor to make it precess rapidly about the vertical
    axis, while at the same time having trapped flux signals sufficiently
    constant to allow simple subtraction of their d.c. component

2. adding gas to make the rotor spin down rapidly, in which case,
    if there is little precession, the variation of London moment
    with spin speed may be observable,

3. computation and correction for trapped flux utilizing data from
    a three axis magnetometer system.

On March 11 this year we began getting London moment data by a
combination of methods (1) and (2) using data collected from the
three axis readout to prove the stability of the trapped flux signals.

In making the London moment observations we were confronted ultimately
with two serious problems. First, the trapped flux in the rotor had
to be reduced to an acceptable level; second, we had to be wary of
spontaneous increases in flux caused by small discharges from the
suspension plates.

With the three axis readout the London moment can perfectly well be
detected in the presence of a trapped field equal to or larger than
itself, even if the trapped field is slowly varying, provided it has

simple dipole form. The problem comes when the trapped field is non-uniform. When the field in the large dewar was nulled to levels at or below the London moment at 30 Hz, it had gradients which yielded significant components of trapped flux in the ball right up to the sixth harmonic. Not only had we no method of processing such a complex signal, we found also that the strong harmonic content seriously threw off the first order calculation. The proper answer is to greatly reduce the ambient and trapped fields, as we plan to do in the new gyro test facility.

As the field levels were reduced we ran into difficulties with field changes originating in electrical discharges from the suspension. Often activity that was not enough to make the rotor strike the walls would noticeably alter the trapped flux. The underlying cause of the discharging is almost certainly the imperfect quality of the electrodes in the ceramic housing, which has suffered heavy punishment and had many repairs during the last four years. We expect the new quartz housing to be much more satisfactory. For the London moment observation, however, we could do little but wait for quiet periods or shut down for further electrode repairs.

In these circumstances our technique for observing the London moment was to measure the spin speed dependence of the total magnetic moment parallel to the spin axis (which is in general the sum of the London moment and axial components of trapped flux) and

to use transverse flux data to check the constancy of the axial
trapped flux. Doing so required a properly calibrated three axis
gyro readout; this we began building in November 1974.

In principle the three axis readout was a logical extension of the
single axis system that we had previously used, but several small
problems had to be solved before the three axis system worked well.
One was the temperature stability of the SQUID magnetometer. The
single SQUID previously used was attached to the gyro baseplate and
not well anchored thermally to the helium bath. The rf level loop
developed last year corrected the problem to the extent of maintaining
correctly the SQUID rf bias, but we had reason to suspect that the
temperature gradients generated thermoelectric currents and hence
magnetic fields in the damping cylinders, giving rise to readout
errors. We improved the heat sinking of the two new SQUIDs by
attaching their housings directly to the bolt circle of the inner
well of the dewar, and also sought to reduce thermal gradients in
the damping cylinder by applying the dewar-within-a-dewar concept
to the SQUID assembly. The damping cylinder was heat sunk at one
end and surrounded with a simple dewar that isolated the assembly
from external sources of heat. Since there were no significant
heat sources inside the shield dewar, thermal gradients, and hence
thermoelectrically generated fields, were minimized. Thermal
stability of the SQUIDs was substantially improved by these
procedures.

By the end of 1974 we had built three magnetometer electronics
packages with all the necessary circuits for control of the rf box

and with current feedback circuits to read out the magnetic
field. Early in 1975 we installed the two additional SQUIDs and
damping cylinders in the dewar along with all the necessary cables.
Room temperature tests showed that the three rf boxes interfered
electrically with each other, but this problem was easily solved
by grounding them together. Later when the SQUIDs reached super-
conducting temperatures we turned on the magnetometers. They all
worked. This was very encouraging as we had never before run two or
three SQUIDs simultaneously.

The original SQUID was attached to the readout loop wound on the
centering ring at right angles to the parting plane between the two
halves of the gyro housing, identified as channel I of the gyro
readout. For this we applied a special counterwound coil, described
in the September 1974 Status Letter, which had the property of
measuring the full magnetic moment in the gyro rotor but being
nearly insensitive to changes in the ambient magnetic field.
Shortage of time and practical considerations dissuaded us from
applying counterwound coils in the other two readout channels.
We found that when the suspension system was turned on the
performance of magnetometers I and III (the new magnetometers),
sharply deteriorated, because they were using most of their
capability to follow a 20 kHz signal from the suspension, which
greatly reduced their margin for other signals. Tests showed
that all three damping cylinders were working; however the damping
cylinders for channels I and III, being made at a different time

from channel II, had somewhat different characteristics; furthermore for channel II the counterwound coil helped considerably in rejecting 20 kHz pickup. Later tests showed that this coil cancelled changes in the ambient field by a factor between 10 and 25. We tried several techniques to recover from the lack of counterwound coils in channels I and III. We eventually succeeded by applying 20 kHz bucking, i.e. by deliberately injecting 20 kHz signals of appropriate phase and amplitude into the readout channels. We had developed the bucking method 18 months earlier, as explained in the 1973 Annual Report, to cancel large 20 kHz fields, but found it hard to set up and too unstable to rely on. For the small fields now interfering with the magnetometer, however, it worked well, and the three axis readout operated excellently with the gyro suspended.

To facilitate readout of the London moment we added a three channel signal conditioner for the magnetometer outputs. These preprocessing circuits, which were among the last of Nikirk's contributions to the program, separated the readout signal from each magnetometer into d.c. and a.c. components and so produced signals that would with appropriate processing isolate the London moment.

Figure 1 shows the London moment data obtained during an 18-hour run on March 11. The measurements of parallel flux agree with the theoretically predicted spin speed dependence of the London moment to within the 10% accuracy of the sensitivity calibration of the pick up loop. The data cannot be explained away by attributing the variation with spin spped to a variation of the parallel component of trapped flux. No more than 2 or 3% of the observed signal
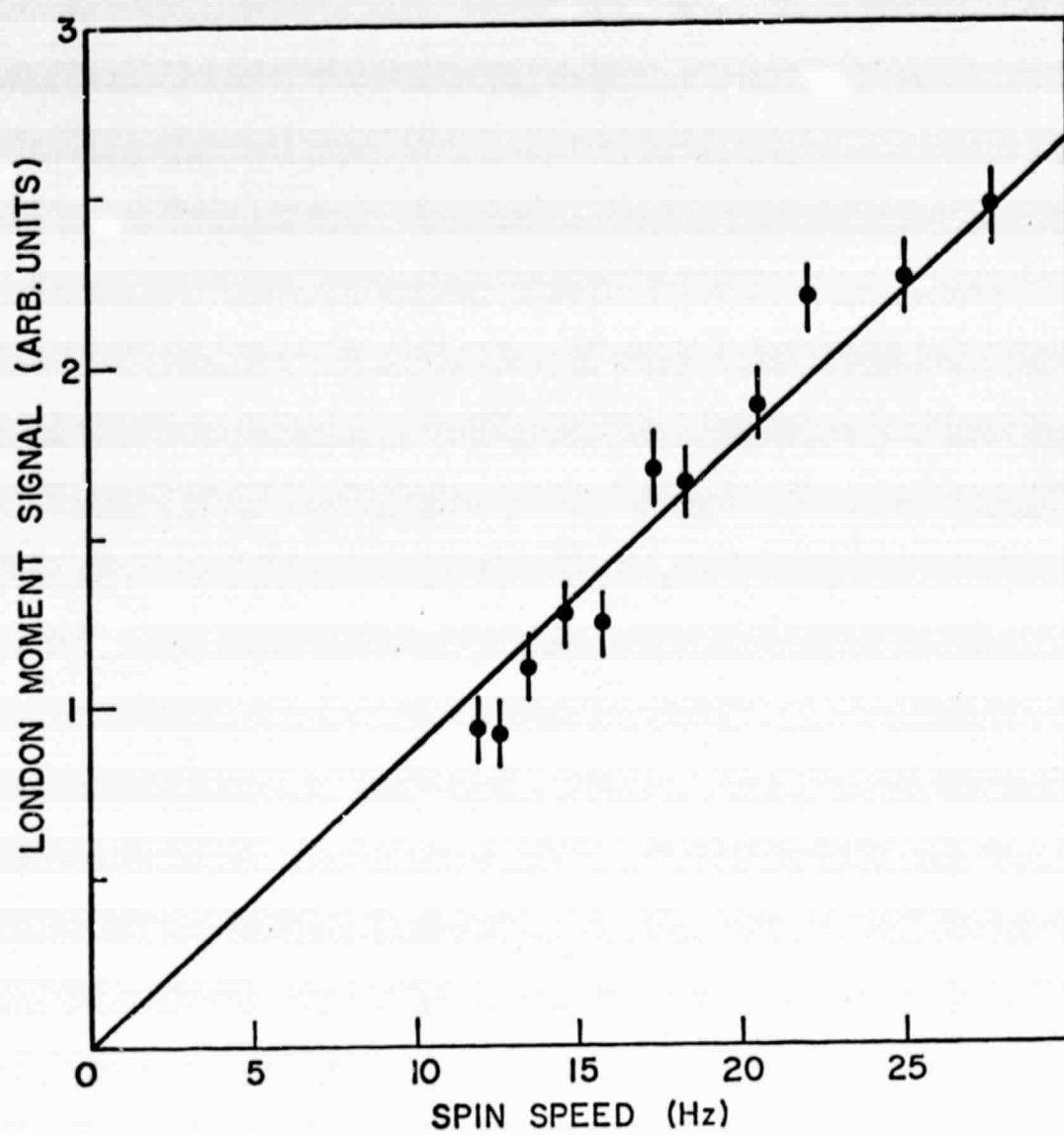
FIGURE 1

