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A GUIDE FOR EVALUATING PRECISION GYROS FOR BALLISTIC MISSILE TYPE APPLICATIONS

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MAY 1960

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By

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ABSTRACT

This study recommends production testing procedures for evaluation of precision gyros used to stabilize inertial platforms in a ballistic missile environment. It is recommended that tumbling tests be used for measurement of the drift coefficients (g-insensitive, g-sensitive, and g^2-sensitive drifts); that the long-term stability of the drift coefficients be measured on sample gyros selected from the production line and on gyros recycled from systems in the field; and that by means of three cogging tests, the short-term repeatability of the drift coefficients be measured. "Short-term" is defined for the purpose of this study as a period comparable to missile flight time. This study does not recommend usage of the 24-hour servo tests for applications of the ballistic missile type.

CONTENTS

I. INTRODUCTION

A survey of precision gyro manufacturers has indicated a lack of uniformity in specifying and evaluating gyro performance characteristics. It appears that each manufacturer has independently arrived at a set of preferred test procedures to evaluate essentially the same gyro characteristics. Differences in these procedures cause difficulty when evaluating test data in terms of effect on system performance and lead to varying degrees of confidence in the validity of test results.

Limitations in test accuracy continue to be a significant factor affecting determination and specification of gyro performance. One reason for the wide variation in test procedures is the general attempt to minimize the effect of testing errors on gyro performance data. It appears that too little attention has been devoted to relating test procedures to system application.

The purpose of this report is to specify a set of production test procedures for a precision gyro. The assumed gyro application is for platform stabilization in a high acceleration and vibration environment. The specified tests are only those considered necessary for each production gyro and do not include the wide variety of special purpose tests required for design evaluation.

While the tests specified in this report are generally applicable to all types of precision gyros, the terminology used is limited to the single-degree-of-freedom rate integrating gyro for simplicity. Details of the test procedures would vary slightly with individual gyro design characteristics.

II. SYSTEM APPLICATION

The gyro evaluation tests discussed in this report are applicable to the class of inertial guidance systems characterized by the utilization of a stable platform attitude reference, operating periods of less than 10 minutes, and acceleration levels from 0 to 20 g's. Included in this category would be guidance systems for intermediate and long range ballistic missiles, satellite launching and injection vehicles, space probe boosters, and re-entry vehicles.

In these applications the gyros are used to define an inertial reference and to maintain the stable platform aligned to this reference during missile flight. Thus, a spurious change in the gyro reference, i.e., gyro "drift," is directly translated into drift of the guidance system attitude reference.

The guidance system may be programmed to compensate for gyro drift if the drift is a predictable function of time and acceleration. Successful application of this compensation obviously requires a knowledge of the coefficients describing the drift as well as assurance that these coefficients are stable with time. However, there is always a residual uncertainty in the drift coefficients which is not predictable and hence cannot be eliminated. This uncertainty places a basic limit on the ultimate performance of the guidance system.

III. DATA REQUIREMENTS

A comprehensive gyro test program must include a series of design evaluation tests on a representative number of units and a set of production tests to be performed on all manufactured units. The purpose of the design evaluation program is to thoroughly evaluate all design characteristics of the gyro. The purpose of the production test program is to verify proper workmanship during gyro manufacture and to supply auxiliary performance data for system compensation and prediction of system accuracy. In general, production tests are designed to quantitatively evaluate those gyro characteristics which may vary from unit to unit and have a significant effect on system performance. This usually includes evaluation of absolute magnitude, short-term repeatability, and long-term stability of fixed and acceleration sensitive drift coefficients.

A test program should be designed to evaluate gyro performance characteristics under test conditions simulating both the actual mode of operation employed in the system and the actual environment expected in flight. This is normally accomplished during design evaluation testing, but practical considerations usually prohibit a program of this magnitude for each production unit. An alternate approach for production testing is to establish a model of the gyro which can be used for analytical prediction of system accuracy. Production tests are then designed to evaluate appropriate gyro characteristics as defined by the model.

For the single-degree-of-freedom gyro, the drift rate model proposed for this particular application is

$$\omega = R + U_I a_S - U_S a_I + 2K a_S a_I \quad ,$$

where ω is the instantaneous drift rate and a_S and a_I are the components of acceleration (including both steady-state acceleration and vibration) along the spin and input axes, respectively. R, U_I, U_S, and K are called the gyro drift coefficients. This model assumes that the significant drift characteristics which must be determined for each production unit are completely described by the foregoing equation. Similar models may be established for other types of gyros.

