High-Energy Physics Laboratory

W. W. Hansen Laboratories of Physics

STANFORD UNIVERSITY

STANFORD, CALIFORNIA

ANNUAL REPORT FOR THE YEAR 1973 TO 1974

On A Program to

PERFORM A GYRO TEST OF

GENERAL RELATIVITY IN A SATELLITE

AND DEVELOP ASSOCIATED CONTROL TECHNOLOGY

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Submitted to the National Aeronautics and Space Administration

by the

W. W. Hansen Laboratories of Physics

and the

Department of Aeronautics and Astronautics

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Stanford, California 94305

November 1974

<u>TABLE OF CONTENTS</u>

A. INTRODUCTION

The period November 1973 to October 1974 has been one of solid progress for the Stanford Gyro Relativity program. Since the first low temperature spin tests of the quartz gyro rotor in June 1973 we have concentrated a large effort on gyro operations and gyro readout development We have now accumulated about 400 hours of gyro testing at liquid helium temperatures with spin speeds up to 30 Hz. Readout by observing trapped magnetic flux in the spinning rotor by means of the sensitive SQUID magnetometer is now a routine matter. We have made great progress towards developing the full London moment gyro readout.

A full description of the gyro and readout developments is given in sections B, C, and D below, along with a discussion of the remaining tasks in obtaining London moment readout. The following are highlights in the development this year:

November 1973	first operation of SQUID magnetometer with the rf/ feedback loop closed and locked while the gyro was suspended
January 1974	reduction of field levels in dewar from 10^{-2} gauss to 10^{-4} gauss
March 1974	first operation of SQUID magnetometer with gyro spinning
April 1974	trapped flux readout and cancellation tests
July 1974	field cancellation to 2×10^{-5} gauss achieved; gyro spin speed raised to 30 Hz
October 1974	null drift in gyro readout reduced nearly two orders of magnitude down to a level of 10^{-6} gauss, i.e. a factor of 20 below the Londom moment at 30 Hz.

The gyro readout tests with the ceramic gyro housing have provided the main thrust of our research this year, but we have done other tasks as follows.

1. sputtering work
2. dewar improvements
3. fixed base simulator
4. construction of star/collimator unit
5. quartz gyro housings
6. equivalence principle accelerometer

In addition to the laboratory experiment we have continued to work on the flight program. In last year's Annual Report we described the prospects for a preliminary relativity experiment of 0.1 arc-second/year accuracy to be launched on a Scout vehicle under the Explorer program. A study of the Scout mission was completed for NASA by Ball Brothers Research Corporation in June 1973 (BBRC Report F73/03). Although the Scout mission has merits, weight and cost are a problem, and further study has persuaded us that a more hopeful prospect for the first flight lies in a Delta or Shuttle launch of an 0.01 arc-second/year experiment. This would offer a higher scientific payoff, but could still be performed at tolerable cost, and it might allow NASA to add inexpensive guest experiments to the spacecraft. We recently submitted a proposal in response to AO#6 to define such a mission.

Contributors to the present Report are: J. T. Anderson (sections D,E), R. R. Clappier (section D), D. B. DeBra for D. Klinger(section K), J. A. Lipa (sections B,C ,J), J. R. Nikirk (sections B,F and Appendix), F. J. van Kann (sections G,H), R. A. Van Patten (section F), P. W. Worden,Jr. (Appendix).

B. GYROSCOPE OPERATIONS AND APPROACH TO THE LONDON MOMENT READOUT

Research on gyro readout is described both here and in sections C and D. This section concentrates on questions related to the cryogenic system and gyroscope; section C on field cancellation techniques, section D on magnetometry.

Detection of the London moment in the Relativity Gyroscope means observation of a magnetic field of about 10^{-4} gauss over a region of about 11 cm^2 with a ball speed of 200 Hz. This would appear to be a fairly straightforward task, given commercially available magnetometers with sensitivities up to 10^{-11} gauss - cm^2. Further we have always maintained it is possible to resolve the London moment to better than one part in 10^8 which corresponds to a 0.001 arc-second experiment. Our problem for the past eighteen months has been to reduce the sources of spurious signals to the point where we can deal with them and generate the London moment signal as output. Once this stage is reached we will be able to use our experience to build up the more sophisticated systems which we have argued all along will produce the ultimate accuracy.

First of all, in the present phase of development we must accept a penalty in the size of the signal to be detected, for three distinct reasons:

a) Since we have only one finished gyro housing, we dare not risk high speed gyro operations which might damage it. Accordingly we limit ourselves to a maximum spin speed of about 30 Hz as compared with 200 Hz for the final gyroscope We have observed that setting the ball down at speeds greater than 15 Hz generates visible abrasion marks on the surface, though not bad enough to hamper further spin tests. Once a set-down at 30 Hz caused the metal coating to break away from the quartz over an area of about 0.2 cm^2. After such set-downs the spin-up lands in the housing look unusually well polished, indicating abrasion we would sooner avoid. Although we do often have many hours of trouble-free operation with the gyro suspended, we still occasionally have unexplained shutdowns that apparently originate in the gyro. The limitation of speed reduces the signal because the London moment is proportional to spin speed.

b) We cannot yet use readout loops very close to the ball. One such loop is available, but it is a delicate task to join the SQUID to the fragile leads, and a big job to replace the leads if one is damaged. We use instead a wire wound around the housing. This causes a loss of about 30 % in sensitivity, and the system is appreciably more sensitive to fluctuations in the ambient fields. The combination of (a) and (b) means that our effective signal in the readout loop is about 1.5×10^{-5} gauss.

c) The third penalty occurs when the signal is fed into the SQUID input coil. For magnetometer configurations like ours there is an inherent inductance mismatch between the input coil and the readout loop. The resulting signal reduction in our case is presently a factor of approximately 1000. Ultimately we expect to be able to reduce this to a factor of 100. For the present it is not a significant problem because all signals detected by the readout loop are similarly affected, the main result being to raise the apparent SQUID noise figure with respect to the London moment.

Given a spinning gyro and a magnetometer of adequate inherent sensitivity we face three main problems in detecting the London moment:

(1) operation of the magnetometer in the presence of gyro suspension signals
(2) reduction of trapped magnetic flux in the gyro rotor to a level at or

below the 1.3 X 10^{-5} gauss London moment signal.

(3) elimination of magnetometer null drift and of varying magnetic fields, in particular, of fields generated by thermoelectric currents caused by temperature gradients in the experimental chamber.

The first problem has been completely solved as explained in section D. The second problem is not completely solved; but we have made enough progress to reduce the trapped flux levels to 2 X 10^{-5} gauss, which is sufficient to demonstrate the London moment readout. See section C.

Temperature gradients in the experimental chamber have two sources:
(a) the high heat load into the experimental chamber which seems to come from having inadequate radiation traps in the dewar neck-tube,
(b) heat dissipation in the gyro housing caused by the combination of the rather high electrical resistance of the gyro electrodes and the high suspension currents required to support the gyro rotor on earth. The root of the first trouble is the neck-tube itself, which has inadequate provision for heat-sinking the radiation baffles to the cooling-coils for the boil-off gas. We have now built a completely redesigned neck-tube, which is ready for installation. To solve the gyro dissipation we have decided on the drastic step of coating the electrodes with superconductor. Doing so will cause some distortion of the London moment field; eventually we will probably revert to ordinary conductors, but at present the use of superconducting electrodes seems to be the best step.

The reduction in temperature gradients in the experimental chamber should substantially reduce fluctuations in the ambient magnetic field, improving both the readout null stability and also the prospects of reducing trapped flux by the field cancellation techniques to be described in section C. Reduction of the heat dissipation in the gyro itself has another important advantage. Under the present operating conditions the dissipation tends to warm up the gyro and drive the superconducting rotor normal. To prevent this exchange gas has to be present in the experimental chamber at a fairly high pressure (about 10^{-4} torr); and gaseous friction then decelerates the gyro rotor with an exponential spin-down time of a few hours. With the new electrodes we shall be able to work at much lower pressures.

