STRAPDOWN GYRO TEST PROGRAM

TELEDYNE SYSTEMS CO., NORTH RIDGE, CALIF

OCT 1977
STRAPDOWN GYRO TEST PROGRAM
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BY
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These proceedings contain papers included in the Eighth Biennial Guidance Test Symposium. This symposium, hosted by the Central Inertial Guidance Test Facility, is directed toward the exchange of information, stimulation of new ideas, and discussion of recent developments in the field of guidance testing. The papers presented in these proceedings include such topics as aircraft inertial navigators, strapped-down guidance systems, component evaluation, and analysis techniques. The included papers were those presented in the
unclassified sessions of the symposium. Papers presented in the classified portion of the meeting are being published as Volume II.
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I. SCOPE

This report summarizes the work accomplished and testing performed using the equipment provided by the NASA Marshall Space Flight Center under the no-cost Contract, Number NAS 8-31909, during the period of 1 June, 1976 through 1 September, 1977.

II. INTRODUCTION

The primary purpose of the testing conducted which utilized the GFE provided under this contract was to determine the power spectral noise characteristic performance of the Teledyne two-degree-of-freedom dry tuned-gimbal gyroscope. These tests were conducted using a current configuration SDG-5 Gyro in conjunction with the NASA Marshall SPC provided test equipment with minor modification. Additionally, some long term bias stability tests were conducted on Gyro S/N 606 as well as some first-difference performance testing at the Martin Marietta Corporation - Denver facility.

III. HARDWARE DESCRIPTION

The descriptions of the gyro, test equipment and the testing performed utilizing this hardware are contained in Appendix A. The SDG Test Electronics Box caging electronics was modified for the 7 Hz bandwidth requirements of DRIRU II. The block diagrams and Bode plot characteristics of the capture loops are described in Appendix A, Section III, Figures 4, 5, 6 and 7.

IV. TESTING

The PSD testing performed is described in Appendix A, Section 4. In addition, first difference performance tests were conducted on Gyro Serial Number 069 at the Martin Marietta Corporation - Denver facility. This data is presented in Appendix B along with appropriate definitions. Finally, some long term bias stability data taken at Teledyne at an earlier date on Gyro S/N 606 is presented in Appendix C.
V. CONCLUSIONS

The general conclusions from the PSD testing performed are presented in Appendix A, Section VIII. It was concluded from this test series that the SDG-5 Gyro as a sensor would meet the equivalent noise angle performance requirements for DRIRU II. These tests were a significant milestone that led to Teledyne's selection as the contractor for the DRIRU II development.

It may be concluded from the first-difference test data of Appendix B, that the Teledyne SDG-5 Gyro is an excellent sensor for gyro-compass of self-contained alignment inertial systems.

The long term bias data presented in Appendix C shows excellent stability over a three year period which will result in minimal recalibration requirements for the sensor when implemented in DRIRU II.

VI. RECOMMENDATIONS

It is recommended that the GFE hardware used in this contract be dispositioned to the DRIRU II Contract for use and support of further testing for new requirements as they arise.
APPENDIX A
EIGHTH BIENNIAL GUIDANCE TEST SYMPOSIUM

AN EXAMINATION OF LOW POWER SPECTRAL DENSITY (PSD) NOISE PERFORMANCE OF A DRY TUNED GIMBAL TWO-DEGREE-OF-FREEDOM GYROSCOPE, AND METHODS FOR FURTHER NOISE REDUCTION

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ABSTRACT

Recent test and evaluation of dry, tuned gimbal, two-degree-of-freedom gyroscopes has revealed power spectral "noise" levels that compare favorably with floated gyro standards currently used in high accuracy pointing and attitude stabilization systems. Power spectral density test data on the Teledyne SDG-5 dry tuned gyroscope are presented and compared with published results for single-degree-of-freedom floated gyroscopes. The specific capabilities and limitations of the dry tuned gyro approach for high accuracy pointing applications are discussed.

Gyro noise in the strictest sense may be defined as that component of the angular rate output which does not represent the measurement of the true angular rate input to the gyroscopic sensor, but is a spurious output resulting from sensor imperfections, including the associated control and output interface electrical circuitry. The principal sources of the noise for either floated or dry-tuned gyros may be categorized as follows:

1. Suspension system induced torques.
2. Non-suspension system induced torques.
3. Electrical/Magnetic field noise.

The predominant source of low frequency angular rate noise present in inertial gyros results from angular motions or misalignments of the driven (spin reference) axis with respect to the case fixed (stationary) axes. These motions (which ideally do not exist), although small, result in suspension system induced torques acting upon the rotor, or "noise".

It is shown that it is possible to effect significant reductions in this dominant source of noise by the optimization of the basic design parameters of the dry-tuned gyroscope. In particular, it is shown that this noise reduction is most sensitive to the ratios of rotor inertias to gimbal inertias, as well as to the number of gimbals utilized in the design. Tradeoffs of noise reduction versus gyro maximum shock/acceleration capability are presented. In addition further refinements related to angle pickoff accuracy considerations are described.
I. INTRODUCTION

During calendar year 1976, Teledyne Systems Company initiated a program to accurately determine the spectral noise characteristic for the dry-tuned two-degrees-of-freedom SDG-5 Gyroscope. The demand for this data was quite sufficient from a number of potential users in such applications as high accuracy spacecraft stabilization (e.g. DRIRU II and Space Telescope), high energy laser (HEL) pointing, and a number of other important applications. Initial testing was conducted in-house early in the program where it was determined that more sophisticated data acquisition systems were desirable and, primarily that higher stability well instrumented test piers would be required. Teledyne then contacted the Martin-Marietta Corporation, Denver, Colorado and the Space and Missile Systems Organization (SAMSO), Los Angeles AFS, California where the SDG-5 was added to the list for test of candidates competing for the High Altitude Attitude Reference System (HAARS). Additional testing was accomplished at the Boeing Aerospace Company and at Lockheed Missiles and Space Company.

Sufficient data was obtained to show that the Teledyne SDG-5 gyroscope is an extremely attractive rate sensor for use in fine pointing control system applications where jitter is required in the milliarc-second region and that operate with bandwidths to 10 Hz. The instrument is particularly attractive in view of its high reliability, low relative cost to existing standards and capability of operation over a broad temperature range without the use of temperature control. No selection of instruments was made and units were tested on an 'as available' basis. Standard laboratory analog rebalance loops were employed and no gyro heaters, precision temperature control or temperature compensation was used in the test series.

II. GYRO DESCRIPTION

The Teledyne SDG-5 is a dry gyro and features an elastically supported rotor with a dynamically tuned suspension system. The two-degree-of-freedom strapdown gyro consists of four major subassemblies: the case, torquer coils, pickoffs, and rotor containing its tuned three-gimbal suspension system. These subassemblies are shown in Figure 1 and a schematic cross section of the gyro is shown in Figure 2. The gyro case supports a set of ball bearings which in turn carry the shaft. Mounted on one end of the shaft is the motor hysteresis ring and on the other end is the rotor and suspension system. The torquer coils and pickoff subassembly are attached to the case. The end covers, when soldered in place, provide the hermetic seal for the gyro.
The Teledyne SDG-5 Gyro has an angular momentum of $1 \times 10^6$ CGS units while operating at 6,000 RPM on standard R-4 size ball bearings. A summary of physical characteristics is presented in Table 1 and a summary of key performance characteristics is shown in Table 2.

Table 3 presents a summary of instrument characteristics [4] for single-degree-of-freedom floated gyros and a comparison of the SDG-5 two-degree-of-freedom dry gyro.
Table 1. Teledyne SDG-5 Gyro Characteristics