The data requirements for a production test program may therefore be itemized as follows:

A. Gyro Drift Coefficients

Quantitative values for each of the drift rate coefficients are required. As stated above these are:

1) The "fixed drift" coefficient (R)
2) The "unbalance" coefficients (U_I and U_S)
3) The "compliance" coefficient (K)

B. Long-Term Stability

Since the drift coefficients are initially measured in a laboratory test area and the gyro is then subjected to long periods of use or storage prior to launch, it is necessary to determine the stability of the coefficients with time. Data are thus required on the long-term stability of the four drift coefficients under conditions appropriate to the system application, for example, missile storage and prelaunch testing, and should encompass time periods comparable to the service life on the system.

C. Short-Term Stability

Measurement of the gyro drift coefficients normally results in a mean value for each coefficient obtained over a test period of an hour or longer. Since system accuracy depends on the instantaneous gyro drift during flight, it is necessary to determine the short-term variation of the drift coefficients about this mean value These variations are considered to represent the sum total effect of all parameter changes, such as temperature, supply voltage, etc., not accounted for in the model equation. The short-term stability data should therefore to taken under test conditions similar to the system application with respect to these parameters and should be measured for periods that approximate the flight operating time of the system

IV. RECOMMENDED TESTS

As discussed above, a suitable compromise between complete simulation of the gyro environment and a reasonable expenditure of time and test equipment is necessary. To this end, the following tests are recommended.

A. Determination of Drift Coefficients

Drift coefficients are best determined by the "tumbling" test. For this test the gyro is mounted on a turntable with its input axis perpendicular to the axis of rotation of the table. The turntable is rotated at a constant velocity of approximately 150 deg/hr (10 times earth's rate) by means of a synchronous motor drive. When properly aligned as shown in Figure 1, neither the table rotation nor earth's rotation is sensed as the gyro is rotated in the earth's gravitational field. The output of the gyro is amplified and fed back to the gyro torquer to form a current balance servo which maintains the gyro gimbal at null. The torquer current is thus a measure of the instantaneous drift rate of the gyro and is due entirely to the fixed (R), unbalance (U_I, U_S), and compliance (K) drift rates of the gyro. By reversing the direction of table rotation, the data may be corrected for any residual misalignment of the gyro with respect to the turntable axis.

The output data for this test is the measurement of the balance current as a function of turntable position (ϕ). Fourier analysis of the data yields the following results:

$$\omega = R + U_S g \cos\beta \sin\phi - U_I g \cos\beta \cos\phi + K g^2 \cos^2\beta \sin 2\phi$$

where $\omega = ki$ is the gyro drift rate, k is the torquer scale factor, i is the balance current, and β is the local latitude angle. The drift rate coefficients R, U_S, U_I, and K are identified as indicated with the Fourier coefficients of the output data.

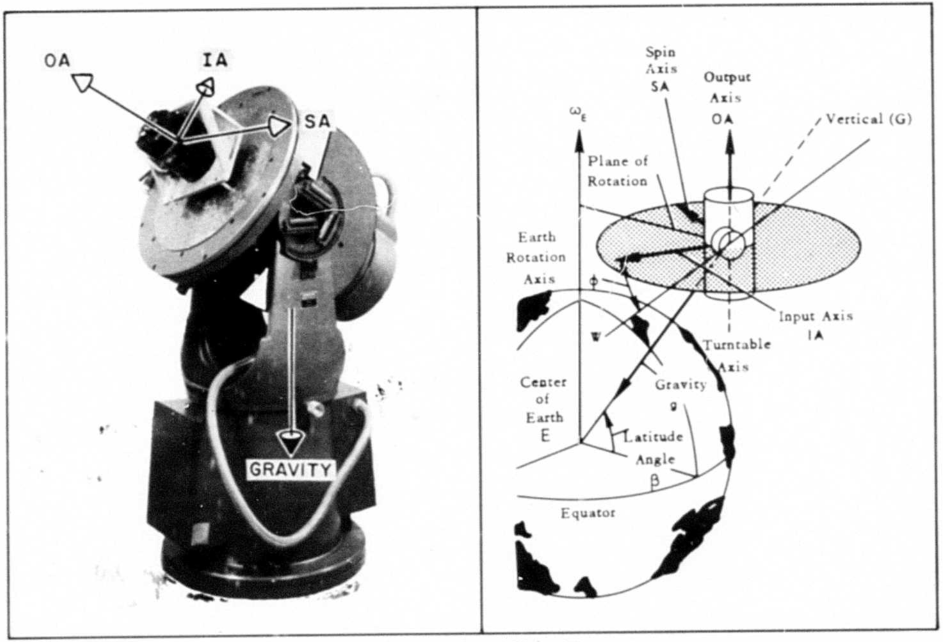


Figure 1. Tumbling Test.