When trapped flux is present in the ball the readout signal over any short interval is a combination of an a.c. component of trapped flux perpendicular to the spin axis, a d.c. component of trapped flux parallel to the spin axis, and the London moment signal also parallel to the spin axis. The trapped flux is tied to the body axes of the ball, so the amplitudes of the a.c. and d.c. components slowly vary as the ball describes its polhode motions. The London moment is, of course, always aligned with the spin axis. At present trapped flux levels three methods exist for reading out the London moment signal, depending on the amount of auxiliary information that is available on the motion of the ball's spin axis.

(1) If the ball can be made to precess about the vertical axis at a rate fast compared with polhode rate (as happened for three out of four runs this year) the d.c. component of trapped flux can be subtracted out when

when the a.c. signal has its first null. The remainder is the London moment signal. This method requires one magnetometer and a readout loop having its normal horizontal and at right angles to the spin axis.

(2) If the ball spins down before its has precessed through an appreciable angle, the change in amplitude of the a.c. signal can be used to correct the d.c. signal for changes in the spin axis. The London moment signal would then remain as a function of spin speed. This method requires a loop with its normal parallel to the spin axis.

(3) With a complete three axis magnetometer readout system, enough information is available to subtract out the trapped flux signal for an arbitrary location of the spin axis and an arbitrary angle between the spin axis and the trapped flux vector.

In the runs made since April 1974 we have concentrated all our efforts on method (1) for three reasons: (a) the readout magnetometer system was undergoing rapid development so that it was imprudent to build three units, (b) from observations with our auxiliary, low sensitivity, fluxgate readout system (which is a three axis system) we knew that the precession of the existing ball was fast and in the horizontal plane; (c) method (2) was excluded because only recently have we become able to guarantee null stability of the readout through the spin-down period.

Most recently we have decided to change over to the three axis readout which will allow <u>any</u> of the above methods to be implemented. Our expectation is to see the London moment signal first by method (3). This is because we only need null stability in one readout magnetometer (the existing one) to see the signal; the essential information from the other two readouts being a.c. We still need a moderate range of precession, say 30 to 45° before spin down, but this should be easily obtained with a deliberately unbalanced rotor.

C. MAGNETIC SHIELDING AND REDUCTION OF TRAPPED FLUX IN THE GYRO ROTOR

For the final relativity experiment the trapped magnetic field in the gyro rotor must be reduced to levels between 10^{-6} and 10^{-7} gauss. Our plan for getting the low field depends on combined use of Mu-metals shields and of the special properties of superconductors, including, if necessary, use of the novel "expanding balloon" technique described in previous reports. During the past year we have made good progress both in the expanding balloon technique and in obtaining low fields by conventional means in our main laboratory dewar.

Work on the expanding balloon technique has proceeded under separate funding. The most important result has been to extend the method to a balloon, or rather a sock, 8 inches in diameter and 4 feet long. A field level of below 10^{-7} gauss was obtained over most of the sock volume. We are planning to set up an 8 inch facility of this type during the next few months for the Gyro program.

The main laboratory dewar has two Mu-metal shields: one external, one mounted on the inner of the two gas-cooled heat exchangers in the super-insulation space of the dewar. The inner shield normally operates at a temperature of 40 K. For most of the present year we have had, in addition to the Mu-metal shields, a superconducting lead shield wrapped on the outer surface of the experimental chamber inside the helium well of the dewar. The purpose of this lead shield has been to stabilize the field from the Mu-metal shields; but we have found in practice that it does little good and some harm, since it does not really stabilize the field, yet it prevents us from making external field adjustments after it is superconducting. We have decided to remove it for the next run: later on we shall, of course, add a more satisfactory superconducting shield close in around the gyro, of the kind to be used in the flight experiment. The final stage in our present field reduction scheme is a set of three orthegonal coils surrounding the gyro, through which currents are passed to cancel the residual field.

For our first low temperature run of the present reporting period, during November 1973, only the inner Mu-metal shield was available. The field level then observed was 3×10^{-2} gauss. Since then we have in progressive stages completed and annealed the outer Mu-metal shield, removed magnetic materials from the helium well and experimental chamber, and added degaussing coils and trim coils to the Mu-metal shields. To measure the field in the experimental chamber we have put in a three-axis flip coil magnetometer with a fluxgate probe. An important step was to make vacuum sealed push-rods to manipulate the flip coil, allowing us to make field measurements with the gyro suspended. By means of the shields and flip coil we now easily get fields of 5×10^{-4} gauss or less at the gyro. A limitation of the present arrangement is that the flip coil is 4 inches above the gyroscope, and we observe appreciable field gradients in the inner well. Thus in the most recent run (October 1974) the field after one test was

4×10^{-4} gauss at the flip coil and fortuitously lower at the gyroscope, being only 2×10^{-4} gauss, as measured from the trapped flux signal.

To go lower we have developed a field cancelling procedure, which consists in applying small known currents to each of the three bucking coils in turn and observing the resultant trapped flux after heating and cooling the gyro each time. By slow iterations the field is then brought down to about 2×10^{-5} gauss. It is hard to conceive of anything more tedious, but the method works. However around the level between 2×10^{-5} and 5×10^{-5} gauss the results begin to be non-repeatable, with considerable variations in the amount of flux trapped in the rotor in successive identical cooldowns. We have guessed at, and ruled out, a number of possible sources of this variability. The most likely explanation seems to be thermoelectric generation of slowly varying fields in the neighborhood of the gyro through temperature gradients in the various metal components of the gyro support assembly. It is possible to get rid of such items, but doing so requires major rebuilding of the apparatus which we do not want to do just yet. Another possible cause, not yet disproved, is thermoelectric currents in the coating of the ball itself. This would be much harder to solve, because we would have to deposit a very thick niobium film on the rotor, and at present we do not know how to do that. See section G .

Figure 1 illustrates gyro readout of the London moment and trapped flux signals. The Cartesian reference frame $\hat{i}, \hat{j}, \hat{k}$ is centered on the ball with axes parallel to the readout loop normals. The vector $\underline{\Omega}$ represents an arbitrary spin axis along which lies the London moment

