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AN APPRAISAL FOR USE IN RELIABILITY ANALYSIS OF THE TEST AND DATA COLLECTION PROCEDURES IN THE MANUFACTURE OF AN INERTIAL GUIDANCE SYSTEM

by

W. S. Connor

W. S. Thompson

for

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FOREWORD

This report describes the test and data collection procedures employed during the production of the CENTAUR IGS (Inertial Guidance System) by the Minneapolis-Honeywell (MH) Regulator Company in its Aeronautics Division facility at St. Petersburg, Florida. An aim of the report is to identify those data which aid in describing the behavior of the first gimbal stabilization loop for a reliability analysis using the Research Triangle Institute reliability model. It was found in this study that the applicable data generated during the production stage of the CENTAUR IGS program is somewhat limited. This finding was anticipated because normal production procedures are not tailored to yield the type of data desired for application of the model.

It is recognized that environmental and stability tests which were lacking in the production process are a normal part of a design and development program. It is customary to prove environmental integrity and long-term stability during developmental testing, but due to economic and schedule considerations, not to repeat these same tests on each production item. However, because of the difficulty in going back into past work and limited resources and time with which to carry out this study, it was judged to be impractical to delve into stages prior to production.

Nevertheless, a considerable amount of data concerning the drift rate of the gyroscope are collected during production, and these data have been successfully used in the Research Triangle Institute reliability model. The tests which produce these data are described in this report and their use in the model is described in reference number [4] on page 43.

I. Introduction

A research study is being conducted at RTI for NASA to develop new methodology for conducting functional analyses of complex systems with emphasis on reliability. A major contribution to current reliability technology resulting early in the study is the formulation of a probabilistic model for systems reliability as reported in [1]. The model in its entirety accounts for both catastrophic failure and all modes of drift behavior and provides a complete framework for considering all sources of variation that affect system reliability.

To demonstrate the applicability of the reliability model to actual NASA systems, the CENTAUR IGS (Inertial Guidance System) manufactured by the Minneapolis-Honeywell (MH) Aeronautics Division, St. Petersburg, Florida was selected as a representative system for analysis and application of the methods advanced by the model. It is emphasized that the CENTAUR IGS was chosen as a tool for applying the newly developed reliability methods and not as a system to be actually evaluated or assessed for reliability.

To limit the investigation within a realistic scope to correspond to the level of avialable effort, the first gimbal stabilization loop of the CENTAUR IGS stable platform was isolated for detailed analysis. A functional analysis of the loop was first performed on the loop and reported in [2]. Simplication for further analysis and identification of specifications was later presented in [3]. The basic approach to analyzing the loop reliability is to describe the loop behavior over time in terms of the joint behavior of the individual loop elements while including the influence of external inputs. Due to inherent randomness, the behavior must be described statistically. To describe the statistical behavior of the elements, both known transfer characteristics and actual observation of element behavior must be considered. Herein lies the basis for the study.

The purpose of this study was to investigate the test and data collection procedures of the CENTAUR IGS program for identifying and analyzing those data which reflect the behavior of the loop elements while operating in the mission profile. The appraisal of the MH procedures for this purpose is intended as an appraisal of how well the RTI methods conform to the MH procedures rather than how well the MH procedures conform to the RTI methods.

The test procedures in any process are strongly a function of the stage of the product cycle and available supporting funds. At the time that this study was initiated, the major portion of the CENTAUR IGS design and development of the present configuration had been conducted. Even though considerable data of the type desired may have been generated earlier in the program, the level of effort required for intensive investigation of these early procedures was not felt to be justified. At the study initiation, the CENTAUR IGS was primarily in the production stage of the product cycle with routine production procedures well established. Since most production tests are usually not designed specifically to yield reliability type data, the amount of data of the type desired was limited. MH has proposed and received support for a greatly expanded test and evaluation program which is expected to yield some data of the type desired; however, the program had not sufficiently progressed to the stage to warrant intensive investigation.

The study of the production stage thus represents observation of the program at a specific point in the cycle when reliability activities were not receiving greatest support from customers. Also, the authors were advised that other MH programs had greater emphasis on reliability.

The report consists primarily of a general description of the production test procedures studied for each element in the first gimbal stabilization loop. To protect the proprietary interests of MH and avoid any possibility of national security classification, data resulting from the tests is not presented herein, but rather, the types of data which were available are briefly described. The study forms the basis for several conclusions presented in a separate section of this report.

This report is introductory to [5], in which the RTI method is applied to data taken from the MH manufacturing process.

II. System Description

The CENTAUR IGS (Inertial Guidance System) is a subsystem of the CENTAUR Astronautic System. GDA (General Dynamics Astronautics) is Prime Contractor to NASA for the over-all CENTAUR System and Honeywell is Subcontractor to GDA for the CENTAUR IGS.

A decomposition of the CENTAUR IGS into major items is briefly illustrated in Figure 1. The CENTAUR IGS is composed of two major subsystems, the CENTAUR MGS (Missile Guidance Set) and the GSE (Ground Support Equipment). The MGS is the airborne portion of the IGS and is the subsystem of major interest in this analysis. The MGS functions primarily to provide an inertial reference and generate the steering commands for the CENTAUR vehicle.

The MGS consists of major "boxes" designated by Honeywell as units. There are five units labeled (1) Platform, (2) Platform Electronics, (3) Coupler (Pulse Rebalance, Gyro Torquer and Power Supply), (4) Computer, and (5) Signal Conditioner. Each of these units performs several functions with a continuous interchange of signals among them.

Each unit is composed of major assemblies each of which may also contain other assemblies and components. The term assembly designates subunit parts that are assembled from smaller parts within the Honeywell Florida Plant. For example, an assembly could be an amplifier, gimbal assembly, or electrical oscillator circuit. The term component is reserved for those items of comparable size to the small assemblies such as gyros, accelerometers, slip rings, and torque motors that are purchased from other sources.

The remaining lower level consists of smaller purchased items used to construct the small assemblies and are called parts. These might be typified by resistors, transformers, and capacitors.

The terminology used by Honeywell as introduced above is primarily hardware oriented instead of functionally oriented. The RTI emphasis on the functional analysis approach to reliability led to introduction of the term element to denote any size system, subsystem, unit, assembly, or piece-part arbitrarily chosen as the convenient size item for which an analysis can be conducted.

To limit the complexity of the study being conducted, a smaller subsystem of the MGS was selected for applying the developed techniques. This subsystem is the first gimbal stabilization loop of the stable platform. The choice of elements for this system was first established in [2] and then simplified in [3]. The elements conform to both the Honeywell assembly level and component level in size and complexity as summarized below. Slip rings are listed twice, since they occur in two positions in the loop.

Element	Honeywell Classification	Location (Honeywell Unit)
1) Gyro & Signal Generator	Component	Platform
2) Preamplifier	Assembly	Platform
3) Slip Rings	Component	Platform
4) Gimbal Control Amplifier	Assembly	Platform Electronics
5) Slip Rings	Component	Platform
6) Torque Motor	Component	Platform
7) Gimbal (Azimuth)	Assembly	Platform

In the above tabulation, it is noted that not all elements of the selected system are located in the same unit. This results from the functional approach taken by RTI instead of the hardware approach used by Honeywell.

III. Analysis of Test Procedures and Data

In system reliability practices a major goal is to obtain the best available prediction of the system reliability. An analysis leading to the best prediction should utilize all existing data pertinent to reliability. For completeness, the data should include that available over the full span of the system life from its very early conception up through the end use of the system. Within this realm, consideration should be extended to every aspect of the system design, development, production, and operation phases for information indicating the reliability performance of the system. Data analysis should be conducted as a continuing effort from the very beginning of the program, and the reliability prediction should be continuously updated as more realistic data become available.

In the early design phases, full use should be made of information about the reliability of systems of both past and present generations which contain parts common with or similar to those employed in the new system. This information, coupled with failure rate data on parts, permits an early crude prediction of reliability for the new system. As the system program progresses beyond the early stages, the pertinent data generated from testing at all levels of system assembly should be used in reliability analyses.

A. General Test Concepts Relative to the Analysis

All equipment tests in a system program normally fall into one of three major categories: 1) Engineering tests, 2) Manufacturing tests, and 3) Use tests. Other test designations such as design qualification test, acceptance test, and environmental test are quite often used, but the specific test considered usually can be classified into one of the above three categories.

Although most CENTAUR IGS tests are not designed to yield reliability information, some tests, even though designed for other purposes, do yield data useful in reliability analyses. Also, some tests which do not now yield data for reliability could readily be modified to provide useful reliability data.

The CENTAUR program was initiated several years ago, and even though some development work is continuing, the CENTAUR IGS is primarily in the manufacturing or production stage of the product cycle. The current reliability analysis of the CENTAUR first gimbal stabilization loop was begun approximately one year ago; therefore, the majority of data considered most readily accessible for the analysis is that resulting from the production process.

Much testing conducted during earlier phases of the program greatly influenced the design of the system currently being produced. These early tests consisted of special engineering tests on assembly breadboard models and prototype models. It is likely that some of the data from these tests would be useful in the current reliability analysis. However, since the analysis was initiated after this stage, the level of effort required for fully investigating the early test procedures and data is not justifiable. The scope of the current analysis is therefore limited to an investigation of the test procedures of the production process and the data resulting therefrom. The emphasis in the current study is on advanced methodology and techniques for reliability, and the detailed analysis of the production process serves well as a demonstration.

In order to isolate the data and test procedures applicable to the selected first gimbal stabilization loop, the chronological stages in the production process for the loop were first defined with respect to the over-all CENTAUR MGS. These stages are summarized in the assembly flow diagram of Figure 2, and even though this diagram is constructed specifically for the production process, the chronological stages during assembly of a developmental prototype system would be very similar.

The over-all production process is initiated with purchased piece-parts that are used to construct assemblies. The assemblies are combined with other purchased items, components, to form larger assemblies. Combination of assemblies yields units and units may be mated to form subsystems. The combination of all five units forms the MGS.

The over-all production process is governed by engineering specifications, which assume a reverse direction of flow. Certain system specifications are imposed on the MGS by the customer. These system specifications are translated to individual engineering specifications to be met at the various levels of the process, all the way back to the vendor items.

Although the method of translation and the validity of specifications are not discussed herein, these factors affect reliability and should be considered in a complete study.

To assure the conformance of the end product, the MGS, to the assigned specifications, certain tests are conducted at each stage of the production process. The designation of these tests for the various stages is as follows:

1) Receiving-Inspection Tests - tests conducted on all purchased items to determine acceptance or rejection of the purchased items.
2) Engineering Specification Tests - tests conducted during assembly of different parts to adjust, calibrate or functionally check the operation of the constructed assembly.
3) Acceptance Tests - tests conducted on the final MGS to demonstrate the conformance of the system to specifications assigned by the customer.

Detailed procedures for assembling and testing at each level of the process are compiled in informal documents called layout summaries. Corresponding data is recorded during the tests; however, the documentation of the data ranges in sophistication from formal data sheets to rough notes recorded in technicians' data books, called production logs. Also, the recorded form of the data ranges from brief summaries to detailed recordings.

In brief summary, each stage of the process described in Figure 2 is governed by engineering specifications to be met. Toward this end, step-by-step assembly and testing procedures are followed with data recorded to verify that the specifications are met.

To predict system reliability it is important to take account of all data which reveal the system behavior over time in the mission environment. The approach taken in the analysis is to separate the system into convenient elements and to estimate the behavior of the system from data which reflect the behavior of the individual elements.

It is observed in Figure 2 that with the exception of the platform gimbal, all parts of the system which were designated as elements logically and conveniently occur at the same level in the production process. Tests at this level are herein designated as element tests. The test procedures and resulting data of these element tests were investigated for possible use in reliability analysis. In addition, tests at higher levels in the production process were also screened for applicable data that reveals the performance of the individual element. A review of these tests relative to each element will be presented in the next section.

The reliability model employed in the analysis of this system permits separation of the catastrophic and drift failures. Since the greatest advance in reliability technology presented by the model is consideration of drift failures, emphasis in this investigation is placed on identifying the data that reveal the drift behavior of the elements. The measured quantities characterizing the drift performance are designated as drift attributes.

This emphasis on drift is not intended to de-emphasize the importance of catastrophic failures; rather, since for some elements drifts do not significantly affect system performance, the only failures to be considered are those of a catastrophic nature. It is assumed that these can be handled by more conventional techniques, not in terms of observing the behavior of a particular attribute, but by a functional indication that the element has abruptly ceased operation. Further discussion of catastrophic failures is presented following the discussion of the individual elements.

In the discussion of test procedures pertaining to each element, a complete list of inputs is tabulated for each. Prior to use in a reliability analysis of any data reflecting the behavior of an element over time, the input test conditions under which the data are observed must be compared to the input conditions expected to occur during operation in the mission. This is necessary to determine if the test conditions simulate any of the mission conditions. An estimate of the absolute reliability of an element operating during a mission can be obtained only by completely simulating all mission conditions during the test, and partial simulation of the mission conditions permits only a reliability estimate which is no longer absolute but conditioned on the particular input conditions under which the element is tested.

