NASA CR- 144724

P—086

IN-ORBIT PERFORMANCE OF THE OAO INERTIAL REFERENCE UNIT

by

Ronald A. Harris

3 June 1974

(NASA-CR-144724) IN-ORBIT PERFORMANCE OF THE OAO INERTIAL REFERENCE UNIT (Draper (Charles Stark) Lab., Inc.) 29 p HC $4.00 CSCL 22B
N76-17181
Unclas
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Approved ____________
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ACKNOWLEDGMENTS

This report was prepared under DSR Project 55-29240 sponsored by the Goddard Spaceflight Center of the National Aeronautics and Space Administration through Contract NAS5-11002.

The publication of this report does not constitute approval by NASA of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

The author would like to express his appreciation to Charline T. Samia for her perseverance in processing the data tapes and developing the data reduction programs and to William D. Koenigsberg and Robert B. Gibson who developed the algorithms for both a weighted-recursive-least-squares filter and a square root formulation of that filter.

This paper is scheduled to be presented at the ION Annual Meeting, San Diego, California, 25-27 June 1974.

ABSTRACT

The Inertial Reference Unit (IRU) used in NASA's Orbiting Astronomical Observatory (OAO-C or Copernicus) uses three single degree of freedom, floated, rate-integrating gyros operated in binary, pulse-restrained torque loops to provide an inertial attitude reference for the spacecraft's attitude control system. Since 21 August 1972 when the spacecraft was launched, more than 15,000 hours of continuous and troublefree operation have been accumulated on the IRU. When prelaunch operation is included, the running times for the gyro wheels range between 17,000 and 22,000 hours.

The drift rates observed on these inertial grade gyros during the 1-1/2 year of in-orbit operation have remained within a band of 16 arcsec per hour peak-to-peak. When the effects of known disturbances are considered, the standard deviation of drift rate appears to approach one arcsec per hour ($< 10^{-7}$ degrees per second).

Included in this paper are a brief description of the OAO and IRU, a summary of the data reduction programs used to calibrate the IRU in orbit, and some thoughts on how gyros with good long-term drift stability could be applied to future spacecraft such as the Large Space Telescope and Earth Observatory Satellite.

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1. INTRODUCTION

NASA's Orbiting Astronomical Observatory OAO-C (Copernicus) was launched on 21 August 1972. As of this writing the satellite has successfully completed over 9000 orbits and 15000 hours of continuous operation. The satellite contains two astronomy experiments. The first is a Princeton University experiment (PEP) that uses a 32-inch telescope to examine interstellar media by measuring its absorptive characteristics in the ultraviolet spectrum using stars as light sources. Some of the Princeton data pertaining to deuterium and hydrogen were cited recently in a Scientific American article.[(1)*] The second is the University College, London experiment that uses three small telescopes to make measurements in the X-ray regions of the electromagnetic spectrum.

When the PEP is making precision observations, some of the light from the main telescope is used to sense motion of the optical axis (i.e., rotation about the pitch and yaw axes). This sensor is called the Fine Error Sensor (FES).[(2)] M. Proise[(3)] has estimated that pointing stabilities of 25 milli-arcsec (long term) and 3 milli-arcsec (short term) have been achieved using magnitude + 2.6 star.

A three axis gyro system called the Inertial Reference Unit (IRU) controls the roll axis during fine pointing and all of the axes during all other normal modes of operation except during brief periods when Gimballed Star Trackers (GST) are used to re-reference the IRU. This paper is confined to describing the function and performance of the IRU on OAO-C and to presenting some thoughts on how this experience with precision gyroscopes could be applied to subsequent programs.

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* Superscript numerals refer to similarly numbered references in the List of References.

2. IRU DESCRIPTION

The IRU consists of two packages, an Inertial Package (IP) and an Electronics Package (EP) with the physical characteristics listed in Table 1. The heart of the system is three single-degree-of-freedom gyros that are operated in binary torque-to-balance loops. By combining two wheel speeds and two torque levels, a 7.4 decade of rate measurements is achieved. The various combinations of wheel speeds and torque levels are identified as modes (HOLD, SLEW, and ISTAB) and are defined in Table 1. Because the gyros were originally designed to operate in the launch environment of a missile, some modifications were made to take advantage of the zero-g environment of the OAO spacecraft. For example, the exterior of the float was "cleaned up" by the elimination of the protruding mechanisms used to adjust the fine balance. Also, the preloading of the wheel bearing was decreased to reduce the power required to drive the wheel. The decrease in preloading may also improve the reliability of the wheel through secondary effects. However this may not be a primary consideration for reliability because five 2FBG-6F gyros with high-g wheels have each operated more than 26,000 hours without a failure.

The Charles Stark Draper Laboratory (CSDL), then a division of The Massachusetts Institute of Technology, was responsible for the design and build of the IRUs. The gyros were built by CSDL in a very successful program; 18 gyros started into the manufacturing cycle, all 18 were completed and each of them met flight performance requirements. The General Electric Company's Spacecraft Department located at Valley Forge, Pennsylvania built most of the flight electronics and performed the initial integration of the flight EPs. Manufacture of the rest of the electronics, system integration, and testing were performed by CSDL. The IRUs were delivered to NASA (Goddard Spaceflight Center) and given to Grumman Aerospace Corporation as GFE for incorporation in the spacecraft.