GYRO READOUT VECTORS

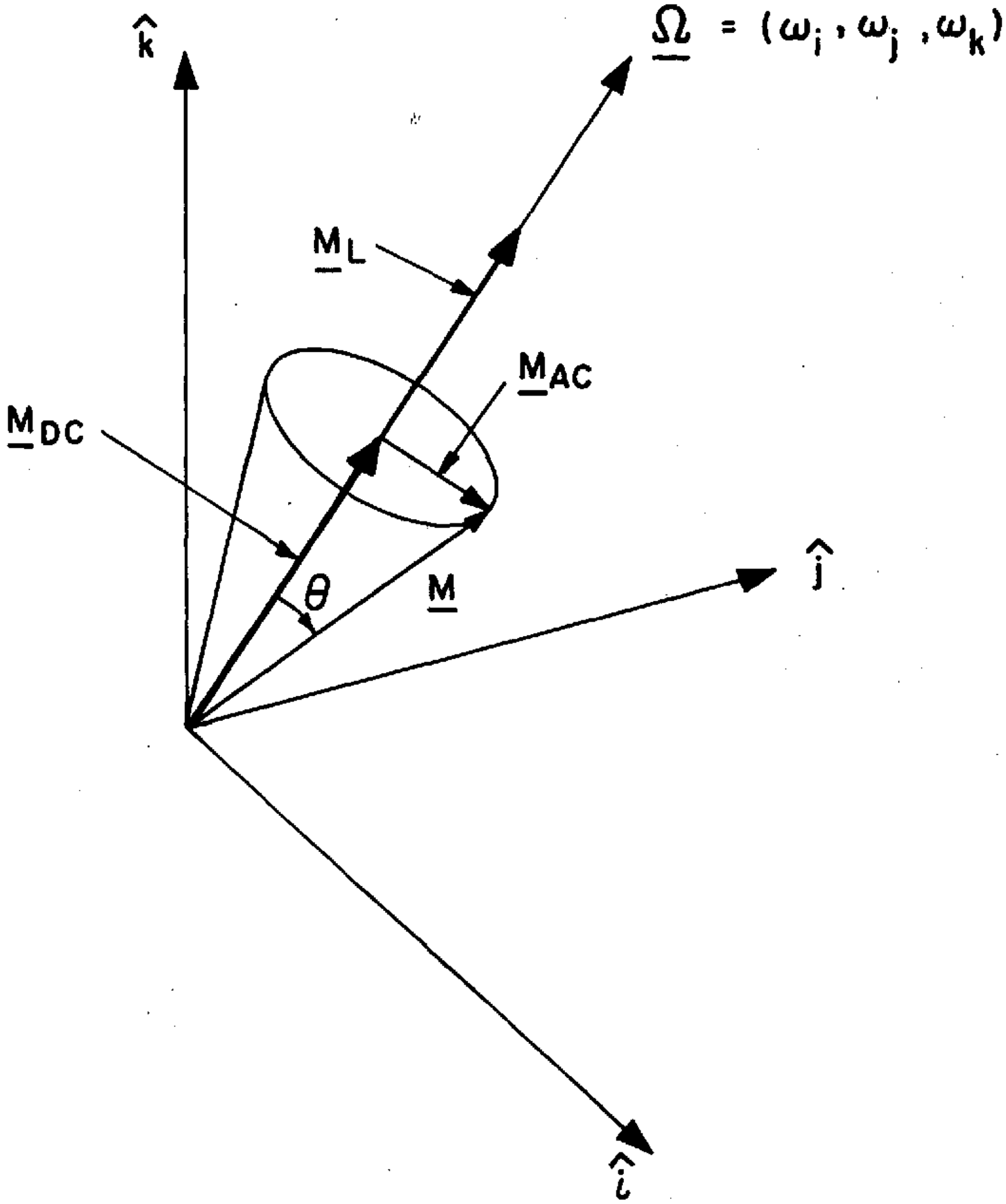

FIGURE 1

vector $\underline{M_L}$, the trapped flux vector M is inclined at an arbitrary angle Θ . The trapped flux signal has a d.c. component $\underline{M_{DC}} = \underline{M}\cos\Theta$ and an instantaneous a.c. component $\underline{M_{AC}} = \underline{M}\sin\Theta$ which links each loop in an amount depending on the direction cosines ω_i , ω_j , ω_k of the spin axis $\underline{\Omega}$. Thus from the ratio of the a.c. signals <u>only</u> we can find the direction of $\underline{\Omega}$ up to an arbitrary sign in the components. Then given the value of $\underline{M}$ determined by some other means we find Θ and hence the d.c. components of the trapped flux $\underline{M_{DC}} = (M^i_{DC}, M^j_{DC}, M^k_{DC})$. This information is all that is needed to determine the components of $\underline{M_L}$ up to an arbitrary constant. Since the quantities M^i_L , M^j_L , M^k_L vary in exactly the same fashion as ω_i , ω_j , ω_k we can make an unambiguous identification of $\underline{M_L}$ if the ball precesses. Such a determination is independent of polhoding action. Depending on the accuracy with which $\underline{M}$ can be determined we can compensate for a relatively large trapped flux signal, provided we have a three axis readout. With only one readout loop appreciable amounts of trapped flux can only be compensated if auxiliary information is available on the motion of $\underline{\Omega}$. Figure 2(a) shows signals observed with a three axis readout system and a large amount of trapped flux. Our interpretation of this data is that the ball is precessing with its spin axis in the horizontal plane and the angle Θ is remaining virturally constant. The repeating nulls in two of the channels are about 90° out of phase, which can only occur if the spin axis becomes normal to each loop in turn. The constancy of the third signal indicates that the spin axis is coning about this loop normal and Θ is almost fixed. Figure 2(b) shows the trapped flux signal during spin-up as observed by the SQUID magnetometer in April 1974

The importance of reducing the field still further needs no emphasis. However for the practical immediate problem of demonstrating London moment readout we believe that with three axis data we could cope with trapped flux signals even higher than these attained so far. In this sense therefore we consider the trapped flux problem to be solved.

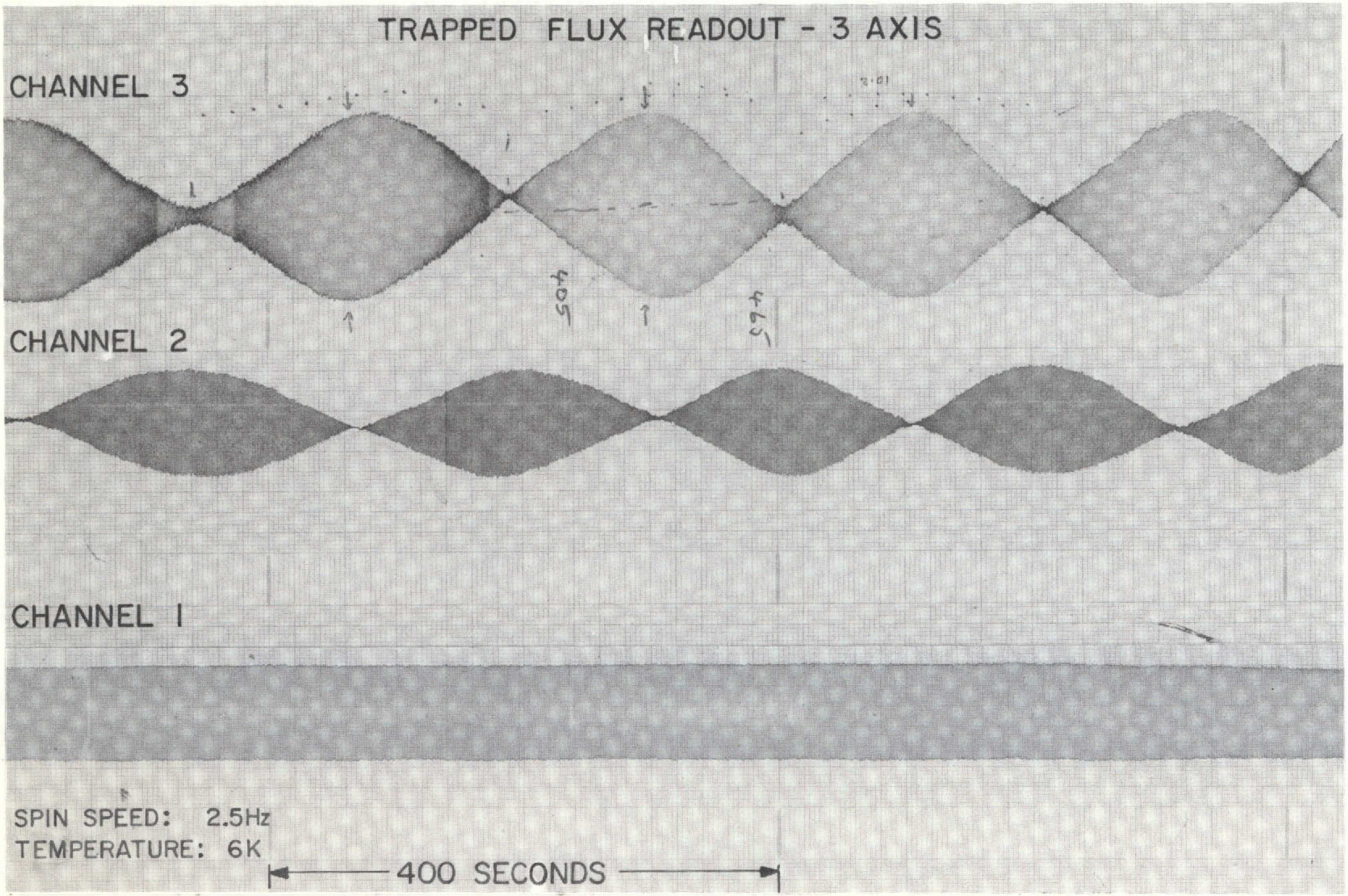
TRAPPED FLUX READOUT - 3 AXIS
CHANNEL 3
CHANNEL 2
CHANNEL 1
SPIN SPEED: 2.5Hz
TEMPERATURE: 6K
400 SECONDS