<table>
<thead>
<tr>
<th>GENERAL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>&lt; 2.3 lbs</td>
</tr>
<tr>
<td>Size</td>
<td>3&quot; dia x 3&quot; long</td>
</tr>
<tr>
<td>Figure of Merit</td>
<td>320</td>
</tr>
<tr>
<td>g-Capability</td>
<td>150 g's</td>
</tr>
<tr>
<td>Rate Capability (Steady State)</td>
<td>100 °/sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROTOR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of Rotor</td>
<td>260 GMS</td>
</tr>
<tr>
<td>Polar Moment of Rotor</td>
<td>1600 GM-CM²</td>
</tr>
<tr>
<td>Angular Momentum</td>
<td>$1 \times 10^6$ GM-CM²/sec</td>
</tr>
<tr>
<td>SUSPENSION</td>
<td></td>
</tr>
<tr>
<td>SPIN MOTOR</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Hysteresis Synchronous</td>
</tr>
<tr>
<td></td>
<td>30 volts</td>
</tr>
<tr>
<td>Run-Up Time</td>
<td>&lt;$30$ seconds</td>
</tr>
<tr>
<td>Operating Power</td>
<td>2 watts</td>
</tr>
</tbody>
</table>

| PICKOFF                  |                      |
| Type                    |                      |
| Excitation Frequency    |                      |
| Excitation Voltage      |                      |
| Nominal Scale Factor    |                      |

| TORQUER                  |                      |
| Type                    |                      |
| Nominal Scale Factor    |                      |

| HEATER                   | None Required       |

- Variable Reluctance Transformer
  - 48K Hz sinewave
  - 7 VRMS
  - 100 V/RAD

- Voice Coil
  - 160 °/Hr/ma
Table 2. Teledyne SDG-5 Gyro Performance Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Specification Value</th>
<th>Typical Value (mean)</th>
</tr>
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<tbody>
<tr>
<td><strong>G-Insensitive Bias</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Value</td>
<td>°/Hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability</td>
<td>°/Hr lσ</td>
<td>0 ± 2.0</td>
<td>&lt; 0.50</td>
</tr>
<tr>
<td>Continuous Operation</td>
<td>°/Hr lσ</td>
<td>0.001 Max.</td>
<td>0.0005</td>
</tr>
<tr>
<td>(Random Drift)</td>
<td>°/Hr lσ</td>
<td>0.01 Max.</td>
<td>0.0016</td>
</tr>
<tr>
<td>Shutdown Repeatability</td>
<td>°/Hr lσ</td>
<td>0 ± 0.02</td>
<td>0.00059</td>
</tr>
<tr>
<td>Temperature Cycle Stability</td>
<td>°/Hr lσ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>°/Hr/°F</td>
<td>0 ± 0.02</td>
<td>0.00059</td>
</tr>
<tr>
<td><strong>G-Sensitive Bias</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Value</td>
<td>°/Hr/G</td>
<td>0 ± 1.0</td>
<td>&lt; 1.0</td>
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<tr>
<td>Stability</td>
<td>°/Hr/G lσ</td>
<td>0.002 Max.</td>
<td>0.0007</td>
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<td>Continuous Operation</td>
<td>°/Hr/G lσ</td>
<td>0 ± 0.02</td>
<td>0.008</td>
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<tr>
<td>(Random Drift)</td>
<td>°/Hr/G lσ</td>
<td></td>
<td></td>
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<tr>
<td>Shutdown and Temperature</td>
<td>°/Hr/G lσ</td>
<td>0 ± 0.02</td>
<td>0.0032</td>
</tr>
<tr>
<td>Cycle Repeatability</td>
<td>°/Hr/G lσ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>°/Hr/G/°F</td>
<td>0 ± 0.02</td>
<td>0.0032</td>
</tr>
<tr>
<td><strong>Torquor Scale Factor</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Value</td>
<td>°/Hr/MA</td>
<td>150 Min.</td>
<td>140</td>
</tr>
<tr>
<td>Linearity</td>
<td>PPM Peak</td>
<td>100 Max.</td>
<td>25</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>PPM Peak</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>PPM/°F</td>
<td>-230 ± 20</td>
<td>-229</td>
</tr>
<tr>
<td><strong>Axis Alignment</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Value</td>
<td>Sec</td>
<td>60 Max.</td>
<td>30</td>
</tr>
<tr>
<td>Stability</td>
<td>Sec</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td><strong>Angular Rate Capability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady State</td>
<td>°/Sec</td>
<td>100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Transient</td>
<td>°/Sec</td>
<td>400</td>
<td>&gt;500</td>
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<tr>
<td>Anisoelasticity</td>
<td>°/Hr/g²</td>
<td>0 ± 0.03</td>
<td>0.01</td>
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<tr>
<td>Gyro Time Constant</td>
<td>Seconds</td>
<td>100 Min.</td>
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Table 3. Summary Comparison of Instrument Characteristics

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<th>Characteristic</th>
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<th>Wheel No.</th>
<th>Homopolar Units</th>
<th>Fase</th>
<th>Speed</th>
<th>Radio Power</th>
<th>Gain</th>
<th>Characteristic Time [s]</th>
<th>Torque Generator</th>
<th>Sensitivity</th>
<th>Max Rate</th>
<th>Signal Generator</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td>Type</td>
<td></td>
<td></td>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Wheel</td>
<td>T-State</td>
<td>0.5 x 10^9</td>
<td>0.7 x 10^9</td>
<td>1.7 x 10^9</td>
<td>0.1 x 10^9</td>
<td>1.2 x 10^9</td>
<td>0.2 x 10^9</td>
<td>1.0 x 10^9</td>
<td>0.1 x 10^9</td>
<td>0.2 x 10^9</td>
<td>1.0 x 10^9</td>
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<td></td>
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<tr>
<td>Speed</td>
<td>RPM</td>
<td>2.94 x 10^5</td>
<td>0.6 x 10^5</td>
<td>3.2 x 10^5</td>
<td>0.2 x 10^5</td>
<td>3.1 x 10^5</td>
<td>0.1 x 10^5</td>
<td>0.9 x 10^5</td>
<td>0.2 x 10^5</td>
<td>0.1 x 10^5</td>
<td>0.9 x 10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Power</td>
<td>Watts</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td>1.5 x 10^9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>NA</td>
<td>1</td>
<td>1.2</td>
<td>0.7</td>
<td>1.5</td>
<td>0</td>
<td>0.7</td>
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<td>NA</td>
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<td>NA*</td>
<td>NA*</td>
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<td>Characteristic Time [s]</td>
<td>Milliseconds</td>
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<td>0.75</td>
<td>1</td>
<td>0.48</td>
<td>0.03</td>
<td>0.15</td>
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<td>0.3</td>
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<td>4</td>
<td>NA*</td>
<td>NA*</td>
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<tr>
<td>Torque Generator</td>
<td>Type</td>
<td>EM (windings)</td>
<td>EM (windings)</td>
<td>EM (windings)</td>
<td>EM (windings)</td>
<td>EM (windings)</td>
<td>EM (windings)</td>
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<td>EM (windings)</td>
<td>EM (windings)</td>
<td></td>
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</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td>2.4 x 10^9</td>
<td>3 x 10^9</td>
<td>2.4 x 10^9</td>
<td>2.4 x 10^9</td>
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<tr>
<td>Max Rate</td>
<td>RPM</td>
<td>100 rpm</td>
<td>100 rpm</td>
<td>100 rpm</td>
<td>100 rpm</td>
<td>100 rpm</td>
<td>100 rpm</td>
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<td>100 rpm</td>
<td>100 rpm</td>
<td>100 rpm</td>
<td></td>
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<tr>
<td>Sensitivity</td>
<td></td>
<td>110 Torque</td>
<td>110 Torque</td>
<td>110 Torque</td>
<td>110 Torque</td>
<td>110 Torque</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rotor DC</td>
<td>rpm</td>
<td>6 x 10^9</td>
<td>6 x 10^9</td>
<td>6 x 10^9</td>
<td>6 x 10^9</td>
<td>6 x 10^9</td>
<td>6 x 10^9</td>
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<td>6 x 10^9</td>
<td>6 x 10^9</td>
<td>6 x 10^9</td>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Axial DC</td>
<td>rpm</td>
<td>1.4 x 10^9</td>
<td>3 x 10^9</td>
<td>1.4 x 10^9</td>
<td>3 x 10^9</td>
<td>1.4 x 10^9</td>
<td>3 x 10^9</td>
<td>1.4 x 10^9</td>
<td>3 x 10^9</td>
<td>1.4 x 10^9</td>
<td>3 x 10^9</td>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Operating Temp</td>
<td>°F</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>125</td>
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<td>125</td>
<td>125</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Mounting Configuration</td>
<td>End Stud</td>
<td>Tapered End Stud</td>
<td>End Stud</td>
<td>End Stud</td>
<td>End Stud</td>
<td>End Stud</td>
<td>End Stud</td>
<td>Center Flange</td>
<td>Center Flange</td>
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<td>Center Flange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>NA</td>
<td>Missile</td>
<td>Missile</td>
<td>Missile</td>
<td>Missile</td>
<td>Missile</td>
<td>Missile</td>
<td>GYRO Compassing</td>
<td>Navigator Satellite</td>
<td>Satellite</td>
<td>30° max.</td>
<td>150° max.</td>
<td></td>
</tr>
<tr>
<td>Life Experience</td>
<td>100K</td>
<td>100K</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100K</td>
<td>100K</td>
<td></td>
<td>100K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Not Available
**Not Applicable
The SDG Electronics/Control Unit [6] contains the necessary analog rebalance electronics to cage both axes of the SDG-5. A photograph of the 19 inch rack-mounted panel is shown in Figure 3. Controls, located on the front panel are used to control the caging process and provide a convenient means for selecting various torque output scaling functions. Generally, the unit contains the necessary regulated and precision DC voltages, the gyro 48 kHz pickoff excitation, caging electronics and precision analog scaling electronics for each gyro axis. Refer to Figure 4 for the functional block diagram and to Figures 5 and 6 for measured cross and direct-axis control loop frequency response curves.

