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TEST RESULTS ON APOLLO
INERTIAL SUBSYSTEM (ISS) #4
by
4415
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April 1964

INSTRUMENTATION LABORATORY

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E-1541

TEST RESULTS ON APOLLO INERTIAL SUBSYSTEM (ISS) #4

ABSTRACT

This report contains the results of the testing of Inertial Subsystem (ISS) #4, the first ISS to be assembled, tested, and calibrated. The purpose and description of ISS #4 are reported, along with problems discovered during the tests and recommendations for their solution.

by James H. Flanders
Richard A. McKern
April 1964

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INTRODUCTION

The Inertial Subsystem (ISS) of the Apollo Guidance and Navigation System consists of a) the Inertial Measurement Unit (IMU) with gyros and accelerometers, b) three Coupling Data Units (CDU's), c) Display and Control (D&C) Panels for the astronaut interface, and d) the Power and Servo Assembly (PSA) providing the electronic support for the IMU, CDU's and D&C. Inertial Subsystem #4 of Block I was the first subsystem to be assembled, tested, and calibrated. The purpose of ISS #4 was to:

a) accomplish ISS integration,

b) evaluate subsystem compatibility with breadboard Ground Support Equipment (GSE),

c) evaluate the draft (ISS/ATP #1,015,497, released Class B on 8 May 1963) and,

d) train MIT and ACSP engineers in testing Block I ISS hardware.

During the summer of 1963, ISS #4 began its tests with a "breadboard" version of the PSA. In the fall of 1963, the "breadboard" PSA was replaced with a prototype operational version packaged in "blue module" hardware. The ISS tests were concluded on November 22, and the ISS #4 was turned over to the System Test Group at MIT Instrumentation Laboratory.

ISS #4 demonstrated the fundamental soundness of the design decisions to meet Block I ground rules. A total time of 1135.8 hours on the subsystem was accumulated without wheel failure or sign of degradation, except for a gyro suspension short to case and a noisy slip ring. ISS #4 was not intended to demonstrate inertial component specifications. However, a one sigma value of stability over a five day period was measured at 1 meru for gyro bias and 0. 44 cm/sec^2 for accelerometer bias.

The following problems were uncovered and corrective programs initiated in the course of the ISS #4 Tests:

a) Torque Pulses in one Pulsed Integrating Pendulum Assembly (PIPA) loop were observed to couple into other PIPA loops. This problem was substantially reduced by using three conductor shielded leads on the torquer lines in the IMU and by redistributing slip ring assignments.

b) The PIPA loop moding was found to be bi-stable, oscillating between its design value of 3:3 and a value of 4:4. An increase in PIPA damping coefficient from 80, 000 to 120, 000 dyne-cm/rad/sec is planned to ensure solid 3:3 moding.

c) The 3200 cps pulse width modulated temperature control system was observed to create 6400 pulse per second trains of spikes throughout the system. Circuit and shielding changes are currently being evaluated at MIT by the Thermal and Inertial Groups in order to provide the best solution.

d) The alignment and calibration of the gyros required modification of the original tests so that large error signals from the two gyros not under test would not bias the values measured on the particular gyro being tested. Appropriate moding changes were requested for the production Apollo Ground Support Equipment (GSE) to provide gyro caging as needed.

I. GENERAL

A. Description of the Apollo Inertial Subsystem.

The Block I Apollo Inertial Subsystem consists of a) the Inertial Measurement Unit (IMU), b) three Coupling Data Units (CDU's), c) Display and Control Panels (D&C) for the astronaut interface, and d) the Power and Servo Assembly (PSA).

The IMU provides a stable platform for three Pulsed Integrating Pendulums (PIP's) by means of a three-gimbal stabilization system utilizing gimbal mounted direct drive DC torque motors driven through stabilization amplifiers by error signals from three platform-mounted Inertial Rate Integrating Gyros (IRIG's). The temperature of the inertial components is maintained by heaters on the units themselves whose average current is proportional to sensed temperature deviation. Heat transfer to the gimbal case is augmented by blowers on the outer gimbal whose frequency of revolution is inversely proportional to heater current. The outer gimbal case contains passages for a water-glycol cooling fluid whose function is to provide a heat sink.

The Block I CDU's are electromechanical servos which provide multiple functions in the ISS. In the Fine Align Mode, they repeat the actual angle of the stabilized platform with respect to the spacecraft both in the form of incremental pulses to the Apollo Guidance Computer (AGC) and as a visual readout to the astronaut. In the Coarse Align Mode, they can receive gimbal angle orientation commands from the AGC and coarse position the stable member to the desired angle. In the Attitude Control and Entry Modes, they can receive spacecraft orientation commands from the AGC and generate an 800 cycle error signal for the stabilization control (SC) system proportional to the difference between the desired and actual spacecraft attitude.

The Display and Control Panels (D&C's) provide the astronaut with the means for operating and monitoring the Guidance and Navigation System. Normally, during ISS tests, the Display and Control will be part of the ISS and will be functionally checked. ISS #4 did not include the D&C equipment as part of its subsystem.

The Power and Servo Assembly (PSA) for the ISS consists of the first seven out of ten trays in the PSA. Electronic circuits are provided for power supplies, stabilization servos, coarse align servos, CDU servos, and pulse encoder circuits, PIPA loops, IRIG pulse torquing, temperature control and monitoring, failure monitoring, attitude error resolution and transmission, and ISS mode control.

B. Purpose of Inertial Subsystem #4.

ISS #4 was intended to be the means for:

a) accomplishing integration of the IMU, three CDU's, the ISS portion of the PSA, simulated D&C, and simulated AGC interfaces into a functioning Inertial Subsystem,

b) evaluating ISS compatibility with the breadboard Ground Support Equipment (GSE) to provide early support to the GSE group at MIT and ACSP in designing and building production GSE,

c) evaluating and correcting the draft Inertial Subsystem/ Assembly Test Procedure (ISS/ATP #1,015,497 released Class B on May 8, 1963) in order to pave the way for release of a Class A document*, and

d) to train MIT and ACSP test engineers in the actual testing of Block I ISS hardware.

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* The geometry and error analysis for the alignment section of this ATP is found in E-1230, Inertial Measurement Unit (IMU) Alignment Tests (Preliminary). The inertial component section of this ATP is supported by E-1297, Inertial Subsystem (ISS) Calibration Tests (Preliminary).

The prototype ultra-precision test table, Fig. 1, was installed in the test area in November, 1962. A first calibration of the table readout system was made at that time, followed by a second series in March, 1963.

The readout was found to be stable and within the specification of not greater than 5 arc seconds of uncalibrated readout error. Periodic monitoring of the laboratory floor stability indicated that within a typical 72 hour period less than 2 arc seconds of variation would be encountered. A breadboard version of the GSE was partially built up by ACSP in Milwaukee and given final form at the MIT Instrumentation Lab. Test cables were constructed and a prototype computer simulator for providing clock pulse generation, and output pulse shaping was fabricated by the Raytheon Company.

C. Plan for Inertial Subsystem #4.

Because of the timing of ISS #4 hardware, prototype CDU's and the IMU were to be ready before prototype or "blue module" PSA electronics. Accordingly, the PSA group built up a breadboard, rack-mounted PSA prototype in order to begin ISS testing. The PIPA loop electronics and IRIG Pulse Torquing Circuitry were provided by the PIPA Development Group. With the breadboard PSA, the first marriage of the ISS and GSE could be accomplished. Initial alignment measurements of physical angles in the IMU (see E-1230) and calibration of the inertial components (see E1297) could be accomplished.

Then, when the blue module packaging of PSA electronics for ISS #4 was accomplished, the checkout, alignment, and calibration could be repeated with the final hardware that would make up ISS #4 as it was to be turned over to the Systems Test Group.

Sections II and III cover the testing activities in narrative form. Specific subsystem problems are discussed in Section IV. The alignment, calibration, and general performance data are summararized in Tables I through VII.