Both the OAO and the IRU have far exceeded their design goal of one year in-orbit operation. Since launch the gyros and IRU have been running continuously and without trouble. This

Table 1. Summary of IRU characteristics

Inertial Package

- contains - 3 gyros and torque loops
  - temperature control electronics
  - crystal
- size - 9" x 9" x 9" plus radiator
- weight - 40 pounds
- power - 25 watts plus 3 to 17 watts for temperature control

Electronics Package

- contains - power supplies
  - frequency and pulse generators
  - rate integrators
  - command logic
  - digital to analog converter for error signal outputs
  - telemetry signal conditioning
- size - 9" x 15" x 6"
- weight - 38 pounds
- power - 50 watts

Electronic Construction

- welded cordwood modules using discrete electronic components
- soldered connections for intratray wiring

Gyros (2FBG-6F-OAO)

- type - floated, rate integrating, ball bearing wheel, soft iron torquer
- operating modes

	Wheel Speed (rpm)	
Torque Level	750	12,000
Low 125 dyne cm	X	HOLD
High 4000 dyne cm	ISTAB	SLEW

- rate capability
  - ISTAB 128 deg/min
  - SLEW 8 deg/min
  - HOLD 0.25 deg/min

For additional details see "Inertial Reference Unit Systems Handbook for the Orbiting Astronomical Observatory," CSDL Report E-2585, May 1970.

speaks very well for instruments whose basic design was completed in 1962 and for the spacecraft whose design was started in the early 60's. The running times of the gyro and IRU electronics are shown in Table 2. We believe that even though these numbers may be impressive, they are consistent with CSDL's experience that reliability and performance are directly related, i.e., the same care in both design and manufacture that is required to achieve good performance is also necessary for reliability.

3. IN-ORBIT CALIBRATION

The design of the IRU and the tests performed on earth were set up to minimize the effects of gravity so that changes in the system's performance would be within the range of in-orbit compensation. This philosophy was reflected in the thermal design of the IRU which emphasized thermal symmetry, tight (0.1°F) temperature control of each gyro end mount, and minimization of convective heat losses. Nevertheless, changes were expected due to normal variation of the electronic components and differences between one-g and zero-g environments.

The calibrations described in this paper are those performed by CSDL for evaluating the performance of the IRU. The Grumman and NASA operations personnel who fly the spacecraft perform the calibration necessary to satisfy spacecraft operational requirements.

3.1 Preprocessing

The first step is to decommutate, interpret, and arrange the data in the proper time sequence. The last step is required because the data used by CSDL was stored on the spacecraft's tape recorder and played back during selected contacts with ground stations. Because the tape recorder is not played back completely at each contact, the various data segments must be put into chronological order. At times this presents quite a puzzle.

A sample of data is shown in Figure 1. There are some points worth noting:

Table 2. IRU(OAO) operating hours (OAO-C satellite) (5/20/74)

	Gyros			System	
	Roll	Pitch	Yaw	IP	EP
At CSDL	2423	6738	2160	1187	1585
In Orbit*	15290	←	—	→	15290
Total	17713	22028	17450	16477	16875

*Launch Date: 8/21/72

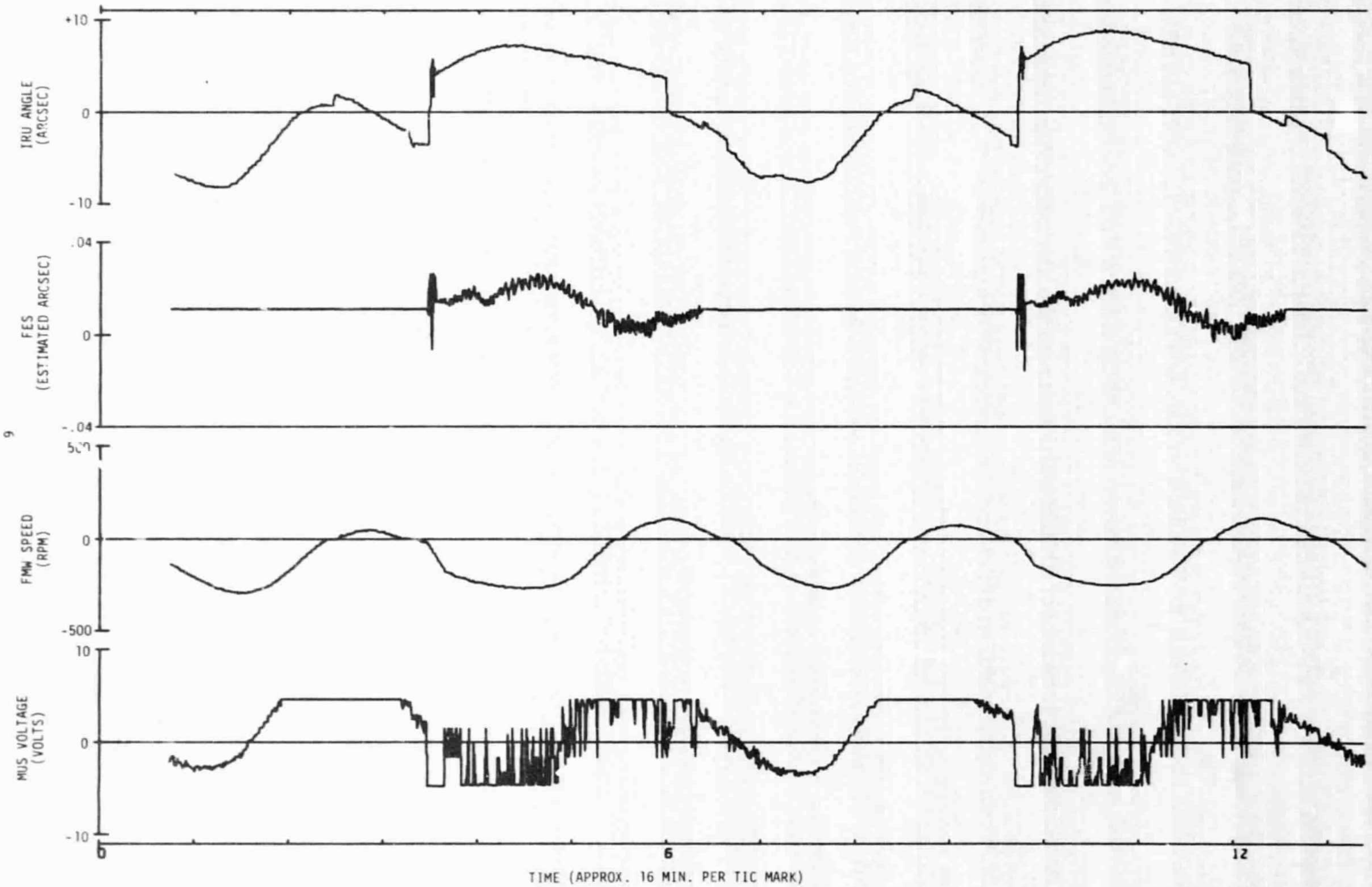

Figure 1. An example of pitch axis data - day 72 253

(1) The IRU data is quite clean. The noise levels seem to be consistent with the 0.15 arcsec telemetry quantization.