The previously described electronics was interfaced with the data acquisition system and the gyro mounted on the test pier as available at the various facilities. The functional organization utilized was as shown in Figure 7.
Figure 4. Functional Block Diagram of Teledyne Strapdown Gyro Test Mechanization
Figure 5. Cross Axis Bode Plot

Figure 6. Direct Axis Bode Plot
Figure 7. Teledyne Strapdown Gyro Test Setup with Data Acquisition System

IV. PSD TESTING PERFORMED

A total of 5 different SDG-5 gyros were used in the test program on an "as available" basis.

Table 4 presents a summary of the testing performed by facility. Most data was taken on SN 069 as it was evaluated by three facilities. Initial testing was performed at Boeing using analog rebalance loops of approximately 1 Hz bandwidth. This was subsequently increased to 7 Hz and standardized for the tests to follow in order to be representative of requirements on anticipated programs. In all cases, the data acquisition system and data reduction was provided by the test facility. Standard methods as described in the references [1], [2] were generally employed.
Teledyne provided two SDG-5 gyros and associated test equipment to the Holloman AFB-CIGTF for evaluation as part of the HAARS testing program. Only S/N 069 was evaluated due to schedule constraints. The data acquisition system, filtering employed, test equipment and data reduction techniques are well described in [1], and are not discussed herein. Figures 8, 9 and 10 present typical PSD gyro outputs in (DEG/HR)/Hz for the gyro evaluated. These data provide a high confidence PSD signature for the unit evaluated over the frequency range 0.001 Hz to approximately 2.5 Hz.

As equipment specifications for hardware (e.g. DRIRU II) sometimes specify the gyro output noise limits in (HR RMS) over a specific frequency range, the noise characteristic for the SDG-5 gyro was measured in approximate units by the Martin-Marietta Corporation. Table 5 presents a comparison of the measured SDG-5 output in (HR RMS) versus the DRIRU II specification. Data as available from the other test facilities are presented in Table 6 for comparison purposes. The data from Holloman CIGTF and the Martin-Marietta Corporation is seen to correlate reasonably well in the frequency band of 0.001 Hz to 5 Hz.

### Table 4: Summary of PSD Testing Performed On Teledyne SDG-5 Gyro

<table>
<thead>
<tr>
<th>Facility</th>
<th>Date</th>
<th>Test Conditions</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holloman CIGTF</td>
<td>1 Jan 1979</td>
<td>Standard Test Equipment</td>
<td>(DEG/HR)/Hz</td>
</tr>
<tr>
<td>Martin-Marietta</td>
<td>15 Feb 1979</td>
<td>Custom Test Equipment</td>
<td>(DEG/HR)/Hz</td>
</tr>
</tbody>
</table>

### Table 5: Comparison of Measured SDG-5 Gyro Output vs DRIRU II Specification

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>DRIRU II</th>
<th>Measured SDG-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>0.01</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>0.1</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
<td>0.24</td>
</tr>
<tr>
<td>10</td>
<td>0.40</td>
<td>0.39</td>
</tr>
</tbody>
</table>

### Table 6: Comparison Data from Other Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Test Conditions</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holloman CIGTF</td>
<td>Custom Test Equipment</td>
<td>(DEG/HR)/Hz</td>
</tr>
<tr>
<td>Martin-Marietta</td>
<td>Custom Test Equipment</td>
<td>(DEG/HR)/Hz</td>
</tr>
</tbody>
</table>
Figure 8. Power Spectral Density Gyro Output of Teledyne SDG-5 S/N 069 (Data Courtesy of Holloman AFB-CIGTF) [8]

Figure 9. Power Spectral Density Gyro Output of Teledyne SDG-5 S/N 069 (Data Courtesy of Holloman AFB-CIGTF) [8]
Figure 10. Power Spectral Density Gyro Output of Teledyne SDG-5 S/N 069 (Data Courtesy of Holloman AFB-CIGTF) [8]

Table 5. Comparison of Measured SDG-5 Output In (°/Hr RMS) vs DRIRU II Specification (Data Courtesy of Martin-Marietta Corp - Denver, Co)

<table>
<thead>
<tr>
<th>Frequency Range (Hertz)</th>
<th>Performance in °/Hr RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Axis</td>
</tr>
<tr>
<td>.01-1.0</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>.01-7.0</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Y</td>
</tr>
</tbody>
</table>
Table 6. Inter Facility Comparison of PSD Test Results on Teledyne SDG-5 Gyro

<table>
<thead>
<tr>
<th>Facility</th>
<th>Measured Gyro Noise Over Frequency (Hz) in ($^\circ$ Hz)$^2$/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.0001-.001</td>
</tr>
<tr>
<td>Boeing Aerospace Co.</td>
<td>Not Measured</td>
</tr>
<tr>
<td>Martin-Marietta Corp.</td>
<td>Not Measured</td>
</tr>
<tr>
<td>Holloman CIGTF</td>
<td>6 x 10$^{-5}$</td>
</tr>
<tr>
<td>Lockheed Missiles and Space Co.</td>
<td>Not Measured</td>
</tr>
</tbody>
</table>

NOTE:
SDG-5 S/N 069, SAV, axis being tested east or west was used for this comparison at the first three facilities listed above. SDG-5 S/N 036 was evaluated by Lockheed Missiles and Space Co.
*Possible aliasing problem in data acquisition system due to incorrect filtering availability at time of test.
VI. COMPARISON OF PSD CHARACTERISTICS OF SDG-5 DRY TDF AND SDF FLOATED GYROS

A comparison of the noise characteristics between the Teledyne SDG-5 dry TDF gyro with data for floated SDF gyros as reported in [4] was made. For convenience in making this comparison, the units of (arc-sec)^2/Hz were used. A graphical presentation of this comparison is presented in Figure 11. The reader is cautioned that the sample size (one or two units) is small and that the data presented for dry TDF gyros is limited to the Teledyne SDG-5. Nonetheless, it appears that the dry-tuned ball bearing gyro performance compares quite favorably in the bandwidth of .01 Hz to approximately 5 Hz with currently used floated standards used in low jitter attitude stabilization and precision pointing systems.

VII. METHODS FOR FURTHER NOISE REDUCTION IN DRY TUNED GYROS

The dry tuned gyro has a number of characteristic features that provide for implementing several methods for noise reduction to even lower levels than determined in the previously described testing. These consist of basic optimization of physical design parameters as briefly outlined in the following discussion.

Physical Increase in Angular Momentum

The angular momentum of the dry gyro can be increased by adding mass to the rotor while maintaining the same spin speed with the attendant decrease in torque generator scale factor. A factor of two increase in angular momentum is readily attainable in the SDG-5. The reduction in scale factor (160°/Hr/ma for SDG-5) to one-half (80°/Hr/ma) is quite acceptable for most pointing applications where maximum rate is limited to approximately ±50°/sec. Teledyne has produced gyros (the SDG-3B) with 2 x 10^6 cgs units angular momentum in lieu of 1 x 10^6 cgs units for the SDG-5. Figures 12 and 13 make the comparison of key characteristics.
Figure 11. Graphical Comparison of Noise Characteristics in (arc sec)$^2$/Hz for Teledyne SDG-5 Dry TDF Gyro with Floated SDF Gyros [4]
APPLICATIONS

Shipboard Inertial Navigation
Spacecraft Guidance and Control, Fine Pointing
Requirements for very Low Drift Rates, Low Noise
and with Moderate Rate Inputs

SPECIFICATIONS

<table>
<thead>
<tr>
<th></th>
<th>SDG-3B</th>
<th>SDG-5 (for comparison)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>3.25&quot; dia x 3&quot; long</td>
<td>3.0&quot; dia x 3&quot; long</td>
</tr>
<tr>
<td>Weight</td>
<td>2.9 lbs</td>
<td>2.3 lbs</td>
</tr>
<tr>
<td>Random drift (lo) (Spec)</td>
<td>&lt;.0005°/hr</td>
<td>&lt;.001°/hr</td>
</tr>
<tr>
<td>Repeatability (day to day) lσ - (Spec)</td>
<td>&lt;.005°/hr</td>
<td>&lt;.01°/hr</td>
</tr>
<tr>
<td>Angular momentum (II)</td>
<td>2 x 10^6 CGS units</td>
<td>1 x 10^6 CGS units</td>
</tr>
<tr>
<td>Spin speed</td>
<td>6000 RPM</td>
<td>6000 RPM</td>
</tr>
</tbody>
</table>

Figure 13. SDG 3B Gyro Characteristics
Incr,..,s_.