at most could be so accounted for. Each data point corresponds to a measurement made when the gyro spin axis was normal to the channel II pick-up loop with low d.c. drift characteristic. There was no detectable change in the trapped flux during the data collection period, either from suspension system activity or any other cause. The trapped flux signal did exhibit a high harmonic content, as has been mentioned: efforts to calculate and subtract out the parallel trapped flux component were not very successful. Hence we have to rely on the constancy of the trapped flux to a greater extent than will ultimately be necessary.

Two extended London moment runs were made in March. Further attempts to get better data in succeeding low temperature runs failed because of excessive suspension noise. We therefore decided to concentrate our efforts on completing an improved gyro housing and building the ultra-low field gyro test facility, described in Section E below.

C. MAGNETOMETRY

The development of improved housings for the SQUIDs and damping cylinders has been described in the account of the three axis gyro readout in Section B. We have also developed a third generation of magnetometer electronics, conducted a survey of improvement to SQUID sensitivity made by other workers in magnetometry, and have purchased a digital computer to process readout data. Work on the

computer is described in section F, together with the new work directed towards making a precision (1 arc-second) gyro readout.

As we have gained experience in using the existing SQUID magnetometers for gyro readout, we have become more aware of what are the important performance characteristics for this task: low d.c. drift, good temperature stability, freedom from pickup, and so forth. We have started to define quantitatively the performance requirements, and have discovered areas where our present magnetometer can be improved. We have therefore designed a third generation magnetometer for gyro readout. The basic design of the existing magnetometer is preserved, but we have made many small circuit changes to improve the drift performance and temperature stability. Changes include a new panel, new control circuits, a new demodulator, and a new feedback card. All but the feedback card have been built, checked out, and reproduced in printed circuit form. The performance of the new circuits looks promising, but extensive testing will be needed to find the degree of overall improvements. The feedback circuit will be built and tested by the end of January 1976. Owing to the severe requirements in precision for these circuits, their design and checkout has taken a considerable effort.

During the past year several workers have made important advances in the sensitivity of SQUIDs. The SHE SQUIDs that we use in our laboratory experiments have an energy sensitivity of about 2.5×10^{-28} joules$/\sqrt{Hz}$. A double Josephson junction d.c. SQUID recently

perfected by Professor John Clarke of the University of
California at Berkeley has an energy sensitivity of about
5×10^{-30} joules/$\sqrt{Hz}$. Double junction SQUIDs have been used
for years by various workers, including ourselves (the ultra-low
field research described in Section D, for example, was done with
one), but Clarke has perfected a thin film double junction SQUID
that is mechanically stable and can be made with a high yield
repeatable process. The new Clarke SQUIDs are robust; their
characteristics remain practically unchanged after months of storage
at room temperature or recycling. They are thought also to have
temperature dependent drifts as low as 5×10^{-9} flux quanta per
degree K, or about 2% of that of the SHE SQUIDs. However the general
stability of the Clarke SQUIDs is not yet so well documented as that
of rf SQUIDs; more information is needed.

The SHE Company has improved the sensitivity of magnetometers
similar to their commercial units by evolutionary changes to
within a factor of five of what Clarke has done. On strictly
experimental magnetometers energy sensitivities better than
Clarke's figures are quoted.

The net result of these improvements, assuming they are as good
as claimed, is that the integration time to resolve 0.001 arc sec
could in favourable circumstances be reduced to about 600 seconds.

D. PRODUCTION OF EXTREMELY LOW MAGNETIC FIELDS

During the past six years under separate support we have developed
techniques for creating regions of extremely low magnetic field by
heat-flushing and expanding series of superconducting balloons. We
are now routinely able to make shields 4 inches and 8 inches in
diameter in which the fields over a length of about 30 inches are
below 10^{-7} gauss. Brief descriptions of this research have been
given in earlier Annual Reports. A complete account of progress up
to January 1975 was given in the docotoral thesis of Blas Cabrera:
"The Use of Superconducting Shields for Generating Ultra-Low
Magnetic Field Regions and Several Related Experiments", which has
been available for distribution since July 1975. Dr. Cabrera also
presented a paper at the LT 14 Conference in Helsinki in August.
Since the work on ultra-low magnetic fields is crucial to the apparatus
for precision gyro readout, it is useful to summarize here the
experience gained so far.

1. Shield Cabling Technique

Once of the special properties of a superconductor is that in most
circumstances the magnetic flux through a closed superconducting
surface is conserved. The goal of the research has been to exploit
this property to create a permanent ultra-low field region by means
of a long sock-like superconductor with zero or extremely low initial
trapped flux. The first idea was to cool a tightly compressed shield

in a low field and then expand it. Since flux is equal to field times area, the increase in area will cause a corresponding decrease in field. A second method of field reduction is by heat flushing. If a temperature gradient is applied along the superconducting sock as it is cooled one end will be superconducting and the other normal, with a transition region somewhere in between. Further cooling will make the boundary more steadily forward, and in suitable circumstances the magnetic field is progressively pushed out of the enclosed volume.

Two opposing mechanisms determine the effectiveness of the heat flushing procedure:

a. As the temperature gradient in the transition region is increased the area going superconducting at any one time will become smaller. Assuming constant ambient field, the flux contained in this area will also decrease with increasing gradient until eventually it is less than half a quantum of flux. At this point no flux can be trapped as the transition region moves from one end of the shield to the other.

b. On the other hand thermoelectric effects in metals generate currents and hence magnetic fields proportional to the temperature gradient across the material. Theoretically it is impossible to generate circulating currents in a conductor having isotropic crystalline structure; however at low temperatures the conductivity of many normal isotropic materials is so high that an anisotropy in the thermopower of only one part in 10^3 or 10^4 is

enough to produce fields larger than the ambient field and hence
interfere with the heat flushing procedure. This anisotropy
originates with anisotropic stresses in the material. Since
thermopower is proportional to temperature gradient, while the
current it generates depends on thermopower divided by the resistance
of the material, the magnetic fields can be reduced by using thinner
materials. An 0.0025 inch lead foil is as thin as is consistent
with our strength requirements.