(2) When the IRU controls the spacecraft, the dominant error is due to gravity gradient torque that is cyclic at twice the orbital rate. (The gain of the FES loop is at least 100 times higher than the IRU loop and, hence, the effect of these disturbance torques are reduced significantly during fine pointing.)

(3) The one or two arcsec step changes seen during IRU control are believed due to two sources. The first coincides with transitions between the dark and light portions of the orbit and, hence, are attributed to the switching on and off of the solar paddle charging circuits. The second coincides with reversal of the reaction wheel speed and magnetic unloading system current and, hence, are attributed to a zero-crossing nonlinearity in the latter system.

(4) During FES control, the telescope must lead the target star by an angle proportional to the ratio between the component of spacecraft velocity that is perpendicular to the line of sight to the star and the speed of light. This velocity aberration effect has a period of once-per-orbit and for the OAO's orbit can have an amplitude of up to 5 arcsec.

The data obtained during IRU control are used to estimate spacecraft parameters involved in torque producing mechanisms (inertia differences and cross-products, spacecraft magnetic moments and magnetic unloading system gains). The reader is referred to Reference 4 for information on this modelling effort. Data obtained during FES control are used to estimate the IRU drift rates.

3.2 IRU Drift Calibration

When the FES is controlling the spacecraft, the change in angle indicated by the IRU from orbit-to-orbit is used to measure the uncompensated drift rates of the pitch and yaw gyros. The roll gyro's drift rate can be measured using a similar procedure and GSTs. However, because the null derived from the GSTs is noisy compared to the FES null, the data are of little use in evaluating gyro performance and, hence, are not included in this paper.

3.2.1 Error Analysis

Three main sources of error are present when the FES is used for calibration:

(1) The quantization of the gyro data causes an uncertainty in measuring the angle sensed by the gyro both at the beginning and end of a sample. In the HOLD mode, the quantization is due to the telemetry system and has a value of 0.15 arcsec. In the SLEW mode, it is due to the torque loop and has a value of 2.6 arcsec. In order to reduce the SLEW value, 20 points are averaged to reduce this quantization error to a theoretical "$\sqrt{N}$" value of 0.6 arcsec.

(2) Any change in the inertial attitude of the optical axis of the FES between measurements is interpreted as gyro drift. When the measurements are taken one orbit apart, the error due to imprecise timing and velocity aberration is approximately 0.005 arcsec/sec. A conservative assumption is that the data across an orbit have a timing error of one minute. This would result in an angle error of only 0.3 arcsec.

The velocity aberration due to the velocity of the earth in orbit around the sun has an amplitude of 20 arcsec and a period of one year. Even in the worst case, this is a negligible effect about two orders of magnitude less than that due to the orbital rate of the satellite about the earth.

(3) Relative motion between the IRU and the optical axis of the FES would also be interpreted as gyro drift. However, inasmuch as there is no independent measure of this effect, there is no choice but to ignore it.

The rss uncertainties due to these error sources are 0.24 arcsec/hour in the HOLD mode and 0.53 arcsec/hour in the SLEW mode.

3.2.2 Drift Performance

The drift rate performance of the pitch and yaw gyros for the first 500 days of in-orbit operation are shown in Figure 2. During the period up to day 73 135 (i.e., the 135th day of 1973) the gyros were normally operated in the HOLD mode except during attitude changes when they were operated in the SLEW mode. After day 73 135, the gyros were operated in the SLEW mode continuously to reduce the errors that develop during attitude changes without having to compensate for the difference in drift rates between the HOLD and SLEW modes. (That difference is approximately 100 arcsec/hour for two of the gyros and approximately 15 arcsec/hour for the third gyro.) The data are shown as if the drift rates were compensated only once in the HOLD mode (72 292) and once in the SLEW mode (73 148). The effects of the other updates (two in pitch and three in yaw) were removed from the data numerically to show actual gyro performance.

The first observation is that, as expected, the "noise" level in the SLEW mode is larger than that in the HOLD mode. The ratio of the noise levels is approximately three or four to one, which is consistent with the above analysis. However, averaging the data is not as effective as expected. For example, the peak-to-peak values predicted for the SLEW mode are 6.2 arcsec per hour without averaging and 1.4 arcsec per hour with averaging. The observed values seem to be between three and four arcsec per hour.

