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# Gyro-Based Attitude Reference Systems for Communications Satellites

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**This paper presents three concepts for gyro-based attitude sensing systems at geosynchronous altitudes, ranging from basic gyrocompassing with a single gyro, an earth sensor, and a sun sensor, to sophisticated three-gyro concepts. Stellar references (other than sun sensors) are specifically excluded. These concepts can achieve a pointing accuracy of 0.05 deg (3-$\sigma$) in pitch and roll and 0.1 deg in yaw, with the best concept achieving 0.01 deg in all axes. Preliminary system mechanizations are also discussed. The detailed analysis includes simplifying the control laws and defining operational requirements and procedures. Finally, the concepts are compared in terms of accuracy, weight, power, reliability, major operational features, and cost/risk factors.**

## Introduction

LONG lifetime (ten years) and high accuracy (0.05 deg pitch/roll, 0.1 deg yaw) for satellite communications missions in the 1980's are the goals of this study. Gyro-based systems are being considered because the projected accuracy requirements are not satisfied cost-effectively by available attitude reference concepts. Three concepts for gyro-based attitude sensing systems at geosynchronous altitudes are presented.

Sensing system concepts that combine high-quality gyros with earth sensors, sun sensors, and decentralized Kalman filter algorithms[1-3] are discussed. This approach results in both high reliability because of the functional versatility of the sensing system, and in high accuracy by the judicious mixing of the sensor outputs with different spectral characteristics. Based on required pointing accuracies, one sensing system concept for each of the following categories is developed: 1) simple methods that use current state-of-the-art technology and techniques and whose performance meets but does not exceed pointing accuracy specifications; 2) methods that use state-of-the-art technology and techniques and whose performance exceeds specifications; and 3) methods that use technology projected to the time of application and whose performance exceeds specifications.

Potential attitude control concepts are defined for the communications mission with performance requirements of 0.05 deg in pitch/roll and 0.1 deg in yaw. It is assumed that the stationkeeping bounds are $\pm 0.1$ deg along the north-south direction and $\pm 0.05$ deg along the east-west direction. A $\pm 2$ deg offset pointing capability around the pitch/roll axes is also required. For this study, a spacecraft of 1000 kg, 1000-1500 W was selected. It has an inertia of 800 kg-m$^2$ along roll/yaw and 400 kg-m$^2$ along pitch. The first flexure mode frequencies are 0.7 rad/s and 0.9 rad/s for roll/yaw and pitch, respectively.

Reaction wheels are used as the primary actuators for normal on-orbit control; hydrazine reaction jets are used both as thrusters for $\Delta V$ maneuvers and as torquers to maintain attitude during stationkeeping and momentum unloading maneuvers.

## Sensing System Analysis

### Analysis Procedure

Attitude control system errors were divided into two groups: control system errors (attitude errors due to control loop disturbances) and sensor system errors (those due to sensor errors). The control and sensing systems can be designed independently by allocating the total accuracy specifications between these two error categories. Equal allocations and quadratic addition were assumed for design purposes, resulting in nominal allocations of 0.035 deg (3-$\sigma$) for pitch and roll and 0.07 deg for yaw.

Classical control laws, designed to meet the control error allocation for the wheel and jet control loop, impose bandwidth and accuracy requirements on the attitude sensing system. Three cases were treated: normal control using reaction wheels, stationkeeping control using reaction jets, and transition from stationkeeping to normal control using wheels. A special transition controller is needed to damp out

**Table 1 Summary of design criteria for sensing system**

| Design requirements | Pitch | Roll | Yaw |
|---|---|---|---|
| Normal control (wheels) | | | |
| Accuracy, 3$\sigma$ (deg) | 0.035 | 0.035 | 0.07 |
| Bandwith, rad/s | 0.035 | 0.016 | 0.007 |
| Stationkeeping and momentum unloading control jets | | | |
| Accuracy, 3$\sigma$ (deg) | 0.035 | 0.035 | 0.07 |
| Bandwidth, rad/s | 0.55 | 0.39 | 0.36 |
| Transition control (wheels) | | | |
| Accuracy, 3$\sigma$ (deg) | 0.035 | 0.035 | 0.07 |
| Bandwidth, rad/s | 0.19 | 0.09 | 0.07 |

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residual rates due to jet firings. The wheel controller is designed to operate well below the first flexure mode of the solar panels, while the jet controller is only phase stable for the first few modes. Various error mechanisms were identified and translated into a set of requirements on the control loop design: 1) low-frequency and steady-state gain requirements, 2) medium-frequency or bandwidth requirements, 3) high-frequency requirements due to flexure, and 4) stability requirements (gain and phase margins).

Based on these requirements, design criteria for the sensing system are developed and summarized in Table 1 in terms of bandwidth and accuracy. The sensing system bandwidth required for normal control is minimal and can easily be satisfied with earth sensors for roll and pitch. However, the bandwidth required for the other two modes is much greater because of increased overall control system bandwidth. Furthermore, the sensing system bandwidth is more critical in this case because flexure modes are only phase stable.

Errors in the potential sensing systems were analyzed using the decentralized Kalman filter approach illustrated in Fig. 1. The sensors are separated into two groups. The first group (controlling sensors) is initially used by a low-order Kalman filter to reconstruct state estimates of spacecraft rates and attitudes, which are used by the jet and wheel controllers to control spacecraft attitude. The second group of sensors (calibration sensors) is prefiltered along with the first group and sampled at a much lower rate (every half-hour) for use by the calibration filter. This filter is also a low-order Kalman filter that estimates low-frequency (LF) sensor biases, alignments, and disturbance torques.