FIGURE 2a

GYRO SPIN-UP WITH TRAPPED FLUX AND SQUID READOUT

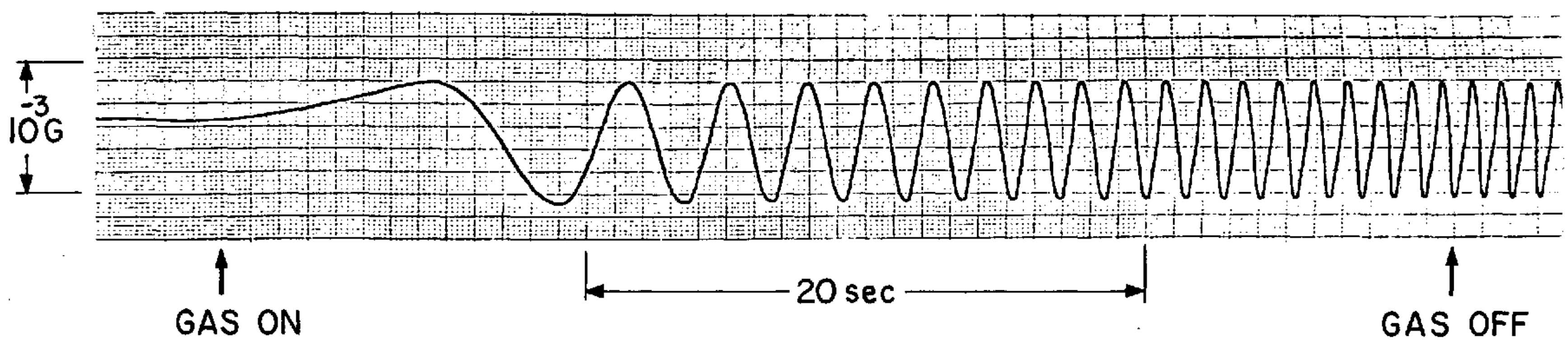

FIGURE 2b

D. GYRO READOUT DEVELOPMENT

The magnetometer readout system has to operate in the presence of 20 kHz and 1 MHz gyro suspension signals, with varying temperatures in the dewar, and in the presence of trapped magnetic flux in the ball. For satisfactory performance, the readout should have an extremely stable null point; it should be linear over a sufficient range; its scale factor should be independent of dewar temperature and also of the signal frequency, at least over the range of frequencies up to the highest seen from the third harmonic of the trapped flux in the rotor, i.e. up to three times the maximum spin speed of the ball. The last desideratum is not an absolute necessity, but it is helpful in sorting out trapped flux signals at the present stage of development.

Throughout the year we have made steady progress in all these areas and have also progressively simplified our system as we have gained a better understanding of the various problems. Important technical accomplishments have been the use of a "damping cylinder" to remove 20 kHz and 1 MHz magnetic signals from the SQUID input, construction of a more reliable and stable magnetometer feedback system, and development of an "rf level loop" to provide the correct operating bias to the SQUID as the dewar temperature changes and alters its critical current. Highlights in readout development were listed in section A.

A large effort has been devoted to eliminating 20 kHz and 1 MHz interference from the suspension system. The problem is now completely under control. Last year's report described the steps taken to provide electrostatic shielding between the leads and tank circuit. Once that was done it became necessary to suppress the residual pickup, mostly magnetic in origin, at the front end of the SQUID. For the first run of the year, in November 1973, we added a resistive filter to the SQUID input, which reduced the 1 MHz interference to acceptable levels and reduced the 20 kHz interference to a level that we thought could be handled with a six-channel bucking circuit built for that purpose. The bucking worked, but it was not very satisfactory. Adjustment of the bucking signals was difficult; moreover proper adjustment turned out to be a function of the ball position so that no single setting of the controls was right. As a result we decided to do more filtering of the signal before it reaches the SQUID, to eliminate the need for 20 kHz bucking. There is a price to pay for the extra filtering, in that a resistive filter generates noise in the readout; however we have progressed through the year to a near optimum arrangement in which the additional noise is not too serious.

The filtering is provided by a "damping cylinder", which forms a low pass filter between the gyro readout ring and the SQUID. The readout ring is connected to a coil around the outside of the cylinder; inside the cylinder another coil is connected to the SQUID. The cylinder is made of a conducting (not superconducting) material. At high frequencies reaction currents flow around the cylinder and effectively shield the interior coil from the signal. At low frequencies the reaction currents are damped by the resistance of the cylinder, allowing low frequency signals to pass. The damping cylinder has the second benefit of substantially reducing capacitative coupling between the two coils. We have experimented with damping cylinder bandwidths ranging from 5 kHz, which passed to 20 kHz pickup, to 5 Hz, which was far lower than necessary. The most recent version has a 300 Hz bandwidth, which suits our present needs.

Mechanically the damping cylinders consist of an 0.5 cm diameter cylinder about 4.5 cm long and 0.025 cm wall thickness. The thickness is varied both by machining and by electroplating. Metals used have been brass or copper for the base, and lead and copper for plating. The present damping cylinder is entirely copper to reduce thermoelectric voltages, which are a source of spurious signals.

The damping cylinder is a dissipative circuit element, and as such, introduces noise. We have investigated L C filtering schemes, but none are feasible because circuit values are unwieldy. At present accuracy levels the noise contribution of the damping cylinder is not significant; in the future magnetometer improvements will allow an increase of the damping cylinder bandwidth with a concomitant decrease in noise.

Another big effort this year has been in developing a new electronics package for the SQUID magnetometer. As we worked with our prototype feedback card we observed many areas for improvement. One was that the critical current of the magnetometer continually drifts away from the set point. When this happens the magnetometer loses lock unless the rf drive level is adjusted. We developed a control loop that continuously adjusts the rf level for best magnetometer operation. Incorporating the circuit into the magnetometer called for major circuit modifications; while we were about it we decided to make other changes based on our experience with the prototype feedback card. We made improvements in every circuit, and designed a new magnetometer control panel and card rack for the new circuits. The card rack houses: 2 cards for the magnetometer feedback circuit, 1 card for the new rf level control loop, 2 cards for the trapped flux bucking system designed last year (which is now integrated with the magnetometer), 1 card to control the rf box, and 1 power conditioning card. New features on the panel and simplified control nodes make the magnetometer much easier to use than earlier versions. Overall dimensions of the new system are 19 inches wide, 7 inches high, 10 inches deep. Figure 3 illustrates the electronics package.

The new magnetometer was completed and checked out by mid-March 1974 and has been used as a single-axis gyro readout ever since. Performance of the rf level loop has been particularly encouraging. It increased the operating range of the SQUID from temperature swings of 0.3 K to 1.5 K. The loss of lock that did occur at the extreme did so only because the critical current became too low or too high for normal SQUID operation. During the past year we have made large and frequent changes of the dewar temperature, while setting the field or spinning up the gyro and the rf level loop has proved its worth. During a spaceflight the dewar temperature should remain constant and this circuit probably will not be needed.

A problem with the rf level loop which has not bothered us in practice, but which we have given a lot of thought to, is that one of the changes in the feedback circuit to make the rf level loop operate reduces the magnetometer slew rate by a factor of two. For present purposes the magnetometer has far more slew rate than is needed, especially since the damping cylinder protects the SQUID from high frequency of the damping cylinder. We have designed some different rf level loop schemes that prevent the degradation in magnetometer performance, but have not built any of them yet.