Each input normally falls into one of the categories of informational inputs, operational inputs, or environmental inputs.

(1) Informational Inputs

These inputs are generally those signals containing information to which the element is designed to respond by performing an operation. For example, the platform angular rate $\dot{\Psi}_e$ is sensed by the gyro, or the stabilization error signal e_1 is amplified by the preamplifier. For test purposes these inputs are normally set to some level convenient for performing the specific test. As further examples, during gyro testing, the gyro is oriented so that earth's rate is not sensed, or the amplitude of the stabilization error signal input for setting the gain of the preamplifier is adjusted to a fixed convenient level for operation in the linear region. During the mission, however, these inputs may assume a continuum of values over the operating range with the distribution of values dependent upon the performance of the system.

(2) Operational Inputs

The operational inputs are those provided inputs which are necessary for the element to perform the required operations on the informational inputs. For example, the DC voltage supply to the preamplifier is an operational input; also, the gyro temperature provided by the temperature control circuit. For normal test purposes these inputs are practically always adjusted to nominal conditions. During a mission these inputs may also assume a continuum of values with the range and distribution of values dependent upon the behavior of the elements supplying the inputs.

(3) Environmental Inputs

Environmental inputs are those inputs which define the operating environment during the mission, for example, temperature, humidity or radiation level. The elements in the single axis stabilization loop considered for analysis are all housed during the mission in metal containers which are sealed, pressurized with inert gas and coated with special materials. This partially isolates the system from the atmospheric and space environment during the mission. While enclosed in these containers, additional environmental factors are introduced by the presence of other operating parts of the system.

The environmental input conditions to the elements during the tests observed depended on the particular tests conducted. The conditions for each test are presented in the discussion for each element. With a few exceptions, the tests below the subsystem level were conducted with elements exposed to normal laboratory or room conditions. Tests at the subsystem level more nearly simulate the mission conditions since the elements were sealed in the containers; however, the data characterizing the individual element performance was limited.

The sealing and pressurization of the units is assumed to effectively reduce the humidity to zero and provide constant pressure during the mission. The room conditions provided during certain tests of all elements are not considered to significantly change the performance from that obtained under mission conditions.

The coating of the unit housings with special materials is provided primarily as a temperature control measure. Temperature, of course, is known to be a critical environment for certain elements such as the gyro, preamplifier and the gimbal control amplifier.

The sealing and coating process for the units affects somewhat the nuclear radiation level, magnetic field, electrical field and acoustic environment during the mission. These effects were not investigated for use in the analysis because no tests were conducted to observe their effect.

The vibration environmental input during the mission is dependent upon the vibration level of the vehicle and the damping characteristics of the mechanical mountings of the elements. Gyro performance is certainly expected to be affected under vibrating conditions while large vibration levels of other elements can sometimes result in catastrophic failures. The gyro was exposed to vibration during gyro tests. However, the vibration was applied between measurements of gyro behavior and not while the behavior was being observed. During the tests at higher levels of assembly of the platform, additional vibration was employed but was only angular sinusoidal vibration of the gimbals to measure the loop frequency responses. No vibration tests were observed for the other elements.

Finally, the acceleration environment is considered to affect only the gyro and gimbal through acceleration sensitive torques. The nominal mission conditions are determined from mission profile data. Both the gyro and gimbal are tested under one-g gravity conditions and the performance linearly extrapolated to the mission conditions.

B. Test Procedures and Data for Elements

As previously stated, the approach to the reliability analysis of the first gimbal stabilization loop is to separate the loop into elements, identify the data which reflects the behavior of the elements over time, then combine the data to estimate the behavior of the loop over time. It is therefore necessary to consider all test procedures which possibly yield observations of element behavior.

All known tests at each stage in the production assembly process were considered. In the following discussion these test procedures are briefly described for each element in the loop. All inputs are first defined in tabulated form for joint consideration with the test procedures. Typical quantities measured throughout the production assembly process are identified for each element. The attempt is to relate the data from each test to its usefulness in describing the behavior of the element tested over time. Even though all quantities are important in absolutely guaranteeing the satisfactory performance of the element, the static nature of some of these quantities allows them to be omitted from extensive investigation or further measurement. If these static quantities meet specifications, it is improbable that they will change in value during the useful life of the element, except possibly when the element fails catastrophically.

No actual data is included in the discussion, only the form in which the data is available for comparison to the form required for reliability analysis.

Element 1: Gyro

The gyro is a vendor item purchased by the Honeywell Florida Division from the Honeywell-Minneapolis Division. As the heart of an inertial guidance system, the gyro is a very delicate instrument; therefore, great care and consideration are given to measurement of its performance characteristics. All tests on the gyro are conducted under precisely controlled input conditions. The list in Table I defines all inputs to the gyro.

Table I. List of Inputs for Element 1 (Gyro)

Inputs	Description
Ψ_e	Platform rotation angle about platform W axis
e_A	Gyro drift trim current
e_B	Gyro pattern field current, Fixed DC
e_C	Gyro spin motor excitation, 3-phase AC
e_D	Gyro signal generator excitation, AC sinusoidal
T_c	Control temperature provided by the gyro temperature control circuit
T_P	Ambient temperature inside platform housing
P_P	Ambient pressure inside platform housing
H_P	Humidity inside platform housing
N_P	Nuclear radiation inside platform housing
M_P	Magnetic field inside platform housing
E_P	Electrical field inside platform housing
A_P	Acoustic environment inside platform housing
m_U	Vibration along the platform U axis
m_V	Vibration along the platform V axis
m_W	Vibration along the platform W axis
a_U	Acceleration along the platform U axis
a_V	Acceleration along the platform V axis
a_W	Acceleration along the platform W axis

In tests the input angular rate $\dot{\Psi}_e = d\Psi_e/dt$ is usually maintained at zero by careful orientation of the gyro and the drift trim current input is dependent upon the type of test conducted. The supply signals e_B, e_C and e_D are always set to nominal value. The flotation fluid temperature T_c is carefully controlled to the nominal value during testing as well as handling. No measurements are conducted under actual vibration conditions and the linear accelerations are only at the 1 g. level due to gravity. The other environmental inputs are maintained at normal room conditions.

A complete list of all gyro quantities measured at least once during the production process are presented in Table II. All quantities are

Table II. List of Quantities Measured for Element 1 (Gyro)

Number	Quantities
1.	Electrical continuity of all electrical circuits (functional check only)
2.	Signal generator primary field resistance
3.	Signal generator secondary field resistance
4.	Torquer primary field resistance
5.	Torquer control field resistance
6.	Spin motor field resistance
7.	Control heater resistance
8.	Warm-up heater resistance
9.	Temperature sensor resistance at nominal operating temperature
10.	Torquer control field at nominal operating temperatures
11.	Signal generator phasing
12.	Spin motor run-up time
13.	Spin motor run-down time
14.	Gimbal friction (functional check only)
15.	Stop voltages
16.	Signal generator null voltage
17.	Elastic restraint
18.	Gyro transfer function (static gain)
19.	Torquer scale factor
20.	CT (Acceleration-insensitive drift rates due to constant torques about the OA)
21.	MUIA (Acceleration-sensitive drift rates due to mass unbalance along the IA)
22.	MUSRA (Acceleration-sensitive drift rates due to mass unbalance along the SRA)
23.	Random drift (Gyro OA Vertical)
24.	Random drift (Gyro OA Horizontal)

important factors in the gyro performance; however, the primary attribute that determines the acceptability of the gyro for use in a system is the gyro drift rate characterized by items 20-24 in Table II. Extensive testing is conducted at all levels in the system production process to measure certain drift factors. A description of gyro drift is presented in Appendix A-I, and measurements of gyro drift rate are described in Appendix A-II. The measurements of gyro drift rate result in two major components: a deterministic component and a random component. During operation in the system, instrumentation is provided to compensate for the deterministic portion. The accuracy of the system is then dependent upon the residual drift rate after compensation.

The total residual drift rate is attributed to the combination of measurement errors, drift instability (actual shifts in the drift rate variables CT, MUIA, MUSRA) and random drifts. All of these uncertainties are accounted for by Honeywell engineers in a technique called the "band" concept. This band concept consists primarily of computing or obtaining bounds within which the residual drift rate is known to lie but is not sufficient for reliability analysis in that it does not include the statistical distribution within the band.

Measurement errors are reduced as low as possible by providing the best instrumentation available for conducting the tests. Drift instability is measured extensively to insure conformance to specifications. The drift instability results from actual changes within the gyro from time to time, for example, actual mass shifts resulting from slop in the bearings supporting the gyro rotor. This instability is not significant during continuous operation of the gyro but is most readily observed in comparing measurements from test to test between which the operation of the gyro has been stopped. To reduce this effect, Honeywell has instrumented a newly conceived and effective technique designated PAST (Phase Angle Shift Technique) which produces a continual phase shift of the gyro spin motor supply voltage during operation of the gyro. This phase shift yields the net effect of producing continual shifts within the gyro, which during the continuous operation are effectively averaged over time. The net result is that the observed drift instability is decreased from test to test.

The random drift component of the residual drift rate is also measured and considered in the band concept. The type of tests for measuring random drift are discussed in Appendix A-III. The normal output of such tests is in the form of a root mean square random drift rate which is not compatible with the data form required for reliability analysis with the methodology being developed.

In the following discussion of each gyro test it becomes evident that the major available data that is suitable for use in a reliability analysis is that describing the gyro drift. A mathematical model of gyro drift rate attributes based on available data is presented in Appendix A-IV.

Element Tests

Tests on the gyro as an individual element of the system consist of vendor tests and standard and special Receiving-Inspection tests. Each of these tests is discussed separately below.

1) Vendor Tests

Extensive testing prior to gyro shipment is required of the vendor by the Honeywell, Florida Division. The tests consist of measuring the standard gyro parameters characterized by items 1-18 in Table II under standard laboratory environmental conditions.

Other vendor tests consist of a standard six position drift test for measurement of the three predominant gyro drift variables, CT, MUSRA, and MUIA, and further tests to measure the instability of these variables resulting from exposure of the gyro to different environments. The drift instability is measured by performing a sequence of standard six position drifts with the gyro exposed to a specific environmental condition (such as vibration at a given level or cooldown to a specific sub-operating temperature level) between each test. Variations of the critical drift variables MUIA and MUSRA from test to test are observed in the sequence and compared to specifications which state the allowed magnitude in the largest and second largest shifts. This sequence of environments provided by the vendor is intended primarily to simulate the environment to which the gyro is exposed during the production process, system test and prelaunch handling and not the mission environment.

2) The Standard Receiving-Inspection Test

These tests consist of measurement of all the gyro characteristics listed in Table II under standard laboratory environmental conditions. The measurement of the drift variables CT, MUIA, and MUSRA are obtained by the standard six position drift test described in Appendix A-II. In addition, two drift tests of a three hour duration for measuring the random drift characteristics are conducted and results analyzed for Honeywell's use as described in Appendix A-III. Tight specifications are assigned for these data. The proposed use of these data in the reliability analysis is described in Appendix A-IV. It is to be noted in that section that under typical mission conditions, the results of the three-hour OA horizontal test find no use in reliability analysis and unless Honeywell can verify other necessities, these tests could be omitted with considerable savings in production costs.

3) Special Receiving-Inspection Tests

If the average values of the drift variables CT, MUSRA and MUIA obtained in the standard Receiving-Inspection six position drift test differ from the values obtained by the vendor, then special tests are conducted to further investigate the drift instability. These tests again are conducted by sequential testing for the drift variables CT, MUSRA and MUIA with the gyro exposed to specific environments between each test as discussed for the vendor tests. Since the conditions stated for requiring this test are met by only a relatively small number of gyros, not all gyros receive this test.

Higher Assembly Tests

Following the acceptance of the gyro as permitted by its conformance to specifications in the Receiving-Inspection tests, the gyro becomes a stock component and is eventually installed in the first gimbal assembly of the stable platform. After completion of the production and testing process, the first gimbal is mated with the second gimbal to form the second gimbal assembly on which certain tests are performed. The tests at these two assembly levels are discussed separately below.

1) First Gimbal Tests

After installation in the first gimbal assembly, the applicable tests on the gyro at this assembly level are engineering specification tests consisting primarily of further measurements of the gyro drift variables CT, MUIA and MUSRA. In the particular gyro drift tests at this assembly level, the gyro is operated in a low rate servo loop as a rate gyro. The gyro drift variables are normally measured twice during the assembly tests, once before the gyros are physically aligned in the platform and once after the alignment. If a gyro in later tests is found to be defective, these same tests are rerun on the replacement gyro.

2) Second Gimbal Tests

Tests at the second gimbal assembly level do not include any tests on the gyro other than functional check indicated by proper operation of the system during other tests.

Unit Tests

Tests at this level are called the Platform Final tests. These do not include any tests on the gyro other than functional check indicated by proper operation in conjunction with other tests.