Figure-of-Merit (Fm)

If one considers a figure of merit for the elastically supported gyro as defined by [9] as follows:

\[ F_m = \frac{C + \sum_{1}^{n} A_n}{\sum_{1}^{n} (A_n + B_n - C_n)} \]

where:

- \( C \): principal moment of inertia of the rotor about the Z or spin axis
- \( A_n, B_n, C_n \): principal moments of inertia of the nth gimbal about the \( X_n, Y_n, Z_n \) axes respectively
- \( n \): number of gimbals

It can be shown that the \( F_m \) is approximately inversely proportional to the number of gimbals employed. This \( F_m \) for the standard SDG-5 three-gimbal gyro is 320 and can be increased to approximately 1000 by reducing the number of gimbals from 3 to 1. There is an attendant reduction in environmental "g-capability" by approximately 3 and some potential increase in \( 2N \) angular sensitivity. Teledyne has produced a small quantity of 1-gimbal units that have demonstrated extremely low random drift characteristics. No attempt to measure PSD for the 1-gimbal configuration has been made to date. This area is recommended for future investigation and evaluation for applications with relatively low environments requirements.

Mechanization of Gimbal Angle Pickoffs

The dry gyro lends itself to incorporation of an additional instrument angle pickoff which measures the angular motion of the gimbal with respect to the case. This mechanization has been shown by [3] to provide a signal which may be used to directly compensate for "noise". As a natural consequence, a highly accurate rotor angular nulling signal, independent of the usual pickoff mechanical instability or creep is automatically provided. To the extent that the undesired shaft-to-case motion is inducing the gyro output noise, the power spectral density of this noise may be reduced by compensation by a factor which is determined essentially by the total
mechanization scale factor error. If this error is assumed to be on the order of 1.5%, as is readily achievable, then a reduction of the basic gyro output noise spectral noise by a factor of 0.015 could be realized. Teledyne is currently developing under contract from the USAF-AFAL/FDL an instrument called the Spin Coupled Accelerometer Gyro (SCAG) which is equipped with both rotor-to-case and gimbal-to-case angle pickoffs. The instrument has the necessary output information to effect the angular rate noise compensation as discussed by [3].

This same gimbal angle pockoff concept has been considered for incorporation in the SDG-5 and appears attractive.

VIII. SUMMARY AND CONCLUSIONS

The following conclusions are made based on the foregoing data and discussions:

1. The SDG-5 gyro output noise power spectral density characteristics have been determined to a high confidence level in the frequency band of 0.001 Hz to 1 Hz by the testing accomplished to date.

2. The SDG-5 is an excellent candidate gyro for fine pointing applications where low noise performance below 1 Hz are specified in milliarc-seconds and that operate with control system bandwidths in the region of 1 Hz.

3. The SDG-5 PSD performance compares quite favorable with currently used SDF floated gyros below 1 Hz and from 1 Hz to 10 Hz the SDG-5 performance compares midrange with other state-of-the-art precision gyroscopes.

4. A number of attractive methods for effecting a further decrease in the SDG-5 noise characteristics are readily available and should be pursued.

IX. ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the following organizations for their cooperation in conducting the reported testing in a demanding schedule environment and on an as-equipment/gyro availability basis:

The Martin-Marietta Corporation
Holloman AFB-CIGTF
The Boeing Aerospace Company
The Lockheed Missiles and Space Company
REFERENCES


APPENDIX B

FIRST-DIFFERENCE PERFORMANCE DATA ON
TELEDYNE SDG-5 GYRO
The subject attached data (Attachment 1) was taken on Gyro Serial Number 069 at the Martin Marietta Corporation - Denver. This data essentially shows the RMS drift performance as a function of sample interval. It is also a good measure for judging the gyro performance in terms of gyro-compass quality.

Attachment 2 describes the data reduction technique and provides some additional interpretation.

R. B. Irvine

Attachments


Distribution
D. Eller
SDG-5 File
J. Dowell
S. Kinsinger
P. Donoghue
L. Cotter
F. McNair
H. Erdley
D. Doty
H. Halamandaris
A. Schmitt
R. VanAlstine
L. Krieger
K. Green
J. Ritter
G. Napjus
T. Wirt
G. Wunder

B2
First-difference drift tests have been completed on the Teledyne gyro, ID number D007013. These tests were done at the Martin Marietta Inertial Guidance Laboratory under IRAD task 48641. The test configuration used and the test results are shown below.

<table>
<thead>
<tr>
<th>Sample Interval (Seconds)</th>
<th>First Difference (RMS, Degrees/Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Input Axis East-West</td>
</tr>
<tr>
<td>.1</td>
<td>.0376</td>
</tr>
<tr>
<td>1</td>
<td>.00425</td>
</tr>
<tr>
<td>10</td>
<td>.000761</td>
</tr>
<tr>
<td>100</td>
<td>.000235</td>
</tr>
<tr>
<td>1000</td>
<td>.000104</td>
</tr>
</tbody>
</table>

TABLE 1. TEST RESULTS
FIGURE 1. TEST CONFIGURATION

John Tietz
Guidance & Controls
Inertial Guidance Laboratory
FIGURE 2. FIRST DIFFERENCE VS SAMPLE INTERVAL
TRIM—A GYROMONITOR IMU INCORPORATING THE GYROFLEX GYRO

by
ROBERT L. GATES
Singer-General Precision, Incorporated
Little Falls, New Jersey

AIAA Guidance, Control and Flight Mechanics Conference
SANTA BARBARA, CALIFORNIA/AUGUST 17-19, 1970

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TRIM - A GYROMONITOR IMU
INCORPORATING THE GYROFLEX<sup>®</sup> GYRO

Robert L. Gates
Senior Staff Member
Singer-General Precision, Inc.
Kearfott Division
Little Falls, New Jersey

Abstract

The concept and theory of operation of a self-calibrating gyromonitor inertial measurement unit is described. The mechanization utilizes the redundant azimuth gyro as the measurement axis to obviate the need for an additional gyroscope. An experimental model of the platform using the GYROFLEX Gyro is described and test instrumentation and test data are presented. Performance predictions are made in terms of cruise navigation accuracy showing the improvements possible with reduction of uncertainty gyro drift. Also discussed are the advantages of explicit in-flight gyro calibration in terms of confidence in the accuracy of a pure inertial navigator.

I. Introduction

The concept and theory of operation of an experimental gyromonitor inertial measurement unit is presented; the end product should be particularly suited for cruise type applications. Some interesting aspects of navigation systems incorporating this concept are as follows:

1. Rapid, self-contained azimuth gyro calibration is possible for a pure inertial navigation (only method known to the author).

2. Gyromonitoring is accomplished without the requirement for a redundant instrument. The azimuth gyro redundant axis is used in a mechanization described further on.

3. The TRIM concept may dissolve up to 90° of the "dead reckoning" associated with a pure inertial navigator.

Experimental test data have been obtained which indicate solid potential for achieving gyro performance for an unaided inertial navigator in the .002 to .005 η hr range. This performance is compatible with better than 0.5 nm/hr performance.

II. Theory of Operation

The basic idea is a simple one which takes advantage of the normally unused redundant axis of the platform azimuth gyro that is present when two-degree-of-freedom gyro are used in the platform. The platform cluster is constructed by mounting the gyro in tumtable modules that permit the gyro to be independently repositioned at the cardinal angles. The case rotations are made around the gyro spin axes. During rotations, signal resolves direct the gyro outputs to the proper gimbal axes. The gyro are not torqued during the slew interval.

*In Avionics terminology, the "azimuth" gyro is the one of the orthogonal set which controls the stable member around the vertical axis. The "vertical" gyro has its input axes in the horizontal plane.

The self-calibration is accomplished by taking simultaneous samples of gyro command and capture signals for the two parallel gyro input axes (see position 1 of the sketch below), one of which is always the azimuth gyro rate captured redundant axis and the other will be one of the two axes of the vertical gyro. Summing or differentiating of the simultaneous measurements permits implicit cancellation of platform inertial rate (known or unknown) around the monitor axis thereby permitting operation on a fixed or moving base (aircraft carrier or airborne). This is the well known principle of the gyromonitor. (3,4,5,6)

The gyro drift coefficients are recovered from a set of samples*" such as data from relative positions 1, 2, and 3, see sketch below. The accelerometers are not required in the measurement loops and do not contribute error. The four relative gyro positions are shown below. Positions 1, 2, and 3 are required for data acquisition and are achieved by sequentially indexing the vertical gyro. Position 4 places the calibrated azimuth gyro X' axis into the azimuth position completing one calibration cycle. Note that X' is the redundant axis for relative positions 1, 2, and 3 and that Y' is the redundant rate axis in position 4.