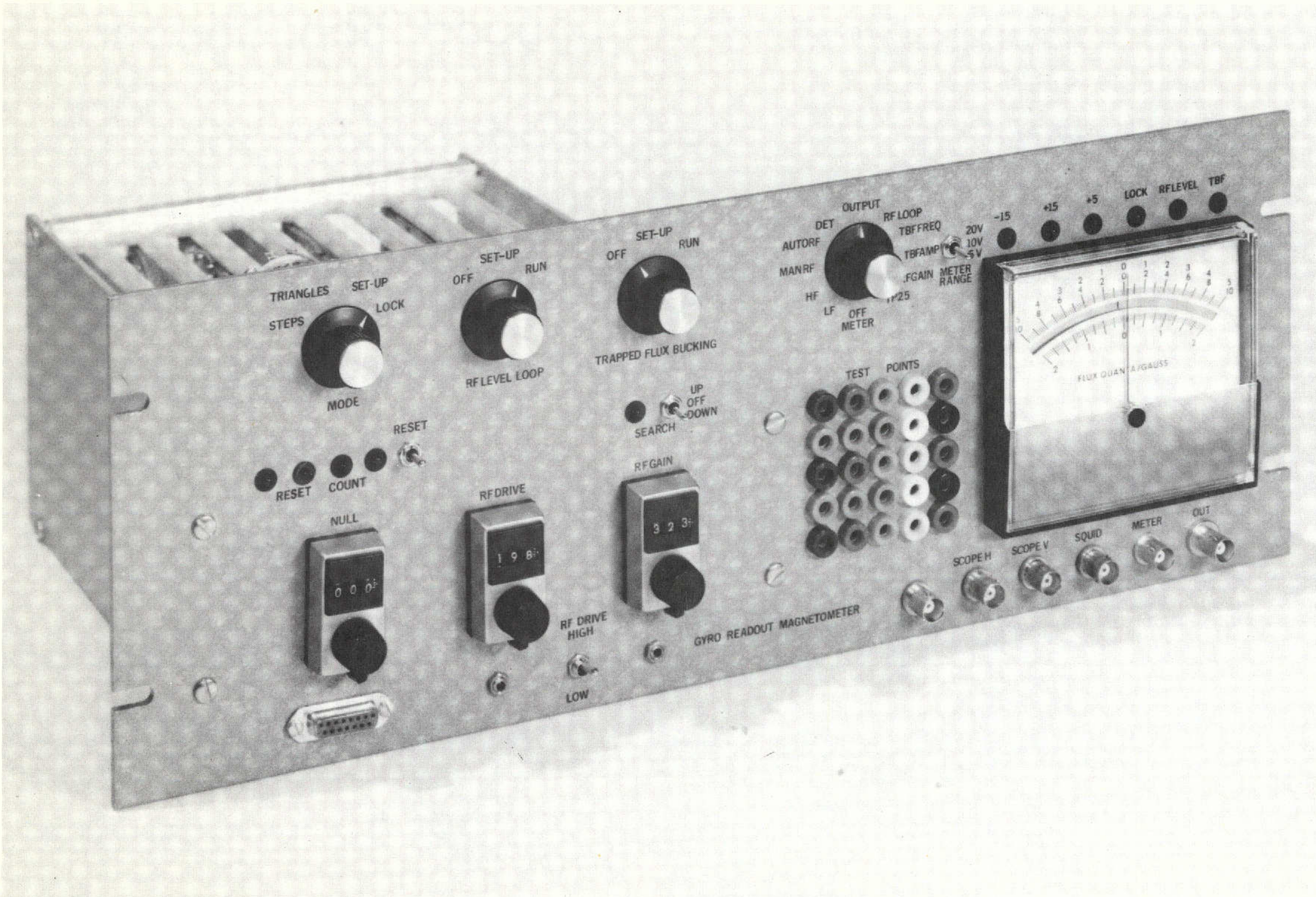
TRIANGLES
SET-UP
STEPS
LOCK
MODE
OFF
SET-UP
RUN
RF LEVEL LOOP
OFF
SET-UP
RUN
TRAPPED FLUX BUCKING
DET
OUTPUT
RF LOOP
AUTO RF
TBF FREQ
MAN RF
TBF AMP
HF
LF
OFF
METER
20V
10V
5V
METER
RANGE
-15
+15
+5
LOCK
RF LEVEL
TBF
TEST POINTS
UP
OFF
DOWN
SEARCH
RESET
RESET
COUNT
NULL
RF DRIVE
RF GAIN
RF DRIVE
HIGH
LOW
GYRO READOUT MAGNETOMETER
SCOPE H
SCOPE V
SQUID
METER
OUT

FIGURE 3

The changing heat loads and changing gas pressures in the experimental chamber cause temperature changes which make the gyro readout drift. Besides the dewar improvements described in section B, we took several measures to stabilize the temperature of the SQUID and damping cylinder, including: (1) heat sinking the SQUID enclosure to the inner well by a thick copper post (2) use of indium between metal parts to improve heat transfer (3) surrounding the SQUID enclosure by a heat shield connected to the bottom of the inner well to lessen the effects of changing gas pressure on SQUID temperature (4) addition of an active temperature controller first to the SQUID enclosure and then to the gyro housing. These measures have been quite successful. The results with the temperature controller were surprising. It stabilized the SQUID temperature but we discovered that it introduced thermal gradients and noise that actually degraded the temperature performance of the readout. Some of the performance was recovered by the improvements in heat sinking and shielding, but the real step forward came through applying the SQUID temperature controller to control the gyro temperature! We found that when the gyro temperature is stabilized the readout drift is reduced to a level well below that needed to detect the London moment. We do not yet have a complete interpretation of this result, but it is nice to know what to do.

Early in the year we ran tests using the trapped flux bucking system with the spinning gyro. The system worked well, reducing the trapped flux signal at the SQUID as hoped. However in recent runs the flux trapped in the gyro has been so low that the magnetometer can cope with it easily without the trapped flux bucking system.

To facilitate analysis of gyro readout data containing trapped flux, we built a compensation filter for the magnetometer damping cylinder. Throughout most of the year, the damping cylinder used had a bandwidth of 4.5 Hz, which meant that the trapped flux signal was attenuated and distorted at spin speeds about 1 or 2 Hz. Since quantitative knowledge of the trapped flux signal helps in detecting the London moment signal, we built an analog filter to compensate for the attenuation. With this filter installed the magnetometer frequency response was flat to within ± 0.5 db between d.c. and 100 Hz. However with the new 300 Hz bandwidth damping cylinder the filter is no longer necessary.

Elimination of the damping cylinder compensator is part of a trend we have established this year towards a simpler readout system. We have already mentioned elimination of the complex 20 kHz bucking and trapped flux bucking subsystems. The resulting readout is more reliable and much easier to operate.

After the first new magnetometer proved itself we built two more like it. One is for a second axis of gyro readout to be used in the next run (January 1975); the other is for the equivalence principle accelerometer. With these additional units we have streamlined and formalized the checkout procedures so that they are now routine.

E. MAGNETOMETER SHAKE TEST, SURVEY OF COMMERCIALLY AVAILABLE SQUID MAGNETOMETERS, AND POSSIBLE DEVELOPMENT OF A PRECISE WIDE ANGLE GYRO READOUT APPLICABLE TO OTHER SPACE PROGRAMS

The point-contact SQUID magnetometer, which may be the most sensitive commercially available magnetometer, has an appearance of great fragility. Fears have often been expressed that such devices would never survive the launch environment. Tests that we have performed this year show that those fears are groundless.

In collaboration with the SHE Corporation and Ball Brothers Research Corporation we have shake-tested a niobium, toroidal point-contact weak-link SQUID manufactured by SHE Corporation. We performed routine magnetometry tests before and after vibration tests at BBRC. To approximate flight qualification figures applicable both to the four-stage Scout vehicle and the two-stage Delta, BBRC took a composite of the vibration spectra for the two vehicles, using the higher figures from each, and then, on the basis of OSO flight experience formulated an estimate of the response of the spacecraft taking into account amplification through structural resonances. The qualification test consisted in applying 20 g accelerations on all three axes through the frequency range 50 Hz to 2 kHz, together with a simulated shock test made by applying 30 g's for one second at 1 kHz. The SQUID operated perfectly before and after the shake tests. No changes in electrical performance were discernible beyond the limits of measurement errors.

The SQUID has been roughly handled and abused in our laboratory without any qualitative change in its electrical characteristics. With respect to its mechanical stability this SHE SQUID is flightworthy. It costs $900.

The SQUID used in the shake test is still on loan to Stanford. We have built a test probe for it, which can be inserted in standard helium storage vessels. We have saved much time in designing and testing magnetometer electronics through using this probe.

To assess the current level of readily available technology we have made a survey of commercially available SQUIDs. Three U.S. companies make SQUIDs and associated electronics: SHE, SCT and Develco. The SHE SQUIDs have point-contract weak-links; the others have thin film weak-links. Indications are that the SHE device is the most sensitive by a factor of two, although definite comparisons are hard to make because specifications have not been standardized. With the SHE unit the gyro readout would give 0.001 arc-second resolution in 10^4 seconds of observation time.