Subsystem Tests

A subsystem is formed by the marriage of the Platform unit and the Platform Electronics unit. Engineering specification tests at this level are designed primarily to insure conformance of the completed platform stabilization system to overall specifications. Several of the standard tests performed at this level requiring the proper functional operation of the gyro are:

1) Stabilization Loop Gain Test
2) Stabilization Loop Threshold Test
3) Stable Element Isolation Test
4) Angular Acceleration Test

The results of the above tests are strongly dependent on the gain and bandwidth characteristics of the gyro; however, the stated gyro characteristics cannot be specifically isolated since the gyro is operating jointly with other elements having certain gain and bandwidth characteristics also contributing to the measured system responses.

In addition to the above tests, a six position platform drift test is conducted. Since the platform drift resulting in this test is contributed primarily by gyro drift, the test yields additional estimates of the gyro drift variables CT, MUIA and MUSRA. Due to the test procedure followed in these tests, the estimates of the variables are more refined than the estimates obtained from previous platform tests at the higher assembly level.

System Tests

The MGS, referred to herein as the system, is formed by the connection of the five units, Platform, Platform Electronics, Coupler, Computer and Signal Conditioner. The normal testing routine at this level consists of two tests, a Confidence test and an Acceptance test.

1) Confidence Tests

Two Confidence Tests are conducted in sequence using the same test procedure as that for the Acceptance test. The purpose of these tests is to insure that all defects have been corrected so that the system is ready for the Acceptance test. Since the tests are identical, the discussion below on the Acceptance test suffices for a description of both.

2) Acceptance Tests

Acceptance tests are required by the customer (in this case GDA) to demonstrate that all assigned specifications of the system have been met. The Acceptance test procedures are followed twice resulting in two sets of test results. Specific performance variables are measured during the tests; however, proper operation of the system during all the operational modes employed in the test reflect satisfactory functional performance of all parts of the system.

The measurements during the Acceptance tests that pertain to the gyro performance again results in estimates of the drift variables CT, MUIA and MUSRA. Since the tests are system tests, the gyros are drift trimmed by compensation torquing signals provided by the computer. The test starts with best known values of the critical drift variables set into the computer. The test results reflect the platform drift resulting from errors in the drift variables programmed into the computer, i.e., the residual drift resulting after drift compensation for the particular platform orientation. The measured platform drift is then referenced back to the particular gyro causing the drift and used to update or correct the value of the drift variable initially assumed. The refined estimates of the drift variables become the best known values for the repeat test.

The initial best known values for the first run of the Acceptance tests are those obtained from the Confidence tests and the initial values for the Confidence tests are usually those obtained from the subsystem six-position drift test described above.

Element 2: Preamplifier

The preamplifier is a part of a larger assembly containing three gyro preamplifiers and three accelerometer preamplifiers. This assembly is constructed within the facility of the Honeywell Florida Division. The individual preamplifier employed in the first gimbal stabilization loop of the stable platform is isolated as an element for considerations herein and all inputs to the element are listed in Table III for further reference. The tests performed on the preamplifier quantities measured is presented in Table IV.

Table III. List of Inputs for Element 2 (Preamplifier)

Inputs	Description
e_1	Stabilization Error Signal from gyro signal generator
e_E	Platform DC voltage supply

Additional Inputs T_P, P_P, H_P, N_P, M_P, E_P, A_P, m_U, m_V, m_W, a_U, a_V, a_W are the same as those defined for element 1.

Table IV. List of Quantities Measured for Element 2 (Preamplifier)

Number	Quantities
1.	Gain at nominal operating frequency
2.	Linearity
3.	Saturation Level
4.	Null voltage output
5.	Input Impedance

Element Test

The preamplifier is tested in the final phase of the production process in construction of the multiple preamplifier assembly. The tests are conducted under room conditions except for controlled temperature with all supply voltages adjusted to nominal values. To control the temperature during the test, the preamplifier assembly is mounted in an oven. The test procedure is briefly outlined as follows:

At Room Temperature

1) Adjust gain.

At 180°F (Allow for approximately 15 minute bake period)

2) Check linearity by measuring the gain at several levels.
3) Measure null voltage
4) Measure input impedance

All the above measurements are conducted at a fixed point in time and are not repeated to measure time variations; therefore, the data is not useful in a reliability analysis. However, the preamplifier is comparatively a simple element and observation of data at other levels in the production process reveal it to be very reliable in terms of both catastrophic failures and drift performance.

Any reasonable drifts in the gain are considered insignificant due to the wide tolerance specified. Drifts in the null voltage yield an effect on system performance similar to gyro drift, but due to good design of the element, this quantity is held well within tolerance. The linearity saturation level and input impedance are quantities of such nature that, once measured within specification, they are not expected to drift out of specification. Therefore, with the above considerations, it is concluded that no performance attributes are required for reliability analysis.

Higher Assembly Tests

The preamplifier assembly is mated with the gyro and other components to form the first gimbal assembly, and later, the first gimbal assembly is combined with other parts to form the second gimbal assembly.

1) First Gimbal Assembly Tests

At the first gimbal assembly level, a test is conducted for measuring and adjusting the preamplifier gain while operating jointly with the gyro. The purpose of this gain adjustment is to match the preamplifier gain with the specific gyro to which it is mated so that the overall gain from the gyro input to the preamplifier output has the correct value. As stated earlier, variations in the gain of any element do not significantly affect the system performance during the mission; however, for later test purposes, the gain adjustment described above is very necessary because electrical measurements of gyro drift are obtained by monitoring the preamplifier output. The gain adjustment yields the proper sensitivity, volts per degree of gyro gimbal deflection, for converting the monitored preamplifier output into the equivalent gyro drift angle.

The final values of the gain after adjustment are recorded; however, since the history of the environment to which the preamplifier has been exposed since initial assembly is not known and due to the wide tolerances on gain for operation during the mission, the data is not considered useful for a reliability analysis.

2) Second Gimbal Assembly Tests

No tests are conducted at the second gimbal assembly level requiring operation of the preamplifier.

Unit Tests

Final tests on the platform at the unit level include another preamplifier gain adjustment similar to that discussed above at the first gimbal assembly level. In addition, successful performance of the unit during other unit tests provides a functional check on the preamplifier operation with no data resulting for reliability.

Subsystem Tests

The standard platform response tests and the platform six position drift tests listed in the gyro discussion above involve no direct measurements on the preamplifier. These tests merely provide a further check on the preamplifier functional operation in the system.

System Tests

System operational checkout and platform drift tests provide merely a functional check on preamplifier operation.

Element 3: Slip Rings

Element 3 consists of four slip ring-contact pairs in series. Each ring contact pair is located in a separate slip ring assembly containing a total of 38 slip ring contact pairs. The slip ring assembly is a vendor item purchased from Electro-Tec. Corp.

The slip ring is a device providing an electrical connection between two members free to rotate with respect to each other with this element providing an electrical path for the stabilization error signal from the preamplifier output to the gimbal control amplifier input. The slip ring assemblies are located at the gimbal axes of rotation. All inputs to the element are listed in Table V.

Table V. List of Inputs for Element 3 (Slip Rings)

Inputs	Description
e_2	Stabilization Error Signal from gyro preamplifier
Ψ_e	Platform rotation angle about platform W axis
Ψ_i	Vehicle rotation angle about platform W axis

Additional inputs T_P, P_P, H_P, N_P, M_P, E_P, A_P, m_U, m_V, m_W, a_U, a_V, a_W are the same as those defined for element 1.

Element Tests

Tests on the slip ring assembly consist of both Acceptance tests by the vendor and Receiving-Inspection tests by the Honeywell Florida Division.

1) Vendor Tests

The vendor data sheets observed indicate only measurements of slip ring noise. Since these measurements are also conducted by Honeywell in Receiving-Inspection, they will be discussed below.

2) Receiving-Inspection Tests

Of the items listed in Table VI, the characteristics of primary interest is the break-away torque resulting from static friction in the ring-contact pairs and the ring to contact electrical resistance. The break-away torque is measured in the Receiving-Inspection test for determining conformance to specifications. This quantity, once measured, can be assumed

Table VI. List of Quantities Measured for Element 3 (Slip Rings)

Number	Quantities
1.	Break-away friction
2.	Dielectric test (functional check only)
3.	Static contact resistance
4.	Slip ring noise

a constant unless some catastrophic type failure occurs. The static contact resistance of each slip ring-contact pair is also measured for comparison with specification.

In the accompanying list of measured quantities, slip ring noise is also included. This noise is not to be interpreted as noise in the conventional sense, i.e., noise resulting from a random process within the assembly, but appears as noise for the particular test procedure used and is merely a manner of specifying the variations in the slip ring to contact resistance as a function of the angular position of the contact on the ring.

A simplified model for slip ring noise as measured is developed by considering the application of a DC voltage to the contact arm while it is being rotated at a constant angular velocity with respect to the ring. With an electrical load applied to the ring, the voltage recorded across the load is directly proportional to the current through the ring-contact pair. A typical time trace of this voltage may appear as shown in Figure 3 where T represents the period for one complete revolution of the contact arm. The periodic noise spike in the trace would indicate a "bad" spot in the ring where the resistance greatly increased causing a reduction in the measured current through the slip ring-contact pair.

The test procedure provided by Honeywell is much more sophisticated than the simple description above. For example, an additional oscillation of less than one complete revolution in amplitude is superimposed on the constant angular rate permitting much more coverage of the slip ring surface by the contact.

It is recognized that the tests do not simulate the environment experienced by the slip rings while operating in the system during flight. The extensive rotation of the slip rings during the test actually provides a considerable overstress on the components, since the amount of actual rotation during flight is small in comparison. However, after the slip ring assemblies are installed in the platform, extensive testing and handling of the platform during production and up through prelaunch checkout yields much rotation of the gimbals and requires proper operation of the slip rings in this environment. Furthermore, it was learned that after installation of the slip ring assemblies into a platform, replacement of a defective assembly is very costly and time consuming. This rightly provides sufficient justification to Honeywell for setting tight specifications on the purchased components. Actually, a resistance of the ring-contact pairs wider than the assigned tolerance can still yield satisfactory performance during the mission, but Honeywell engineers consider failure of the assemblies to meet the assigned specifications indicates a potential defective component during later operation.

With the above considerations, all slip ring-contact pairs that perform satisfactorily up to and including pre-launch checkout can, for all practical purposes, be considered to perform satisfactorily except for failures of a purely catastrophic nature. Hence, the data from the Receiving-Inspection tests are not needed in a drift reliability analysis.

Higher Assembly Testing

The slip ring assemblies are installed in the platform at the higher assembly levels of production. Normally, no specific tests are conducted to measure the electrical resistance characteristics of the ring-contact pairs. Tests at the second gimbal assembly level include measurements of the combined static friction or break-away torque of the slip ring assemblies, torque motor and resolver on the first gimbal axis; however, they do not specifically result in a friction value for the slip ring assembly. Since this frictional torque directly affects the drift performance of the first gimbal stabilization loop, the results could be used in a drift reliability analysis. The data, however, was not readily accessible, being recorded informally in technicians' data books.

Unit Tests

Operation of the platform unit in other tests provides a functional check on the electrical resistance characteristics of the ring-contact pairs. Further tests are conducted to measure the combined break-away torque of the slip ring assemblies, torque motor and resolvers on the first gimbal axis. This data is also recorded informally in technicians' data books and not considered readily accessible for reliability analysis.

Subsystem Tests

Subsystem tests do not normally include any specific measurements of ring-contact resistance characteristics, again yielding only a functional check indicated by successful performance of the platform in other tests. The subsystem closed loop response tests, listed in the discussion of gyro testing, provide a functional check on both the break-away torque and the viscous damping and Coulomb torques of the slip ring assemblies.

System Tests

System tests do not include specific tests to measure the slip ring performance, only functional checks indicated by satisfactory performance of the system in other tests.

Element 4: Gimbal Control Amplifier

The GCA (Gimbal Control Amplifier) is an assembly constructed within the Honeywell Florida Division facility. A list of all inputs to the GCA is presented in Table VII. The different tests on this element are considered below.

Element Tests

Tests on the GCA as an element are conducted in the production phase of the assembly. The production procedures specify two stages of testing, preliminary electrical tests and final electrical tests.