A minimum of two revolutions of the table in the same direction should be taken to establish the consistency or dependability of the data. One or more revolutions in the opposite direction is required to guarantee that misalignment of the gyro to the table has not introduced an erroneous indication of fixed drift.

B. Long-Term Coefficient Stability

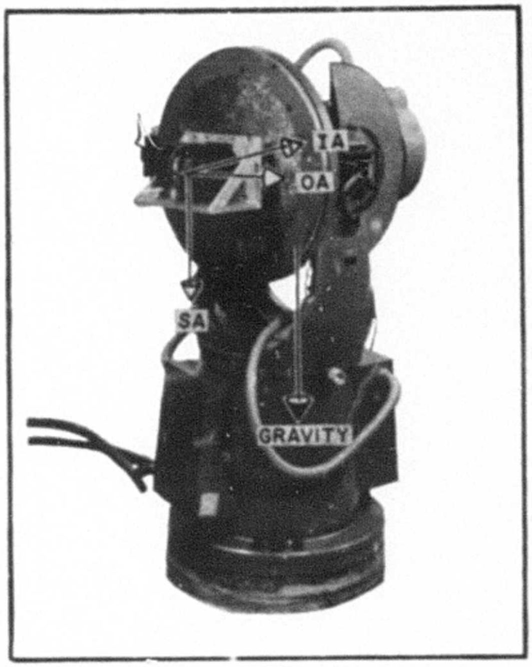
Production gyros should be tested to establish long-term stability of the drift coefficients. Ideally, each gyro should be periodically recycled through a tumbling test identical to that used for initial determination of the gyro coefficients. The optimum period between measurements would vary from three months to a year.

Logistic considerations generally prohibit this type of stability determination for each production gyro. A satisfactory alternative involves long-term stability tests of sampled production gyros supplemented with tests of gyros recycled from system use. Those gyros that are not sampled or recycled should be checked for gross instability during periodic checkout of the system.

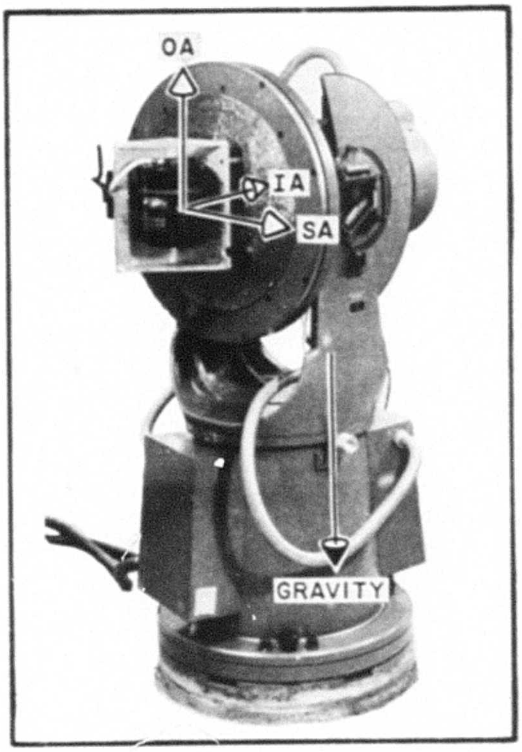
C. Short-Term Repeatability

The short-term repeatability should be measured using three "cogging" tests, in which the gyro stabilizes a servo test table in the same manner that it stabilizes the platform of the system. This requires that the gyro input axis be parallel to the table axis. The table axis is oriented vertical or horizontal in the meridian plane, as required, to operate the gyro with (1) the output axis vertical, (2) the spin axis vertical, and (3) the input axis vertical.