Magnetometers currently under development, in addition to the 10 GHz system being developed at NASA Marshall Center and the University of Alabama under the present program, include a Develco SQUID operating at 10 GHz which has a signal sensitivity at 1 kHz 100 times that of the SHE unit, but a d.c. sensitivity no better than that for the 30 MHz systems. The d.c. sensitivity is what counts for gyro readout. Robert Buhrmann of Cornell has an experimental SQUID system operating at 440 MHz that does seem to have a d. c. sensitivity about ten times that of the SHE unit. It is claimed to be stable. These advanced systems may be useful fo the Gyro experiment.

Not much study has been done of the long term drift stability of SQUIDs. The only results we know of are those done by SHE, which yield drifts below 10^{-4} flux quanta (corresponding to 0.25 arc-second gyro readout) during an overnight test in a dewar without magnetic shielding or temperature control. The stability in such adverse conditions is remarkable.

During the course of this year we have taken occasion to study the possibility for applying the special properties of quantized flux in superconductors in a high-precision all-angle version of the London moment gyro readout. Doing so calls for the application of the "flux-counting" techniques that have been developed in other applications of Josephson junction magnetometers. We are of the opinion that a readout with a resolution of 24 bits/ quadrant may be feasible, which corresponds to an absolute angular precision approaching 0.01 arc-second over the entire range. This extraordinary figure, which can only be discussed because of the absolute character of the quantum of flux, should be compared with the outside limit of 17 bits/quadrant that applies to conventional angular encoders. Development would be a major undertaking but it may be of long-term interest to NASA for programs such as the Large Space Telescope.

Both a high accuracy limited range readout and an all axis, full range, moderate accuracy readout may be useful to the Gyroscope experiment. The latter would be of value in the second gyro test facility (see section H). We are continuing to study the feasibility of an all-axis readout.

F. ELECTRONICS AND INSTRUMENTATION FOR LABORATORY EXPERIMENT

Most of the electronics work on the laboratory experiment has been described under section B through E above; various other small projects were completed to help make the experiment run more smoothly. They include gyro and magnetometer temperature sensing bridges; a three axis magnetic bucking circuit for nulling the residual field around the gyro; a temperature servo which controls cooling and warming of the gyro at a predetermined rate; and most recently a servo amplifier to drive a piezoelectric valve which controls the exchange gas used to keep the experimental chamber cool. The last item will be incorporated during the next run into a servo system controlling the pressure of the inner well.

The Stanford gyro suspension system built last year has proved its worth. It had three failures during a year of hard use; two of which were induced by accidental mishandling on our part. However we continue to observe occasional erratic performance of the suspended gyro, sometimes leading to shutdowns or rapid ball motions with no real known cause. We will continue investigating these effects as new ideas or tests are thought of, for example non-linear effects of the suspension itself.

Some work was done on a new power supply for the suspension system, but we have had trouble with manufacturers in replacing unsatisfactory batteries and the issue is not yet resolved to our satisfaction.

The Astrionics Laboratory at NASA Marshall Center manufactured a run of 12 hybrid a.c. amplifiers for us, which proved to be very successful. We plan to use these as spares for our suspension system as well as for other future needs. They are now working on a hybrid demodulator driver circuit. Prototypes should be available early in 1975.

G. SPUTTERING WORK

Not much sputtering was done in the first part of the year owing to shortage of funds. However, through the generosity of the Research Corporation, which provided a Grant to cover 50% of F. J. van Kann's salary for one year, we were able to resume a strong sputtering effort in June 1974. We also received a small contract from Honeywell Incorporated to sputter electrode test pieces for them to use in one of their gyro development programs. This rare instance of an industrial company requesting a university laboratory to provide research services followed our earlier success in developing high quality sputtered electrodes under the present Grant. Breakdown voltages with the sputtered electrodes were approximately twice those achieved with conventional plated electrodes. See also a letter from C. W. F. Everitt to N. Roman dated May 7, 1974.

We have continued general sputtering services in support of the laboratory experiment. Work in this area has included coating the new gyro rotor received from Marshall Center in June 1974 ; repair of some damage to the other gyro rotor after the July run; and the beginning of an effort to sputter superconducting niobium on to the electrodes of the ceramic gyro housing, in order to reduce heat dissipation from the suspension currents. Another task was to sputter niobium on quartz tubes, 5/8 inch diameter and

5 inches long, which are being used in an experiment to determine their flux trapping properties.

Under the Honeywell contract we performed sputtering and electrical breakdown tests on several ceramic and stainless steel substrates prepared by Honeywell. High voltage tests on several of the samples gave excellent results; some were found to withstand 6 kV/mil (peak to peak) before breakdown. The test pieces together with the Stanford test jig and a preliminary report were dispatched to Honeywell on August 20.

Through special support from NASA Marshall Center we are in process of obtaining a new sputtering system at a very competitive price. We have devoted careful attention to choosing the most desirable features for the system. Our principal wish has been to sputter films of both metals and dielectrics with greatly improved purity and uniformity, at considerably higher rates and with lower heat dissipation in the substrate than formerly. We found out that such a system could be assembled largely from commercially available components. Specifications were communicated to E. Urban at NASA Marshall Center who initiated the purchase.

The target assembly has already been delivered; the pumping system and vacuum gauges are expected in late December. The only components not commercially available are the vacuum chamber and some of the internal fixtures for it. Plans and specifications for the vacuum chamber have been sent to Marshall Center; a contract for constructing it should soon be awarded to an outside company. We have begun constructing several internal fixtures at Stanford; a new gyro rolling jig is ready for final assembly.

H. SECOND GYRO TEST FACILITY

A six foot long, 12 inch diameter helium dewar has been ordered from Cryogenics Associates and is scheduled for delivery early in December. The dewar is a standard model SD-12 with some special modifications according to Stanford specifications to reduce helium boil off and increase the hold-time. We have designed Mu-metal magnetic shields for the test facility; plans and specifications have been sent to several companies for quotation.

We have begun design of the gyro chamber for the new test facility. On April 22-25, 1974 J. B. Hendricks of the University of Alabama, Huntsville and NASA Marshall Center spent four days at Stanford reviewing the designs of the equivalent test facility which he is building up at Marshall Center. The two groups are coordinating the designs as closely as feasible to make it easy to exchange gyro tests between Stanford and NASA Marshall Center.

J. QUARTZ GYRO HOUSINGS

Two Honeywell quartz gyro housings are in different stages of completion. They are commonly referred to as Quartz Gyro Housing No. 2 and Quartz Gyro Housing No. 3. The original Housing No. 1 was broken by Honeywell in April 1972. Housing No. 3 is a replacement being fabricated by Honeywell at Company expense.

Housing No. 2 was delivered to Stanford in June 1972. The design was in most respects similar to the final design, but in order to reduce the risk of manufacture we decided to compromise in one respect and have it made without raised lands around the spin up channels. We took this course in light of earlier difficult experiences at Honeywell. Electrodes were sputtered on the housing at Stanford in mid 1973 and the parts were shipped to NASA Marshall Center for lapping of the electrode surfaces before completion of the final sputtering processes. A slight imperfection was noticed on one of the electrodes. In December 1973 we held a review with W. Angele and R. Decher of NASA Marshall Center on the status of this and other gyro housing work. Mr. Angele had then conceived a new method for fabricating gyro housings in which the electrodes would be recessed below the primary reference surface by means of a special lapping machine. This procedure was conceptually similar to the method of "plunging" electrodes tried unsuccessfully by Honeywell in 1968, but the new lapping machine showed great promise for doing the job successfully. At the review in December 1973 we decided that the new recessing method might well be the ideal approach to fabricating the gyro housing, and at the same time provide the crucial step towards arriving at a commonly acceptable gyro design embodying the best features of the Stanford and MSFC designs. Accordingly we left Quartz Gyro Housing No. 2 and Marshall Center to recess the electrodes on it. Unfortunately a succession of delays and difficulties, coupled with Mr. Angele's retirement from NASA and the reorganization at Marshall Center, have prevented any work being done on the Stanford Gyro Housing for the past eleven months, so at present we are at rather an impasse. Work on recessing electrodes has been proceeding on the MSFC Gyro Housing. We are giving careful consideration to the situation and will communicate further with NASA shortly.