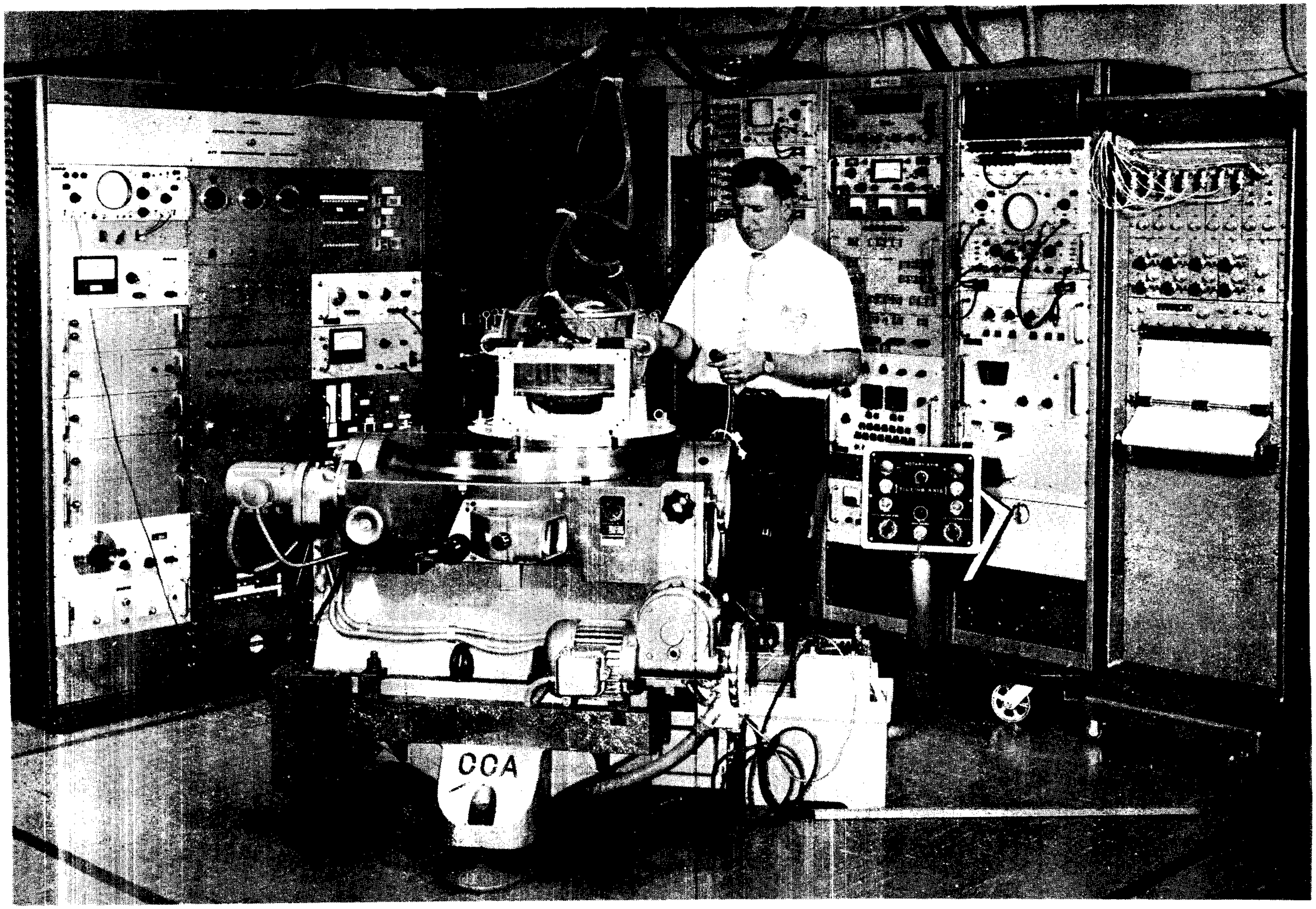

Figure 1. Inertial Subsystem #4 under test (Breadboard PSA version).

II. ISS #4 PHASE I - BREADBOARD, PSA VERSION

A. Buildup.

The IMU and the breadboard PSA were first mated in the PSA Laboratory without the GSE. This was possible because the rack-mounted PSA included its own DC power source, clock pulse generator, and a simplified moding with resolver command features. The stabilization loops were closed and found to be marginally stable. The temperature controller was checked out and the coarse align loops using simulated CDU's were successfully closed.

The IMU and the PSA Rack were moved to the ISS Test Station on May 29th with 3 hours of IMU-PSA running time. The IMU fixture's alignment to the table rotary axis had been measured with the prototype optical alignment bars (see Figs. 2 and 3). When placing IMU 4 onto the fixture, difficulty was experienced in getting the IMU case to settle down over the long pins on the IMU fixture. As part of normal procedure, the table was tilted to 90° so that the IMU was "hanging on the pins" before final tightening of the mounting bolts to 150 in-lbs. The reason for this is to try to simulate as closely as possible the gravity loading which will prevail when the IMU is fitted to the navigation base in the Command Module.

Integration of the ISS with the GSE continued through the month of June. The usual phasing problems between the IMU resolvers and the CDU's were encountered and solved. A 6.4 K pps spike train was found to be generated on the ducosyn excitation voltage because of cross coupling within the breadboard 3200 cps supply from the 20 v square wave generator to the 2 v ducosyn output. On the 21st of June, Z IRIG #1A1 was removed because a TG suspension short-to-case was detected. The replacement IRIG was #1A3. This occurred at 12.2 hours elapsed test time in the

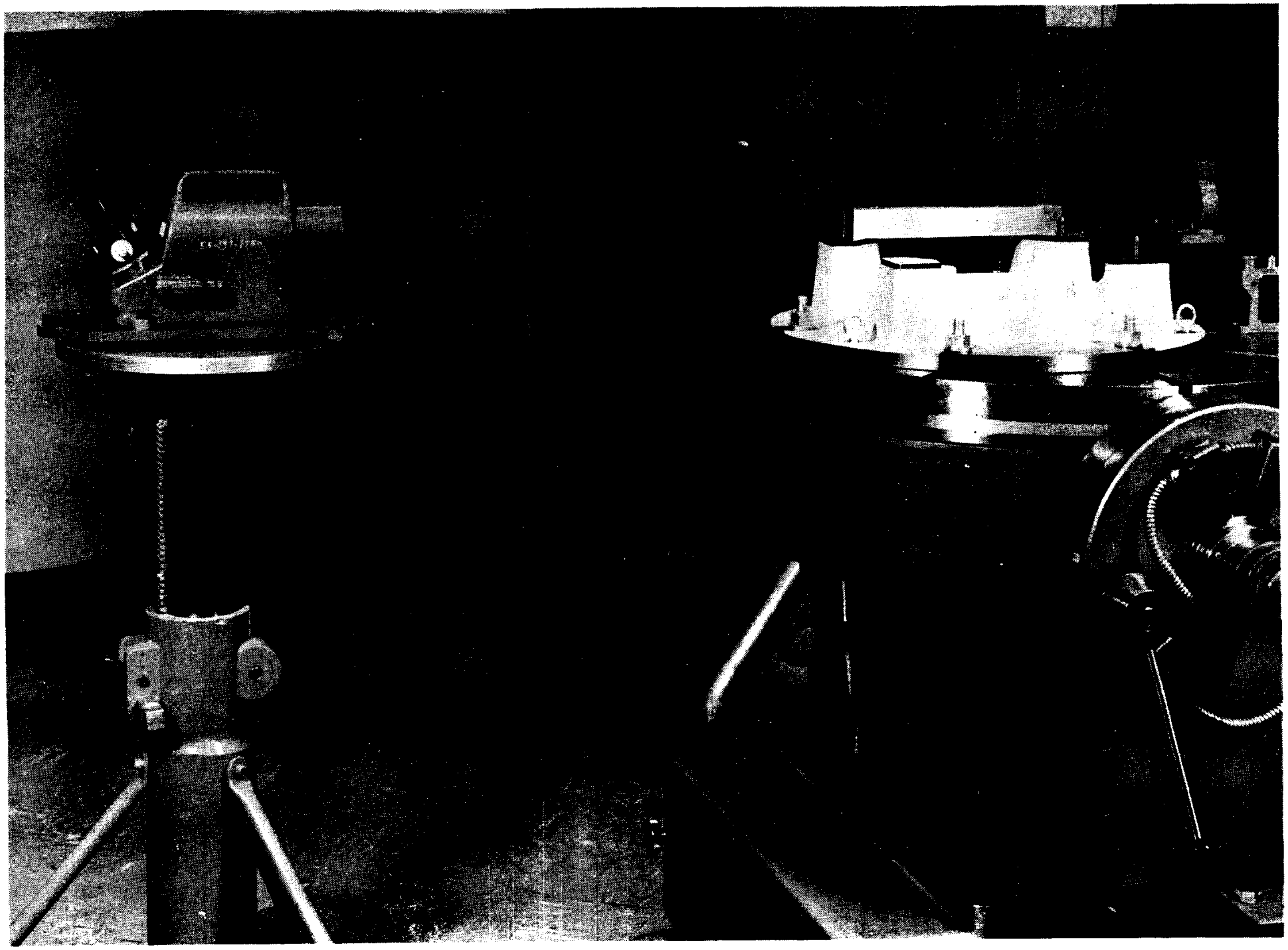

Figure 2. Measuring IMU fixture axis alignment to table - top axes about X and Y. (JDC 00011)