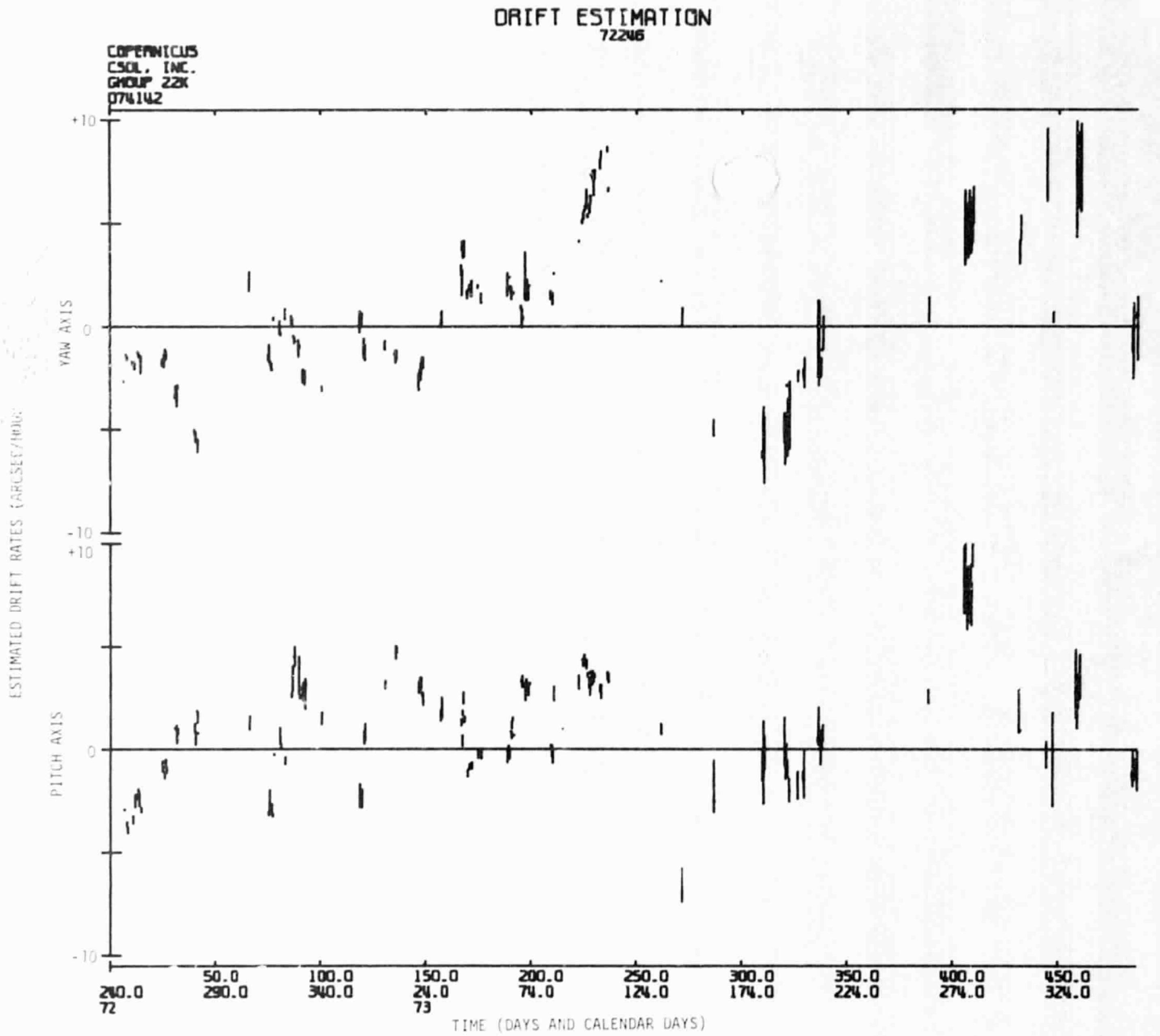

Figure 2. Estimated drift rates for the IRU (OAO)

This suggests that the torque loops may be operating in a 2-2 mode rather than a 1-1 mode.

The second observation is that there is no long-term trend in the data. This differs from long-term, on-earth tests of OAO type gyros that showed trends resulting in drift rate changes of 10 arcsec per hour over a 30-day period. One explanation of this difference is that the trend producing mechanism is excited by gravity. A second possibility is that the trends observed during tests performed on earth are actually segments of exponential behavior which would reach a steady-state value if operated continuously as the IRU has been. This supposition is supported somewhat by the exponential behavior of the pitch gyro after turn-on and after changing to continuous operation in the SLEW mode. On the other hand, the yaw gyro does not reveal similar exponential behavior.

The third observation is that the peak-to-peak value of the drift rate has remained bounded within a band with a peak-to-peak value of 16 arcsec per hour during the entire 500-day period. Even though this performance is very good, it appears that a significant part of the changes may not be intrinsic gyro noise. A close examination of the data shows that the drift rate changes coincide with changes in the spacecraft's attitude. When the spacecraft's attitude changes, the excitations to the magnetic unloading system's torquer bars are changed to account for the different orientation of the magnetic system with respect to the earth's magnetic field. Because the gyros are sensitive to magnetic fields, the drift can change. A typical sample of drift rate data taken during a period of constant spacecraft attitude is shown in Figure 3. Data such as this (which probably includes some systematic errors due to the daily rotation of the magnetic field) leads to the conclusion that the variations of drift rates of the OAO gyros probably are less than two or three arcsec per hour peak-to-peak.

In summary, our model for the in-orbit drift rate of the OAO gyros based on 500 days of data is a constant mean process