This capsule description indicates how gyromonitoring is feasible without a redundant gyro. Also apparent is the very simple but important idea of periodically replacing the uncalibrated azimuth axis with an axis of the same gyro which has been explicitly calibrated in the horizontal plane. The redundant axis calibration does not include spin axis mass unbalance; for this reason, the unique characteristic of the GYROFLEX wherein mass unbalance stability is superior proves valuable (the spin axis bearings do not contribute to spin axis mass unbalance). (2) A laboratory model of this type of IMU is shown in Figure 1.

**See Appendix A
III. Performance Prediction

The iterative recovery of gyro drift coefficients strongly qualifies the use of the modern filter theory in the system software. In fact, a real-time history of gyro performance during the mission will be available in the system computer. When compared to standard expected coefficient variations during flight, a measure of performance quality may be determined.

For example, the first test would be to verify that the coefficient is within the ±3 sigma limits from each coefficient mean established as the acceptable day-to-day (or on-off) performance of the gyro; these limits with the gyro-monitor mechanization can be an order-of-magnitude larger than conventional system limits (say ±0.3°/hr). The second test will be against the magnitude of change of the coefficient with each major cycle of the TRIM Mode. The Figure 2 shows a plot of actual TRIM IMU data which would be representative of changes between samples (first differences) available within the computer. The RMS value of the changes is representative of gyro performance. For this particular run, the RMS value was 0.0038°/hr based upon one-minute duration samples.

IV. Navigation Accuracy

A DELTA Curve for the GYROFLEX is shown in Figure 3. The concept of this method of data presentation is discussed in detail in Appendix B.

This function is obtained by computing the RMS of first differences as a function of integration time which is varied over the sample times of interest. Figure 3 shows a gyro in steady state operation. From Figure 2 we can see that the gyro contributes, about 0.0021°/hr to the RMS level of 0.0038°/hr at the IMU level. Figure 4 shows a drift rate ramp analytically included to simulate the warmup transient of a trending gyro.
The standard gyromonitor system utilizing single-degree-of-freedom gyros requires forced precession of the gyro spin vector with gyro indexing. This results in the requirement for a settling time period which slows reaction time. TRIM gyro case rotations are around the spin axis and since each gyro is geometrically stabilized by the gimbal servos, the rotor must remain undisturbed with each indexing. This should permit the reduction of monitor "off time" (slew and settling time) by a factor of 3 to 7 resulting in a significantly shorter mode cycle time.

VI. Test Results

An experimental IMU (see Figure 1) has been fabricated to investigate the performance potential of this mechanization. The hardware was intended for laboratory use and will be used for experiments in support of design tradeoffs and for feasibility demonstration. The unit is basically a multi-axis servo table. The cluster mounted turntables for indexing the gyros are derived from a gyrocompass system designated GUARD which is in production for the Air Force. Pitch, roll, and azimuth isolation axes are provided between the outer housing and the cluster for dynamic simulation of an operational IMU. A support electronics console is used to provide power supplies, gyro and accelerometer excitation and temperature control and capture loop circuits, gimbal servo electronics and readout instrumentation. The analog-to-digital conversion instrumentation is discussed in Appendix B. An automatic electromechanical programmer is used to cycle the system through the TRIM Mode.

Test Objectives

A number of questions were to be answered, and experimentally verified, with respect to gyro performance and IMU performance.

1. Can the "implicit" cancellation of inertial rates common to the parallel axes be demonstrated? And, can the absolute value of the gyromonitor recovered coefficient be verified?
2. What is the accuracy and reaction time potential of the concept at the system level?
3. What is the RMS level of performance with and without filtering?
4. In a more detail sense, what are the deleterious effects, if any, of indexing the gyros?

Test Data

The figure entitled "Implicit Noise Cancellation" (Figure 7) demonstrates two important facts. One is a confidence verification that the proper absolute value of drift coefficient is being recovered in the gyromonitor mode. The other is a demonstration of "implicit cancellation" of unknown platform rates that might be thought to interfere with the concept.
FIGURE 7. TRIM IMPLICIT NOISE CANCELLATION

The data were taken with the platform in an earth slaved mode. The redundant axis of the azimuth gyro was sequentially indexed from nominally East to nominally West (although absolute heading is immaterial to the test). At each position, simultaneous and average rate outputs were separately recorded from the redundant axis and the parallel vertical gyro axis for 60-second intervals.

The plot on the left was derived by using the redundant axis data separately to calibrate its fixed drift coefficient $D(Y'_F)$. This was done in an analogous fashion to standard two-position gyro testing wherein one-half the sum of East and West readings yields fixed drift and earth rate coupling is cancelled. The large scatter (0.149 hr peak-to-peak and 0.041 hr RMS) is a result of cluster motion during the short sample time.

The plot on the right is achieved by “mixing” the same redundant axis data with data from the parallel vertical gyro input axis. The simultaneous samples are alternately summed and differenced to implicitly cancel the common inertial noise rate. Note that the RMS scatter in calibrating $D(Y'_F)$ is reduced by an order-of-magnitude. Also, note the excellent agreement in the average value of $D(Y'_F)$ (difference of 0.00269/hr) obtained by the separate methods. The parallel vertical gyro axis is calibrated simultaneously although the plot is omitted for clarity.

The figure entitled “Day-to-Day and Random Drift Error Reduction with TRIM” (Figure 8) is a clear picture of the concept value. Test data have been obtained pointing to a pure inertial navigation system accuracy of 0.35 nm/hr or better.

The test data points (triangles) are the results of more than 9 runs and 6 shutdowns with some 144 complete TRIM cycles comprised of either 3 or 6 indexing positions each cycle. It is anticipated that slightly better results (X plot) will be achieved in the brassboard experiment with some refinements. The curve of results with filtering should be realized when the data are reprocessed through either a minimum Kalman filter or a limited least-squares fit routine. The triangular data plots are the RMS values of first differences of adjacent coefficient recoveries.

An example of reaction time data are presented in Figure 9.

FIGURE 9. DRIFT COEFFICIENT RECOVERY DURING WARMUP

The plotted points represent the pure “unmodeled” drift coefficients plotted in terms of magnitude change between recoveries. Improved results will be obtained with a more optimum heater power distribution to the gyro and to the cluster structure. Nevertheless, the data from the 5.2 to 7.8 minute interval are accurate to 0.0159/hr.

Figure 10 presents a plot that is typical of gyro drift settling following a slew. The plot shows that the gyro recovers in about 8 seconds. These data were taken from the rate captured horizontal monitor axis of the azimuth gyro (spin axis horizontal). Therefore, for the GYROFLEX Gyro, data accumulation may begin 8 to 10 seconds following a case slew.

FIGURE 10. GYRO SETTLING CHARACTERISTIC
In comparing the data to other instruments, we have noted that floated single axis gyros may require 60 to 100 seconds settling time following case indexing around the output axis.

The redundant axis rate data may also be used for platform gyrocompassing, or in a more exact sense, heading determination. With the cluster leveled in a conventional leveling mode and earth slaved in azimuth, the redundant axis will sense a component of horizontal earth rate proportional to the deviation of the azimuth gyro spin axis from the meridian plane. This is true at the 0° and 180° positions. Heading may be determined by differencing the two measurements and solving for the heading angle (fixed drift D(X) is implicitly cancelled).

\[ \phi = \frac{\omega_0 - \omega_{180}}{2 \Omega \cos \lambda} \]

For repetitive heading determinations, the non-repeatability or random error will be primarily a function of fixed drift change between samples. Figure 11 shows the results of a run where the heading determinations are plotted.

**FIGURE 11. TRIM GYROCOMPASS DATA**

Note that the platform had a mean heading of 1645 arc seconds and that the standard deviation for 16 individual determinations was 35 arc seconds. In this case, the gyro was in thermal steady state and the sample time was reduced to 30 seconds.

References


**APPENDIX A**

**TRIM-IMU Functional Equations With Gyro Error Model**

**Introduction**

This section derives and presents the basic functional equations for navigation computer recovery of the vertical and azimuth gyro drift coefficients (bias values) for a GYROFLEX Gyro platform mechanized for the TRIM gyromonitor mode. The implicit cancellation of some drift terms and platform command rates are presented in the derivation. The four relative gyro positions are shown below.