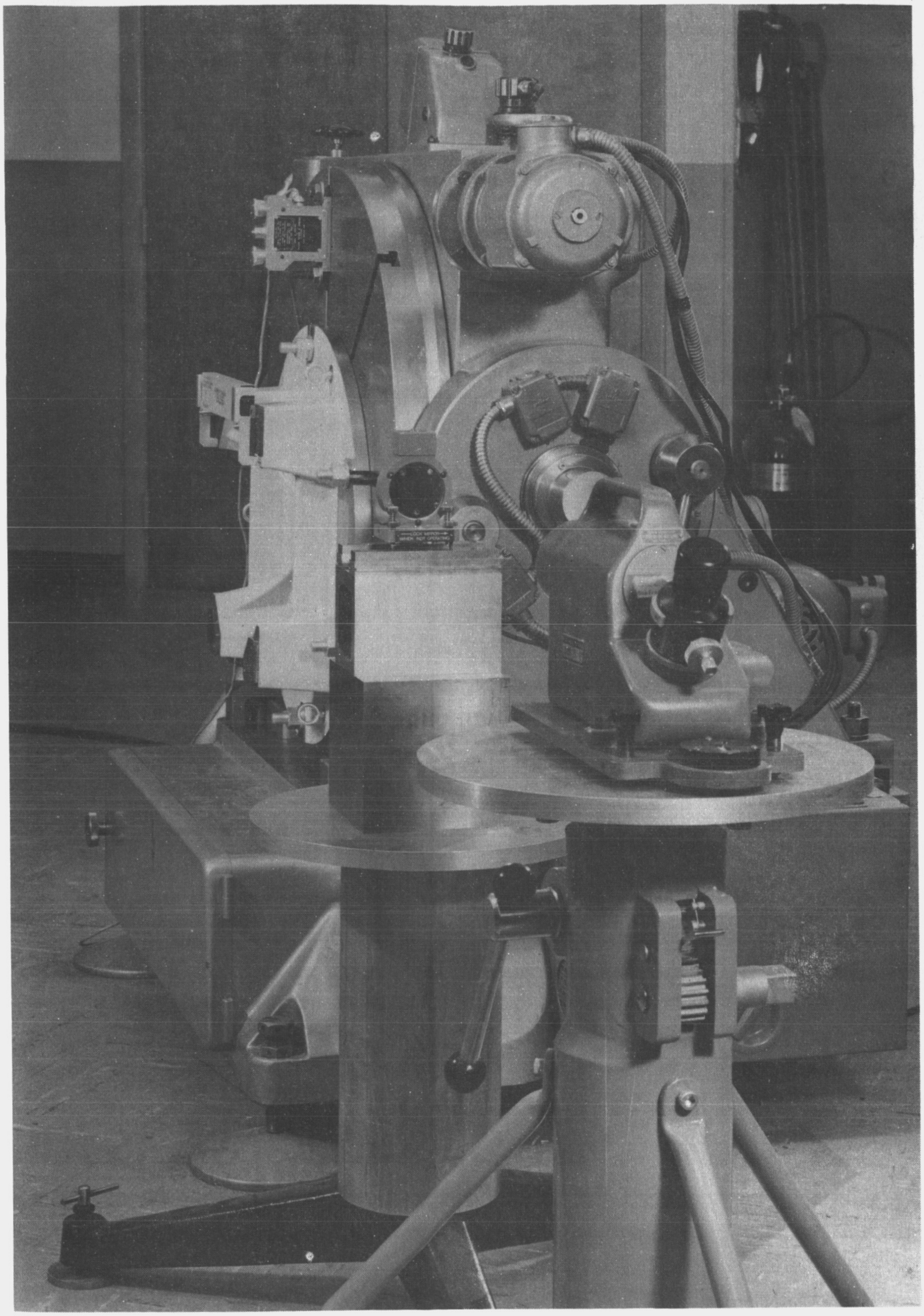

Figure 3. Measuring IMU fixture axis alignment to table - top axes about Z (JDC 0012).

ISS area, (See Malfunction Report #2). *

During this phase, attention was paid to noise levels on the torque motor voltages. With the long ISS test cable runs, the levels were typically 10-12 volts peak-to-peak. When short, direct cables were substituted, the levels dropped to well below 10 volts, peak-to-peak. 300kc oscillation on the IRIG error outputs was reduced to an acceptable low level by floating the individual shields along the interconnect cables to reduce existing cable line capacitance.

On June 28th, the Middle Gimbal Intergimbal Assembly was replaced because the E-4 slip ring proved to have intermittent high resistance (See MR #3).

By July 1st, the GSE panel had entire control of ISS moding. Two-shift test operations were initiated. Elapsed time on the ISS was 41.8 hours.

B. Initial Testing.

Early in July, the initial JDC's in the ATP were completed in the area of power supplies, CDU performance, and moding. Temperature Control JDC's were not run at this time.

The precision set feature in the GSE was found to be stable and to drift less than 0.20 seconds of arc in one hour. The test crew continued to encounter problems with system noise at 1600 cps and 300 kc. It was also determined that the 3200 cps power supply frequency dropped too low when free running in the backup mode. By the end of July, it became apparent that difficulty would be encountered in the alignment JDC's of the ISS/ATP which depend on precise, closed loop PIPA nulls to measure angles internal to the IMU. A stable null on one PIPA loop was made impossible by the bi-modal pulsing on another PIPA loop. On July 31st, 313 hours

*Malfunction Reports (MR's) were filled out and forwarded to the Apollo Reliability Group on every hardware deficiency encountered, providing it was clearly identifiable and was not a breadboard item. ISS #4 MR's were numbered consecutively.

had been accumulated on ISS #4.

The cross-coupling between PIPA loops was given a great deal of attention. Grounding changes were made both in the cables and the PIPA electronics drawer, cables were separated, separate 30 volt and 120 volt power supplies were used, and changes were made to the cards of the PIPA circuitry. No satisfactory improvement was obtained.

On August 8th, alignment JDC's were begun using only one PIPA loop at a time. The alignment procedure was successfully completed in 28 hours of continuous running. Extra PIPA bias measurements were made between JDC's to eliminate bias shifts where they might have contributed directly to alignment error. The resulting alignments are listed in Table I. This phase was completed at an elapsed time of 446 hours. It was discovered that the middle gimbal pot in the precision set middle was defective because of intermittent wiper arm contact. (See MR #5)

IRIG alignment tests were initiated in mid-August. The theoretical approach specified in E-1230 was not immediately successful. Small misalignments had to be measured by small outputs of the IRIG preamplifiers with the stabilization loops open. It was learned that cross-coupling existed between IRIG error signals when the measured signal was small and the other IRIG floats were in the stops and causing maximum output. This is a result of all IRIG error signals being generated with respect to a common low line. The IRIG alignment tests were modified to minimize this problem to an acceptable level, by careful nulling and caging and by driving the driven gimbal with IRIG pulses in fine align.

During August, much attention was given to the problems of PIPA bi-stable moding and cross-coupling by the personnel of the PIPA Group and by the ISS Test crew.

C. PIPA Loop Experiments.

During September, the PIPA loops were gradually broken out between the instrument in the stable member and the PIPA drawer in the PSA rack. Separate pre-amps were used outside the IMU and all slip rings and IMU connectors and harnesses were by-passed. In this configuration, cross-coupling was greatly diminished and on September 10th a Y PIPA null of 8 minutes duration was obtained with the Z PIPA loop closed. The step-by-step replacement of PIPA loop wiring back to operational paths was carefully done to determine the steps which caused the biggest increase in cross-coupling. The most significant degradation came when the torquer signals were changed from external temporary wiring between the stable member and the outside of the IMU to the internal path through harnesses, connectors, and slip rings. Accordingly, the conclusion was reached that the PIPA torquer leads should be shielded in the IMU to the maximum extent possible and that the respective PIPA torquer leads should be separated on the slip rings where possible.

October 2nd, 3rd, and 4th were spent getting some basic thermal response data on the stable member. Then the ISS was shut down for changeover to the blue-module tray-mounted version of the PSA. The elapsed time on the ISS was 860 hours.

D. Summary

To summarize phase I, a large part of the Inertial Subsystem integration problems was uncovered and analyzed even before the blue-module PSA arrived. A complete set of alignment data was recorded. The inertial components were calibrated and a beginning was made on the attainment of stable inertial performance. The draft ATP was evaluated and changes recommended to refine testing methods.

III. ISS #4 PHASE II - BLUE MODULE, PSA VERSION

A. Buildup.

On October 7th, the PSA Test J-Box was mounted on the Test Table, and the test cables were installed from this J-Box to the GSE J-Box, the Computer Simulator, the CDU Rack, and the IMU. The PSA Test J-Box is on the Test Table near the IMU so that short cable lengths can be maintained in the PIPA loop. This configuration is shown in Fig. 4.

Each individual tray was checked out by installing it empty into the table-mounted test fixture where it also is plugged into the J-Box. 28 volt system power was applied to the J-Box and every module pin located on the empty tray was checked with a Simpson volt ohmmeter to be sure that 28 volts was on only the correct pins and that only ground pins had a low resistance to ground.

Each module was visually checked upon receipt. By taking this care, it was possible to find shorted leads, broken wleds, and components which extended beyond their heat sink cavities. Initially, difficulty was experienced in attaching the modules to the PSA trays. The specified torque value on the screw of 15 in-lbs sometimes resulted in fracture of the screw. Primarily, this was due to the threaded holes in the tray not being properly cleaned out.