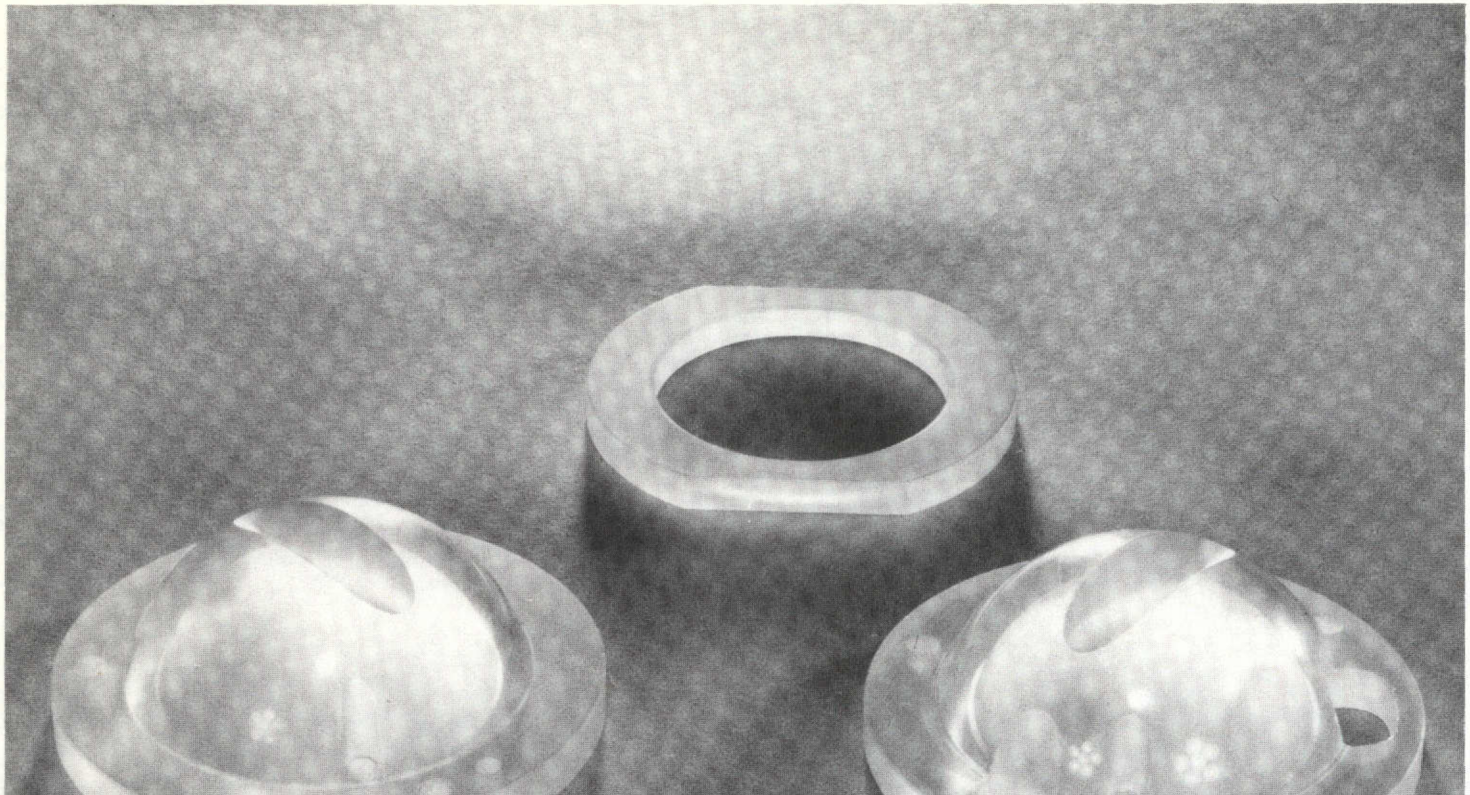

FIGURE 4

The first stage of manufacture of Quartz Gyro Housing No. 3 was completed by Honeywell successfully in June 1974. Figure 4 illustrates the partially finished envelope parts. The next step is to be deposition of electrodes and completion of the spin up channels. During the present year we have taken the opportunity to reconsider the methods for forming the raised spin up lands. The procedure we had intended to follow had been that of quartz inserts, which had been developed by Honeywell more or less successfully on the destroyed Quartz Gyro Housing No. 1. However in the course of our sputtering work over the last three years we have gained a large amount of experience that leads us to look once more at three methods partially tried earlier at Honeywell but rejected, namely

i) metallized ridges made from sputtered or electroplated copper

ii) metallized ridges fo layered construction: titanium, aluminum, copper

iii) sputtered quartz.

The ceramic housing we have been using routinely for the past few years has metallized edges. On both ceramic and quatz housings the ridges are about 0.002 inches high above the spherical surface of the housing; they need to conform to the sphere to within ± 50 microinches or about 2 % of their heights.

The obvious objection to metallized edges is that they will tear away from the quartz on cooling because of differential contraction. This was what Honeywell found. On the other hand we have been able to coat a two-mil thick copper layer on the gyro ball with no ill effects, so the story is not quite as simple as that. Early in the year we experimented with sputtered copper on a quartz test hemisphere, and found as Honeywell had done that the metal cracked away in places after cooling. However the experience with the gyro rotor suggests that there still may be possibilities of getting arong that effect.

Sputtered quartz would avoid the differential contraction. Considerable progress has been made in quartz sputtering technology since 1969 to 1970 when Honeywell tried experiments on this method. The difficulty then was that the quartz came down with a very irregular granular structure, and deposition was exceedingly slow. In the past two years or so, very high rate sputtering systems have become available, capable of depositing quartz. As part of the new sputtering system described in section G, we have ordered a quartz target. There are three main advantages in using the system: (1) the deposition rate for quartz should be 50 to 100 times that in conventional systems, reducing the time from about 120 hours (as found by Honeywell) to about 2 hours; (2) the increased rate reduces likelihood of contaminating the film; (3) the plasma of the new sputtering head is well confined, allowing cooler substrates throughout deposition. This will allow better mask definition, as well as lower impurity levels and much less stress in the deposited film. We plan to start experimenting with quartz sputtering in the Spring of next year.

K. FIXED BASE SIMULATION, STAR/COLLIMATOR UNIT, PREPARATIONS FOR ALL-UP TESTS OF THE GYRO-TELESCOPE PACKAGE

We have described several times our plan for all-up testing of the experiment. Briefly the idea is as follows. The entire gyro-telescope package is placed in a gimballed fixture inside our existing 30 inch non-magnetic dewar, which is then tilted to an angle of approximately 37° to align it with the Earth's polar axis by means of a large external gimbals mounted on a concrete pad in the main basement laboratory. External reference for the telescope (or for a mirror on the gyro package) is provided by a star/collimator unit mounted on a second concrete pad. Pointing servos drive actuators on the inner gimbals to keep the telescope aligned with the beam of light from the star unit, and a data instrumentation system subtracts and processes signals from the gyro and telescope readouts.

The most important step foward this year has been construction of the star/collimator unit. The unit comprises a bright point source of light, a 200 inch focal length off-axis parabola mirror, tipping plates, and sundry other optical elements, in an eleven foot high evacuated chamber. The instrument produces a $6\frac{1}{2}$ inch or 8 inch diameter parallel beam of light, which is reflected by a plane mirror at the upper end of an angle of 37° down in the dewar. Thus the instrument serves as a North Star simulator. Separate optical attachments allow it to be adapted as an autocollimator. A fabrication contract was issued to Optical Instrument Design Company on May 7, 1974. Construction of all the parts is now finished. An acceptance test will be conducted at the West Covina plant in January 1975. Delivery to Stanford is scheduled for February 10, 1975. After delivery the unit will have to be set up and aligned in our laboratory by D. E. Davidson. We tentatively schedule commencing alignment in April 1975.