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1. Vertical Gyro
2. Azimuth Gyro
3. Forward
4. Down

**Positions**

**Derivation - TRIM MODE**

The gyromonitor equations may be derived by considering the inertial angular rates and the drift rates T of the gyro pair with respect to a reference inertial coordinate frame XYZ. Consider first the rates Ω for the navigation (N) gyro vertical X axis with respect to the reference frame.

\[ \dot{\gamma}_X N = -\omega_{XC} + D(X)_T \]

where,

\[ \omega_{XC} = \text{command rate to X axis of vertical gyro which can be expressed as } S_\gamma Y_N \]

\[ D(X)_T = D(X)_F + D(X)_S \]

Further,

\[ D(X)_F = \text{gyro drift (9/hr) about the X axis which is insensitive to acceleration.} \]

See general GYROFLEX error model in latter part of this Appendix.
\[ D(\text{X})_S^* = \text{gyro drift (g/hr)} \text{ about the X axis attributable to acceleration (a)}_X^* \text{ along the spin axis.} \]

\[ D(\text{X})_SS = \text{gyro drift (g/hr)}^2 \text{ about the X axis attributable to acceleration squared (a}^2_X) \text{ along the spin axis.} \]

\[ S_Y N^i Y N = \text{the product of Y axis torquer scale factor (g/hr/ma) and the average value of the command current (ma) for the vertical gyro navigation (N) axis.} \]

so,

\[ S_Y N^i Y N = -\Omega^i X N + D(\text{X})_T \]  \hspace{1cm} (A)

Likewise, for the monitor axis,

\[ \Omega^i X M - \Omega^i X N = D(\text{X})_F^* + D(\text{X})_Y^* \]

As a rate captured axis, \( \Omega^i X M \) is analogous to the capture rate \( S_Y N^i Y M \), hence,

\[ S_Y M^i Y M = -\Omega^i X N + D(\text{X})_F^* + D(\text{X})_Y^* \]  \hspace{1cm} (B)

Simultaneous differencing of equations (A) and (B) permits implicit cancellation of the inertial rate term \( \Omega^i X N \) and the residual contains the drift coefficients of interest,

\[ S_Y M^i Y M - S_Y N^i Y N = D(\text{X})_F^* + D(\text{X})_Y^* - D(\text{X})_T \]

A more practical approach from the mechanization viewpoint in the presence of noise and disturbance inputs, is to consider differentiating the average or fitted values of the terms on the left side for a finite sample interval (say 20 to 100 seconds duration) in each measurement position designated by the symbol \( \Theta \).

\[ (S_Y M^i Y M - S_Y N^i Y N) = (D(\text{X})_F^* + D(\text{X})_Y^* - D(\text{X})_T) \]  \hspace{1cm} (C)

**Navigation Gyro (Y axis, position \( \Theta \))**

Similarly, the equations are derived for position and sample \( \Theta \), this time involving the navigation gyro Y axis.

\[ \begin{align*}
  \Omega^i X N &= -\omega^i Y C - D(\text{Y})_T \\
  S_X N^i X N &= -\Omega^i X N - D(\text{Y})_T
  \end{align*} \hspace{1cm} (D) \]

Equation (B) still applies for the monitor axis since its attitude is unchanged with respect to the reference frame. Similarly, inspection of equations (B) and (D) reveals that the inertial rate for the new position/sample interval \( \Theta \) may be cancelled by differencing, i.e.,

\[ (S_Y M^i Y M - S_Y N^i Y N) = (D(\text{X})_F^* + D(\text{X})_Y^* + D(\text{Y})_T) \]  \hspace{1cm} (E)

**Navigation Gyro (X axis, position \( \Theta \))**

This position places the navigation gyro X axis 180° from the first set (sample \( \Theta \)).

\[ \Omega^i X N = \omega^i X C - D(\text{X})_T \]

which becomes

\[ S_Y N^i Y N = -\Omega^i X N + D(\text{X})_T \]  \hspace{1cm} (F)

Equation (F) is summed with the monitor equation (B) for position/sample interval \( \Theta \):

\[ (S_Y M^i Y M + S_Y N^i Y N) = D(\text{X})' + D(\text{X})_Y^* \]

The vertical gyro X axis drift may then be explicitly recovered by subtracting equation (C) from equation (G),

\[ D(\text{X})_T = \frac{1}{2} (S_Y M^i Y M - S_Y N^i Y N) \]

Likewise, the equations associated with positions \( \Theta \), \( \Theta \), and \( \Theta \) may be combined to recover \( D(\text{Y})_T \) to complete vertical gyro calibration.

\[ D(\text{Y})_T = \frac{1}{2} (S_Y M^i Y M - S_Y N^i Y N) \]

The fixed drift of the azimuth gyro monitor axis \( \text{X}' \) is also recoverable.

\[ D(\text{X})' = \frac{1}{2} (S_Y M^i Y M - S_Y N^i Y N) \]

The so-called "quadrature" term \( D(\text{X})_Y \) is present because of the presence of 1 g along the azimuth axis and is included for completeness. If truly measurable, this term will be "tagged" at the component level and the computer will remove its contribution. This term does not effect a conventional IMU.

X: Azimuth gyro drift around the new gyro axis may be written as:

\[ \Omega^i X = D(\text{X})' - D(\text{X})_X^* a_X^* + D(\text{X})_X^* a_X^* \]

All significant drift terms are now known. The fixed drift coefficient \( D(\text{X})' \) was recovered from equation (J) above. The spin axis mass unbalance term \( D(\text{X})_X^* \) is a computer stored coefficient available from factory or periodic calibration. Present indications are that the g squared coefficient \( D(\text{X})_X^* \) is negligibly small.

**Hallman GYROFLEX Error Model**

The performance model assumed for the GYROFLEX is:

\[ S_{TG Y}^i Y = D(\text{X})_F^* + D(\text{X})_X^* a_X^* + D(\text{X})_Y^* a_Y^* + D(\text{X})_S^* \]

\[ + D(\text{X})_X^* a_X^* + D(\text{X})_S^* a_S^* + D(\text{X})_X^* a_X^* \]

\[ + D(\text{X})_X^* a_X^* + a_X^* a_X^* - \omega^i X \]

\[ S_{TG X}^i X = D(\text{Y})_F^* + D(\text{Y})_X^* a_X^* + D(\text{Y})_S^* a_S^* \]

\[ + D(\text{Y})_Y^* a_Y^* + D(\text{Y})_S^* + D(\text{Y})_Y^* a_Y^* + D(\text{Y})_S^* a_S^* + D(\text{Y})_S^* a_S^* + \omega^i Y \]

where \( \omega^i X = \frac{1}{2} \).
**Definition of Performance Model Terms**

- **i_Y** current flow through the Y axis torque generator (ma)
- **S_TGY** sensitivity of the Y axis torque generator (°/hr/ma)
- **i_X** current flow through the X axis torque generator (ma)
- **S_TGX** sensitivity of the X axis torque generator (°/hr/ma)
- **α_X** acceleration along the X axis (g)
- **α_Y** acceleration along the Y axis (g)
- **α_S** acceleration along the spin axis (g)
- **D^m_F** gyro drift (9/hr) about the X axis which is insensitive to acceleration
- **D(Y)_yx α_X** gyro drift (9/hr) about the Y axis which is insensitive to acceleration
- **D(X)_yx α_X** gyro drift (9/hr) about the X axis attributable to acceleration along the X axis, where \( D(X)_x ω_X \) (9/hr/g) is a drift coefficient
- **D(Y)_yx α_Y** gyro drift (9/hr) about the Y axis attributable to acceleration along the Y axis, where \( D(Y)_y ω_Y \) (9/hr/g) is a drift coefficient
- **D(X)_yx α_Y** gyro drift (9/hr) about the X axis attributable to acceleration along the Y axis, where \( D(X)_y g \) (9/hr/g) is a drift coefficient
- **D(Y)_yx α_X** gyro drift (9/hr) about the Y axis attributable to acceleration along the X axis, where \( D(Y)_x g \) (9/hr/g) is a drift coefficient
- **D(X)_xs α_S** gyro drift (9/hr) about the X axis attributable to acceleration along the spin axis, where \( D(X)_s g \) (9/hr/g) is a drift coefficient
- **D(Y)_xs α_S** gyro drift (9/hr) about the Y axis attributable to acceleration along the spin axis, where \( D(Y)_s g \) (9/hr/g) is a drift coefficient
- **D(X)_xx α_X** gyro drift (9/hr) about the X axis attributable to the square of acceleration along the X axis, where \( D(X)_x g^2 \) is a drift coefficient
- **D(Y)_yy α_Y** gyro drift (9/hr) about the Y axis attributable to the square of acceleration along the Y axis, where \( D(Y)_y g^2 \) is a drift coefficient
- **D(X)_ss α_S** gyro drift (9/hr) about the X axis attributable to the square of acceleration along the spin axis, where \( D(X)_s g^2 \) is a drift coefficient
- **D(Y)_ss α_S** gyro drift (9/hr) about the Y axis attributable to the square of acceleration along the spin axis, where \( D(Y)_s g^2 \) is a drift coefficient
- **D(X)_xy α_X α_Y** gyro drift (9/hr) about the X axis attributable to the product of accelerations along the X axis and Y axis, where \( D(X)_x g^2 \) is a drift coefficient

**APPENDIX B**

**DELTA Curve - An Inertial Component Evaluation Concept**

**Introduction**

The technique developed by the author presents a new viewpoint which has proven to be very useful in interpreting inertial sensor test data and in specifying performance. Figure 8-1 is a curve for the two-degree-of-freedom Kearfott GYROFLEX Gyro. Once understood, the DELTA Curve provides an excellent tool for gyro performance prediction.