The first loops to be closed were the coarse align loops. Phasing problems were encountered and solved between the IMU 1-X Resolver and the CDU. Inadequate grounding between the CDU Motor Drive Amplifiers and Tray 5 caused excessive CDU drift. A temporary improvement was obtained by using a star washer between the module heat sink and the tray. A residual Motor

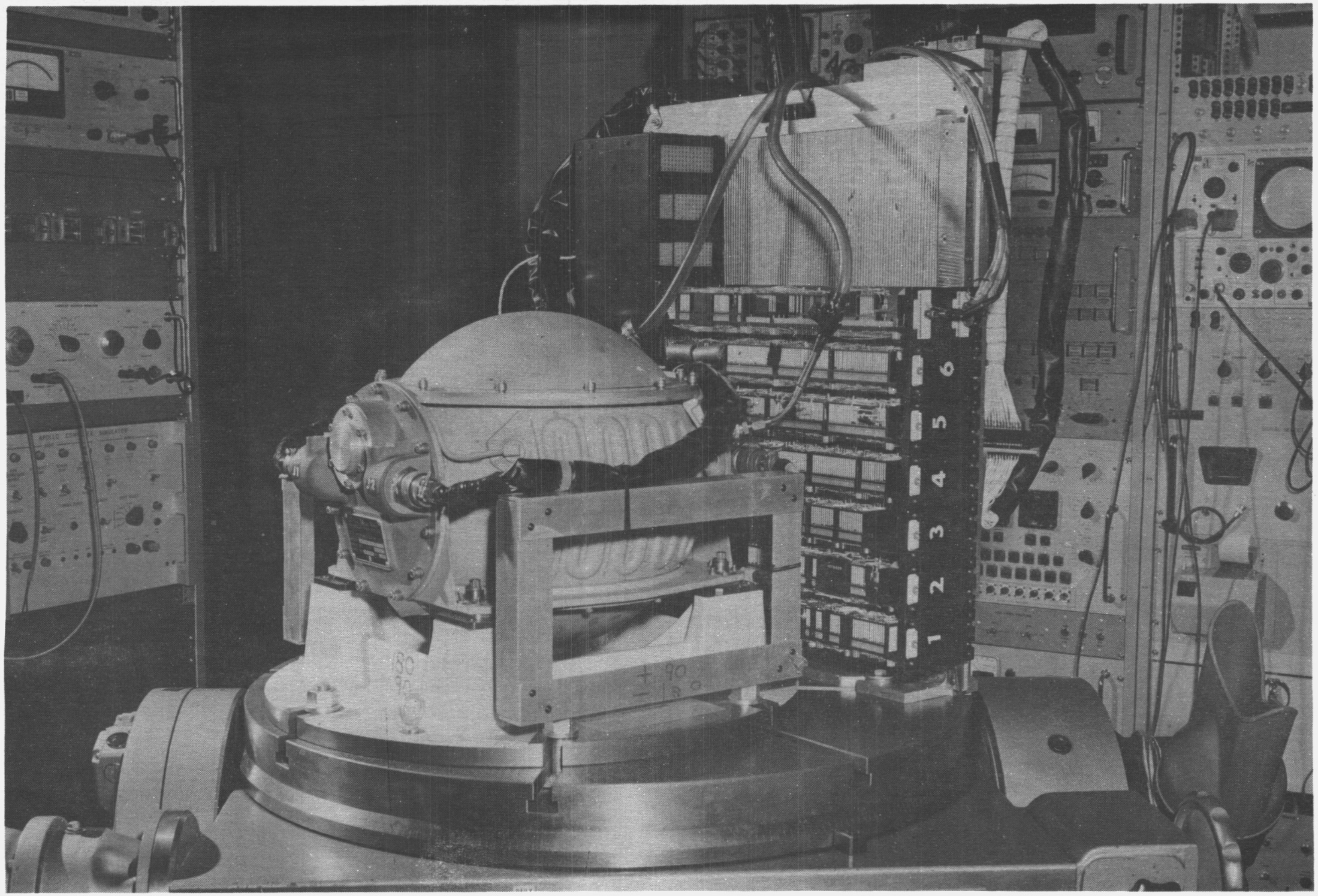

Figure 4. Test configuration for Block I ISS (Blue Module PSA version).

On November 8th, following definitive PIPA cross-coupling tests with 1024.3 hours on ISS #4, test activities were shut down to rewire IMU #4 so as to separate and shield the PIPA torque wires. At the same time, all three IRIG's were turned over to the IRIG Test Station for calibration at the component level. The Z PIPA and its calibration module were turned over to the PIPA Test Station for similar calibration. The X and Y PIPA were stored in an oven.

B. Final Test Activities

On November 14th the Inertial Subsystem was re-assembled and the power turned on. Complete sets of IRIG and PIPA calibration data were taken. In addition, the PIPA cross-coupling was reduced to the point where it was barely detectable. Subsequently, the PIPA torquer shielding on the Stable Member was by-passed to ascertain how much improvement came from inter-slip ring shielding only. Test results indicated that stable member shielding was not the principle contributor to the decrease of the cross-coupling phenomena. Instead this beneficial decrease was attributed primarily to the shield changes installed between one set of slip rings and the next within the IMU.

The final step taken on ISS #4 was to repeat enough of the Alignment JDC's to reset and seal the 16X Resolver electrical nulls to within the following values (See Fig. 5):

$$\epsilon_{OGR} = -24 \pm 8 \text{ seconds of arc}$$

$$\epsilon_{MGR} = -0.5 \pm 7 \text{ seconds of arc}$$

$$\epsilon_{IGR} = -13.5 \pm 4 \text{ seconds of arc}$$

Finally, on November 22nd with 1135.8 hours of elapsed time on the subsystem, the tests were concluded. The IMU was removed from the table (See Fig 6) and the trays were removed from the fixture in preparation for release to the System Test Group. A recheck of the levelling of the unloaded table showed

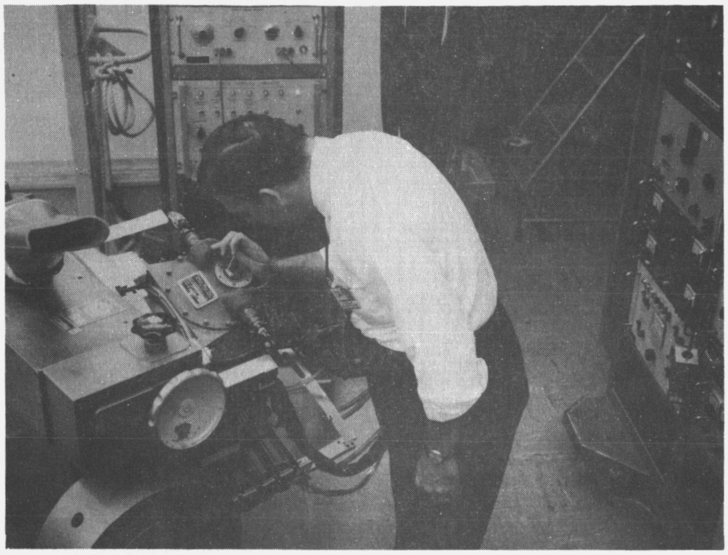

Figure 5. Applying indicator sealant to IMU #4 Resolver Zero Adjustment Module.

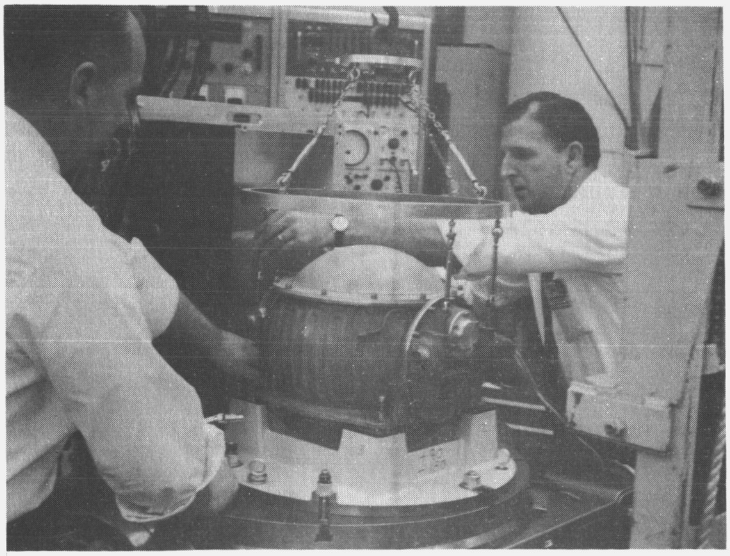

Figure 6. Removing IMU #4 from test fixture.

that, with the tilt angle $\phi = 0^{o}00'00''$, the Rotary Axis was only 6 arc seconds from local vertical.

IV. ANALYSIS, CONCLUSIONS, AND RECOMMENDATIONS

A. General.

It is the purpose of this section to discuss subsystem problems which were discovered while testing ISS #4. This discussion will be divided into the same three general groups which compose the individual tests or Job Description Cards (JDC's) of the ATP, namely 1) Operational Tests (JDC 0009 through 00160 and JDC's 00190 through 00193), 2) Alignment Tests (JDC 00161 through 00188), and 3) Calibration Tests (JDC 00200 through 00244).

B. Operational Tests.

The power supply tests (JDC's 0040 through 0046) were completed without difficulty, on both the breadboard PSA and the blue module PSA, except that the free-running or unsynchronized operation could not be tolerated because the ducosyn supply frequency dropped so low that the inertial component suspension was degraded significantly. Also, the dynamic range of the automatic gain control of the ducosyn power supply had to be increased to make up for line losses from the module to the stable member.

The temperature control tests (JDC's 00050 through 00060) were never completely performed on ISS #4. The Temperature Monitor Panel in the breadboard GSE was available for the Phase II Blue Module PSA tests. However, the temperature loop dynamics tests (JDC's 00057, 00058, 00059, and 00060) take a long time and the schedule did not permit trying them out.

The PIPA loop operational tests (JDC's 00065 through 00070) are designed to determine whether these loops are operating properly, without regard to their precision or stability. These tests were completed without difficulty.