In achieving absolute magnetic fields below 10^{-7} gauss over large
regions, we have dealt with the tradeoff between the two effects
of temperature gradients partly by applying the heat flushing
technique to a long tightly folded shield, which is cooled through
its transition temperature and expanded to gain the advantage of
the geometrical field reduction already mentioned, and partly by
cooling a series of shields one inside another. The latter pro-
cedure allows the ambient field at the transition region to be
powered in steps, reducing the temperature gradient needed in each
step. In general the applied gradient cannot be allowed to become
smaller than the characteristic temperature fluctuations in the
material, since the fluctuations would generate local superconducting
paths enclosing normal regions, and hence trapping flux.

Our original cooling procedure was a quasistatic one, which involved
bringing the helium level very slowly up around the folded shield
over a 12 hour period, controlling the motion by cutting back the
gas flow and venting through the top of the vacuum tube containing

the shield. More recently we have performed several successful

coolings using a different technique that avoids this time

consuming procedure. In this we have allowed a calibrated helium

gas leak into the vacuum space of the tube, thus providing trans-

verse heat flow along the entire length of the shield. The new

method has three distinct advantages (1) the heat leak along the

entire tube reduces the temperature gradient in the shield and

hence also reduces the gradient induced magnetic fields (2) the

small temperature gradient ensures that the liquid level will not

oscillate, allowing a faster cooling rate, (3) it is no longer

necessary to monitor the apparatus constantly to reduce the gas

flow while preventing oscillations.

2. <u>Magnetic Fields Associated with an Empty Syperconducting Shield</u>

Before a superconducting shield is cooled and expanded the magnetic

field must be reduced to a level below that at which any point on

the surface sees the critical field; otherwise as the shield is

opened flux may penetrate it. In bulk superconductor the critical

field at $4.2°K$ is about 550 gauss, but there are two circumstances

that reduce the maximum allowable external field to much lower

values. For a thin walled hollow shield the first question is

whether the thermodynamic Gibb's free energy is lower if the flux

is excluded (the Meissner state) or penetrates the shield (the

intermediate state). This problem is solved in general for cylindrical

and spherical shields in Chapter 1, section D of B. Cabrera's doctoral

thesis. For an 8 inch diameter lead cylinder of 0.0025 inch wall

thickness, the "effective critical field" above which the field

penetrates is about 14 gauss rather than 550 gauss at 4°K.

If the first condition is met the shield will normally continue to

exclude most of the flux even if nucleation sites exist where H is

greater than H_c. However even local penetrations of the field at

nucleation sites are often unacceptable, so it is desirable to

eliminate their possible formation. Especially critical are the

effects of self-demagnetizing fields near the sharp edges of a

folded or crinkled balloon. Chapter 1, section D of Cabrera's

thesis applies the standard demagnetizing factor for ellipsoids to

estimate fields at a sharp edge and hence calculate a limit on the

ambient field. We have found both empirically and theoretically

that a single Mu-metal shield giving an ambient field of a milligauss

is sufficient to guard against unstable local penetrations as well

as the free energy effect previously discussed. In one instance we

observed an irreversible field penetration occurring in the lower

part of a lead shield transported through the Earth's field (0.5 gauss).

This can probably be attributed to unstable changes initiated by the

self-demagnetizing fields at the sharp edges of the balloon.

Once one has assured that the shield is kept in the Meissner state

there are three major sources and several possible minor sources

of remanent field as follows:

1. Trapped flux in the shield wall is the dominant contribution

to the field until enough shields have been cooled to eliminate it

from the last shield. Our present absolute field sensitivity of 10^{-8} gauss is not enough to ensure getting shields with no trapped flux; however we deduced that in the best shields produced so far there is less than one impaired quantum of flux for every 20 cm^2 of surface area.

2. With a cylindrical shield having an open top the external field comes in through the opening. For uniform fields applied in the axial and transverse directions the residual fields at a distance z below the top are proportional to $e^{-3.83\ z/a}$ and $e^{-1.84\ z/a}$ respectively, where a is the radius of the cylinder. In general the attenuation for any localized magnetic field either inside or outside a cylindrical shield must be at least $e^{-1.84\ z/a}$. We have verified this result to 1% for a half inch diameter shield (see Figure 7.3 of Cabrera's thesis).

3. The fall-off of an external axial field through a small hole in the wall of a crlindrical shield was also studied. The attenuation at the center is approximately proportional to (r/a) where r is the radius of the hole and a again the radius of the cylinder. We have also verified this result qualitatively (see Figure 4.14 and equation 4.26 of Cabrera's thesis).

During prolonged use of the shield substantial amounts of frozen air are condensed as a result of repeated insertions and removals of apparatus from the cold dewar. To check whether the solid air had remanent magnetization we brought a volume of 10cc within 3 cm of the magentometer flip coil, but found it made no measurable difference to the field. Thus although solid oxygen is appreciably

paramagnetic it exhibits no ferromagnetism at 4.2 K.

Two other identifiable sources of field are smaller than we can at present measure. The London moment from the Earth's rotation produces a uniform field of 8.3×10^{-12} gauss. A temperature gradient across a superconductor should also produce magnetic fields if there is any anisotropy. This effect is certainly much smaller than the thermoelectrically generated field in normal metals; however V. L. Ginzberg and others have predicted that it should exist.

3. Fields Associated with Apparatus inside the Shield

Given an ultra-low magnetic field region, what precautions are necessary to avoid field generation in the apparatus that goes inside it? There are three contributions: the remanent magnetization of materials, their susceptibility and thermoelectrically generated fields.

A study of the remanent magnetization of commonly used cryogenic construction materials is reported in Chapter 6 of Cabrera's thesis. Besides the few specimens that clearly exhibit bulk ferromagnetism, many of the common grade materials contain ferromagnetic contaminants in the form of randomly distributed dipoles.

Often trapped flux in the superconducting elements of an apparatus can be the largest contribution to the field. Careful cooling

can reduce this, but the effects of normal metals in the proximity of the apparatus have to be taken into account. We have already described the difficulties caused by thermoelectrically generated fields in our progress towards the London moment observations (section B) as well as their effects on obtaining a low field region (this section). Chapter 5 section D of Cabrera's thesis describes results of one comparison of theoretical and experimental data on this effect, with fairly good agreement.

The susceptibility of the materials becomes significant when stable uniform fields are needed inside a shield. There are two clearly separable cases. Paramagnetic and diamagnetic susceptibilities of normal materials are less than 10^{-5}, so such effects are only important when applied fields are more than 10^5 times the instrument sensitivity. On the other hand a superconductor has a perfect diomagnetism susceptibility of $-\frac{1}{4}\pi$ and its presence can therefore signficantly distort the field. The implications of these results are discussed in Cabrera's thesis.

Progress in ultra-low field technology has gone hand in hand with our ability to measure even smaller absolute fields with the magneto-meter. In fact the absolute sensitivity of our magnetometers has consistently lagged behind our ability to produce better shields. During the past year we have made a factor of ten reduction in the magnetometer background fields by increasing the distance between the aluminum flip coil of the magnetometer and the SQUID with its trapped flux, and by an extensive cleaning of the flip coil housing,

which resulted in the detection and removal of several tiny slivers of nickel plating originating, we believe, in the blades of the jeweler's screwdriver used in assembling the probe. All plated tools are being replaced by titanium ones. The resulting magnetometer background field is now 10^{-7} gauss, allowing us to determine the shield-fields to a sensitivity of 10^{-9} gauss.

We expect to reduce the background field still further by replacing the aluminum flip coil housing by an all fused quartz system. The quartz flip coil is made and will soon be installed. We are also in process of replacing the old double-point contact niobium foil SQUID by an epoxy-cased torroidal SQUID specially constructed for us by SHE Corporation.