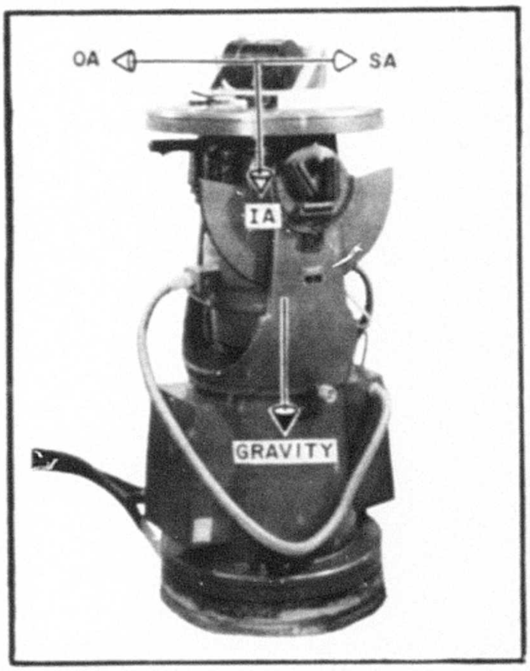
These orientations are shown in Figures 2a, b, and c. The servo table will rotate relative to the earth since the gyro input axis is not perpendicular to the earth's axis. The short-term stability of the gyro's performance may be determined by repeated measurements of the table rate, obtained by measuring the time required for the table to pass



b. Spin Axis Vertical.



a. Output Axis Vertical.



c. Input Axis Vertical.

Figure 2. Orientation of Table Axes for Cogging Test.

through an angle of about one degree. This time will be from 5 to 10 minutes, depending on the particular orientation and the latitude, and is comparable to the missile flight time.

When the table has traversed the one-degree angle, a torquing current is applied to the gyro torquer to slew the table back to its initial position. The current is then removed and the table again permitted to rotate through the same one-degree angle. The time is again measured. The standard deviation for several runs is computed and represents the short-term repeatability of the gyro coefficients. A typical numerical value is given in the appendix.

The gyro attitude for each of the three tests emphasizes the instability of one or more of the drift coefficients. With the gyro output axis vertical (Figure 2a) the repeatability of the fixed or g-insensitive coefficient is measured. The equation for the table rate is:

$$\omega_T = R - \omega_\varepsilon \cos \beta$$

where

ω_T = table rate of rotation (deg/hr)

ω_ε = earth's rate of rotation (deg/hr)

β = latitude angle

R = drift rate due to fixed torque acting on the gyro float

The 1σ value of the output axis vertical drift rate is considered to be the fixed drift repeatability (δR).

With the gyro spin axis vertical (Figure 2b), the repeatability is a function of the fixed drift and the g-sensitive term due to the component of the unbalance along the input axis (U_I). The equation for the table rate in this orientation is

$$\omega_T = R - \omega_\varepsilon \cos \beta - U_I g$$

where U_I is the drift rate due to the component of unbalance along the input axis. The 1σ value of the spin axis vertical drift rate is therefore

$$\sqrt{\delta R^2 + \delta U_I^2}$$

where δU_I is the 1σ value of the input axis unbalance repeatability.

In a similar manner the repeatability of the fixed drift term and the g-sensitive term due to the component of unbalance along the spin axis (U_S) can be obtained with the gyro input axis vertical (Figure 2c).

V. DISCUSSION OF RECOMMENDED TESTS

A. Coefficient Determination

The tumbling test has been chosen for quantitative measurement of gyro coefficients. This test is easily mechanized and provides relatively good test accuracy. Errors associated with the test method are mainly a function of gyro characteristics such as torquer uncertainties and nontypical loading effects on the suspension system. Test accuracies from 0.01 to 0.05 degree per hour can be obtained with proper care in design of external amplifier and instrumentation circuitry.

Some predominant characteristics considered in choice of the tumbling test were as follows:

1) Advantages

   a) All drift coefficients are obtained from a single, continuous revolution of the table.

   b) Being continuous and automatic, the test conditions are well controlled and insensitive to human errors; and the test data may be reliably interpreted.

   c) Table drive can be simple and easily mechanized.

2) Disadvantages

   a) Torquer operation introduces errors due to non-linearities, heating, and magnetic coupling.

   b) Rotation of the gyro about the output axis produces nontypical loading effects on the suspension system.

   c) Output current is proportional to rate and therefore noisy, requiring considerable smoothing of the data.

   d) The compliance coefficient may be difficult to evaluate if the value is small relative to the other coefficients.