**FIGURE B-1. GYROMONITOR EVALUATION--DELTA CURVE**

**SHORT-TERM PERFORMANCE - GYROFLEX SN 113**
The DELTA Curve was created by a need to predict gyrocompassing accuracy when case rotation techniques become known. The DELTA Curve is a display of a probable drift rate change of the gyro between mean values of any adjacent samples of gyro output that are of the same duration. The curve shows that the ordinate is a display of the drift rate change and the abscissa represents the sample time.

In its broadest sense, the curve is a display of a probable drift rate change of the gyro between mean values of any adjacent samples of gyro output that are of the same duration. The curve shows that the ordinate is a display of the drift rate change and the abscissa represents the sample time. The DELTA Curve is best at displaying the short-term performance of the gyro. For example, in Figure B-1, if the gyro instrumentation output is set to provide samples of 100 second averages, the probable drift rate change between these samples will be 0.0015%/hr for the pitch axis and 0.0016%/hr for the roll axis.

The inertial guidance hardware that are most suitable for analysis using this method are those systems which are in some sense self-calibrating. That is, they have a designed-in ability to reject long term or day-to-day bias errors. Hence, methods must be found for predicting system error that describe gyro drift variations during the interval of use instead of how drift changed from the last time the instrument was run (see Figure B-2).

**FIGURE B-2. RUN-TO-RUN DRIFT LEVEL CHANGES**

Gyromonitor Inertial Measurement Unit

The gyromonitor inertial platform makes use of a redundant axis of an inertial instrument to calibrate the navigation gyro axes. The monitoring axis is placed parallel to the navigation axis, a discrete sample of both axes outputs is taken and stored. The monitoring axis is then mechanically reversed 180° and a second sample is taken. The data sample pair may then be used to calibrate the navigation axis. The DELTA Curve is a direct measure of gyro stability between adjacent outputs of length Tt. It has been found that the dead band that appears between samples because of the time required for the 180° reversal does not significantly change the amplitude or shape of the curve. Given the sample time, the system analyst can determine directly the gyro drift contribution; conversely, given a gyro performance requirement, he may determine the required sample time.

**Instrumentation for Data Acquisition**

To insure precision and to eliminate human error, a digital output instrumentation loop is recommended. An excellent set-up which is receiving continually greater acceptance is shown in Figure B-3.

**FIGURE B-3. INSTRUMENTATION**

The inertial instrument is operated in a capture mode. For the gyro illustrated, current in the "torque-to-balance" loop is proportional to the total rate output \( \omega_i \) of the gyro, i.e.,

\[
\omega_i = K_i i(t) = \dot{\theta} + R + \ldots 
\]

where,

- \( K_i \) = gyro torquer scale factor (\%/hr/ma)
- \( i \) = capture current (ma)
- \( \dot{\theta} \) = inertial rate sensed by the gyro (dependent upon gyro orientation with respect to earth rate vector)
- \( R \) = drift coefficient for the gyro (\%/hr). Multiple drift terms may be present dependent upon the orientation of the gyro and the complexity of the assumed error model.

The A/D converter detects voltage across a fixed resistor. Proper scaling permits direct printout of rate in degrees-per-hour to obtain the average value of \( \omega_i \) for the selected sample time \( T_t \).

When we difference consecutive samples, the kinematic rate coupling term \( \dot{\theta} \) is implicitly cancelled and the residual is representative of drift coefficient variation over the interval of the sample pair; for example,

\[
\omega_{T_1} - \omega_{T_2} = R_{T_1} - R_{T_2}
\]

Similarly, the outputs of pulse restrained (captured) instruments may be recorded to accomplish the same purpose. Typically, 5000 or more test data points form the basis for a performance curve which boosts confidence in the statistical significance. Referring back to Figure B-1, we also observe that the optimum smoothing time for this gyro is approximately 1000 seconds wherein the drift rate changes reach the exceptionally low value of 0.0004%/hr. For sample times longer than 1000 seconds we can see that performance is beginning to degrade as indicated by the positive slope of the curves. This may be justified by the theory of the increasing dominance of instabilities of the gyro and the instrumentation in terms of voltage variations, temperature variations, base motion and other predictable disturbances.
Construction of the Curve

What we are interested in is the RMS (Root-Mean-Square) value of first differences of constant-interval means $(\mu, t_1)$ of $T_s$ duration. Sample time $T_s$ is extended from the shortest sample of interest to the longest sample time that will provide enough first differences to be of statistical significance. This sounds involved so let us take it one step at a time.

First of all, the instrumentation may be adjusted to take the data directly as consecutive average values of drift with the sample time set at the shortest time of interest indicated as $T_{s1}$. This technique is graphically sketched in Figure B-4.

First differences are simply the differences in the drift value of all adjacent samples, i.e.,

$$\Delta \mu_n = \mu_n - \mu_{n+1}$$

or

$$\Delta \mu_n (T_{s1}) = \mu_n - \mu_{n+1}$$

where,

$\mu_n$ = the average value of drift rate, in this case for sample time $T_{s1}$.

The RMS value of all the first differences of drift rate for the sample time $T_{s1}$ is then calculated in the standard method.

$$\Delta \mu_{rms} (T_{s1}) = \sqrt{\frac{\Delta \mu_1^2 + \Delta \mu_2^2 + \Delta \mu_3^2 + \ldots + \Delta \mu_{N-1}^2}{N-1}}$$

This is simply the square root of the sum of the squares of individual drift rate differences divided by the number of differences. We now have the first data point for the DELTA Curve. It is plotted at the point labeled $T_{s1}$ in Fig. B-5.

We have gained our first indication of short term gyro performance. Assuming the system is operating by averaging the gyro output for time $T_{s1}$ (for most of our long gyro runs we set $T_{s1} = 60$ seconds), the expected change between any consecutive outputs is of the magnitude $\Delta \omega_{rms} (T_{s1})$ with a probability of about $68\%$ (based upon equating RMS to one sigma).

The next curve point $(T_{s2})$ is obtained using the same basic data that makes up the original drift run. For convenience we double the original sample time to get $T_{s2}$. Using the original average drift values, average values for $T_{s2}$ are calculated; a plot illustrating this is shown in Figure B-6.

Again, first differences are taken and the RMS value for sample time $T_{s2}$ is calculated forming the second point on the curve.

This process is repeated until the individual samples are so long compared to the total run duration that we have fewer than 5 or so first differences. Thus, for a maximum sample time of one hour, a run of six hours is required for 5 first differences. Of course, the more samples the better the statistical significance of the right side of the curve. Obviously, the number of computations and iterations required suggests a simple computer program for data reduction. It is suggested that all first differences for $T_{s1}$ be printed on the output listing to permit screening of the data for anomalous data points.

Transient vs. Steady State Analysis

An interesting method of studying systematic drift effects is possible with the curve. Initially, a DELTA Curve is constructed based upon data taken with the gyro behaving normally in steady state. The systematic drift (such as a ramp...
rate function present during warm-up) is then superimposed analytically to construct a composite curve. A parametric composite DELTA Curve can then be used to study acceptable levels for the system.

For example, for a ramp (change in drift rate $\frac{\text{deg}}{\text{hr}}$), the equation for RMS becomes:

$$\Delta \omega_{\text{rms}} = \left[ \frac{\sum_{i=0}^{N-1} \Delta \omega_i^2}{N} + \frac{5 \Delta T (\sum_{i=0}^{N-1} \Delta \omega_i) + (5 \Delta T)^2}{N} \right]^{\frac{1}{2}}$$

New terminology in this equation are:

- $S = \text{ramp (}\frac{\text{deg}}{\text{hr}}\text{)}$
- $\Delta T = \text{interval of separation of midpoints of adjacent samples}$

The middle term can be neglected if the gyro does not have the characteristic of "jogging" and the number of first differences $N$ is large. Jogging is a step change in drift due to gyro motor disturbances. The equation then simplifies to:

$$\Delta \omega_{\text{rms}} = \left[ \frac{\sum_{i=0}^{N-1} \Delta \omega_i^2}{N} + (5 \Delta T)^2 \right]^{\frac{1}{2}}$$

This equation simply represents the RSS (Root-Sum-Square) of the ramp contribution with DELTA Curve contribution of drift rate. However, this calculation must be made for each point on the curve since $\Delta T$ changes with sample time. Figure B-7 shows the impact of an $0.03/\text{hr}$ ramp upon a navigation gyro. It is worthy of note that better than $0.005^\circ/\text{hr}$ performance is still present with samples up to 550 seconds duration.