E. DEVELOPMENT OF THE ONE ARC-SECOND GYRO READOUT EXPERIMENT

We explained in section A that the successful detection of the London moment in a live gyro during March 1975 ushered in a new era in the Gyro Relativity program. For further improvement in readout accuracy it was clear that the gyro would have to be operated in an ultra-low magnetic field, below 10^{-7} gauss, and that meant a new apparatus. We held a series of group meetings beginning in April 1975 to define a realistic goal for the next phase of operations and to develop a strategy to achieve it. Our conclusion, which was carefully reviewed at the meeting at NASA Headquarters on May 5-8, 1975, was to redefine the purpose of the "second gyro test facility" (the construction of which was already fairly well advanced) and use it to obtain a gyro

with readout approaching 1 arc-second accuracy. To achieve this
goal we find it necessary not only to build a new facility with an
ultra-low field shield, but also to use a quartz rather than ceramic
gyro housing and to have computerized operation and data processing
of the experiment.

1. Design of the new facility

The new facility has to allow reasonably high spin speed of the gyro
(at least 100 Hz) in an ultra-low magnetic field (less than 10^{-7} gauss).
We decided also that the design should be such that the turn round time
between runs is short and that the apparatus should be constructed as
far as possible using known technology and existing or commercially
available components.

We gave considerable thought to the layout of the laboratory. The
requirements to assemble the apparatus at a clean bench and test it
first at room temperature, then liquid nitrogen temperature and finally
at liquid nitrogen temperature poses interesting problems of logistics
and room layout. As Figure 2 shows, the assembled apparatus is mounted
above floor level and is surrounded by electronics and other support
equipment, including the clean bench, protected from dirt in a nearby
alcove. Traditional cryogenic practice is that in a small apparatus
the probe is held fixed and the dewar is raised and lowered around it,
while in larger apparatus the dewar is fixed. After much thought we
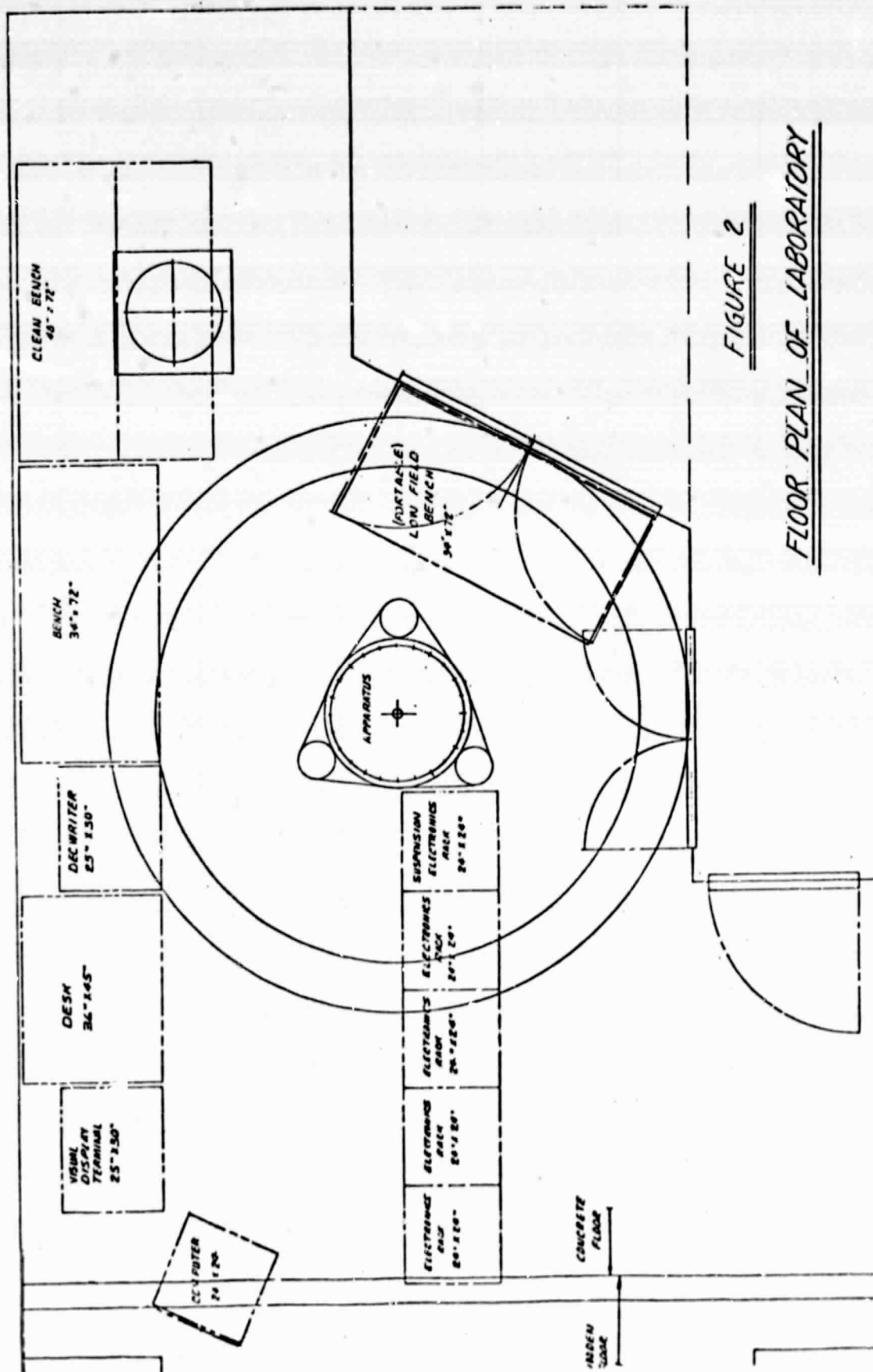
FIGURE 2

FLOOR PLAN OF LABORATORY

concluded it was best to make the dewar movable and the probe fixed in a rigid frame but detachable and transportable to the clean bench.

Figure 3 illustrates the planned apparatus with the assembled probe and dewar. The probe assembly is about six feet long and is bolted with its top plate seven feet above floor level to an aluminum tripod with slightly splayed legs formed from tubular columns over 8 inches in diamter.