1. Preliminary Electrical Tests

During the preliminary electrical tests the GCA is a complete amplifier assembly except for the compensation network and minor final production operations of cleaning, cementing, coating and inspection. The tests are primarily of the calibration type for adjustment of items 1-10 listed in Table VIII. The GCA is mounted in an oven for environmental temperature

Table VII. List of Inputs for Element 4
(Gimbal Control Amplifier)

Inputs	Description
e_3	Stabilization error signal from preamplifier via slip rings
e_F	Demodulator reference signal, AC sinusoidal
e_G	Platform Electronics DC voltage supply
e_H	Carrier reference signal, AC sinusoidal
e_I	Power demodulator reference signal, AC sinusoidal
T_E	Ambient temperature inside Platform Electronics Housing
P_E	Ambient pressure inside Platform Electronics Housing
H_E	Humidity inside Platform Electronics Housing
N_E	Nuclear radiation level inside Platform Electronics Housing
M_E	Magnetic field inside Platform Electronics Housing
E_E	Electrical field inside Platform Electronics Housing
A_E	Acoustic environment inside Platform Electronics Housing
m_x	Vibration along the vehicle x axis
m_y	Vibration along the vehicle y axis
m_z	Vibration along the vehicle z axis
a_x	Acceleration along the vehicle x axis
a_y	Acceleration along the vehicle y axis
a_z	Acceleration along the vehicle z axis

Table VII. List of Quantities Measured for Element 4
(Gimbal Control Amplifier)

Number	Quantities	Number	Quantities
1.	Demodulator Null Voltage	7.	A2 Section Gain Balance
2.	Modulator Null Voltage	8.	Saturation Level
3.	Motor Null Current	9.	Amplifier Phasing
4.	A1 Section Gain	10.	Input Impedance
5.	A1 Section Gain Balance	11.	Compensation Network Frequency Response
6.	A2 Section Gain		

control and all supply voltages are set to the nominal values. Temperature is the only controlled environmental variable. The test station includes a standard compensation network for substitution into each GCA when it is tested. This is not detrimental to the test results in that all compensation networks are composed only of passive devices (resistors and capacitors) with no significant variation to be expected from measurements over time or from network to network. The over-all test procedures is briefly outlined as follows:

At Room Temperature

1. Demodulator Null Adjust
2. Modulator Null Adjust
3. Output Null Measurement
4. Gain Adjust and Gain Balance Check

The gain balance check consists of gain measurements to insure equal gains for both positive and negative input signals.

5. Repeat procedures 1-4 above until all specifications are met. Record all final measurements.

At 160^{o}F (Allow for approximately 30 minute warm-up period)

6. Repeat procedures 1-5 above

At 120^{o}F

7. Saturation Level Measurement
8. Over-All Amplifier Phase Check
9. Input Impedance Measurement

\- - - - - - - - - - - - - - - -

Decals placed on

\- - - - - - - - - - - - - - - -

At 150^{o}F

10. Bake for a minimum of one hour

Data from the above tests consist of static measurements of the parameters at some fixed point in time and do not reflect the behavior of the amplifier over time; therefore, this data is not in a form for optimum use in the reliability sense. Instrumentation to measure the amplifier behavior throughout the one hour bake period at 150^{o}F could yield some very pertinent data. A discussion of this type of test is presented below in connection with the final electrical tests.

2. Final Electrical Tests

After the cleaning, cementing, coating, and inspection process, the amplifier is submitted to the final electrical tests. For these tests the amplifier is again placed in the oven with all voltage supplies set to nominal.

The principal test is a four hour burn-in test conducted at an elevated temperature of $180^{\circ}F$ for the purpose of weeding out and replacing those weak or defective components that would be likely to fail during the early life of the amplifier. In conducting the tests the level of the input signal to the amplifier is adjusted to yield an output signal (which is DC) having a convenient readout level. After continuous exposure to the elevated temperature for a period of two hours, the phase of the input signal is reversed 180° for the last two hours of the test. A continuous time plot of the nominal output current of the amplifier during this test would appear as shown in Figure 4. The phase reversal insures that all piece-parts of the amplifier are placed under stress.

After completion of the four hour burn-in test, the amplifier is readjusted at a temperature of $160^{\circ}F$ using the same calibration procedures as outlined for the preliminary electrical test discussed above.

A catastrophic failure of the amplifier during the four hour burn-in test would be revealed by a sharp discontinuity in the constant current segments of the plot in Figure 4. Also, considered important from the reliability viewpoint is the drift or degradation in the amplifier characterized by changes in attributes over time. Two possible drift attributes for the GCA were listed in [3] as the null voltage output and the static gain. The null voltage output is represented by the combination of items 1-3 in Table VII while the static gain is represented by the combination of items 4-7. Drifts in these quantities would be reflected in the time plot of Figure 4; however, there was no indication in the review of these tests that continuous values of the output signal were recorded during this four hour period. Due to the wide tolerances in static gains permitted for the elements in the loop, it is reasonable to assume that drifts in gain over time do not significantly degrade the system performance, and, therefore, can be omitted from present consideration. However, since drift in the GCA null voltage has an effect on system performance similar to the effect of gyro drift, this attribute could be conveniently observed continuously in conjunction with the test and the measurement results included in a reliability analysis. The desirability of doing so is confirmed by the tight specification assigned to the null voltage output.

The time variations in the GCA null output under these test conditions could be recorded with comparatively little additional instrumentation. So as not to confuse any drift in DC bias with drifts in gain, the test procedure could be revised to obtain a higher rate of input signal phase cycling. A continuous recording of the nominal output without drift then appears as shown in Figure 5(a). Assuming linearity in the amplifier, any drift in the DC null voltage would appear as a bias on the output current characterized by the type of time plot shown in Figure 5(b). This effect is then easily distinguished from that shown in Figure 5(c) indicating the observed effect of drift in static gain. Such recordings over time will also readily yield data on other drift effects such as the AC null voltage or changes in the static gain balance of the system.

Such measurements would permit observation of the drift behavior of the amplifier for a specified time under one specific stress condition, viz., an elevated temperature environment with all other factors nominal or at laboratory conditions. Use of this drift data in a reliability analysis of the amplifier operating in ths system during the mission would require the basic assumption that

> the drift behavior of the amplifier measured during the very early life of the amplifier is characteristic of the drift behavior it will exhibit at some later time in life during the mission.

This assumption is felt to be quite valid on the basis of experience with the drift behavior of high quality equipment in systems of this type.

The elevated temperature employed for the four hour burn-in test provides intentional overstressing of the amplifier to overemphasize the defective piece-parts. Observation of the drift behavior at that temperature provides an estimate of the drift behavior of the amplifier during operation in the mission if extrapolation of the data from the overstressing temperatures back to more nominal temperature conditions is possible. This extrapolation may require some additional testing to obtain an empirical relationship for drift as a function of temperature. One golden opportunity for observing behavior at another temperature level is presented by the one hour bake period at $150^{\circ}F$ during the preliminary electrical tests described above.

More meaningful reliability data could be obtained by designing the tests to reflect the amplifier behavior over a number of test conditions to include other environmental stresses and other levels of supply voltages other than nominal. If the population of amplifiers were sufficiently large, these additional conditions could be efficiently investigated by a statistical design of the tests to optimize the test conditions employed.

Higher Assembly Level Tests

The completed and calibrated GCA is mated with other small assemblies in the Inner Housing Assembly of the Platform Electronics unit. Standard engineering specification tests on this higher level assembly includes additional tests on the GCA. These tests are conducted under normal laboratory environmental conditions with all voltage supplies nominal. The regular system compensation network is also included in the assembly for operation with the GCA.

The tests are designed to recheck the calibration of items 1-10 in Table VIII and for readjustment so that they meet specifications. Those parameters that are measured and are out-of-specification indicate some drift behavior in the amplifier over the time and in the environment experienced since the final electrical tests in the assembly process of the GCA. For these tests there was no evidence of documentation of the measured value of any out-of-specification parameter observed, of the elapsed operating time of the amplifier since the previous measurement, or of the environmental conditions experienced by the amplifier since the previous measurement. Therefore, the data from these tests are of no practical use in a system analysis to estimate the reliability of the GCA in the system mission. In addition to the specific tests for measuring parameters of the GCA, a functional check inherently results while the assembly is operating for the purpose of testing other items.

Unit Tests

The final engineering specification tests of the Platform Electronics unit include additional tests on the GCA. The specific tests and procedures pertaining to the GCA are identical to those conducted during the Inner Housing Assembly tests considered in the discussion above.

The engineering specification document for the Platform Electronics provides for measurements of the frequency-response characteristics (gain and phase shift) of the compensation network, item 11 in Table VIII; however, no evidence was observed that this measurement was included in the standard test procedures described by the test layout summary. These tests are of a static nature (i.e., measurements at one point in time) and, due to wide tolerances in the measured parameters, any expected drift variations over time would not significantly affect the system performance. Therefore, the results were not considered sufficiently pertinent to reliability and the test and test results were not further investigated.

Subsystem Tests

Subsystem tests do not include specific measurement of the GCA performance. The closed loop response tests, listed in the discussion of gyro tests, are measurements of the stabilization loop gain and bandwidth characteristics. Since the GCA gain and bandwidth characteristics are included in these for the over-all stabilization loop, satisfactory results of this test indicate satisfactory performance of the GCA.

In addition, satisfactory completion of the platform six-position drift test indicates further satisfactory functional performance of the GCA operating in the system.

System Tests

System tests do not include specific tests on the GCA, but serve as a further functional check on the GCA operation in the system.

Element 5: Slip Rings

Element 5 consists of three slip ring-contact pairs in series used to maintain an electrical connection from the GCA output to the torque motor. All inputs are defined in Table IX. The tests for this element are the same as those described for element 3.

Table IX. List of Inputs for Element 5 (Slip Rings)

Inputs	Description
e_4	Torque motor input current from GCA

Additional inputs Ψ_e, Ψ_i, T_P, P_P, H_P, N_P, M_P, E_P, A_P, m_U, m_V, m_W, a_U, a_V, a_W are the same as those defined for element 3.

Element 6: Torque Motor

The torque motor for the first gimbal stabilization loop of the stable platform is a vendor item purchased from Inland Motor Corporation. All inputs are listed in Table X.

Table X. List of Inputs for Element 6 (Torque Motor)

Inputs	Description
e_5	Torque motor input current from GCA via slip rings

Additional inputs Ψ_e, Ψ_i, T_P, P_P, H_P, N_P, M_P, E_P, A_P, m_U, m_V, m_W, a_U, a_V, a_W are the same as those defined for element 3.

Element Tests

Element level tests on the torque motor consist of both Acceptance tests by the vendor and Receiving-Inspection tests at the Honeywell Florida Division facility. Typical quantities measured in these tests are presented in Table XI. Those quantities of primary interest in characterizing the performance of the torque motor operating in the system are the static friction or break-away torque and the motor sensitivity or amount of torque delivered per ampere of DC current input. Both the vendor tests and the Receiving-Inspection tests are similar in nature yielding measurements at some fixed time in the life of the torque motor for assurance of conformance

Table XI. List of Quantities Measured for Element 6 (Torque Motor)

Number	Quantities
1.	Static friction or break-away torque
2.	Dielectric Tests (functional check only)
3.	Polarity (functional check only)
4.	Contact resistance
5.	Armature resistance
6.	No-load torque
7.	Sensitivity (static gain)

specifications. The two quantities are not expected to change significantly in value over the useful life of the torque motor except for failures of a catastrophic nature, or at least any reasonable drifts in the sensitivity are considered insignificant due to the wide tolerance permitted.

The gain data is excluded in a reliability analysis of drift effects; however, the break-away torque is a significant variable affecting the performance of the stabilization loop.

Higher Assembly Tests

The torque motor is installed in the platform at the higher assembly levels of production. Tests on the first gimbal assembly do not directly include measurement of the torque motor characteristics. Tests on the second gimbal assembly consist of measuring the combined break-away friction of the torque motor, slip ring assemblies and resolver on the first gimbal axis. Use of this data was covered in the discussion on the slip rings.

Unit Tests

The platform tests include further measurements of the combined break-away friction of the torque motor, slip ring assemblies and the resolver with the use of the data covered in the discussion on the slip rings.

Subsystem Tests

Subsystem tests do not normally include any specific measurements of torque motor characteristics, but the subsystem closed loop response tests listed in the gyro discussion provide a functional check on both the break-away torque and the viscous damping and Coulomb torques of the torque motor. This data helps define the dynamic and static characteristics of the overall stabilization loop and, therefore, is considered useful in a reliability analysis.

Satisfactory performance of the stabilization loop permits a further functional check on the torque motor operation in the system.

System Tests

No specific measurements are conducted to measure the torque motor characteristics, but a functional check is provided by satisfactory system performance.

Element 7: Gimbal

The gimbal is isolated functionally as an element for convenience since it is the stable element proper. The inputs are listed in Table XII.

Table XII. List of Inputs for Element 7 (Gimbal)

Inputs	Description
T_M	Motor torque delivered by torque motor
T_{GF}	Torque motor, frictional torque
T_R	Gyro reaction torque
T_3	Slip ring (element 3) frictional torque
T_5	Slip ring (element 5) frictional torque

Physically, the gimbal is a metal casting on which the inertial components and certain associated equipment are located. The physical characteristics (such as mass unbalance and moment of inertia) that affect the stabilization loop performance are considered as those represented after all components and equipment are installed on the metal cast. This leads to no difficulty in constructing the system functional diagram for reliability. The measured quantities listed in Table XIII, once adjusted to specification, are not considered to change over time except for failures of a catastrophic nature.

Table XIII. List of Quantities Measured for Element 7 (Gimbal)

Number	Quantities
1.	Mass unbalance
2.	Moment of inertia

The gimbal casting is a purchased item and arrives in rough unmachined form. After machining to specifications, the components and associated equipment are installed on it to form the first gimbal assembly.