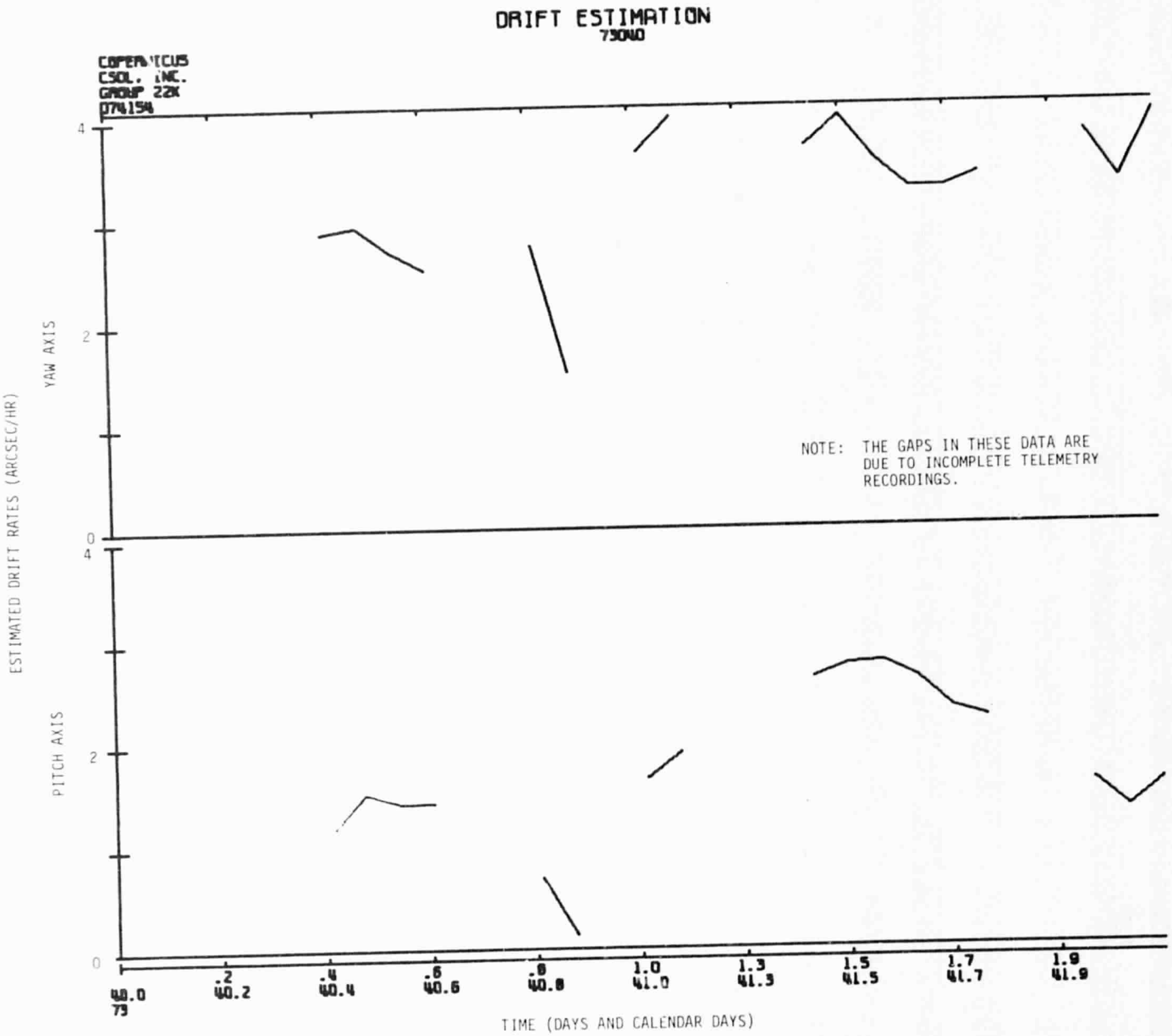

Figure 3. Short-term drift rates for the IRU (OAO)

with bounded variations shown to be less than 16 arcsec per hour peak-to-peak in the present OAO attitude control system. It is believed that the OAO gyros are capable of operating within a band of two or three arcsec per hour peak-to-peak when shielded to reduce their sensitivity to external magnetic fields.

3.3 Scale Factor and Misalignment Calibration

The program used to estimate the plus and minus scale factors and the two misalignment angles of each gyro uses data obtained during normal spacecraft attitude changes.

The approach used is to model the problem as a constant parameter system and propagate both the initial errors and those generated during the slew sequence into final errors. The initial and final errors are measured with the FES (pitch and yaw) and a GST (roll). A square root formulation of a weighted, recursive least squares filter is used to do the estimation.

3.3.1 Error Analysis

All the error sources are errors in angle and, hence, their effects can be reduced by using data from large slews. The information from the FES is "truth" by definition and thus has no error associated with it. The GST information, on the other hand, can have errors of 30 arcsec or more. Two precautions are taken to minimize these. First, roll data are obtained from the same star tracker on both ends of the slew where possible. Second, the GST data are assumed to have ten times the uncertainty of the FES and weighted accordingly.

The various sources of error and their contribution to the estimates for a 10-degree slew are shown in Table 3. The actual errors depend on the slew profiles and the weighting of the GST data. However, we would expect that the calibrations are limited to accuracies of near 200 ppm with the principal error contributor being the GST. The real test of this calibration procedure is the manner in which the estimates converge and whether or not they remain constant for many different slew sequences.

Table 3. Errors affecting IRU calibration

Error Source	Worst Case Error (arcsec)	PPM Error for a 10 Deg Slew	
		Worst Case	Est 1σ
Command (1)	10	280	80
FES	0	0	0
GST	30	830	240
Velocity Aberration (2)	10	280	80
IRU			
Quantization	2.5	70	20
Drift (6 hrs)	2	60	20

(1) The slews are quantized in increments of approximately 20 arcsec. These could be compensated.

(2) The velocity aberration error can be calculated and could be compensated.

The program concepts (i.e., the ability to make correct estimates for the problem as modelled) and software were checked out by generating some slew data using a program that had been used for an earlier IRU performance analysis.[5] The results of this simulation effort showed that for (1) angle errors with standard deviations of 10 arcsec in pitch and yaw and 30 arcsec in roll and (2) attitude changes that were representative of OAO maneuvers, a deterministic set of data would give estimation errors up to 100 ppm and 15 arcsec, and that these errors would be reduced to 10 ppm and 2 arcsec when the redundant data from 20 attitude changes were included.

3.3.2 Real Data

A special calibration exercise was performed in preparation for observation of the comet Kohoutek. This provided a chance to exercise the calibration program with data that was close to ideal because the attitude errors were accurately measured before and after each single axis slew. Table 4 shows the results of this exercise. The deterministic set was formed from six single axis slews, i.e., a positive and negative slew about each axis. The redundant slews and the multilegged* slew serve as checks on the estimates. From this limited set of data it appears that where redundant checks are available, the yaw estimates should be good to 200 ppm and 60 arcsec while the other parameters seem to be closer to 100 ppm and 10 arcsec. These results are encouraging because they are consistent with the simulations. However, more data will have to be processed to confirm the procedure and to evaluate the IRU's performance in these areas.

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*A multilegged slew is an attitude change consisting of a sequence of single-axis slews. Optical sensor information is generally available before and after the attitude change only.