The probe vacuum shell consists of three sections, a 3 foot long neck-tube section, a double walled precooling chamber and a main vacuum chamber. The neck-tube is constructed from G-10 low thermal conductivity plastic, and consists of a 6 inch diameter high vacuum pumping line surrounded by several 2 inch diameter tubes which contain all the electrical and other feedthroughs. These tubes are self-contained and readily detachable to facilitate their assembly independently of the probe itself. The precooling chamber at the bottom of the neck section has two main functions : (1) the probe can be precooled by circulating liquid nitrogen through the space between the double walls. (2) It also allows the use of a $7\frac{1}{2}$ inch diameter vacuum chamber to contain the gyro, considerably smaller than the 11 inch overall diameter of the neck-tube, and therefore allows us to use a small diameter of ultra-low field shield. Interconnections between the feedthrough tubes, the gyro
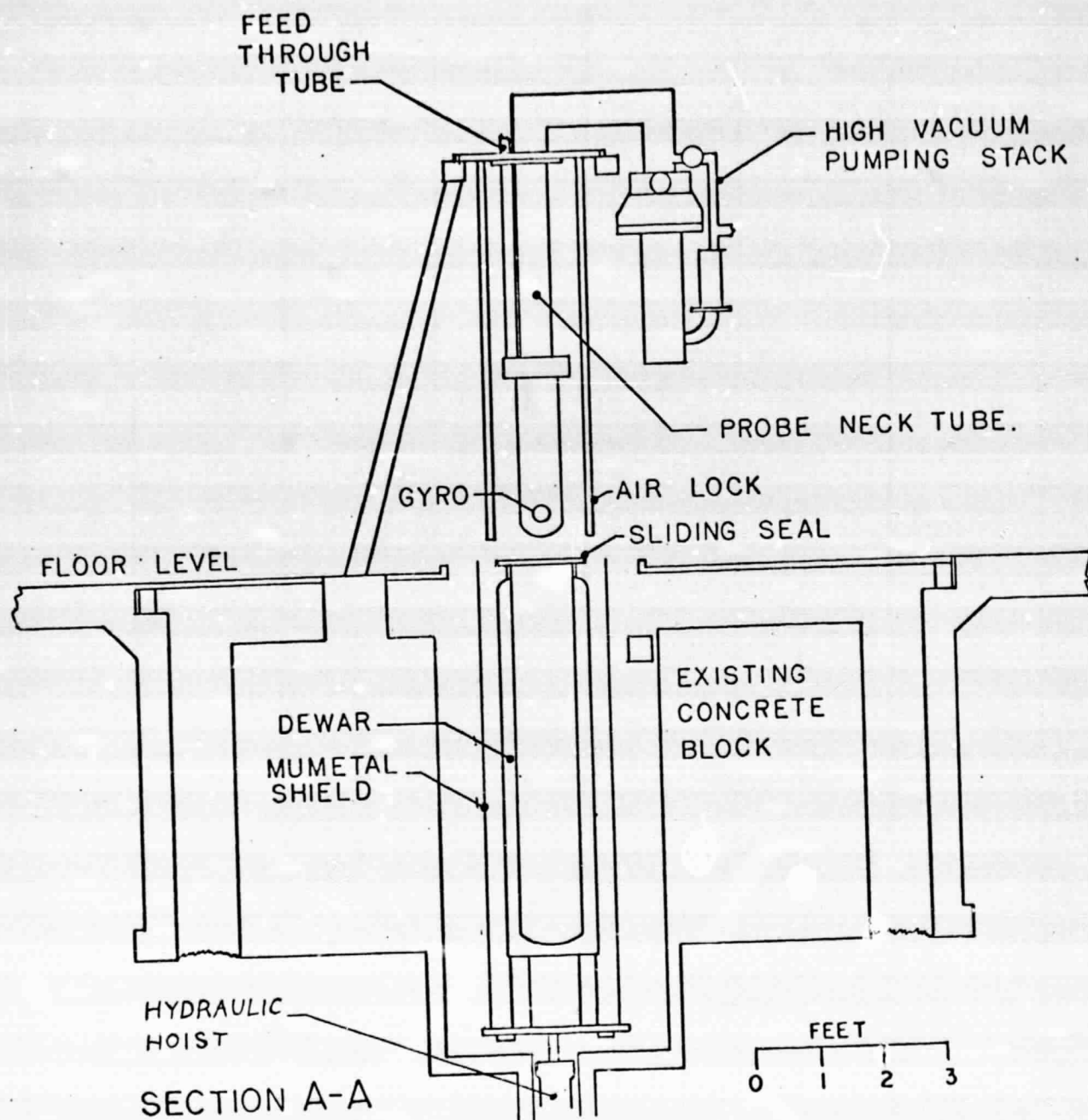
FIGURE 3

CROSS SECTION THROUGH APPARATUS

and the magnetometer are made inside the precooling chamber. The
magnetometers are in separate housings bolted to the bottom around
the vacuum can. Two vacuum cans, about 30 inches long are used
interchangeably with the probe. One is made of pyrex and is used to
get the lowest magnetic field environment. The other is of
aluminum and being more robust is used whenever the field requirements
are not critical.

The gyro is mounted with its center about 4 inches from the bottom
of the vacuum chamber, and with its spin axis aligned parallel to
the earth's polar axis.

A standard 6 inch diffusion pumping system is used to evacuate the
probe. The pumping stand is attached to the concrete floor while the
two elbows are fixed to the probe but are detachable from the pumping
system for transport of the probe to the clean bench. We gave con-
siderable thought to the design of the pumping system. Since the
gyro will spin at high speeds for long periods failure from any cause
such as power or water failure or a breakage of the belt for the fore-
line pump would be catastrophic. To protect against this the 6 inch
diffusion pump, equipped with the appropriate automatic valves, is
backed by an internal sorption pump at helium temperatures inside the
apparatus, which is normally valved off but is available to take over
automatically in the event of any failure of the main pump.

The apparatus is designed to operate with two interchangeable helium dewars of essentially identical form, one of which contains an ultra-low field magnetic shield while the other does not. The dewar assembly consists of a slightly modified Cryogenics Associates model SD-10 dewar, 12 inches in internal diamter, surrounded by two Mu-metal shields and a protective aluminum outer shell. The dewar and inner shield are readily detachable by a bayonet mount mechanism similar to a camera lens. Six Teflon rollers, which slide on three vertical guide rails on the probe frame, are attached to the outer shell. The assembly is raised and lowered by a hydraulic lift, and is accommodated in its lowered position in a hole $3\frac{1}{2}$ feet in diameter and 9 feet deep, bored through an existing 10 foot diamter 5 foot thick concrete pad, located with its top surface a foot below floor level and physically isolated from the building structure. The hydraulic cylinder goes in a further hole 9 inches in diameter and 9 feet deep under the center of the main hole.

The use of two interchangeable dewars has several advantages. The two crucial and sophisticated tasks of preparing the ultra-low magnetic field shield and testing the dewar probe can proceed independently in different laboratories, minimizing schedule conflicts and providing ample time to make a good ultra-low field region (below 10^{-7} gauss). Further when the shielded dewar is not being used with the new test facility it is available for other work, including measurements of remanent magnetizations of probe components. It becomes in effect a "part-time" ultra-low field test facility.

Two Mu-metal shields are used in conjunction with the two dewars. An
outer shield 23½   inches in diameter and 88 inches long, is permanently
mounted inside the outer aluminum shell. In addition the dewar con-
taining the superconducting shield has a 17½ inch diameter 78 inch
long inner shield which provides a 10^{-3} gauss region suitable for
preparation of the ultra-low field shield. When the dewar without the
extra shield is placed inside the aluminum shell the probe can be cooled
down in a field of 10^{-3} gauss for preliminary gyro testing. When the
dewar with the superconducting shield and extra Mu-metal shield is
placed inside the aluminum shell the trapped field in the superconducting
shield itself is 10^{-7} gauss or less, and the leakage fields from the
top are also kept to the same level through the initial reduction of
the ambient field to about 10^{-4} guass by the two Mu-metal shields.
Thus the ambient field at the gyro is reduced below 10^{-7} gauss.

The expanded balloon shield is produced by the techniques described
in section D above. The shield lines an 8 inch inner diameter 40
inch long well mounted in the bottom of the dewar. The shield itself
is constructed of 0.0025 inch pure lead foil with a welded seam. The
use of a 8 inch diameter shield in the 12 inch dewar, together with the
two Mu-metal shields, reduces the leakage field to a negligible level.
It also lets us use the existing paraphernalia for degaussing.

Use of a superconducting shield requires that the helium level in the
dewar be maintained while positioning and removing it from around the
probe. Also air must be prevented from condensing into the dewar,

pressurization for back transferring helium must be possible and the heat leak from the apparatus must be reduced to an acceptable level. These needs are met by an air lock, consisting of a 19 inch internal diameter G-10 tube into which the dewar and inner Mu-metal shield slide on a teflon piston seal, located in a plate attached to the mouth of the dewar. The G-10 tube is insulated by a one-inch thick layer of polyurethane foam on its outer surface. The airlock also acts as a primitive dewar during precooling of the probe and as a protective sheath against physical damage and magnetic contamination during transportation of the probe to the clean bench.

The effective laminar flow area of the clean bench is 47 inch high by 72 inches wide, allowing ample room for all assembly procedures. To facilitate the assembly and disassembly a mounting fixture in the area allows rotation of the probe.

2. Quartz gyro development

The London moment detection work described in section B brought home to us how important completion of the quartz housings was. The ceramic housing which we have worked with for the past four years has three major problems. Its rough surface makes deposition of high quality electrodes difficult; its magnetic properties are very suspect at ambient field levels below 10^{-6} gauss, and the ceramic material makes it difficult to deposit satisfactory superconducting readout rings on the housing. Thus it is imperative to finish depositing the electrodes

and readout rings in the quartz housings manufactured by Honeywell. Work on the new housings has two aspects. We already have the two partially completed quartz housings which appear adequate for immediate needs; in the longer term we are concerned with housings suitable for the final space mission. We want to have the best housing now without compromising requirements for the final design.