Element Tests

Tests at the isolated element level are considered only those physical measurements on the machined casting and are considered irrelevant to reliability analysis.

Higher Assembly Tests

Tests at the higher assembly level of production were not observed to include any measurement of gimbal characteristics pertinent to reliability analysis.

Unit Tests

Tests on the platform unit consisting of measurements on the gimbal which are pertinent to reliability are mass unbalance measurements of the first gimbal. Data from these measurements is informally recorded in technicians data books and for practical purposes is considered inaccessible for use in reliability analysis.

Subsystem Tests

Tests of the subsystem tests do not consist of measurement of specific characteristics of the gimbal.

System Tests

System tests also do not consist of measurement of specific characteristics of the gimbal.

C. Additional Sources of Data

In addition to the tests described in the previous section, other possible sources of data have been considered. Some of these sources briefly discussed below for illustration are the test and evaluation program, discrepancy reports and equipment summary reports.

1) Test and Evaluation Program

Several tests are identified under the test and evaluation program. First, one or more systems as required may be designated for performing special engineering evaluation tests. The primary purpose of these tests is to evaluate design changes that occur later in the system program and to provide data for special analyses. For these tests the inputs are controlled to nominal or laboratory conditions. With the exception of platform drift tests under the controlled conditions, none of these tests were observed to measure the system behavior over time. The platform drift data could have been obtained and integrated with that available from the routine production tests; however, for the purpose of demonstrating data usage in reliability analysis the drift data from the routine production tests was sufficient in quantity.

Some systems were designated for special reliability tests. These tests consist of system operation in a mild environment of temperature and vibration at levels that simulate the mean environmental conditions during flight with several hundred hours of operating time apportioned over several systems. At the time of this study this test program was not sufficiently far along to justify intensive investigation for possible use of the data in the reliability analysis.

Qualification or "Flight Certification" tests were designated for two systems. These tests fall into the general realm of design approval tests at the systems level and are designed primarily to demonstrate proper performance of the MGS while operating in specific environments of temperature, altitude (pressure), humidity and vibration. The tests consist of operating and measuring the performance before, during, and after exposure to the environments. Different stress levels of the first three environments are achieved by locating the MGS inside a temperature chamber which, in turn, is placed inside a vacuum chamber. The vibration environment is independently provided by a vibration table and the acceleration environment by a centrifuge. The measurements in these tests that pertain to the first gimbal stabilization loop are observations of the equivalent gyro drift rate variables as discussed in connection with the gyro. The tests permit observation of the value of these variables as a function of the several chosen environmental stress levels. Data of this type coupled with operational profile data describing how the stress levels vary during the mission can be readily employed in the reliability analysis. However, at the time the study was conducted this test program was in its infancy with no data available at that time.

Some additional tests scheduled for the test and evaluation program are vehicle integration tests, overstress tests and flight tests. These tests also can be expected to yield useful reliability data but were not sufficiently far along in planning to warrant intensive investigation.

2) Discrepancy Reports and Equipment Summary Reports

A standard discrepancy reporting form is employed in the production process to report equipment discrepancies at all levels of system assembly from the designated element level of assembly to final operational use of the system. Typical discrepancies reported are catstrophic failures, out-of-specification measurements, production errors, design modifications and any event that prevents the equipment from moving forward in the normal assembly flow. The essential information provided by the completed discrepancy report is identification of the equipment, process operation in which the discrepancy was noted, elapsed operating time if available, description of the discrepancy, equipment disposition or rework instructions and the final action taken on the equipment.

Disposition of the equipment for which discrepancies are noted depends upon the type of discrepancy and the effect it has on the system operation. When possible, the discrepancies are corrected without removing the equipment from its installed position. More serious discrepancies require replacement with the defective component or assembly returned to its proper production source for repair.

MH makes extensive and efficient use of the discrepancy reports in their process. Of notable interest is the failure report summaries prepared by the reliability data center. The system for providing these summaries is computerized; essential data from the discrepancy reports is entered on punched cards and used for compiling periodic listings of all failed assemblies and components. This greatly assists in identifying continuous "troublemakers" or unsatisfactory components and assemblies in the system.

For those discrepancies that occur during unit or system operation, the elapsed operating time of the unit is available from an ETI (elapsed time indicator) mounted on each unit and is reported on each discrepancy report origination at these assembly levels. Using the reported failure for which the elapsed time is thus available, the MTBF (mean time between failure) for the MGS is computed by the MH reliability group. Since the failure data for computing the MTBF is collected during the production process, the computed figure represents an estimate of the MTBF for the system in the production environment but can be misleading to assume that this represents the MTBF during the flight environment. However, MH can make efficient use of the computed MTBF as a system indicator revealing over a period of time how design modifications and changes in production practices improve the system failure rate.

Within the framework of the RTI reliability model, the data provided by the discrepancy reports is not in sufficient detail to permit any better estimate of reliability than is already accomplished by MH. More efficient use of the data from the discrepancy reports could be made if the environmental conditions for the equipment were continually defined. Equipment logs accompanying each unit provide a time history of significant events such as equipment starts, tests performed, functional checks and discrepancies occurring during the life of the unit but are not maintained in sufficient detail to provide the environmental data required. If the environmental conditions were known during operation, they possible could be screened for those conditions which simulate the flight profile. The added expense of obtaining this required information would, of course, have to be compared to the tentative benefits for possible justification.

D. Summary of Test Procedures and Data

The test procedures and data from the CENTAUR IGS production process have been reviewed for relevancy to the data requirements for a reliability analysis of the first gimbal stabilization loop with the RTI reliability model. The goal in the study was to identify for later use any data which reflects the behavior of the loop or its elements over time under the influence of input conditions simulating all or part of the mission profile. Since the major contribution to reliability techniques advanced by the RTI model is the inclusion of drift effects in a reliability analysis, the emphasis was on observing those tests which reflected drift behavior of equipment.

The investigation was, of necessity, restricted to fairly routine production type tests; and, as anticipated, the data of the desired type was sparse. Sufficient data was available to identify the gyro as the major source of drift in the loop; hence, the gyro drift rate was designated as a drift attribute to be considered in detail. Gyro drift rate data was available and its use in a drift reliability analysis will be demonstrated.

Another tenative source of element drift affecting platform drift was identified as the GCA null current. No tests were observed which yielded observations of its drift behavior over time, but for purposes of demonstrating its applicability it will be included in the analysis with artificial data inserted for illustration.

Another source of variation in the loop is the break-away frictional torques of the torque motor and slip rings. These are not designated as drift attributes but can definitely be included in a complete analysis to include the non-linear behavior of the system.

The gimbal could possibly represent a source of variation through mass unbalance effects; however, in practice it can be trimmed to near perfect balance so that its contribution to platform drift is very small. All evidence indicated the remaining element, the preamplifier, to be very reliable in terms of drift behavior.

For the reliability analysis of the first gimbal stabilization loop, great assistance is provided by a functional diagram of the loop. Following simplification of the original representation presented in [2] and consideration of the available data as presented herein, the final and most simplified functional representation is presented in Figure 6. All symbols in the figure are defined in the tables contained in the text of the report. In the lower portion of the diagram the functional interconnection of all elements is presented. The pertinent drift attributes as identified are limited to the gyro drift rate and the GCA null current output.

The external inputs to the elements are indicated by the lettered functional connections with the specific inputs into the functional connectors defined at the top of the diagram. For example, through connector B the gyro receives inputs of e_B, e_C, and e_D from the system power and frequency supply and through connector F receives the indicated environmental inputs through the platform housing.

In describing the behavior of the attributes over time it is desirable to include the influence of the behavior of the inputs. Since the tests were mostly conducted under precisely controlled nominal and laboratory conditions and the variations expected during the mission were not simulated, their influence could not be evaluated. An exception to this, as pointed out in the text, was the influence of acceleration inputs to the gyro.

IV. Conclusions

An investigation of the CENTAUR IGS (Inertial Guidance System) test and data collection procedures has been conducted to identify those data which aid in describing the behavior of the first gimbal stabilization loop for a reliability analysis using the Research Triangle Institute reliability model. Comparison of the data requirements for application of the model with the actual data generated during the production stage of the CENTAUR IGS program results in an immediate conclusion that the amount of applicable data from the production stage is limited. This situation was anticipated because normal production procedures are not usually tailored to yield the type of data desired for application of the model and the contractor in this case was not funded to provide the testing and data collection procedures required to fully apply the model.

Since it was not adjudged practical to investigate other test and data collection procedures during the program stages prior to production, no concrete conclusions can be drawn about the applicability of the data from these stages. However, it is felt that some of the data from the early stages would have been applicable, particularly some of that from design approval tests where the influence of some environmental stresses on the equipment performance was considered.

Some familiarity was gained with the expanded system test and evaluation program which was just getting underway and it was concluded that some applicable data from these tests would definitely result. The data from these tests could more appropriately be applied by treating the system units as elements, or perhaps, the whole system as a single element.

As has been indicated in this report, the principal source of data collected during production was measurements of gyro drift rate. These data have been successfully used in the Research Triangle Institute reliability model, as is described in reference number [4].

V. Acknowledgment

The authors wish to express their sincere appreciation to the Minneapolis-Honeywell (MH) Regulator Company for its contributing role in this study by providing ready access to its Aeronautics Division facility at St. Petersburg, Florida. The cooperation and assistance rendered by the MH personnel are greatly appreciated, with particular thanks extended to Mr. Marion Smith and his staff for coordinating the activities.

VI. References

[1] Lewis, J. B. and Wells, W. T., "Probabilistic Models for Predicting System Reliability," Working Paper No. 3, September, 1962, Contract NASw-334, Research Triangle Institute, Durham, North Carolina.

[2] Thompson, W. S., "Probabilistic Models for Predicting System Reliability-Application to CENTAUR IGS," Working Paper No. 4, December, 1962, Contract NASw-334, Durham, North Carolina.

[3] Thompson, W. S., "Data for the Reliability Analysis of the CENTAUR Azimuth Gimbal Stabilization Loop," Working Paper No. 6, (CONFIDENTIAL) January, 1963, Contract NASw-334, Research Triangle Institute, Durham, North Carolina

[4] Connor, W. S. and Thompson, W. S., "Reliability Analysis of the CENTAUR IGS First Gimbal Stabilization Loop," Working Paper No. 11, December, 1963, Contract NASw-334, Research Triangle Institute, Durham, North Carolina.

[5] Thompson, W. S., "Functional Description of a Single-Axis Stabilization Loop of a Stable Platform System," Working Paper No. 8, August, 1963, Contract NASw-334, Research Triangle Institute, Durham, North Carolina.