![Figure 7. Navigation Gyro in Presence of a Ramp Drift](image)

**References**

APPENDIX C

GYRO S/N 606 LONG TERM STABILITY EVALUATION
TELEDYNE

MEMORANDUM

NO: TMW-2822

TO: SDG Design File

FROM: T. M. Wirt

DATE: 13 November 19

SUBJECT: Gyro S/N 606 Shows A Long Term Trend Of 0.01°/Hour/Year Over A Three Year Period

REFERENCE:

Gyro serial number 606 and its support electronics have been returned after 35 months of extensive testing at NASA's Marshall Space Flight Center and MIT's Draper Labs.

A 30 day repeatability test was started on this unit beginning 28 Oct 75 in the TSC Inertial Labs with a data point (four point-spin axis vertical) to be taken every day. This unit was evaluated in a similar manner in Dec '72 prior to shipping. Comparing the present thirty (30) day test results with those obtained in Dec '72. The following table lists these two test results.

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<tr>
<th>Parameter</th>
<th>Dec '72 Tests</th>
<th>Nov. '75 Tests</th>
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<tr>
<td>Mean value of X-Axis Bias (°/Hr)</td>
<td>-.0057</td>
<td>-.0551</td>
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<tr>
<td>Standard deviation of X-Axis Bias (°/Hr)</td>
<td>.00185</td>
<td>.00167</td>
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<td>Mean value of Y-Axis Bias (°/Hr)</td>
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<td>.00217</td>
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<td>Number of data points</td>
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<td>30</td>
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<tr>
<td>Test duration (days)</td>
<td>5</td>
<td>34</td>
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If the change in bias over that 35 months period is assumed to be a long term trend then the x-axis trend is .0165°/Hr/Year and .0050°/Hr/Year for the y axis with an average value of .01°/Hr/Year.
It is worthwhile noting that the gyro support electronics contains scaling resistors and buffer amplifiers between scaling resistors and the torquer axes outputs. Thus this bias change includes any offset voltage changes in these buffer amplifiers.

The following pages contain a copy of the Dec '72 test report and a copy of the nov '75 test data to date.

T. Wirt
<table>
<thead>
<tr>
<th>Part Name:</th>
<th>Strapdown Gyro</th>
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<td>8005303-5</td>
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<tr>
<td>Serial Number:</td>
<td>606</td>
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<tr>
<td>Date(s) of Test:</td>
<td>12/8/72  12/13/72</td>
</tr>
<tr>
<td>Test Console No:</td>
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**Test Equipment Used:**

1) Loop closure electronics and test fixture designed by Teledyne and supplied with gyro for test purposes.
2) Teledyne Rate Fixture 8006993.
3) Electronic counters (2) - Hewlett Packard Model 5325B.
4) V-F converters (2) - Hewlett Packard Model 2212A.
5) Digital printer - Newport Model 806.
6) DC Nullmeters (2) - Hewlett Packard Model 413-AR.
7) Chart Recorder - Texas Instruments "Recti/Riter".
8) DC Voltage Standard (2) - Analogic Model AN-3100.
9) Oven, Delta Design MK2300

**CONTRACT NO. NA58-27452**
PERFORMANCE SUMMARY FOR STRAPDOWN GYRO S/N 606

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<th>Y Axis</th>
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Test by ________________________________  Date 12/13/72
Q.A. Inspection __________________________  Date 12/13/72
ENTER 1 IF YOU WISH TO USE N-1; ENTER 0 IF YOU WISH TO USE N

ENTER READINGS AND FREQ. IN DATA STATEMENT FORM (100-200)

1.E-1 100 DATA 3, 5, 6, 3, 2 WHERE 3, 5 AND 3 ARE READINGS
AND WHERE 6 AND 2 ARE FREQ.'S
WHEN DATA IS ENTERED; TYPE GO TO 90

>100 DATA 0, 2, -5, 1, -7, 2, 1, 11, -1, 1, -1, 5, 1, 1, 5, 6
>GO TO 90
ENTER SCALE FACTOR FOR DATA POINTS
1.00323
TOTAL DATA POINTS = 24
RC SIGMA VALUE = 2.5427347E-03
X AXIS 1C = .00254

DO YOU WISH TO TRY NEW VALUES? (Y OR N)

ENTER STATEMENTS 100-200
WHEN DATA IS ENTERED; TYPE GO TO 90

>GO DATA 0, 3, -5, 1, -2, 4, -2, 3, 2, -2, 2, 1, -2, 5, 13
>GO TO 90
ENTER SCALE FACTOR FOR DATA POINTS
1.00302
TOTAL DATA POINTS = 24
RC SIGMA VALUE = 2.669E-03
Y AXIS 1C = .00287

DO YOU WISH TO TRY NEW VALUES? (Y OR N)

LONG TERM DRIFT

SN 606
12-12-72

T.C. 44
PROGRAM COMPUTES ONE SIGMA VALUE FOR ANY NUMBER OF INPUTS

ENTER 1 IF YOU WISH TO USE N-1; ENTER 0 IF YOU WISH TO USE N
7 0
ENTER READINGS AND FREQ. IN DATA STATEMENT FORM (100-200)
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AND WHERE 6 AND 2 ARE FREQ.'S
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ONE SIGMA VALUE= 1.8548511E-03

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DELETE STATEMENTS 100-200
WHEN DATA IS ENTERED; TYPE GO TO 90

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>GO TO 90
ENTER SCALE FACTOR FOR DATA POINTS
? .00309
TOTAL DATA POINTS= 12
ONE SIGMA VALUE= 1.45664E-03

DO YOU WISH TO TRY NEW VALUES? (Y OR N)
? N

M-7
TURN ON TO TURN ON RELIABILITY

GYRO CASE TEMPERATURE = 81.5°F

GYRO 5/31 809 12:18:72

ORIGINAL PAGE IS OF POOR QUALITY
FIVE PT. SPIN AXIS VERTICAL TEST

DATE 12.8.72  OPERATOR LD1C  GYRO NO. 60.6

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<td>2</td>
<td>270°15'</td>
<td>X_T EAST, Y_T SOUTH</td>
<td>+0.62355</td>
<td>+0.0003</td>
</tr>
<tr>
<td>3</td>
<td>180°15'</td>
<td>X_T SOUTH, Y_T WEST</td>
<td>+0.0004</td>
<td>-0.06715</td>
</tr>
<tr>
<td>4</td>
<td>90°15'</td>
<td>X_T WEST, Y_T NORTH</td>
<td>-0.06245</td>
<td>+0.0023</td>
</tr>
<tr>
<td>1</td>
<td>15°</td>
<td>X_T NORTH, Y_T EAST</td>
<td>-0.0010</td>
<td>+0.6198</td>
</tr>
</tbody>
</table>

COMMENTS: Para. 6.0 & 6.1 of ATP

M-10
<table>
<thead>
<tr>
<th>INPUT RATE (°/sec)</th>
<th>COUNTS/REV.</th>
<th>AVERAGE COUNTS/REV.</th>
<th>TIME/REV (sec)</th>
<th>AVERAGE TIME/REV (sec)</th>
<th>DRIVING VOLT TO TABLE</th>
<th>SCALE FACTOR (°/sec/volt)</th>
<th>FIXTURE TEMP (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.625°/sec</td>
<td>+</td>
<td>1720160</td>
<td>9.829184</td>
<td>1</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.612°/sec</td>
<td>-</td>
<td>1720836</td>
<td>9.83263</td>
<td>1</td>
<td>20.719 ± 0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1170</td>
<td>+</td>
<td>1708278</td>
<td>170.36345</td>
<td>1</td>
<td>21.120 ± 1‰</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1131</td>
<td>-</td>
<td>-1702530</td>
<td>170.54247</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.1221</td>
<td>+</td>
<td>-1704499</td>
<td>170.04378</td>
<td>1</td>
<td>21.12 ± 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.1222</td>
<td>-</td>
<td>-1704533</td>
<td>170.04369</td>
<td>1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>12.2414</td>
<td>+</td>
<td>1704502</td>
<td>8.52245</td>
<td>2</td>
<td>21.120 ± 0.3</td>
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<tr>
<td>12.2404</td>
<td>-</td>
<td>-1704648</td>
<td>8.52265</td>
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</tr>
</tbody>
</table>
30 DAY BIAS REPEATABILITY
S/N 606
DATA REDUCED FROM 4-POINT SPIN AXIS VERTICAL TEST

X-AXIS

\[ X = -0.0551 \]
\[ \sigma_X = 0.0167 \]

Y-AXIS

\[ Y = 0.003 \]
\[ \sigma_Y = 0.00217 \]