The various approaches to gyro design have been fully discussed in earlier reports. The three possibilities are (1) a tumble-lapped housing with inserts to provide the spin up channels and raised lands, (2) a tumble-lapped housing with sputtered quartz lands , (3) a housing in which the primary reference surface is that of the spin up lands and the electrodes are recessed by the techniques developed at NASA Marshall Center. Our present plan is to complete the first Honeywell housing with recessed electrodes to avoid difficulties with the raised lands and then to deposit niobium or niobium/copper for the electrodes. Superconducting electrodes are required to avoid dissipation from the suspension currents which in an earth based gyro leads indirectly to spin down owing to the need for helium exchange gas to get rid of the heat. With the new sputtering hardware described below we expect to achieve a uniformity of deposition equal to or better than the lapped quartz surface. Doing this eliminates the need for further lapping at least in the immediate future. Indeed it may prove good enough for the final mission. Use of the quartz housing virtually eliminates magnetic contaminants, although some uncertainty remains about the affect of the superconducting electrodes and readout rings.

Possibly some undesirable magnetic effects may occur when they go

through their transitions, causing a higher trapped flux in the ball.

Ideally the ball should be coated with a superconductor having a

transition temperature appreciably higher than the outer materials.

In June 1975 the group at NASA Marshall Center began work on recessing

the electrodes in Honeywell Quartz Housing No. 2, for which the

mechanical fabrication was otherwise completed. The work went smoothly,

and the finished gyro was delivered to Stanford on October 7. Tolerances

were within ±50 microinches about the mean spherical surface. One problem

is that the electrodes were plunged deeper than we had wanted, which

means higher suspension voltages and less centering control. However

the discrepancy does not seem critical.

Meanwhile at Stanford we set up a high rate cylindrical magnetron

rf sputtering system to allow us to deposit the electrodes and do

other tasks. The new sputtering system has the best geometry

available to date for obtaining uniform coatings in the housing,

besides its high deposition rate. We hope to achieve uniformities of

±15% or better in depositions on the hemispherical cavity, as

contrasted with ±30% uniformity in the past. The films should then

have tolerances equal to or better than the quartz surface itself,

thus reducing the need to lap the surfaces after deposition. Our

experience is that lapping of a metallized surface can degrade its

properties. We have done some tests verifying the deposition pattern

and are now evaluating the electrical and mechanical characteristics

of the films. The masking fixture for the housing has been built and is ready for installation.

In the course of thinking out our plans with the two Honeywell quartz housings we reviewed the longer term problem of obtaining a housing suitable for the final mission. Of the three methods mentioned above for fabricating the raised spin up lands the only one which has actually been carried to completion is the recessed or plunged electrodes (method 3). This technique has a significant penalty, however. The electrode concentricity and sphericity is appreciably degraded below the level attainable with hemispherical tumble lapping. The tolerances claimed for the method are ±30 microinches; in fact they may be worse owing to nonlinearities in the measuring device. The tolerances for an 0.001 arc-second relativity experiment are ±15 microinches required and ±5 microinches desired. Tumble lapping, on the other hand, gives better results. Tolerances as small as ±5 microinches have been experimentally demonstrated. The chief problem at this level is the alignment and pinning of the two halves of the housing, which have to be very carefully done to achieve 5 microinch accuracy.

Fabrication of the raised ridges by the insert technique was tried some years ago on Quartz Gyro Housing No. 1. The results were close to being successful. The inserts were installed but one has a small chip out of it which we judged (perhaps mistakenly) to be too detrimental to the gas spin up performance. Rework of this part lead to an accident in which it was destroyed. After negotiations which we have

reported elsewhere, Honeywell agreed to try a once through effort to replace the parts at Company expense. The result has been Housing No. 3 which currently awaits the final step of fabricating the spin up channels and raised ridges. The beauty of the insert approach is that the delicate cuts on the ridges can be made on small pieces of quartz with much less investment on them than on the housing, while at the same time the electrode areas can be tumble lapped for optimum finish. Once the inserts are fabricated they have to be installed but the tolerances in this area are less severe than in the electrode areas.

The idea of building up the lands by electroplating or vapour deposition techniques was first tried in 1968. Metallic films cracked off at low temperatures, while sputtered quartz was of poor quality. However technology advances. We decided with the advent of commercially available high rate magnetron sputtering systems to reeaxamine the possibilities in test depositions on flat quartz and glass substrates.

Our attempts at thick film quartz deposition with the new Sloan rf sputtering system were successful. Films of up to 1.9 mils thick were deposited. We encountered significant contamination through flaking off of deposits of quartz on the system anode, but this could easily be solved by inverting the geometry of target and substrate. We subjected the films to abrasion tests and cycling to nitrogen temperatures without noticeable degradation. However after some weeks the test pieces began to fall apart. One had cracked and another was

crumbling along part of its edge. Under the microscope we could see clean fractures right through the film and substrate with no activity at the interface. The effect is puzzling. Stress in the film may have caused delayed fracturing of the substrate; if so one would suspect that the film of deposited quartz is in compression. Further work needs to be done before thick film quartz sputtering can be considered acceptable for the present task. A number of possibilities could be explored. Some improvement in dielectric film properties is reported in depositions using a figher than normal substrate bias. The plasma bombardment causes an appreciable amount of relocation of the atoms after they have been deposited and a reduced collection rate. However substrate heating is expected to be higher. Another technique is to use reactive sputtering with a silicon target. The argon plasma is supplemented with 1 to 5 % of oxygen, enough to oxidize the sputtered silicon and yield quartz. A third possibility is to use the technique for mirror coating of evaporating silicon monoxide, and then oxidizing it to form quartz. Silicon monoxide films are known to be particularly rugged, but are normally much thinner than our requirement.

Development of the precision ball coating equipment has continued. After a lot of trouble with the supplier, the vacuum chamber for the new sputtering rig has been delivered and is currently being installed. It promises to be a very useful system. We developed a program modelling the distribution of material being sputtered on to the rotor and explored possible sequences of deposition angles. With sequential deposition on a stationary rotor the tetrahedral four position sputtering

arrangement is about as good as any. The next step is to investigate the distributions with various rolling sequences. The Rotorond precision measuring device in the Department of Aeronautics and Astronautics has been recommissioned. We will use it to give roundness information on both the metallic coating and the original quartz sphere, in supplement to the precise uniformation obtained with the more sophisticated machines at NASA Marshall Center.

3. Precision Gyro Readout

The goal of a one arc-second readout puts considerably more stringent requirements on magnetometer performance than does just seeing the London moment. The magnitude of the London moment as observed in March 1975 corresponded to a few flux quanta at the magnetometer. A one arc-second readout at 50 Hz spin speed corresponds to about 5×10^{-5} flux quanta.

To meet the high stability requirements we have begun to investigate sources of magnetometer drift. One is the drift in the SQUID which is called out at about 0.05 flux quanta/°K. That alone has specified temperature controlling the SQUIDs to within 0.001 K. Other suspected sources of drift are thermoelectric currents in the damping cylinders, thermoelectric voltages in the feedback lines, drifts in the rf bias level and changes in line turning. Some of these are practically eliminated in the third generation magnetometer electronics; others require detailed testing.

The need for long helium hold times in the new apparatus has dictated the use of low heat leak rf cables for the SQUIDs instead of the relatively high heat leak coaxial cable which we used in the past. The lines must also have low electrical losses, a property usually incompatible with low heat leak. We have found that the heat leak can be brought within acceptable bounds with only minimal electrical losses.

Cryogenic testing of the new SQUID probes will be performed both in a 25 ℓ. storage dewar now being modified to have an enlarged access tube of about $\frac{7}{8}$ inch diameter, and in a 3 inch diameter liquid helium/liquid nitrogen dewar pair to be assembled shortly.