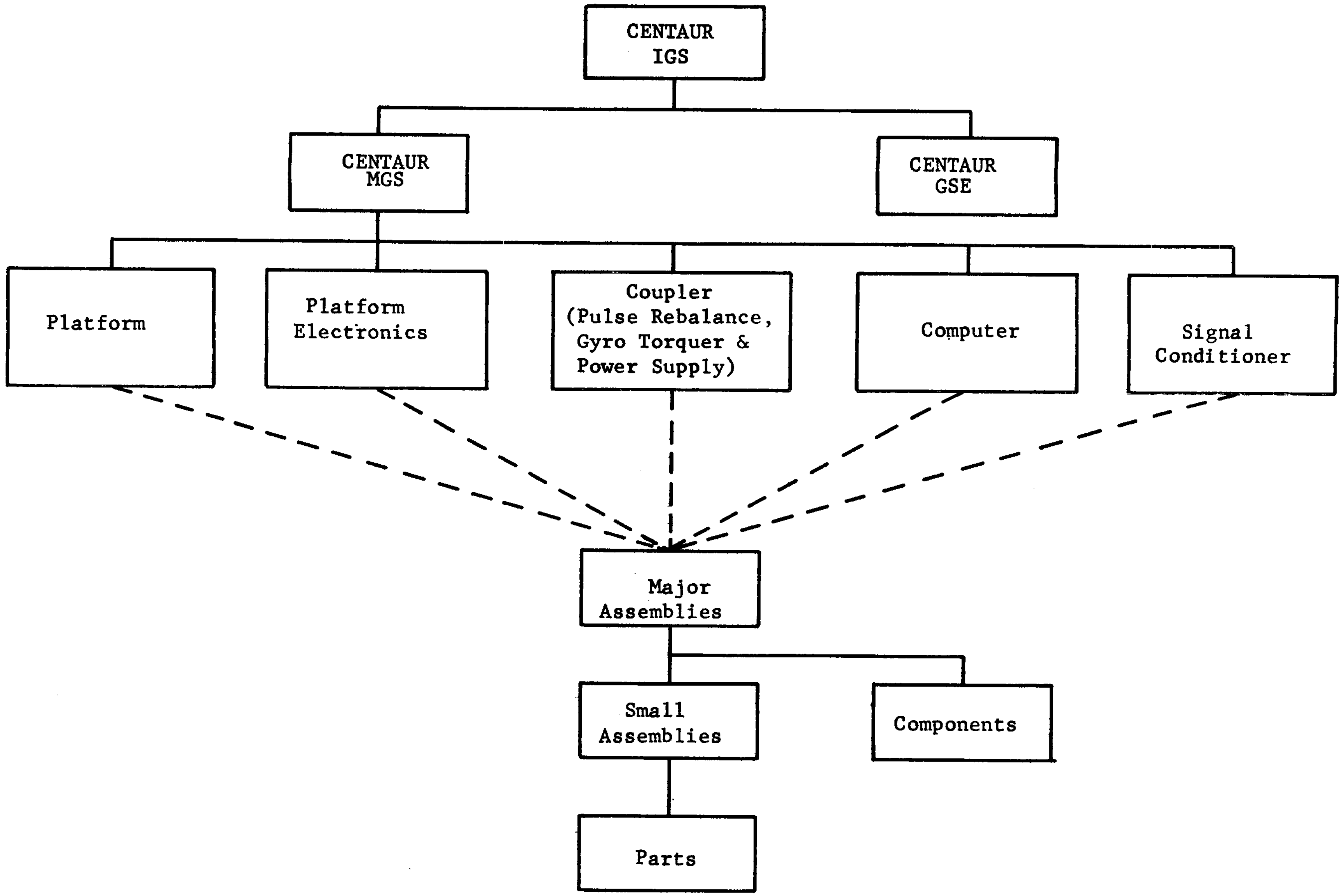


Figure 1. Equipment Identification of the CENTAUR IGS

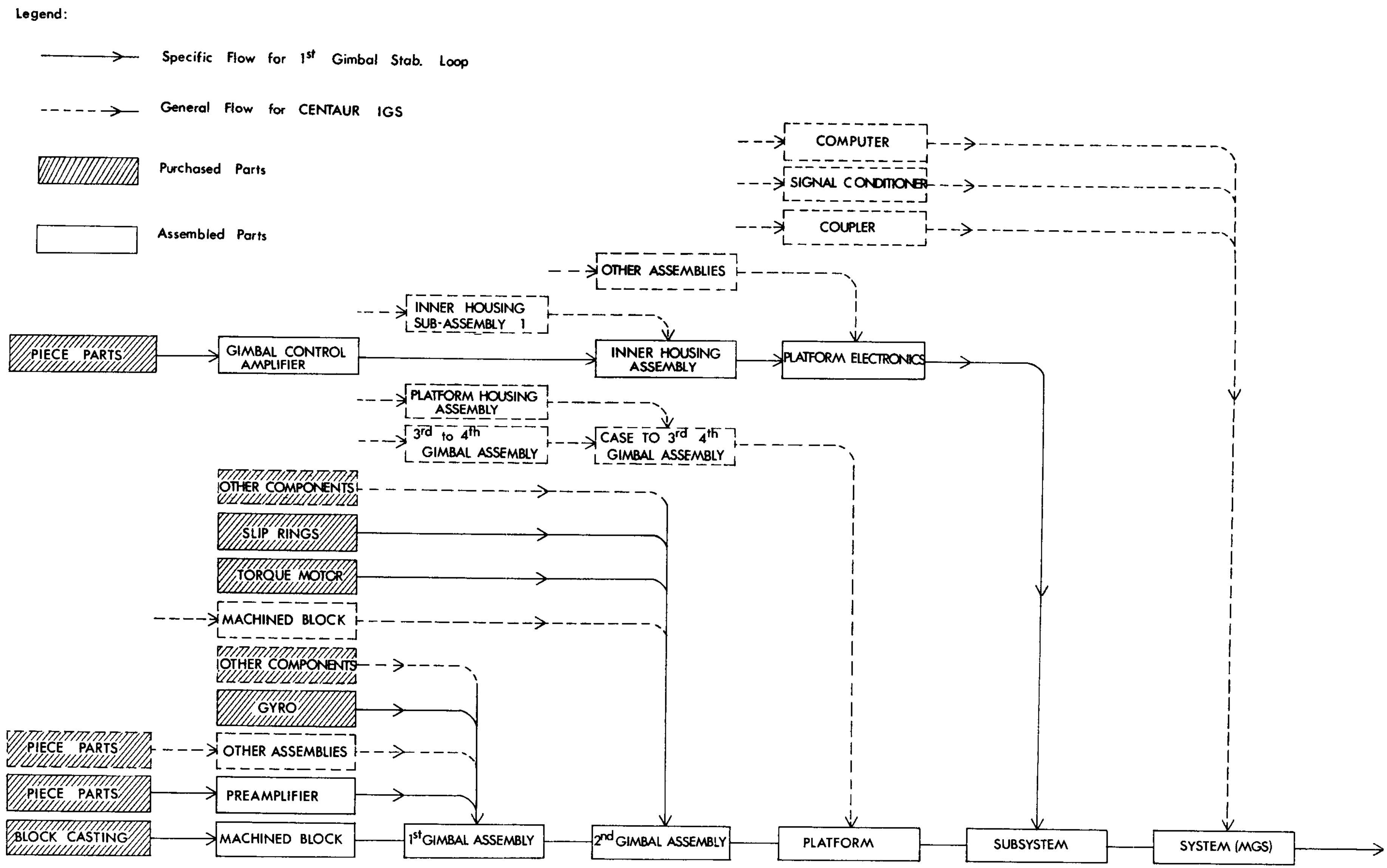


Figure 2. ASSEMBLY FLOW FOR THE FIRST GIMBAL STABILIZATION LOOP

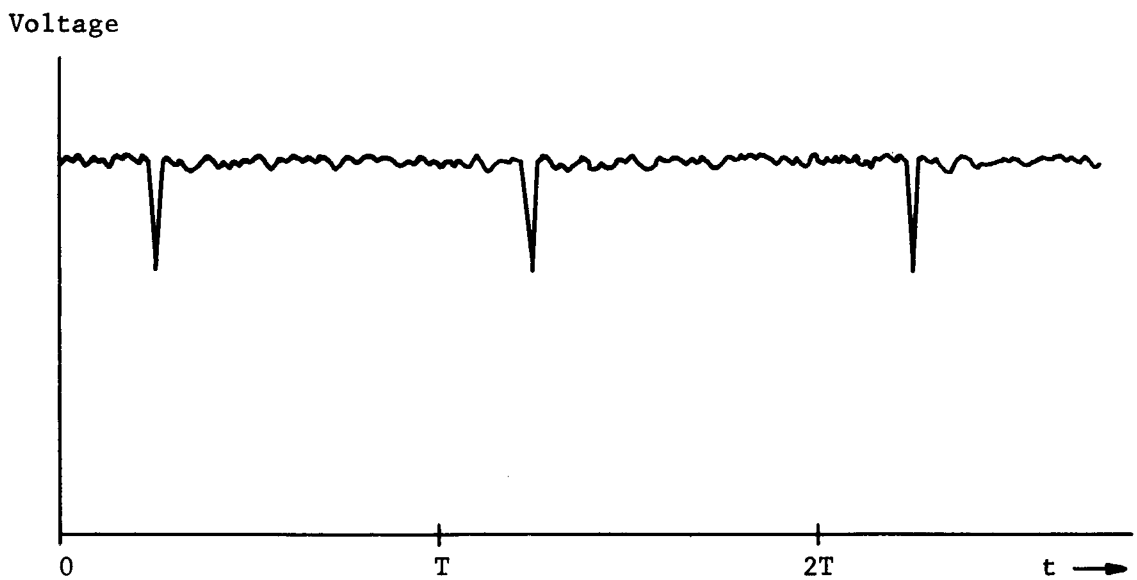


Figure 3. Illustration of Slip Ring Noise Measurement

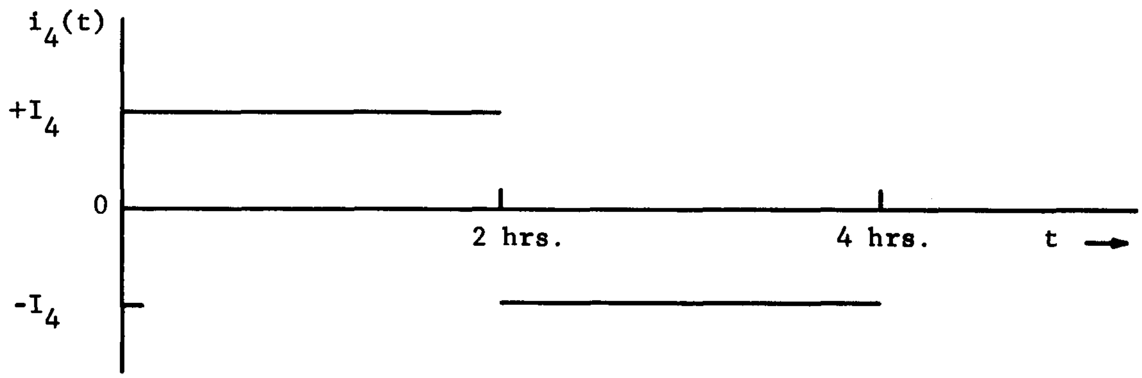


Figure 4. Nominal GCA Output Current During Four Hour Burn-in Test

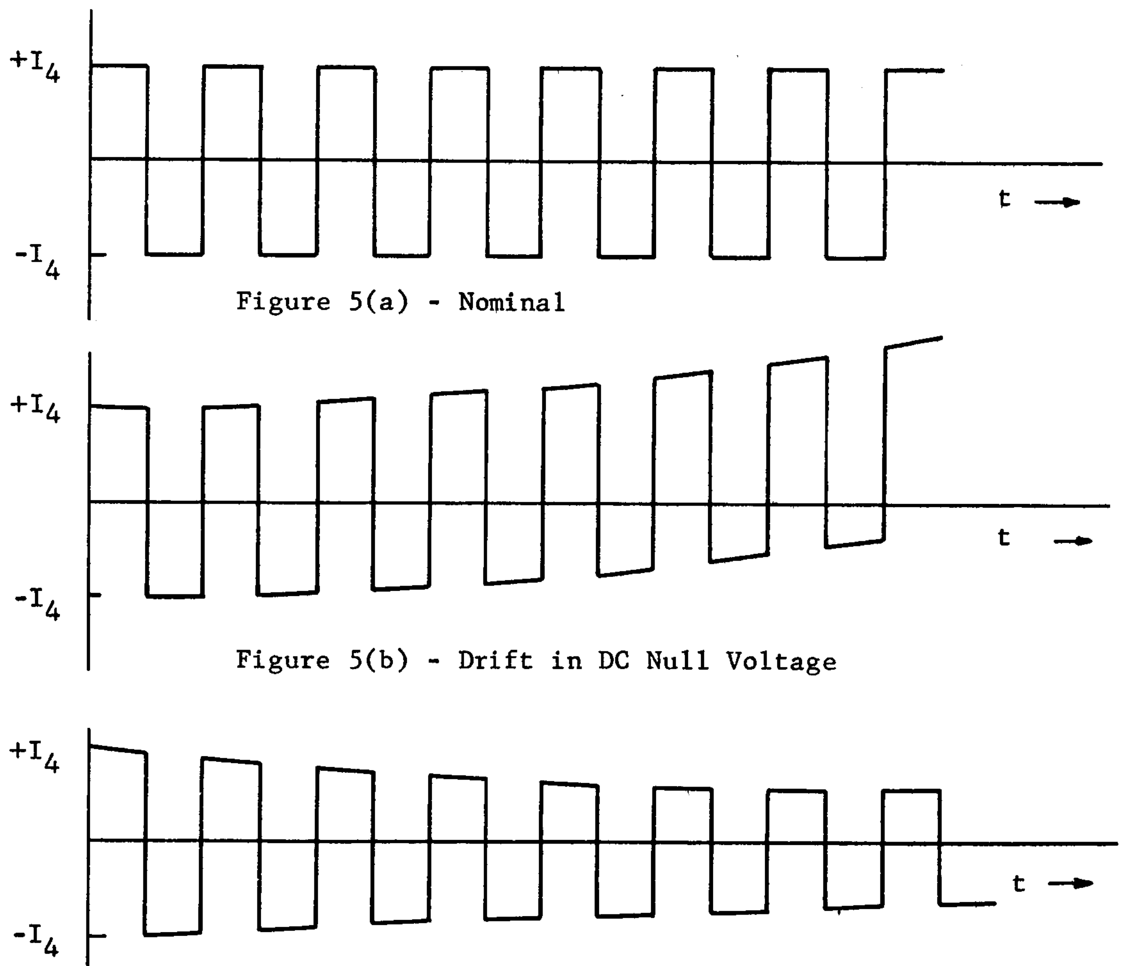


Figure 5(a) - Nominal

Figure 5(b) - Drift in DC Null Voltage

Figure 5(c) - Drift in Static Gain

Figure 5. Continuous Recordings for Observing Amplifier Drifts

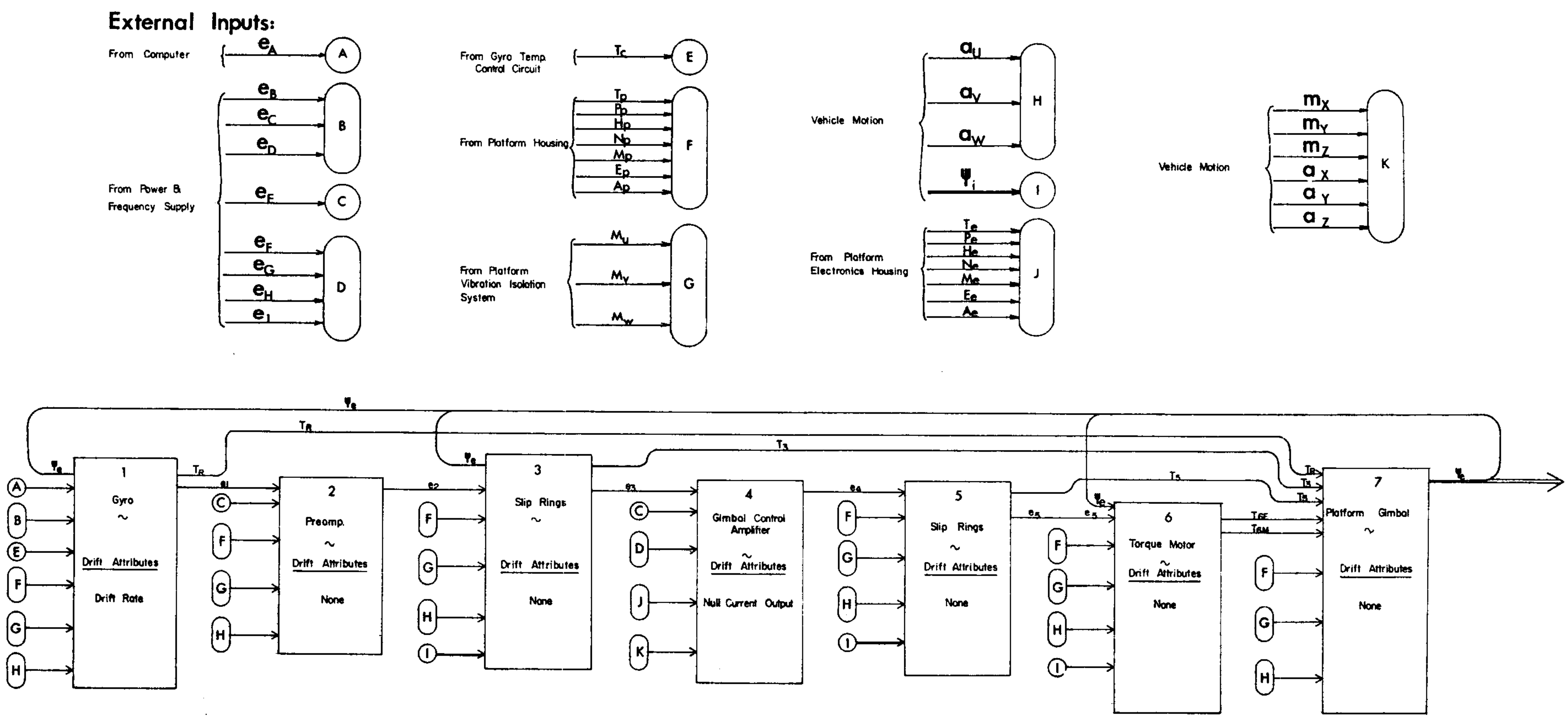


Figure 6. FUNCTIONAL DIAGRAM OF THE FIRST GIMBAL STABILIZATION LOOP

APPENDIX A-I. DESCRIPTION OF GYRO DRIFT

The stable platform of the CENTAUR IGS employs miniature rate-integrating gyros as inertial sensors. The functional operation of the gyro is described in [5]. Since gyro drift is usually the serious and significant degradation factor of the stable platform, its origin, classification and treatment in analysis are described in more detail.

As explained in [5], gyro drift results from disturbing torques acting on the gyro gimbal about the gyro OA (output axis). For purposes of analysis the disturbing torques are classified as either

1) Acceleration insensitive torques such as constant (fixed or reaction) torques, temperature dependent torques or torques dependent upon the magnetic environment, or
2) Acceleration sensitive torques resulting from mass unbalance of the gyro gimbal which is sensitive to both linear and vibratory acceleration along both the gyro IA (input axis) and SRA (spin reference axis).

Both classes of torques are considered to contain both deterministic and random components. The goal in the use of the gyro in a system is to maintain the random torques to a minimum by rigid acceptance test specifications on the gyros and good control of the gyro operating environment and to measure and compensate for the deterministic torques.

Compensation for the deterministic torques is accomplished with the aid of a gyro torquer as illustrated in Figure A-1. $U_D(s)$ represents the total of all disturbing torques on the gyro gimbal. Prior to the mission the deterministic torques are measured and programmed into the system computer. During the mission, the computer feeds an electrical current e_A into the gyro torquer which produces compensating torques $U_c(s)$ about the gyro OA. The residual torques $U(s)$ acting about the gyro OA contains the random torques plus the error in the deterministic compensating torques.

Gyro tests are not usually designed to measure the disturbing torques per se, but rather, the effect of the torques on the gyro drift performance. For the type gyro considered, a convenient performance attribute is the effective gyro drift rate resulting from the residual disturbing torques. The total angular rate $\dot{\theta}$ of the gyro gimbal about the OA is then conveniently expressed as

$$\dot{\theta}(s) = \dot{\theta}_g(s) + \dot{\theta}_d(s) \tag{A-1}$$

where

$$\dot{\theta}_g(s) = \frac{H}{Is + D} \dot{\Psi}_e(s) \tag{A-2}$$

is the angular rate resulting from gyroscopic torques caused by platform motion $\dot{\Psi}_e(s)$ and

$$\dot{\theta}_d(s) = \frac{1}{Is + D} U(s) \tag{A-3}$$

is the gyro drift rate due to the residual disturbing torques U(s).

APPENDIX A-II. SIX POSITION DRIFT TEST

Gyro tests are conducted to measure the drift rates due to both deterministic and random torques. The six positions drift test is designed to measure primarily the drift rates due to deterministic torques which for the type gyro employed in the CENTAUR IGS are considered to belong to the following three types:

CT - drift rate due to constant torques about the OA

MUIA - drift rate due to mass unbalance along the IA, and

MUSRA - drift rate due to mass unbalance along the SRA.

CT is acceleration insensitive and both MUIA and MUSRA are acceleration sensitive.

In conducting the six position gyro drift test to measure the above drift rates, two test techniques are employed depending upon the desired accuracy or sophistication. The first of these techniques is to connect the gyro into a low rate servo loop by providing a feedback path from the signal generator output to the gyro torques via a feedback amplifier and monitoring the torques input current. The resulting loop is defined by the diagram in Figure A-2. The electrical feedback acts as an electrical spring and essentially converts the gyro from a rate-integrating gyro into a rate gyro. The gyro open loop transfer function without drift compensation is normally

$$e_1(s) = \frac{k_s H}{s(Is + D)} \dot{\Psi}_e(s) + \frac{k_s}{s(Is + D)} U_D(s) , \qquad \text{(A-4)}$$

but with the negative feedback path provided, the closed loop transfer function becomes

$$e_A(s) = \frac{k_A k_s H}{Is^2 + Ds + k_A k_s k_T} \dot{\Psi}_e(s) + \frac{k_A k_s}{Is^2 + Ds + k_A k_s k_T} U_D(s) . \qquad \text{(A-5)}$$

In (A-4) $e_1(s)$ is directly proportional to the integral of the input rate and the integral of the disturbing torque, but in (A-5) $e_A(s)$ is directly proportional to the input rate and the disturbing torques themselves. Since $e_1(s)$ in open loop operation is proportional to the integral of the gyro rate $\dot{\theta}(s)$, $e_A(s)$ in closed loop operation is proportional to $\dot{\theta}(s)$ in open loop operation. The feedback adds stability, for without it the gyro operation in open loop would be unstable by just sensing any input rate and disturbing torque and integrating off against its mechanical stops.

Comparison of (A-4) and (A-5) reveals some difference in bandpass characteristics; however, the linear proportionality at low rates is considered of more importance.