The stabilization loop operational tests (JDC's 00075 through 00076) analyze the performance of the system stabilization loops in the Fine Align or inertially stabilized mode. JDC 00075 measures the in-phase and quadrature components of the steady state gyro error signals. In general, the quadrature levels were always well below the specified level of 1.2 volts. Under some circumstances the in-phase error voltage at null exceeded the desired value of 110, 75, and 70 millivolts for the inner, middle, and outer gimbals respectively. This is not of major concern for this developmental system. Torque motor voltages in the steady state are specified as ± 6.25 volts. The actual level was found by measurement to be very sensitive to ground loops and cable capacitance in the ISS test configuration.

Step responses and frequency responses were taken in JDC's 00076 and 00077. The frequency responses, corrected for recorder dynamics, are displayed in Figs. 7, 8, and 9. The secondary resonances displayed by the middle and outer gimbals at 40 and 35 cps were not predicted by the linear transfer function* for IRIG Error Response to a test input. This function has a first order lead term in the numerator at 161 rads/sec and a second order denominator term at 278 rads/sec with a damping ratio of 0.8. A synchronizing transient was found when going from the coarse align to fine align mode which is in excess of the expected transient due to coarse align loop standoff and IRIG float freedom. This transient causes up to 10^{o} of gimbal angle offset and is attributed to a condenser charge at the torque drive amplifier input of the servo amplifier. This condenser charges up in coarse align mode from the demodulated IRIG error signal and is discharged upon entering the fine align mode. This problem is under study for a Block I change.

The CDU Operational Tests are covered in JDC's 00085 through 00097. These tests check the CDU loops in all modes. The CDU's in ISS #4 were Class B prototypes and it was not expected that they would meet the subsystem specifications in all cases. (Ref: 10 July 63)

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*Ref: Performance Function - Apollo Stab. Loops - ACSP/XDE 34-5-519, Rev B