Table 4. Results of IRU calibration

These results are based on data obtained from single-axis slews performed during the calibration exercise on days 74 020 and 021, one attitude change on day 74 021 that consisted of a sequence of four single-axis slews.

Estimated Errors

	*	Redundant Slews				74 021
		+Y	+P	-P	+R	-R,+R,+P,-R
δSF^{+}_{R} ppm	-843				-888	-846
δSF^{+}_{P} ppm	-627		-526			-554
δSF^{+}_{Y} ppm	+276	+ 50				
δSF^{-}_{R} ppm	- 96					-124
δSF^{-}_{P} ppm	+ 75			- 33		
δSF^{-}_{Y} ppm	+153					
ε_{RP} arcsec	+ 68				+ 72	+ 72
ε_{RY} arcsec	- 24				- 22	- 19
ε_{PY} arcsec	+ 73		+ 52	+ 45		+ 45
ε_{PR} arcsec	-214		-210	-202		-203
ε_{YR} arcsec	-235	-186				
ε_{YP} arcsec	- 63	- 54				

*Deterministic Set

4. OAO OPERATION

Perhaps the most significant aspect of the IRU effort has been the demonstration that when proper care is taken, gyros are reliable. Further, it also has been shown that it is not necessary to sacrifice reliability to achieve performance. As stated previously, CSDL's experience over the years has shown that instrument reliabilities and performance have improved together. In fact, the efforts of all contractors associated with both the OAO-2 and OAO-3 spacecraft have demonstrated that reliable systems can be built even though these systems are complex and some of the hardware is -- shall we say -- vintage.

The successful operation of the IRU has shown that spacecraft operations can both be simplified and made more efficient by the use of gyros. One of the original purposes of the IRU was to decrease dependence on the gimballed star trackers. This has been achieved. During normal operation, the GSTs are used for two purposes: (1) a GST is used once per day to correct the error due to the uncompensated drift rate of the roll gyro, and (2) GSTs are used to correct for errors accumulated during the slewing. The system operations have been simplified because control of the spacecraft's attitude is transferred directly from the IRU to the FES. This has two implications. First, because fewer commands are needed for attitude control purposes, more on-board memory locations are available to store commands needed by the experimenter. Second, the attitude errors that exist when control is transferred from the IRU to the FES are usually small and rapidly nulled out. It has been estimated that the performance of the IRU has permitted the experimenters to make the equivalent of one extra observation per day.

Perhaps all of this is summed up in the statement: "The IRU has made flying the OAO a boring operation."

5. FUTURE APPLICATIONS

The good high frequency noise characteristics of gyros have been used for some time. The most common application has been in the stabilization loops of gimballed systems. Newer gyros may have low enough noise levels to make them useful parts of precision pointing systems such as the Large Space Telescope.[6,7] Application of gyros in the "inner loop" of an attitude control system provides error signals that are much quieter than horizon sensors and most star sensors. The low noise error signals drive the actuators efficiently and, hence, should require less power for attitude control. It should also be possible to relax the bandwidth requirements of optical sensors because they would have to respond only to orbital rates and not attitude control system noise. Gyros also provide continuous data whereas optical sensors must contend with intermittent light sources.

The long-term drift stability of gyros extends the length of time of autonomous operation. This could permit the use of strapped down optical sensors instead of gimballed sensors. It could also reduce the computation rates required for either real time or post flight estimation of the spacecraft attitude.

One final point is to relate the long-term drift to the short-term noise. The emphasis has, in general, been to look at only the random variations in drift when evaluating a gyro's performance during periods of say less than an hour. However, in order to achieve pointing stability that is consistent with the noise, systematic components must also be compensated to the same degree. For periods of up to 100 seconds, the random variation in drift rate may result in random angular motion of 10 milli-arcsec or less. Except for the LST satellites, angle measurements of this level are impractical. Therefore, the usual procedure for calibrating drift rate is to use longer time bases and angle sensors with larger uncertainties. The drift rate must be stable not only during the time of measurement but also between the calibrations. This is illustrated by the following example.

Consider two gyro models with the noise described by the power spectral densities in Figure 4; model 1 has better long-term drift rate stability whereas model 2 has lower random angle noise for periods of 100 seconds and less. Note that these models were selected to illustrate a point and it does not necessarily follow that an instrument with better long-term drift characteristics need have more high frequency noise. Good design should permit minimization of one noise source without increasing another noise source.

In order to use a gyro in orbit, the drift rate must be measured so that it can be compensated. Assume that the optical sensor used for in-orbit calibration is capable of making angle measurements with an uncertainty of one arcsec. Then the uncertainty of drift rate calibration will be

$$(U)W = \frac{\sqrt{2}(U)A}{T}$$

where (U)W = uncertainty in rate measurement (arcsec/hour)
(U)A = uncertainty in angle measurement (arcsec)
T = time between angle measurements (hour)

This relationship is plotted in Figure 5 along with the standard deviation of the drift rates for the two gyro models. It is seen that the best drift rate calibration would be 0.05 arcsec/hour for model 1 and 1 arcsec/hour for model 2. Figure 6 shows how this impacts the high frequency noise. The curves labeled B show the standard deviation of angle noise that can be expected from only the random variations in drift rate. As should be expected from the selected models, model 2 has less random noise than model 1 for periods up to 100 seconds. However, when the uncertainty of compensating the systematic error is included as represented by curves B, model 2 has less noise for periods of only 5 seconds or less. It is also noted that the random drift rate also dominates model 2's output for periods longer than a month.