The other technique is to connect the gyro into a high rate servo loop and observe the torquer current required to make the gyro drift rate zero. The gyro is mounted on a servo table and the feedback around the gyro is via the servo table electronics and torque motor. For all practical purposes, the operation is identical to that of a platform itself when operating in laboratory tests, i.e., the system is not subjected to accelerations.

Three basic gyro orientations for testing are illustrated in Figure A-3. These three orientations may typically represent three of the six orientations used in the six position drift test, the remaining three obtained by rotating the gyro 180 degrees about the OA for each of the positions shown.

By observing the gyro drift in each of the six positions so obtained the indicated drift rate variables may be observed. In the first orientation the OA is oriented and maintained along local vertical (along the local gravity vector). The force on the mass unbalances about the IA and SRA due to gravity is directed parallel to the OA, hence does not cause torques about the OA. The only disturbing torques are the ever-present constant torques causing an observed drift rate α_1. α_1 is actually a random variable and is known to vary (but with small standard deviation) from test to test. The object in each test is to estimate the current value of α_1 for either determining the amount of drift compensation required for later use or for comparing with other values to estimate the amount of shift in α_1.

In the center orientation the mass unbalance along the IA is being subjected to 1 g. (32.2 ft./sec.^{2}) of gravity acceleration giving rise to an additional drift rate α_2 with the total observed drift rate being $\alpha_1 + \alpha_2$. α_2 is also a random variable that may vary from test to test.

The third orientation similarly results in a drift rate α_3 due to mass unbalance along the SRA being subjected to 1 g. acceleration with the direction of torque for this orientation defining α_3 to be in the negative direction. The total drift rate is then $\alpha_1 - \alpha_3$ where α_3 is also a random variable that may vary from test to test.

The remaining three orientations resulting by the 180° rotation about the OA permit observations of α_1, $\alpha_1 - \alpha_2$ and $\alpha_1 + \alpha_3$ which when considered simultaneously with the above observed values of α_1, $\alpha_1 + \alpha_2$ and $\alpha_1 - \alpha_3$ provide separate estimates of α_1, α_2 and α_3.

The six positions discussed and the observations conducted are somewhat simplified but serve to illustrate the techniques and usefulness of the six position drift test. More sophisticated orientations are used in actual practice, for example, instead of using the earth's north pole for inertial reference as implied in Figure A-4, true north can be conveniently employed.

In addition to testing the gyro as an element the six position technique is also employed in testing for platform drift. In the platform six position drift test the stabilization servo loops are closed so that the gyro is operating as an open loop element in the closed loop. In each position the platform drift is first stabilized by supplying the necessary drift compensating current to the gyro torquer. The platform loops are kept closed for a period of several minutes and the total platform drift angle at the end of the period is observed. The platform drift rate is then computed and related back to the particular gyro in the loop causing the platform drift. The magnitude of the initial drift compensating current to the gyro torquer may be determined by trial and error as that required to instantaneously stabilize the drift or may result from estimates of the drift rate obtained from previous tests.

APPENDIX A-III. THREE HOUR DRIFT TEST

The three hour drift test is employed to measure the gyro drift rate due to random disturbing torques about the OA. With the gyro operating in the low rate servo loop and oriented with the OA vertical as illustrated in the left diagram of Figure A-3, a continuous trace of the drift rate may be obtained over time. Such a trace may be illustrated by the trace labeled OAV in Figure A-4. The initial or starting value is α_1; however, observations over time indicate variations about α_1. These random variations appear to take the form of a long term trend plus a higher frequency process. A possible model for describing the overall drift rate process for OAV is

$$\dot{\theta}_d = \alpha_1 + \beta_1 t + \beta_2 t^2 + x(t) \tag{A-6}$$

where α_1, β_1 and β_2 are all considered random variables and x(t) is sufficiently represented by a stationary random process.

With the gyro oriented with OAH the initial or starting value is $\alpha_1 \pm \alpha_2$ or $\alpha_1 \pm \alpha_3$ depending upon the particular orientation chosen. The drift rate trace is also illustrated in Figure A-4 by the trace labeled OAH. Both the trend effect and the random process are again observed.

Conventional treatment and use of the three hour drift rate data is for merely determining the acceptability of the gyro for installation in a system. The drift rate over the three hour period is averaged over short term intervals of, say, six minutes duration, either by hand calculation or instrumentation with an integrator, and then the standard deviation of the six minute averages computed and compared to specification for determining acceptability.

More extensive use of this data is intended for the reliability analysis to be conducted and is discussed further in Appendix A-IV.

APPENDIX A-IV. A MATHEMATICAL MODEL OF GYRO DRIFT RATE

A discussion of gyro drift rate measurements was presented in Appendices A-II and A-III. For analysis it is desirable to combine the variables observed into a single model to describe the drift rate with the gyro operating in the mission.