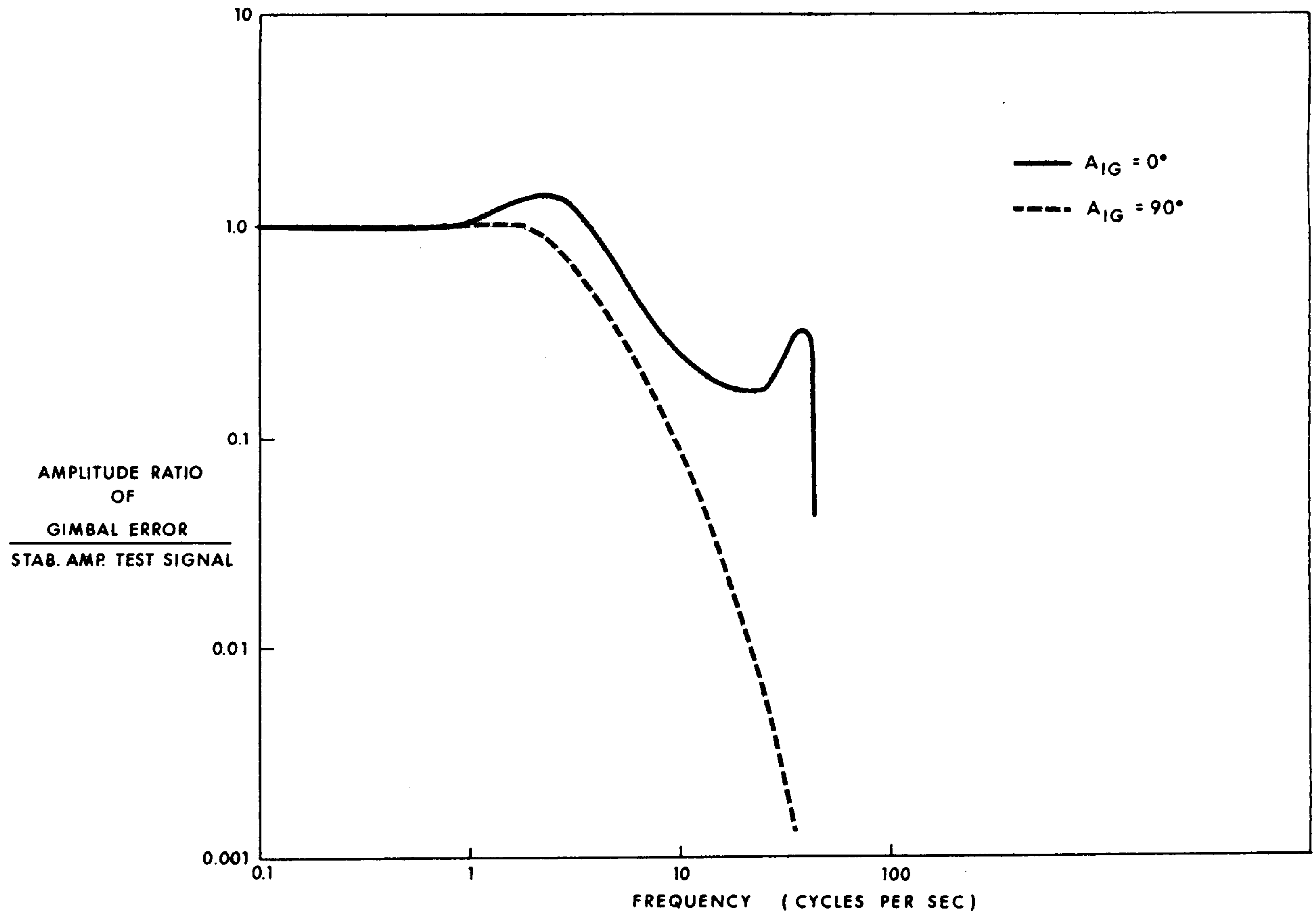

Fig. 7. Outer gimbal frequency response

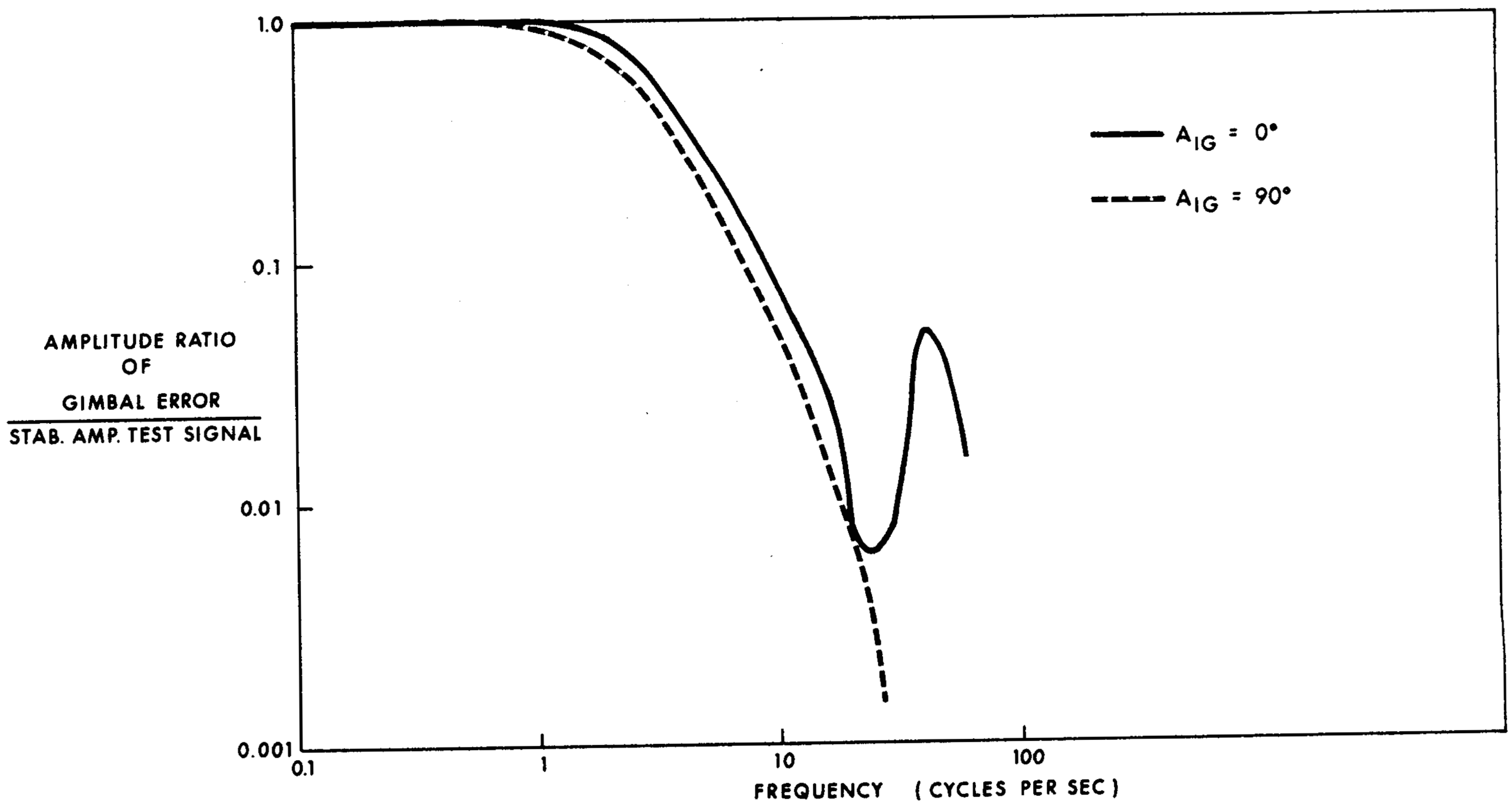

Fig. 8. Middle gimbal frequency response

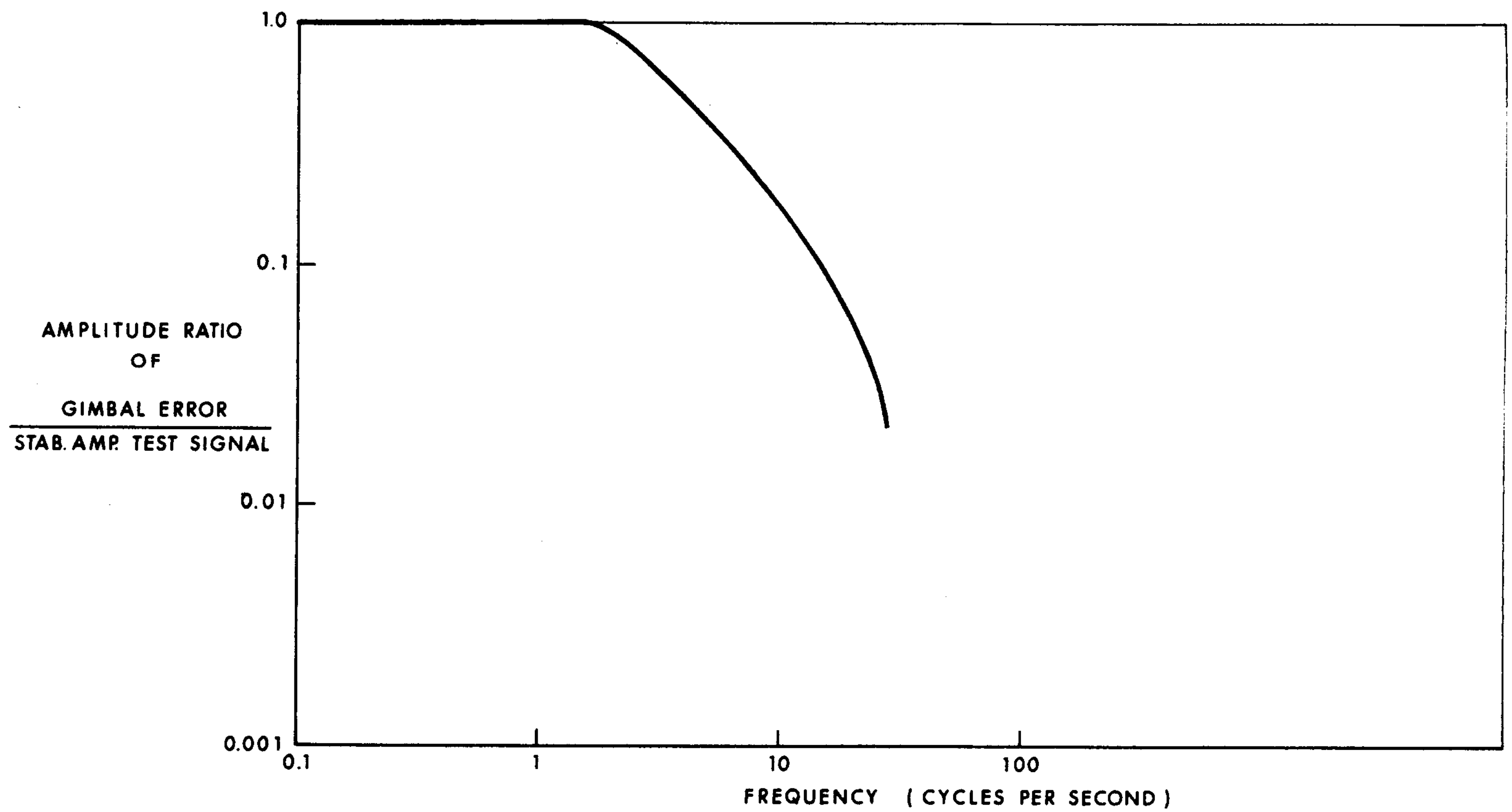

Fig. 9. Inner gimbal frequency response

In general the Subsystem Mode Tests, as covered in JDC's 00097 through 00112, and the G&N Inidcator Panel JDC 00119 could not be done because the ISS #4 configuration did not include any D&C. Moding was accomplished only from the control panel of the Breadboard I GSE.

It was not possible to operate ISS #4 with the Blue Module backup system because the 3200 cps ducosyn frequency dropped so far (2900 cps) that the PIPA's and IRIG's would lose suspension. The Blue Module Failure Detect Module was checked out successfully in the subsystem.

The cardinal point checks of the signal to the Ball Attitude Indicator (JDC's 00190 through 00193) were done successfully on a simulated basis. The maximum and minimum coupling outputs were within specification.

This concludes the discussion of the operational JDC's as they were done on ISS #4.

C. Alignment Tests.

The alignment tests are based on the theory and procedures outlined in E-1230 Inertial Measurement Unit (IMU) Alignment Tests, Preliminary. Data on alignments existing inside the IMU is based on the IMU 16X Resolvers, PIPA's and IRIG's used in a succession of combinations. The results of these JDC's 00161 through 00188 are summarized in Table I.

Two questions of interest in this section are a) how good are the tests and b) how good were the alignments. Before going into further detail on the PIPA alignment test results, a discussion of the PIPA loop cross coupling problem is in order.

ISS #4 was troubled by current being coupled between torquer lines of one PIP to the next. This cross-coupling was seen when the test engineer was trying to null the PIP. A sudden change of moding between 3. 3 and 4. 4 on another PIP would change the time sequence of cross-coupled energy into the PIP under test. The average coupled current level on the torquer lines continuously changes its magnitude and polarity with respect to the required current under these conditions. Sometimes plus current pulses are coupled and sometimes negative pulses are coupled with the result that the PIP under study can be nulled at one angle with respect to local vertical and then suddenly a new angle for null is required.

The change made to minimize cross-coupling effects on PIP torquer lines was to shield the positive, negative, and return torquer lines with three conductor shielded wire from the IMU connector, J4, to the individual PIP's. Careful attention was paid to the use of shielding on all torquer lines to the slip rings and reassigning the torquer lines to different slip rings so as to separate one PIP from another as far as possible. It was not possible to provide shielding inside the slip rings.

Next there follows a discussion of various figures of merit on the alignment test results. One such figure of merit can be the shift of the parameter θ_{HOGA} between two widely separated measurements.

θ_{HOGA} is the table rotary axis angle at 90^{o} of table tilt which places the gimbal case Outer Gimbal Axis a) in the local horizontal and b) approximately East. Page 19 of E-1230 lists the maximum expected uncertainty of θ_{HOGA} as ± 5.8 seconds of arc. A comparison follows between the value measured with IMU #4 and the Breadboard PSA on August 8th and the value measured with the same IMU #4 and the blue module PSA #4 on November 21st.

	θ_{HOGA}	
BB PSA (8 Aug)	259^{o} 31′	36.5′
BM #4 (21 Nov)	259^{o} 31′	7.5′
Shift		-29.0′

This shift exceeds the predicted uncertainty and has not been explained as yet.

A second shift was measured which was more significant. ϕ_{HRA} is the tilt angle to place the table rotary axis in the horizontal plane. It is measured by rotating about the table rotary axis bearings and using X PIPA nulls. ϕ_{HMGA} is the tilt angle necessary to put the Middle Gimbal Axis in the horizontal plane, when the Rotary Angle = θ_{HOGA}. This is measured by rotating about the Middle Gimbal bearings and using Z PIPA null. Finally ϕ'_{HMGA} is the tilt angle necessary to put the Middle Gimbal Axis in the horizontal plane, when the Rotary Angle = $\theta_{HOGA} + 90^{o}$. It is measured by rotating about the table tilt axis bearings and using Z PIPA nulls. A comparison of data for these intermediate test parameters follows.

	ϕ_{HRA}	ϕ_{HMGA}	ϕ'_{HMGA}
BB PSA (8 Aug)	$90^{o}0'\,08''$	$90^{o}0'\,04''$	$89^{o}59'\,10''$
BM PSA #4 (21 Nov)	$90^{o}1'\,15''$	$90^{o}0'\,47''$	$89^{o}59'\,47''$
Shift	$+67''$	$+43''$	$+37''$

The sign of the shift is unexpected because the November data is taken with a greater off-balance tilting moment of such a direction that one would expect a level indication at a lower magnitude angle than the August value. The conclusion drawn from this data is that over a three-month period unexplained shifts occurred between a half and one arc minute of magnitude.

On a short term basis, the stability of θ_{+1g} (the angle set into the table for alignment of an accelerometer with local vertical) is a useful figure of merit. During both the August and November PIPA alignment runs, frequent accelerometer bias checks were made giving repeated values of θ_{+1g}. The stability of this number is an indication of floor, table, fixture, and precision set stability over the test run interval. Over the 28 hour period of the August run, the one-sigma variation of θ_{+1g} for all three accelerometers was 8 arc seconds. Fewer data points were secured when the alignment tests were run for the blue module PSA. This data is summarized in Table II.