Our work on fixed base simulation has also been described in earlier Annual Reports. The aim has been to develop on a simple test stand methods of evaluating gyro and telescope performance which get round the difficulty that the designed performance of the instruments themselves is better that that of any available test instruments. In essence what is needed is to develop information processing techniques which use the gyro and telescope to evaluate each other, recognizing that the noise sources in the two instruments have quite different spectral compositions.

During earlier reporting periods a Fixed Base Simulator was built, partly under the present Grant and partly under the Air Force Supplement (now terminated) to Develop Associated Control Technology. The Relativity Gyro was simulated by two surplus Atlas guidance system gyros, the telescope by means of a precise autocollimator designed and built at Stanford. The gyros were mounted on a surplus Minuteman I platform; much of the electronics from the Minuteman guidance system wad available, and with the addition of several key amplifiers we were able to combine the nominally 400 Hz Atlas instruments with the 4,000 Hz Minuteman I equipment to make a workable test bed.

Data from the autocollimator and gyros were interesting in themselves, revealing the types of differences to be expected from the two types of instrument. The Atlas two degree of freedom gyros have a ball bearing spin motor which generates sharp vibration spikes in the gyro performance spectrum. Using autocorrelation and cross-correlation techniques, we were able to identify with surprising clarity, not only the individual noise characteristics of the instruments but also to identify when disturbances originated outside the instruments. One interesting example was in the bearing characteristics of the Minuteman platform. For very small angle deflections the ball bearings behaved more like a spring restraint than a bearing. We observed and modelled highly non-linear amplitude characteristics. The non-linear amplitude dependence emphasizes the importance of operating instruments at the level of motion and disturbance that will be used in the final application.

The numerical programs and interpretation of data obtained on the fixed base simulator form an important library and body of experience applicable to the Relativity instruments. We have already made use of two of the computer programs in transcribing data from the 3-axis fluxgate readout of the Relativity gyroscope from fm recording analog tapes into a convenient digital form for use on the Sigma 5 computer. We are also giving consideration to applying in gyro tests the Fast Fourier Transform techniques and PSD (power spectral density) analysis developed for the simulator.

An account of the fixed base simulation work is given in the Ph. D. thesis of D. L. Klinger "Error Modeling of Precision Orientation Sensors in a Fixed Base Simulation" (Stanford University Aero-Astro Department Report SUDAAR No. 481 July 1974).

L. REVIEW OF STATUS AND RATE OF PROGRESS

We have taken the opportunity while writing this Annual Report to survey progress over the past 12 months. In the 1973 Request for Continuation submitted to NASA on April 30, 1973, we presented a flow diagram for the development of the experiment, and a schedule based on the proposed funding rate of $410,000 for the 12 month period of the Grant renewal. In fact the funding for October 1, 1973 to September 30, 1974 was $250,000 under the regular continuation Supplement 17, and $70,000 under special Supplement 18, making a total of $320,000 or 77% of the proposed amount.

We were able to cut a few corners to help maintain the pace, but progress in certain areas has been slower than we had hoped. The biggest delay has come because the final phase of research in developing the first London moment gyro readout has proved decidedly harder than we had expected. The temperature dependent magnetic fields in the dewar have added greatly to the labor in attaining field levels comparable with the London moment at 30 Hz spin speed. This problem is now partly under control.

In a few areas progress has been better than expected. Thus we had not anticipated obtaining this year a point-contact SQUID magnetometer that would withstand the launch environment.

The flow diagram prepared in April 1973 had a total of 81 critical points up to analysis of data from the final flight experiment, of which 60 covered the period up to freezing of flight hardware. We reviewed the situation first on July 31, 1973 and then again on November 30, 1974. By July 1973 there had been substantial progress on 10 of the 60 items (with none complete) and slight progress on 15 other items. By November 1974 two items had been dropped as no longer necessary, there had been substantial progress on 20 others, with 6 complete or nearly so, and slight progress on 17 further items. The original view at the full funding level had been a three-year effort before freezing flight hardware. Copies of the flow diagram with the progress data will be made available upon request.

Preparation of the Proposal in response to AO#6 gave the opportunity for a useful reassessment of the management plan and pricing of a flight program. The flight proposed under AO#6 is a simplified version of the original Delta mission defined in the first Ball Brothers Mission Definition Study. We thank Ball Brothers for assistance in preparation of the AO#6 proposal.

It was gratifying to discover that despite the 10% per annum cost inflation since 1971 pricing could be held down to a total of $23 million 1974 dollars, with many items at levels near or in a few instance even below the 1971 figures. The cost savings came about through the combined effects of progress in the laboratory and the following sources: (1) simplification of procedures in documentation and quality control from NASA guideline HB 5300, (2) use of a protoflight approach, (3) a spares plan based in most cases on carrying critical piece parts, replacement modules or plug-in circuit boards rather than comple "black boxes", (4) allowance for progress on key items of exponent hardware since 1971, (5) allowance for progress in electronic piece parts (integrated circuits), and greater selection of off-the-shelf components (black boxes).

THE EQUIVALENCE PRINCIPLE ACCELEROMETER

Work on the Equivalence Principle Accelerometer was started under Grant 05-020-019, but during the current reporting period it has been supported entirely by three other Contracts: MIT subcontract on NASA Grant 22-009-735;a Grant from the CalTech President's Fund PF 066; and related support from Johns Hopkins Applied Physics Laboratory Contract 600054. For continuity, and because of the high interest of the Equivalence Principle Experiment to NASA we shall continue reporting progress on it along with the Gyro Experiment.

A very large amount of progress has been made on the experiment during the past year. At the time of the last Annual Report (November/December 1973) only the central assembly of the experiment existed, and that was incomplete. Work has proceeded in two main directions: construction of the mechanical portions of the apparatus, and design and construction of a control loop and subtraction network for the test masses.

Construction of the mechanical hardware proceeded in stages. From January to April 1974 the levitation coils were wound, cast in place and tested. The inner levitation coil was completed quickly; however, we experienced considerable difficulties in constructing the outer levitation coil. The filled plastic backing for the coil did not stick properly to the copper cradle. As a result we ultimately decided to make do with a coil that had a deviation fron an ideal cylinder of ± 0.003 cm instead of ± 0.0003. The consequence will be a loss in signal/noise ratio for the apparatus: we will try to do better later.

A dewar stand of adequate mechanical properties was started in April and completed in July; it serves as a vibration isolation support for the dewar and magnetic shield set. A large portion of the dewar probe was also completed during this period. Design and construction of some superconducting control transformers and peripheral apparatus occupied several months. The final assembly was completed early in October.

Simultaneously with the above work we went ahead with design and construction of the controllers and subtraction network. Estimates of parameters for the test masses and control coils helped define the control problem early in the year. We soon found seismic noise to be a potentially serious problem. Accordingly we made a detailed study of the seismic noise background at the experimental location, made modifications to the design of the dewar stand, and went through several iterations in controller design. The existing vibrations isolation now appears to be just about adequate.

The data subtraction problem consists in trying to read out the difference incontrol effort to 1 part in 10^8, in order to obtain a sensitivity in the Eotvos ratio of 10^{-11}. Extensive analysis has shown that this can be done over a limited temperature range if the control gains are matched initially to 1%. We believe the matching can be provided by changing the standing currents in the control coils using a superconducting transformer. The design of the superconducting control transformers was considerably complicated by the need for extra windings to provide this matching function. The data subtraction system was conceived as an analog/digital system.

Only the analog portion is being built at present as we have not yet obtained a digital data acquisition and processing system. Recently we have worked on an interim visual digital readout system using analog/digital converters already purchased. Much of the electronics construction for both the controllers and the subtraction system has been done.

The main apparatus was cooled down in October. We soon found a number of minor problems: vacuum system leaks, inoperable heat switches, and broken wires. No fundamental problems showed up, but the lesser problems were sufficient to prevent taking any data on the actual operation of the levitation cradles or controllers. The dewar had a satisfyingly low boil off rate, only about 0.28 liquid liters of helium per hour, allowing about $4\frac{1}{2}$ days of operation with 30 liters of helium above the top of the experiment.

At present we are refurbishing the apparatus for a second run. We are making various modifications for greater ease in assembly and disassembly as well as even lower helium boil off.