The six position drift test yielded measurements permitting estimates of the drift rates α_1, α_2 and α_3 in units of, say, deg./hr. where α_2 and α_3 are to be specifically identified as the drift rates at 1 g. acceleration since they represent acceleration sensitive drift rates. Assuming a linear extrapolation to other acceleration levels during the mission, α_2 and α_3 can be used as constants of proportionality in the extrapolation with units of deg./hr./g. to estimate the drift rates due to mass unbalance at other acceleration levels. The drift rate during the mission due to mass unbalance along the IA is then $\alpha_2 \, a_{SRA}$ where a_{SRA}, the acceleration along the SRA, is directed normal to the IA. Similarly, the drift rate during the mission due to mass unbalance along the SRA is $\alpha_3 a_{IA}$ where a_{IA}, the acceleration along the IA, is directed normal to the SRA.

Including these terms in (A-6) a drift rate model is postulated as

$$\dot{\theta}_D = \alpha_1 + \alpha_2 a_{SRA} + \alpha_3 a_{IA} + \beta_1 t + \beta_2 t^2 + x(t) \ . \qquad \text{(A-7)}$$

This model is considered sufficient in the proposed analysis. The β_1 and β_2 coefficients and the x(t) process represent those drift factors observed in the OAV three hour drift test. Experimental evidence has shown that these effects are insensitive to acceleration, and, at any rate, even if they differ in the OAH test, no mission is immediately conceived where accelerations are sustained over the long periods of time as simulated in the OAH three hour test.

$\dot{\theta}_D$ in (A-7) represents the actual inherent gyro drift rate before gyro drift compensation. Drift compensation in the system is provided by storing estimated values of α_1, α_2 and α_3 into the system computer and computing a drift compensation signal using measured accelerations. Letting a carat (^) represent estimated quantities and an asterisk (*) represent measured quantities, the drift compensation effectively provides a compensating drift rate of

$$\dot{\theta}_c = \hat{\alpha}_1 + \hat{\alpha}_2 a^*_{SRA} + \hat{\alpha}_3 a^*_{IA} \quad . \tag{A-8}$$

For analysis the primary interest is on the residual drift rate after drift compensation and is expressed by

$$\begin{aligned}\dot{\theta}_d = \dot{\theta}_D - \dot{\theta}_c = \alpha_1 - \hat{\alpha}_1 + \alpha_2 a_{SRA} \\ - \hat{\alpha}_2 a^*_{SRA} + \alpha_3 a_{IA} - \hat{\alpha}_3 a^*_{IA} \\ + \beta_1 t + \beta_2 t + x(t) \ .\end{aligned} \tag{A-9}$$

Assuming the errors in the measured accelerations are small, a convenient assumption is

$$a^*_{SRA} = a_{SRA} \ ; \ a^*_{IA} = a_{IA} \quad . \tag{A-10}$$

Substituting the conditions of (A-10) and factoring out a_{SRA} and a_{IA}, the residual drift rate becomes

$$\dot{\theta}_d = \Delta\alpha_1 + \Delta\alpha_2 a_{SRA} + \Delta\alpha_3 a_{IA} + \beta_1 t + \beta_2 t + x(t) \tag{A-11}$$

where each $\Delta\alpha = \alpha - \hat{\alpha}$ with appropriate subscripts. In the analysis the accelerations from the nominal operational profile for the mission can be employed.

Equation (A-11) represents the model of the residual gyro drift rate to be employed in the proposed analysis. Each term in (A-11) represents a random drift component with the combined first five terms representing a deterministic random process (assuming the accelerations are deterministic function of time) and the last term an entirely random process. The above model serves well to illustrate and demonstrate the application of the different types of random drift behavior outlined in the system reliability model of [1] .

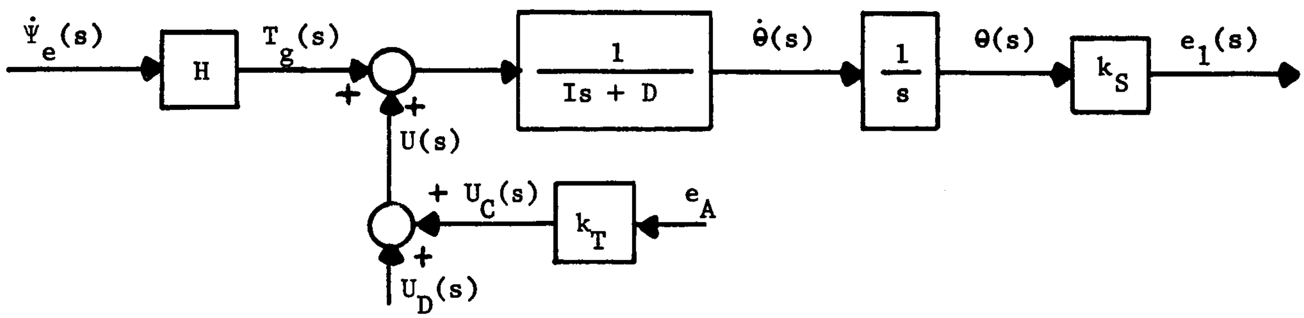


Figure A-1. Floated Rate-Integrating Gyro with Torque Compensation

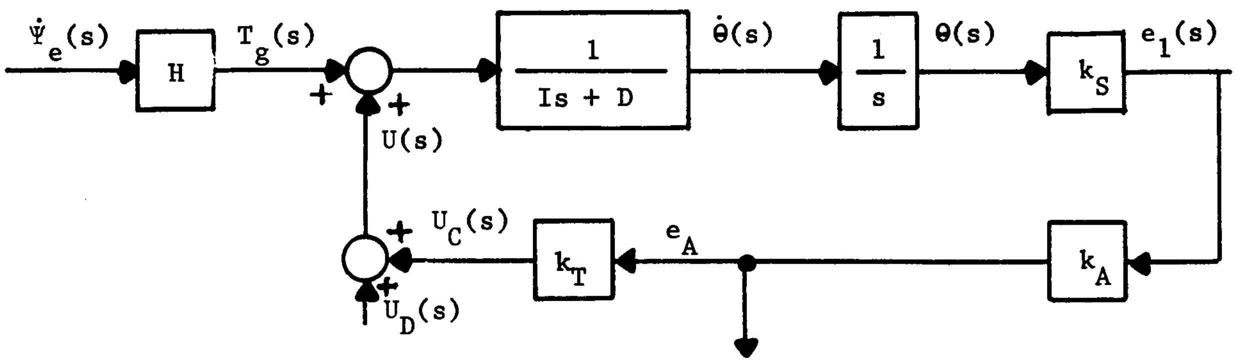
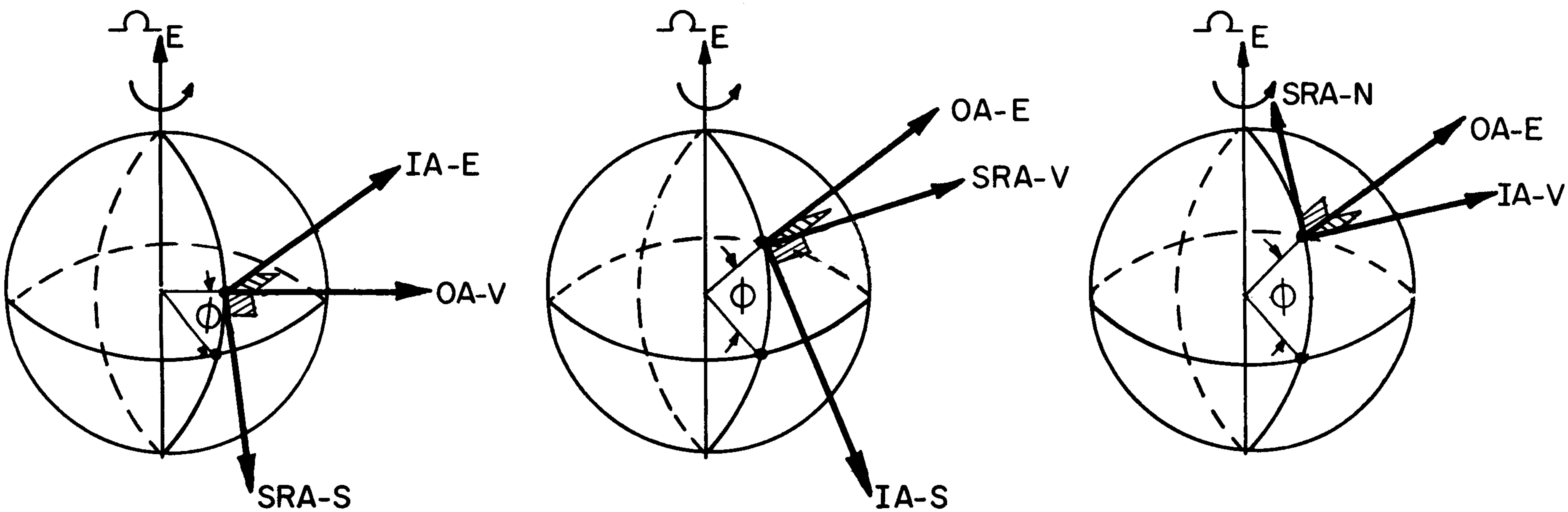


Figure A-2. Gyro Test in Low Rate Servo Loop



$\mathring{\Theta}_d = \alpha_1 = CT$

$$\mathring{\Theta}_d = \alpha_1 + \alpha_2 = CT + MUIA$$

$$\mathring{\Theta}_d = \alpha_1 - \alpha_3 = CT - MUSRA$$

Figure A-3. TYPICAL GYRO ORIENTATIONS FOR MEASURING GYRO DRIFT RATE VARIABLES

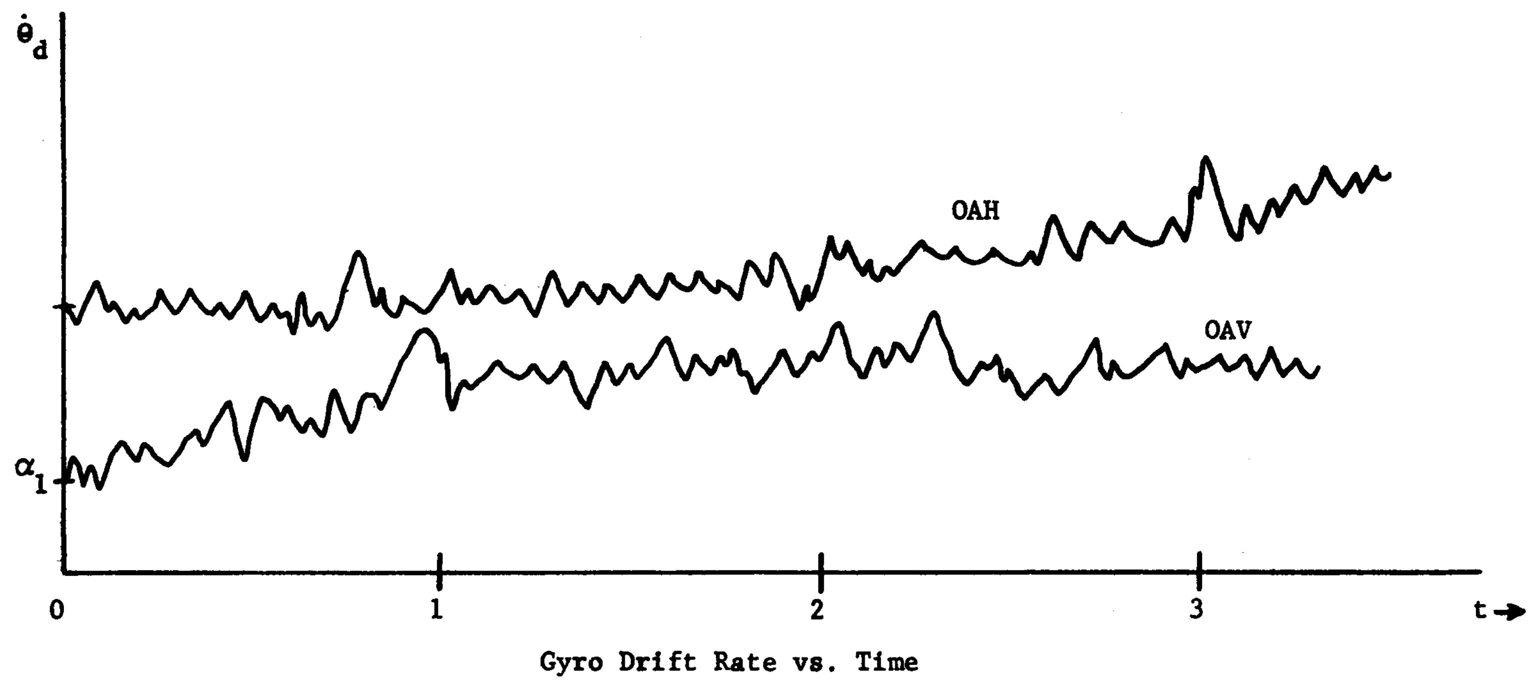


Figure A-4. Variations in Gyro Drift During Extended Tests