A final evaluation of the PIPA alignment section of the JDC can be obtained by examining the residual values of ϵ_{OGR},

ϵ_{MGR}, and ϵ_{IGR} 16 X resolver null misalignments. These residual values remain after using the adjustment in the Alignment Module to null a PIP whose input axis has been offset from local horizontal by the detected value of null misalignment.

The final values are given below:

	ϵ_{OGR}	ϵ_{MGR}	ϵ_{IGR}
JDC #	167	171	174
Aug.	- 4″	+ 2′07.5*	- 08.5″
Nov.	- 24″	- 0.5″	- 13.5″

In concluding this discussion, it is clear that the specified objectives of the tests from the standpoint of accuracy were not achieved by the two versions of ISS #4. However, the feasibility and soundness of the concept were established. It remains for the later systems with Class A hardware to prove that the stability and accuracy predicted for these tests can actually be achieved.

The IRIG Alignment tests, as described in E-1230, proved to have a number of shortcomings when it came to their practical application with ISS #4 hardware. The tests themselves consist of driving a given gimbal and monitoring the open loop float angle (Signal Generator output) of a given IRIG whose input axis is supposed to be perpendicular to the axis of rotation. The output voltage can then be related to the misalignment.

The gyro whose alignment is being measured may provide a relatively small voltage output. In the original test concept, the other two gyros were open loop and jumped into their stops in the course of the test rotation. These latter two gyros thus put out large signals which, because of electrical cross-coupling, swamped out the signal coming from the measured gyro. The cross-coupling is believed to be caused by bringing out gyro pre-amplifier signals and resolved gimbal error signals all on a common low path. This is not a problem during system operation because with closed stabilization loops all three gyros operate nearly at null.

* This large value is due to handicap of a defective module potentiometer.

The test procedure was modified on August 21 to decrease the cross-coupling problem. The gimbal, instead of being driven by the CDU in Coarse Align, was driven in Fine Align by pulse-torquing the appropriate gyro from the Computer Simulator. Thus, this gyro was kept near null. The second gyro was kept caged by introducing a selective caging capability into the GSE. Finally, the third gyro was pulse-torqued to null, the bias was reset with positive pulses and left in open loop to respond to misalignment inputs as originally planned in E-1230.

The change achieved by this procedure is shown in Table I, Section B.

D. Calibration Tests.

PIPA Calibrations were originally described in E-1297, Inertial Subsystem (ISS) Calibration Tests (Preliminary). The test was specified as using the output of the forward-backward counter module since the counter was designed on the assumption that the PIPA loops would have a solid 3:3 mode. Under this assumption, the counter output would be the true net count desired for the test. ISS #4 actually turned out to have bi-stable PIPA loops that operated between 3:3 and 4:4 modes. This meant that the output of the counter on one line would not represent a true net count because of the 4:4 pulses.

The test was changed to recognize this fact and the test setup and equations were changed to use the "P" or "N" line of the Binary Current Switch. This line was used to control the counter gate in the same manner as had been planned for the forward backward counter output. Knowing that the sum of positive or "P" pulses and negative or "N" pulses has to equal 3200 in any second, it is possible to reconstruct net pulses as originally planned.

$$
\begin{aligned}
P - N &= P - (3200 - P) \\
&= 2P - 3200 \\
&= N_A \text{ as defined on page 13 of E-1297.}
\end{aligned}
$$

During the Breadboard PSA operations, the calibration tests were worked out, and it was found possible to adjust bias and scale factor. More extensive PIPA calibration was done after converting to the Blue Module PSA. This date is listed in Table III. In each case, the first value listed is the final calibration module setting.

Special testing was done on the Z PIPA to evaluate the effects of loop closing on Scale Factor uncertainty. The results shown on November 5th were run in succession with the PIPA loops turned on after allowing the float to reach its stop. On closing the loop, it was found that the PIP preamp would go from a saturated signal through null and overshoot before the PIPA loop would actually close. This is caused by the saturation effects during the build-up of the +28 volts on the PIP preamp at the time of loop closure. The effect lasts for more than one second and it therefore outlasts the 300 millisecond delay built into the 120 volt supply.

Notice that upon the seventh closure, the Z PIPA scale factor changed by more than 600 parts per million. The testing done on the 6th of November included the effects of a back-to-back diode circuit, mounted just after the phase shift network at the PIP preamp input, to limit the input signal. Although the tests of November 6th were limited, the diode circuit seemed to decrease the probability of a turn-on Scale Factor shift. Further work will be done on this problem in Inertial Subsystem #5.

The one sigma variation of X, Y, and Z PIPA closed loop biases combined for the November 15, 18, and 20th data points is 0.44 cm/sec^2.

The IRIG calibration method, as proposed in E-1297, consists of tracking a single IMU gimbal with the CDU as it drifts in response to earth rate on a particular gyro in a particular orientation. One pair of orientations produces non-compensated bias drift (NBD) and acceleration drift along the spin reference axis (ADSRA). A second pair of orientations produces a second and redundant value of NBD and the acceleration drift along the input axis (ADIA). Finally, gyro pulse torquing Scale Factor (SF_G) is checked by counting the number of gyro pulses required to achieve a complete 360° rotation of the gimbal under gyro control.

In these tests, both other gimbal axes are held at null by the GSE precision set loops. Both gyros which are not under test are held near null by the special caging capability in Fine Align added to the GSE.

The IRIG calibrations were done substantially as proposed in E-1297. The results of these tests are shown in Table IV. All data given before November 6th is developmental in nature and is indicative of the test problems that had to be worked out. Also listed in the table is data taken at the MIT IRIG Test Station. This data provides a comparison between two test methods and configurations, one at the component level, and the other at the ISS level.

The major uncertainty predicted for this test method is the resolver chain accuracy since the CDU is used to read out actual gimbal angles. This uncertainty was minimized by allowing the drifting gimbal to traverse a trial 64 pulse of 0.7 degree increment from 359.3 degrees to 000.0 degrees. The actual data was taken during the second drift increment from 000.0 degrees to 000.7 degrees. This has the double advantage that unknown transients associated with the start of drift are minimized and the 16X Resolver is used in the identical optimum sector each time.

The absolute error from the IMU 16X Resolver through the CDU chain in the Fine Align mode to the encoder output using one complete encoder revolution is now the major cause of remaining uncertainties. It was determined that an error of approximately 5 arc seconds exists in the chain via special testing of the Outer Gimbal CDU chain from 0° to $+\,000.7^{\circ}$. Compensating the X Gyro Calibration results for this error results in the data shown in Table V, showing a standard deviation in NBD of 1 meru. It is felt that during CDU and 16X Resolver checkout a predicted error figure should be developed for use in compensating the Gyro Calibration Tests for best results.

Limited gyro torquer SF testing was carried out for all gyros to validate the testing procedure. This data is listed in Table VI. The IRIG Calibration modules were not normalized in ISS #4 for perfect scale factor. The 360° torquing of the IRIG's during Scale Factor tests may prove troublesome because of heat input into the torquer end of the IRIG. Specifically, with 114 milliamps of torquer current it was determined that a 3/4 watt thermal input is applied to the IRIG.

TABLE I

SUMMARY OF IMU 4 ALIGNMENTS

A. PIP Misalignments With Respect To Stable Member Ideal Triad

(α_{n_m} = Misalignment of the "n" PIP's case fixed triad about the stable member "m" axis)

NOTE: At the time of these tests the PIP prealignment mounting rings were development items and do not exhibit the accuracy of later mounting units.

PIP #	PARAMETER	PIPA TEST STATION	IMU 4 AUGUST	IMU 4 NOVEMBER
1AP10	α_{x_y} (JDC 177)	-	+1' 43"	—
	α_{x_z} (JDC 170)	- 1'52"	-3' 29"	-2' 31"
1AP11	α_{y_z} (JDC 175)	-46' 35"	-46' 17"	—
	α_{y_x} (JDC 176)	—	+9' 56"	—
AP2	α_{z_x} (JDC 172)	- 2' 33"	-6' 30"	-10' 48"
	α_{z_y} (Zero by definition of Inner Gimbal 16X Resolver Null. Null setting appears as ϵ_{IGR})			

TABLE I - (cont)

B. IRIG Misalignments With Respect To Stable Member Ideal Triad (Units = Milliradians) (γ_{n_m} = Misalignment of "n" IRIG's case fixed triad about the Stable Member "m" axis.)					
IRIG #	PARAMETER	IRIG TEST STATION		IMU 4 (AUGUST) ORIG. TEST	IMU 4 (AUGUST) REVISED TESTS
		ACCEPT	NOV. RECHECK		
66	γ_{x_y} (JDC 181)	—	—	-1.2	-1.5, -1.5
	γ_{x_z} (JDC 182)	< ±.1	-0.9	-2.3	-1.5, -1.4, -1.5
IA2	γ_{y_z} (JDC 184)	—	—	+0.1 -0.1	0.0
	γ_{y_x} (JDC 185)	< ±.1	-0.70	+1.3 +0.8	-0.3 -0.2
IA3	γ_{z_y} (JDC 187)	—	—	-0.1 +0.8	+0.8 +0.8
	γ_{z_x} (JDC 188)	< ±.1	+0.8	+4.0	-1.6
				+4.0	-1.2
				-4.0	-1.7

Specified Maximum γ = 3 Milliradians

TABLE I - (cont)

C. Inter-gimbal Non-orthogonalities

PARAMETER	SPEC.	AUG.	NOV.
Inner to Middle ($_{IGA}$) (JDC # 172)	±60''	-45''	-8''
Middle to Outer ($_{MGA}$) (JDC # 169)	±60''	-44''	-45''

D. 16X Resolver Null Residual Errors

PARAMETER	SPEC.	AUG.	NOV.
ϵ_{OGR} (JDC 167)	±8	-4'' ± 8''	-24'' ± 8''
ϵ_{MGR} (JDC 171)*	±7	2' 08'' ±7''	-1'' ± 7''
ϵ_{IGR} (JDC 174)	±4	-9'' ± 4''	-14'' ± 4''

The large value of ϵ_{MGR} for August was due to a defective potentiometer in the Resolver Alignment Module.