B. Long-Term Stability

Long-term stability is generally the most difficult gyro characteristic to evaluate. Gyros are normally allocated for system installation after initial determination of the drift coefficients. Later drift rate measurements at the system level are usually of insufficient accuracy to quantitatively evaluate coefficient stability.

To assure compliance with the long-term stability requirement, a two part program is recommended. The first part consists of diverting sample quantities of current production gyros to a long-term stability test. These gyros will be stored and operated in accordance with a plan designed to simulate conditions of system usage. The gyro coefficients will be measured periodically by the test used for their initial determination. These gyros will serve as a control group to monitor current production, to permit stability comparison with recycled gyros, and to provide advanced information on stability problems that may result from design changes.

The second part of the program requires periodic cycling of gyros from system use back through the same test used for initial determination of the coefficients. This recycling is truly a measure of the long-term stability of the coefficients. The details of the recycling plan would need to be set up as a function of the system logistic requirements to avoid unnecessary interference with the program This can generally be done because a number of spare systems, as well as systems out of service for repair, will always be available.

The choice of a recycling period must be based on system requirements and anticipated stability of the gyro. An optimum period of recycling would probably fall between three months and a year. Four or five early production gyros, supplemented with a specified percentage of subsequently produced gyros, would be required in the long-term stability test program.

C. Short-Term Repeatability

The cogging test has been chosen for determination of short-term gyro drift repeatability. This test was selected because the gyro is operated in a servo mode similar to the ultimate system application and because the test period is comparable to flight operating time. Test accuracies from 0.005 to 0.01 degree per hour can be obtained by use of accurate angular sensors and a low-noise servo loop. An uncertainty of 0.005 degree per hour corresponds to a measurement repeatability of one second of arc for an angular increment of one degree.

The repeatability data obtained from this cogging test bear a close statistical relationship to the rms residual after Fourier analysis of tumbling data. Both sets of numbers represent several consecutive drift measurements over intervals of a few minutes. The cogging test data will in general provide a better evaluation of short-term gyro performance because of the inherently greater test accuracy. Laboratory tests using both cogging and tumbling techniques on the same gyro have substantiated this fact. Some predominant characteristics considered in choice of the cogging test for evaluation of short-term repeatability were as follows:

1) Advantages

a) The repeatability of the gyro is measured for a period of time comparable to missile flight time.

b) The gyro is used to stabilize a servo table, a mode of operation similar to its final usage.

c) Test accuracy is not affected by uncertainties in torquer characteristics.

d) The cogging tests fulfill the requirement that the test always be conducted through the same angular increment in order to repeatedly define an angle to an accuracy of one second of arc. This requirement is a result of the necessity of measuring the table rate for a period of time comparable to the missile flight time, which imposes constraints on the instrumentation by limiting the test angle to approximately one degree. One second of arc would produce a test equipment repeatability of 0.005 deg/hr. Time measurements are sufficiently accurate to make their error contribution to the test results negligible.

2) <u>Disadvantages</u>

a) The short-term stability of the drift coefficient due to compliance is not measured.

b) Periodic excitation of the torque generator represents a transient condition applied to the gyro. Torquing at low rates can minimize this transient.

c) A servo table is required, and the test is neither continuous nor easily automated (for the complete three-position test).

APPENDIX
ILLUSTRATIVE EXAMPLE

I. INTRODUCTION

An illustrative example serves to summarize and to demonstrate application of the recommended test procedure. This example develops a procedure for testing a single-degree-of-freedom rate integrating gyro for use with a launch guidance platform.

II. GYRO PERFORMANCE REQUIREMENTS

Gyro drift characteristics must be compatible with system accuracy requirements and available prelaunch calibration facilities. For this example, it is assumed that the system concept provides for compensation of both fixed and acceleration sensitive drift rate effects prior to launch. The compensation technique involves insertion of a velocity bias into the airborne guidance computation to counterbalance the effect of gyro drifts.

Determination of compensation bias values will be based on gyro coefficients as measured during the most recent set of tumbling runs, which must, in general, be conducted in the factory. The elapsed time between tumbling tests and system flight will be about one year.