The conclusion here is that it is not sufficient to simply look at the random noise of a gyro in the passband dictated by the

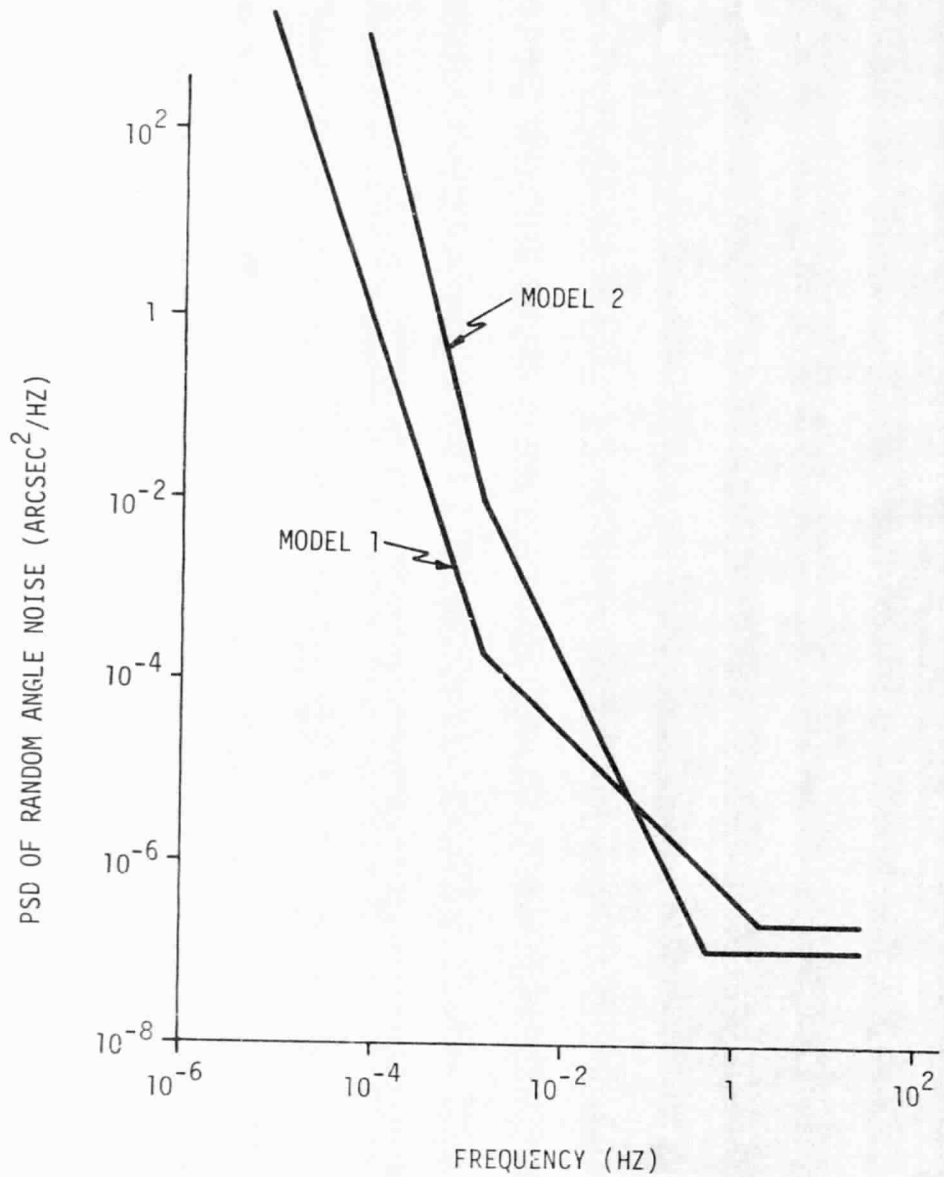

Figure 4. Models of gyro noise

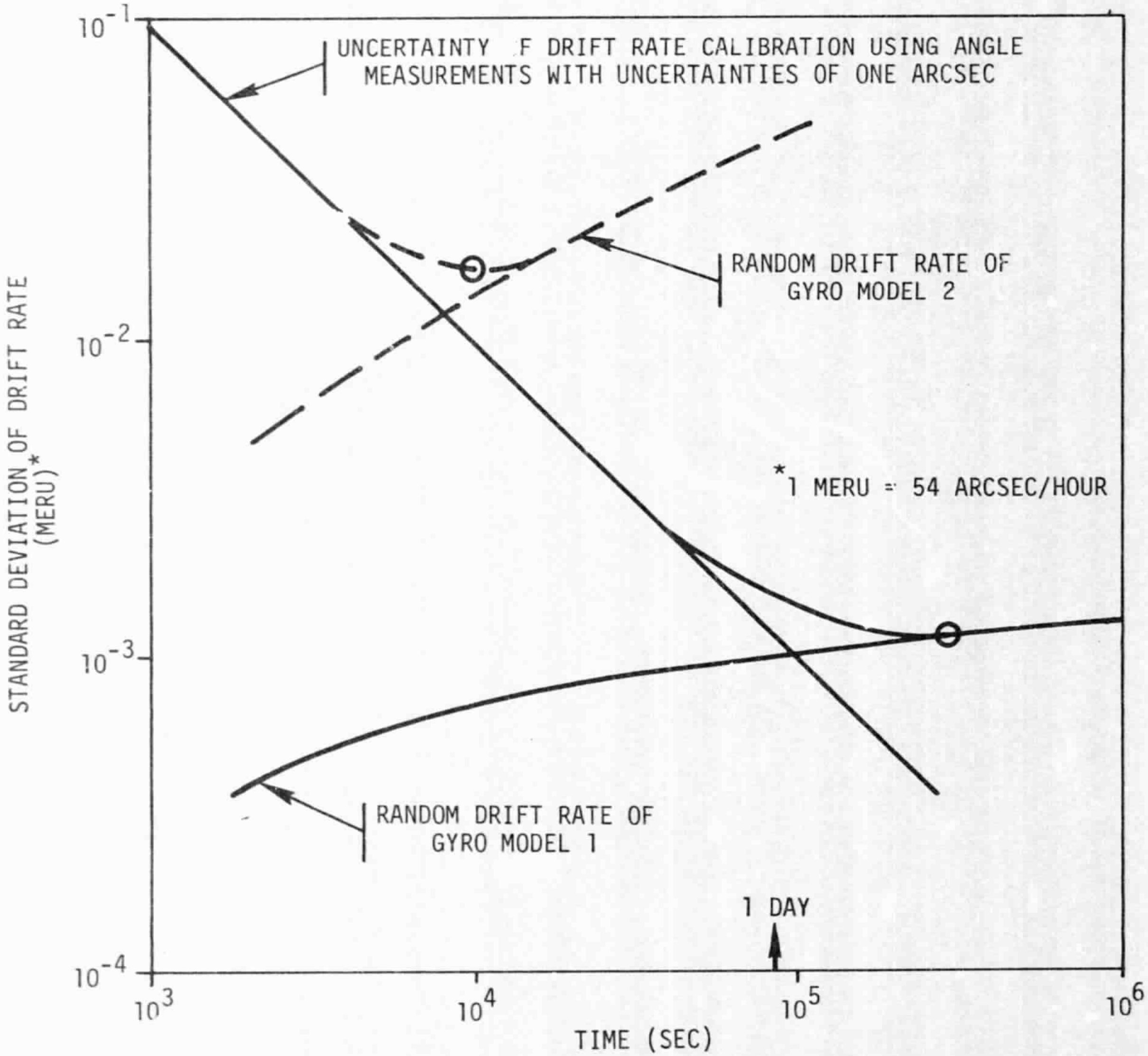

Figure 5. Uncertainty of the in-orbit calibration of the systematic component of drift rate

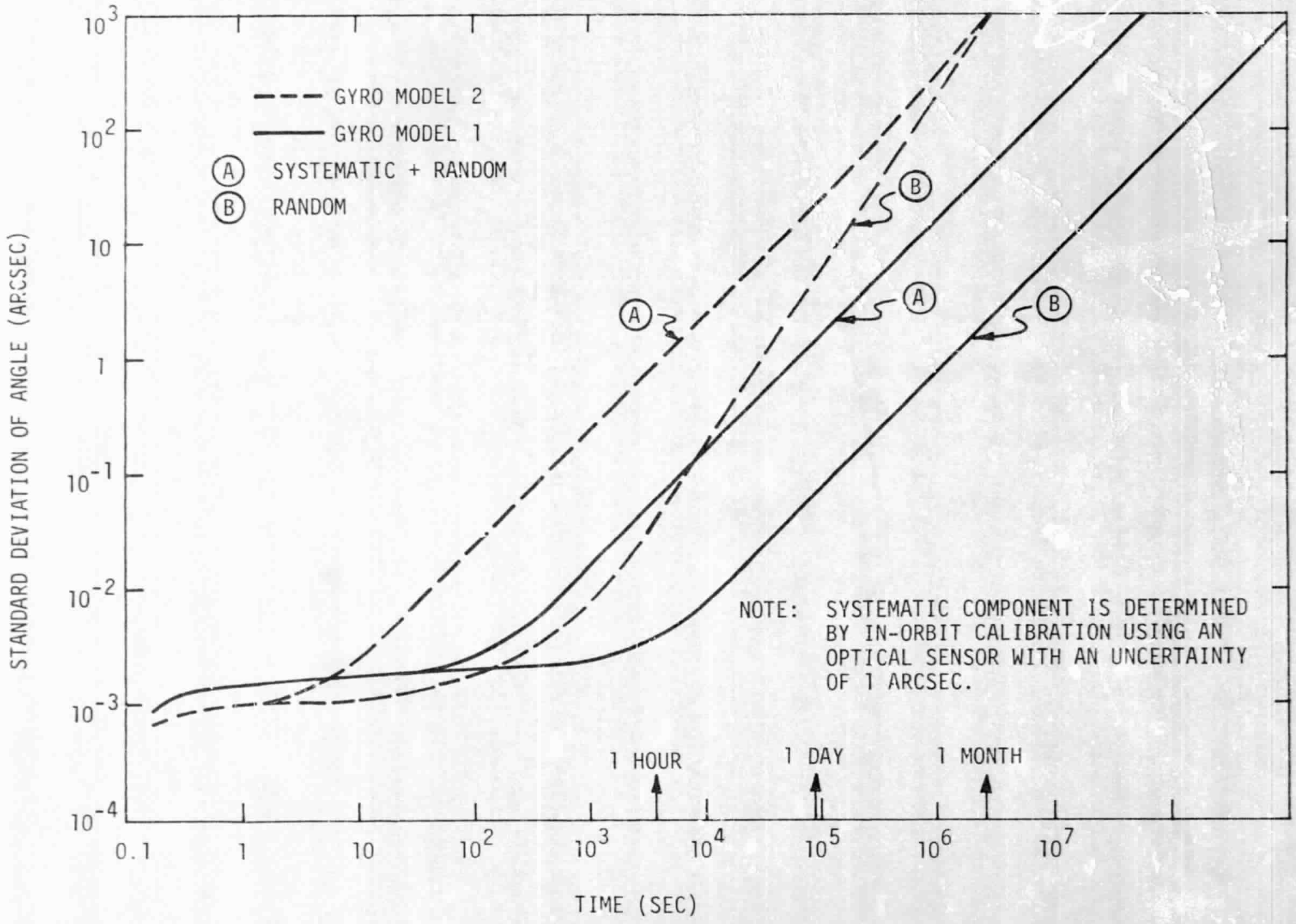

Figure 6. The effect of systematic drift on gyro performance

high frequency requirements of the attitude control loop. Lower frequency noise appears as a "change in bias" in higher frequency passbands and these changes must also be consistent with the required performance levels.

6. CONCLUSION

Based on nearly 22 months of successful in-orbit operation of the IRU on OAO-C and 500 days of drift data that have been reduced to date, it has been demonstrated that inertial grade gyros can provide reliable, low noise attitude information with long-term drift stability that can significantly reduce requirements placed on optical sensors. It was also shown by example that stable, long-term drift is required to achieve performance that is consistent with random noise measured in higher frequency passbands.

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