TABLE I - (Cont)

E. Gimbal Case Misalignment With Respect To Navigation Mounting Or Flange Errors

NOTE: Between August and November values, coolant flow was added to the case changing the thermal conditions. IMU fixture values were not remeasured since the IMU remained on its fixture.

PARAMETER	JDC'	PREDICTED MAX.	AUG. VALUE	NOV. VALUE
Rotation of OGA About Y_{NB} (ϵ_{FL_Y})	169	±21"	-18"	-76"
Rotation of OGA About Z_{NB} (ϵ_{FL_Z})	162	±25"	-19"	+12"

TABLE II

PIPA BIAS AND θ_{1G} VALUES OBTAINED DURING NOVEMBER PIPA ALIGNMENT TESTS

DATE	TIME	cm/sec^2	θ_{1G}
X PIPA 1AP10 (JDC #161)			
21 st	0800	0.055	169° 34' 43.5"
21 st	1100	0.021	169° 34' 43.5"
21 st	1530	0.069	169° 34' 43.0"
22 nd	-	0.019	169° 33' 43.0"
Y PIPA 1AP11 (JDC #163)			
21 st	-	0.347	080° 17' 46"
22 nd	-	0.385	080° 16' 41"
Z PIPA AP2 (JDC #164)			
21 st	1230	0.656	169° 21' 11"
21 st	1700	0.613	169° 21' 15"
21 st	1800	0.513	169° 21' 44"
21 st	1930	0.625	169° 21' 14"
22 nd	-	0.570	169° 20' 9"

Note: θ_{1G} Vertical Position Changes Above Reflect 16X Large Resolver Setting Changes.

TABLE III

PIPA SCALE FACTOR AND BIAS VALUES

OBTAINED DURING NOVEMBER PIPA CALIBRATION TESTS

X PIPA, 1AP10 (JDC #200, 201)					
DATE	TORQUING CURRENT (MA)	SCALE FACTOR Avg. (cm/sec/pulse)	PPM ΔSF (FROM REF.)	CLOSED LOOP BIAS ab (cm/sec^2)	NULL BIAS ab (cm/sec^2)
4 Nov 63	-	5.849910	-15	+ 0.12	+ 0.01
15 Nov 63	103.6773	5.849579	-72	+ 0.65	+ 0.47
18 Nov 63	103.6772	5.848855	-195	+ 1.27	+ 1.24
20 Nov 63	103.6874	5.849145	-146	- 0.26	- 0.35
Y PIPA, 1AP11 (JDC #202, 203)					
5 Nov 63	104.1875	5.849367	-108	+0.01	- 0.01
15 Nov 63	104.1840	5.849095	-155	+0.36	+ 0.36
18 Nov 63	104.1855	5.849179	-140	+0.58	+ 0.53
20 Nov 63	104.1932	5.849844	-27	+0.40	+ 0.32

TABLE III (cont)

Z PIPA, AP2, (JDC # 204, 205)					
DATE	TORQUING CURRENT (MA)	Avg SCALE FACTOR (cm/sec/Pulse)	(PPM) ΔSF/SF FROM NOM	CLOSED LOOP BIAS cm/sec^2	NULL BIAS cm/sec^2
5 Nov 63	104.0407	5.850078	+13	+0.02	0.00
↑	104.0405	5.850161	+28	+0.25	+0.45
	104.0407	5.850014	+2	+0.30	+0.49
	104.0410	5.849891	-19	+0.42	+0.51
[TURN-ON TRANSIENT TESTS.]	104.0424	5.850215	+37	+0.34	+0.46
	104.0416	5.854026	+688	+0.27	+0.42
	104.0416	5.853731	+638	+0.40	+0.56
6 Nov 63	Degaussed 104.0393	5.850232	+40	+1.38	+1.54
	104.0400	5.849884	-20	+1.40	+1.64
	104.0394	5.850734	+125	+1.46	+1.70
↓	Degaussed 104.0393	5.850730	+125	+0.716	+0.80
15 Nov 63	104.0422	5.849954	- 8	+0.04	+0.15
18 Nov 63	104.0421	5.850044	+ 8	+0.97	+1.25
20 Nov 63	104.0542	5.850329	+ 56	+0.87	+0.87

TABLE IV

IRIG COEFFICIENT DATA FOR ISS #4

COMMENT	DATE	X AXIS - MIT #66 NBD MERU (JDC 236)	ADSRA MERU/g (JDC 236)	NBD MERU (JDC 237)	ADIA MERU/g (JDC 237)
ACCEPT.	31 MAR'63	-28.2	-10.8	—	+ 24.0
BREADBOARD	13 AUG	—	—	- 8.0	+152.4
PSA	15 AUG	- 4.6	-30.7	- 5.1	+142.8
	16 AUG	- 8.8	-22.1	- 9.0	+164.6
RE-ACCEPT.	19 AUG	-15.4	-20.5	—	+163.5
BLUE MODULE PSA	6 NOV	-21.5	-35.5	-23.0	+138.0
	7 NOV	-20.6	-32.2	-22.2	+143.6
RE-ACCEPT.	10 NOV	-19.4	-32.5	—	+144.6
	14 NOV	-31.7	-25.4	—	+142.8
BLUE MODULE PSA	14 NOV	-19.6	-25.7	-23.0	+148.8
	15 NOV	-21.6	-27.3	-25.1	+140.3

TABLE IV (cont.)

COMMENT	DATE	Y AXIS - ACSP 1A2			
		JDC 239		JDC 240	
		NBD MERU	ADSRA MERU/g	NBD MERU	ADIA MERU/g
ACCEPT.	17 APRIL'63	- 0.3	+14.4	——	+ 6.7
BREADBOARD PSA	15 AUG	+14.5	- 7.5	+17.7	+ 3.3
	16 AUG	+14.1	- 6.6	+14.2	+14.3
	17 AUG	+ 7.9	-10.6	+ 6.2	+ 5.7
BLUE MODULE PSA	7 NOV	- 0.5	-21.2	+ 3.9	+15.8
RE-ACCEPT.	9 NOV	+ 3.8	-13.3	——	+ 6.4
	12 NOV	+ 1.8	-10.7	——	+ 4.3
BLUE MODULE PSA	14 NOV	- 1.2	-12.0	+ 5.3	- 2.9
	15 NOV	+ 1.2	-13.7	+ 3.8	+ 2.7
				+ 2.6	+ 0.5

TABLE IV (cont.)

COMMENT	DATE	Z AXIS - ACSP 1A3			
		NBD MERU	ADSRA MERU/g	NBD MERU	ADIA MERU/g
		JDC 242		JDC 243	
ACCEPT.	20 JUNE'63	- 7.2	+ 4.9	——	- 3.0
BREADBOARD	13 AUG	- 5.7	-16.5	+ 6.3	-40.5
PSA	15 AUG	+ 8.9	-11.2	+ 5.4	-19.1
	17 AUG	- 4.3	- 6.2	+ 3.4	-21.3
		- 6.8	- 5.7		
BLUE MODULE PSA	7 NOV	- 8.7	-23.7	-11.5	+ 1.1
RE-ACCEPT.	9 NOV	- 6.2	-20.5	——	+ 6.0
	13 NOV	-10.8	-29.0	——	+ 7.0
BLUE	14 NOV	- 8.6	-29.9	-14.2	+ 6.8
MODULE	15 NOV	- 8.2	-30.8	-14.3	- 1.9
PSA		- 9.0	-23.4		

TABLE V

X IRIG COEFFICIENT VALUES OBTAINED DURING NOVEMBER CALIBRATION TESTS AS CORRECTED FOR CDU ERROR

	JDC #236		JDC #237	
	NBD (MERU)	ADSRA (MERU/G)	NBD (MERU)	ADIA (MERU/G)
11/6	-24.5	-35.5	-23.0	+135.0
11/7	-23.6	-32.2	-22.2	+140.6
11/4	-22.6	-25.7	-23.0	+145.8
11/15	-24.6	-27.3	-25.1	+137.3

1 σ Deviation of all NBD's = 1 meru

TABLE VI

PULSE TORQUING SCALE FACTOR
OF ISS #4 IRIGS, UNITS = $\overset{\frown}{\text{SEC}}$/PULSE

X IRIG MIT #66 JDC 238	Y IRIG ACSP 1A2 JDC 241	Z IRIG ACSP 1A3 JDC 244
1.33	1.27	1.38
1.29	1.27	1.34
1.21	1.22	1.25
1.22	1.22	1.26
1.22		

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