4. Computer

The course of work during the months leading up to the London moment detection made it abundantly clear that the time had come to computerize the laboratory experiment, and the need was crystallized as soon as we decided to develop the one arc-second gyro experiment. The primary tasks for the computer are to (a) gather experimental data, (b) perform some on-line processing, (c) display and record the results, (d) execute some control of the experiment. Secondary tasks include performing similar tasks in a smaller facility for use during the quartz gyro development, certain magnetometry tests and further off-line processing of the stored experimental data. As we investigated

the hardware requirements to perform these tasks several things
became clear. We needed a fairly comprehensive analog input/output
system; we should have a disk operating system to facilitate data
file maintenances and development of programs; and we should have
a system that supports high level programming languages to allow
programming without consuming too much time. After reviewing
numerous systems that met these objectives we finally chose a Data
General Nova 2/10 with a 10 megabyte disk and a good disk operating
software system. To communicate with the computer we bought a DEC
writer, which is a high speed keyboard/printer device. We have bought
the computer and the disk, assembled them in a cabinet and connected
them to the DEC writer for testing, but have not worked on any
applications programs. We have not, as of November 1975, decided on an
analog input/output system but an adequate one can be purchased from
Data General or from other manufacturers, or we can build one in-house.
A decision will be reached in January 1976.

5. Summary of progress and schedule on the one arc-second gyro
   readout experiment, as of November 1975

At the time of the redefinition of the second gyro test facility,
the dewar, two Mu-metal shields and most of the components of the
neck-section of the probe were already in existence. The following
list summarizes the progress through November 1975.

i.) The concrete work, including the main dewar hole, the hydraulic cylinder hole, and an additional hole for use in assembly work, has been completed.

ii.) Laboratory preparations, including fabrication of a false floor above the concrete pad, and painting the entire laboratory to minimize dust contamination, has been completed.

iii.) The clean bench has been specified, ordered, delivered and installed.

iv.) The hydraulic lift system has been designed and ordered and several components have been delivered.

v.) The probe frames including tripod, guide rails and probe level and rotational adjustment fixtures have been designed, and critical materials ordered.

vi.) The second 12 inch dewar together with an 8 inch helium well insert, has been ordered. Delivery is expected to take place in January.

vii.) The outer aluminum shell has been designed, contracted out and delivered.

viii.) The design of the Mu-metal shield has been modified for use with the second ultra-low field dewar, and the additional piece has been ordered.

ix.) The fixtures for the dewar and Mu-metal shield assembly, including the bayonet mounts for both dewars, have been designed and fabricated.

x.) The airlock has been designed.

xi.) The sliding seal for the airlock has been designed and the Teflon 0-cup sealing ring has been ordered.

xii.) The 19 inch diameter G-10 tube which forms the cylindrical
surfaces for the sliding seal has been ordered and delivered.

xiii.) The probe vacuum shell has been designed, and all components
are either fabricated or on order.

xiv.) The main pumping line for the neck-tube has been assembled
and leak check at room temperatures.

xv.) The pumping line elbow which attaches to the neck-tube has
been fabricated and leak checked.

xvi.) The precooling chamber has been designed and built.

xvii.) The $1\frac{3}{4}$ inch diameter G-10 tubes originally ordered for the
feedthrough tubes were found to be not leak tight. Replacements
have been ordered from another manufacturer.

xviii.) The pyrex vacuum can has been designed and ordered.

xix.) The aluminum vacuum can has been designed and all parts ordered.

Figures 4 and 5 are the schedule and work density chart covering the
major thrust of our effort in the laboratory. These figures do not
tell the full story but they have been helpful in improving our
efficiency and smoothness of running. On the broadest scale we are
folding about six man years of effort into essentially 10 months, and
spreading the tasks over a dozen contributors. Considering the
elaborate operation involved the work is going very smoothly. It is
too soon yet to predict the progress but an August completion date
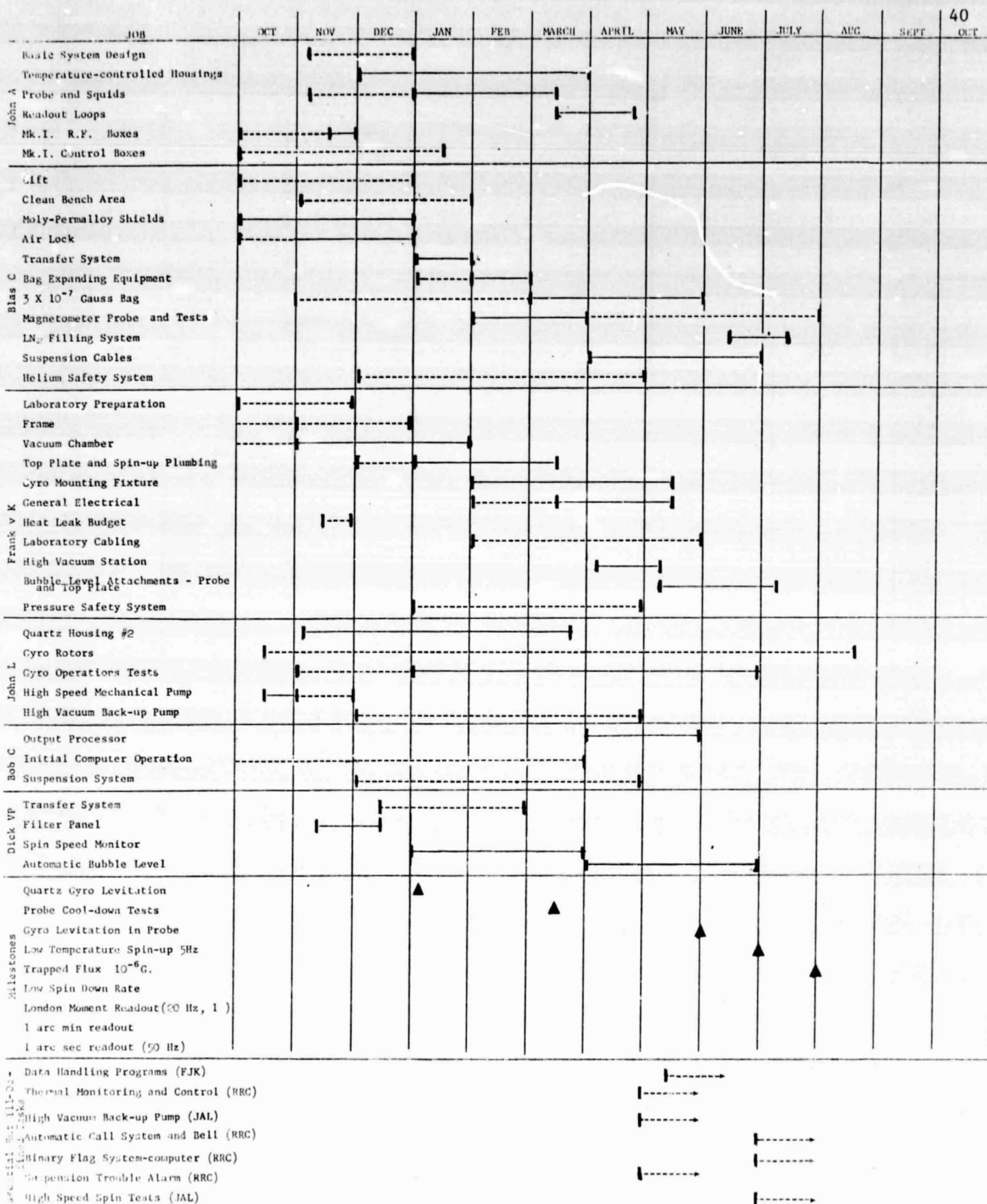looks reasonable.