It is assumed that the following gyro performance requirements have been established to be compatible with over-all system accuracy:

A. Absolute Magnitude of Drift Coefficients

$$R < \pm 0.50 \text{ deg/hr}$$

$$U_S < \pm 0.20 \frac{\text{deg/hr}}{g}$$

$$U_I < \pm 0.20 \frac{\text{deg/hr}}{g}$$

$$K < \pm 0.08 \frac{\text{deg/hr}}{g^2}$$

B. Drift Coefficient Variation About Compensation Value (1σ)

$$\delta R < \pm 0.04 \text{ deg/hr}$$

$$\delta U_S < \pm 0.08 \frac{\text{deg/hr}}{g}$$

$$\delta U_I < \pm 0.04 \frac{\text{deg/hr}}{g}$$

$$\delta K < \pm 0.02 \frac{\text{deg/hr}}{g^2}$$

The stability requirement of the drift coefficient variation about the compensation value represents the allowable 1σ variation during flight from the absolute value measured a year earlier during a tumbling test.

III. GENERAL TESTING SPECIFICATION

The tests to which the gyro should be subjected and the translation of the performance requirements into gyro test specifications are as follows:

A. Drift Coefficient Specification

Each gyro should be subjected to three clockwise and three counterclockwise revolutions of the tumbling test to determine.

1) That no gross manufacturing errors exist in the gyro,
2) That the drift coefficients are within the values specified, and
3) The values of the drift coefficients to be used for system compensation.

B. Defining the Uncertainty Specification

The total uncertainty of the coefficients as given by the error budget must be divided between long-term stability and short-term repeatability specifications for the drift coefficients.

For example, one may assume,

$$\delta R = \sqrt{\delta R_l^2 + \delta R_s^2}$$

where

δR = total fixed drift uncertainty

δR_l = long-term stability

δR_s = short-term repeatability

For the purpose of this example the stability and repeatability have been weighted equally. The specifications then become (in degrees/hour):

Table 1.

Coefficient	Total Uncertainty	Long-Term Stability	Short-Term Repeatability
δR	0.04	0.028	0.028
δU_S	0.08	0.057	0.057
δU_I	0.04	0.028	0.028
δK	0.02	0.014	0.014

1. Long-Term Stability Specification

To assure compliance with the long-term stability requirement, at least three percent of the production gyros are to be scheduled for yearly tumbling test evaluation of gyro performance. In addition, a minimum of five early production gyros are to be subjected to a continuous long-term stability test. The test will be conducted by storing the gyro in accordance with the following schedule and subjecting the gyro to three clockwise and three counterclockwise revolutions of the tumbling test once a month for a coefficient determination.

1st month - Store with gyro fully excited

2nd month - Store at 40°F

3rd month - Store with gyro fully excited

4th month - Store with heaters only

5th month - Store with gyro fully excited

6th month - Store at 40°F

The long-term stability of the gyro coefficients are considered satisfactory if:

a) The peak excursion of each coefficient from its initial value is always less than three times the specified 1σ stability value, given in Table 1, and

b) the standard deviation of the measured coefficient values is always less than the stability value specified.

Results of these tests should either provide early assurance that the gyros will meet stability requirements or will permit early remedial action if stability requirements are not met.

Recycling of gyros from system usage will supplement this program. About 10 percent or 10 gyros, whichever is smaller, will be recycled each month for three clockwise and three counterclockwise revolutions of the tumbling test. Results of this test will be considered satisfactory if the gyro coefficients are equal to their previously determined value within 3 times the limits specified in Table 1.

2. Short-Term Repeatability Specification

To assure compliance with the short-term repeatability requirement each production gyro will be subjected to the three cogging tests prior to system installation. Each test shall consist of 15 cogs. The specification for the cogging test repeatabilities can be derived from short-term requirements specified in Table 1. Specifically, the 1σ repeatability for the cogging tests should be:

Gyro OA Vertical Test (δR)		$\leq$	0.028 deg/hr
Gyro SA Vertical Test	$\left(\sqrt{\delta R^2 + \delta U_I^2}\right)$	$\leq$	0.040 deg/hr
Gyro IA Vertical Test	$\left(\sqrt{\delta R^2 + \delta U_S^2}\right)$	$\leq$	0.064 deg/hr

The assumption has been made that the short-term repeatability of the g^2 term will be acceptable without verification on each production unit. The validity of this assumption would be established by appropriate design evaluation tests.

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