JOB	OCT	NOV	DEC	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT

John ?
- Basic System Design
- Temperature-controlled Housings
- Probe and Squids
- Readout Loops
- Mk.I. R.F. Boxes
- Mk.I. Control Boxes

Blas C
- Lift
- Clean Bench Area
- Moly-Permalloy Shields
- Air Lock
- Transfer System
- Bag Expanding Equipment
- 3 X 10⁻⁷ Gauss Bag
- Magnetometer Probe and Tests
- LN₂ Filling System
- Suspension Cables
- Helium Safety System

Frank V K
- Laboratory Preparation
- Frame
- Vacuum Chamber
- Top Plate and Spin-up Plumbing
- Gyro Mounting Fixture
- General Electrical
- Heat Leak Budget
- Laboratory Cabling
- High Vacuum Station
- Bubble Level Attachments - Probe and Top Plate
- Pressure Safety System

John L
- Quartz Housing #2
- Gyro Rotors
- Gyro Operations Tests
- High Speed Mechanical Pump
- High Vacuum Back-up Pump

Bob C
- Output Processor
- Initial Computer Operation
- Suspension System

Dick VP
- Transfer System
- Filter Panel
- Spin Speed Monitor
- Automatic Bubble Level

Milestones
- Quartz Gyro Levitation
- Probe Cool-down Tests
- Gyro Levitation in Probe
- Low Temperature Spin-up 5Hz
- Trapped Flux 10⁻⁶G.
- Low Spin Down Rate
- London Moment Readout (20 Hz, 1)
- 1 arc min readout
- 1 arc sec readout (50 Hz)

- Data Handling Programs (FJK)
- Thermal Monitoring and Control (RRC)
- High Vacuum Back-up Pump (JAL)
- Automatic Call System and Bell (RRC)
- Binary Flag System-computer (RRC)
- Suspension Trouble Alarm (RRC)
- High Speed Spin Tests (JAL)

FIGURE 4

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	TOTAL
J. Anderson	4	14	24	22	21	16	3	2				106
B. Cabrera	20	28	31	20	30	20	26	26	18	8		227
R. Clappier	19	21	30	26	23	19	21	19	6			184
J. Lipa	7	24	26	30	30	26	28	24	21	2	2	220
F. van Kann	20	27	20	20	15	14	24	16	9	4		169
R. Van Patten	5	5	8	13	10	8	16	14	8			87
J. Gilderoy, Jr.	18	23	14	18	15	15	15	10	9			137
B. Nesbit	1	10	10	10	10	10	10	10	10	10	1	92
W. Holding	8	14	11	9	7							49
G. Jones	4	6	16	16	8	6	16	14	8			94
R. Hacker	5	6	6	2	2		4	3	3	3		34
Machine Shop	4	11	13	21	22	11	5	4	4	2		97
Outside	6	7	1	2			1	1				18

WORK DENSITY CHART FOR ULTRA-LOW FIELD GYRO TEST FACILITY 1975/76. (Entries are in units of man-days.)

FIGURE 5

APPENDIX I :   THE EQUIVALENCE PRINCIPLE ACCELEROMETER

Work on the Equivalence Principle Accelerometer has proceeded steadily
under funding from a Grant from the Caltech President's Fund.

Most of the first half of the year was spent taking data on the
performance of the inner levitation cradle, and on the non-performance
of the outer levitation cradle. The inner cradle performs pretty much
in accordance with the design. The sensitivity as an accelerometer is
at present adjustable in the range 10^{-7} to 10^{-8} cm/sec^2. We expect
this number to improve considerably when the control system for the
test masses is finally completed. Attempts to apply the controller
to the inner test mass were vitiated by instabilities from coupling
between the control coils and the position monitoring circuitry. The
attenuation between the control signal and position monitor was about
120 db, but this was not enough; at least another 20 db attenuation
is needed.

By June 1975 we had decided that the problem with the outer levitation
cradle was from one of two causes. Either the test mass was jammed in
place or there was too much flux penetration. On opening the probe we
found that the levitation coil has split away from its supports and
was pinching the test mass. There was no choice but to rewind the coil.

While rewinding the coil we decided to modify the probe slightly to be able to disassemble and reassemble it more quickly than the minimum of two weeks perviously required. The whole operation now takes 2-3 days excluding warm-up time. The new levitation coil was completed in October. A trial run gave no spectacular results.

The experiment is now inactive until P. W. Worden, Jr. finishes his Ph. D. thesis. Although the apparatus is not yet fully operational, we have gained one nice result through performing an equivalence principle experiment in which the Earth serves as one test body and the inner test mass as the second body, both falling towards the sun. The two bodies obey the equivalence principel to the limit of 1 part in 10 so far achieved in the experiment. A very interesting feature of this particular experiment is that if the accuracy can be improved another four to five orders of magnitude it will supply a test whether the gravitational binding energy of the Earth is equivalent to inertial mass. This feature of experiments using the Earth as a test body was recently pointed out by a group of Russian workers, N. I. Kolostnitsin, V.M. Myheev, A. V. Osipova, and K. P. Stanyukovich of the USSR State Standards Committee in Moscow, who proposed a much more awkward way of doing the experiment. We are not yet sure whether the accuracy of a measurement relative to the Earth can be pushed that far, since seismic noise is a problem, but we are going to try.

APPENDIX II: A NEW TEST OF GENERAL RELATIVITY

WITH COUNTER-ORBITING DRAG FREE SATELLITES.

During the past two years R. A. Van Patten and C. W. F. Everitt
have conceived a new test of General Relativity based on observations
with two counter-orbiting polar drag-free satellites. Papers describing
the work have been accepted for publication in Celestial Mechanics
and Physical Review Letters. The proposed experiment measures the
Lense-Thirring nodal drag of the orbit plane of the two drag-free
satellites, due to the Earth's rotation, an effect which should be
distinguished from the Schiff motional precession of a gyroscope
orbiting the Earth, which is sometimes (wrongly) call the Lense-
Thirring effect. The Lense-Thirring drag is given by the formula

$$\dot{\vec{\Omega}}_{LT} = \frac{2I\omega}{c^2 a^3 (1 - \underline{e}^2)^{3/2}} \vec{n}^{(2)}$$

whereas the Schiff motional precession, which measures the spin-spin
coupling between the Earth and a gyroscope is given by

$$\dot{\vec{n}}_M^{(1)} = \frac{I\omega}{2c^2 a^3 (1 - \underline{e}^2)^{3/2}} \left[\vec{n}^{(2)} \wedge \vec{n}^{(2)} + 3(\vec{n}^{(2)} \cdot \vec{n})(\vec{n}^{(1)} \wedge \vec{n}) \right]$$

where G is the gravitational constant, c the velocity of light
I the moment of inertia and $\underline{\omega}$ the angular velocity of the Earth, R
the orbit radius, and $\underline{n}$, $n^{(1)}$, $n^{(2)}$ are unit vectors describing
repectively the directions of the orbit plane, the Earth's axis and
the gyro spin axis. It is interesting to notice that the Lense-
Thirring drag is independent of the orbit inclination. The

magnitude of the Lense-Thirring drag in low orbit about the Earth is approximately 0.2 arc-sec/year.

The essential idea of the experiment is the analogy between an orbiting satellite and a gyroscope. The satellite may be thought of as a kind of global gyro. If a satellite is drag free the ordinary inertial torques on it are extremely small, and the only important residual torques are those from the Earth's quadrupole and higher order mass moments, and the gravity gradient torques from the sun and the moon.

It turns out to be impossible to measure the Lense-Thirring drag with a single drag-free satellite but relatively easy to do so with two nearly coplanar counter-orbiting satellites since the uncertainties in the various perturbations tend to be nearly equal and opposite for the two "global gyros". In addition to precision tracking data from existing ground stations the experiment uses satellite-to-satellite Doppler ranging data taken at points of passing near the poles to yield an accurate measurement of the separation distances between the two satellites. Very precise new geophysical information on both Earth harmonics and tidal effects is inherent in the polar ranging data. A detailed covariance analysis is now being performed by D. Schaechter and J. V. Breakwell. Preliminary results are very encouraging.