The total pointing error due to the sensing system is given by the root-sum-square (rss) of attitude errors due to high-frequency (HF) random errors and attitude errors due to calibration. Response to HF random errors can be obtained by the steady-state covariance analysis of the closed control loop driven by HF noises. Response to LF errors is determined in two steps. First, the steady-state sensitivity of the HF control loop to LF errors is computed by considering these errors as constants. Second, the covariance of the spacecraft state is computed from this sensitivity and from the covariance matrix of calibration errors, which is determined by propagating the LF calibration filter over several days of orbit.[1]

#### Concept Selections

A survey was conducted to identify components currently available or under development for the control and sensing systems.[4] Error models, performance parameters, and physical characteristics for gyros, earth sensors, and sun sensors were determined. The earth sensors surveyed include both the radiation balance type and the mechanical scanning type. Sun sensor data analyses were limited to the best digital sun sensor available. Test results and performance projections for various gyros are categorized according to their HF random errors and LF drift rates. The gyros surveyed cover most currently available gas-bearing gyros, laser gyros, and high-precision electrically suspended gyros (ESG's).

Many potential attitude reference systems were configured from components identified in the survey, and their performance was evaluated with the decentralized Kalman filtering procedure. The analysis procedure was applied separately to the roll/yaw axes and to the pitch axis of the spacecraft. From all possible combinations of gyros, earth sensors, and sun sensors, two attitude reference concepts for each aforementioned system category were selected for preliminary system mechanization, based on performance predictions.

A concept was selected from each category based on performance, mechanization requirements, reliability, relative cost, and developmental risks. Table 2 includes a summary of the selected concepts, which shows the sensor instrument required and the expected accuracies obtained by the analytical procedure described herein. In this table, the class 2 gyro includes low-drift gas-bearing gyros, and class 4 includes underdeveloped ESG's. For the earth sensors, class 2H covers the scanning earth sensors of the thermistor bolometer type, and class 3 includes the mechanical scanning type with improved LF stability.

### Detailed Analyses of Sensing Concepts

The three concepts selected were subjected to detailed analysis and the results are described in the following subsections.

#### Yaw Gryo Reference (Concept I)

*Concept Simplification*

This concept, which uses a single class 2 yaw gyro, a class 2H earth sensor, and two sun sensors facing the plus and minus roll axis directions, just meets sensing system accuracy requirements with state-of-the-art components. To simplify the concept, the HF Kalman filter/controller will be approximated by simple low-order transfer functions, and the number of error parameters in the LF calibration loop will be properly reduced. Figure 2 summarizes the simplification of the yaw axis high-frequency control loop for concept I. Figure 2a is the original optimal filter/controller with parameter values determined by system noise characteristics. The controller consists of a Kalman filter, which estimates $\Psi$ from compensated rate-integrating gyro outputs, $m_z$, and wheel torque, $\hat{T}_z$. The estimate is used in a classical lead-lag control law to generate control torque commands, $T_{cz}$. These are summed with wheel speed cross-coupling compensation, $I_w \Omega_x \omega_e$, and integrated to produce momentum commands for the set of reaction wheels.

Figure 2b is a magnitude diagram for the transfer function of the controller, $G_z(s)$. Since the control loop cutoff

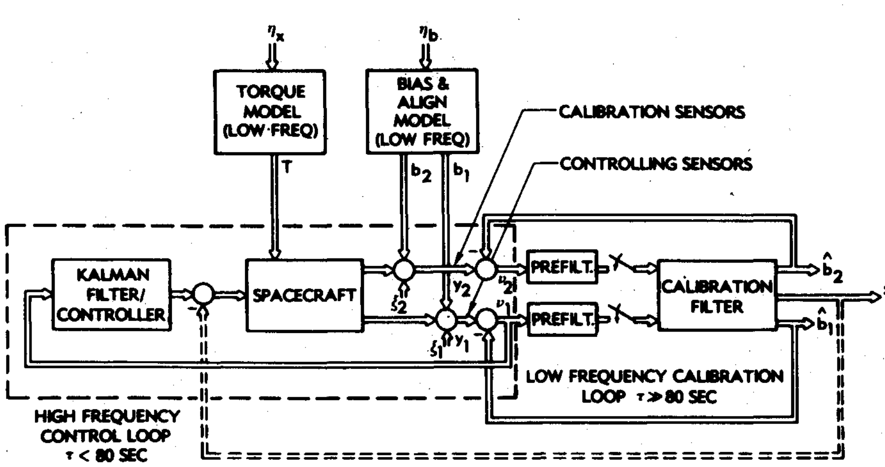



Fig. 1 Sensing system analysis.

Table 2 Concept comparison

| Sensor complement | Concept I— yaw gyro reference No. | Axis/Face | Class | Concept II— two-axis gyro compassing No. | Axis/Face | Class | Concept III— three-axis gyro reference No. | Axis/Face | Class |
|---|---|---|---|---|---|---|---|---|---|
| Gyros | 1 of 3 | $\omega_z$ | 2 | 2 of 4 | $\omega_x,\omega_z$ | 2 | 2 of 7 | $\omega_x,\omega_y,\omega_z$ | 4 |
| Earth sensor | 1 of 2 | $\phi,\theta/+z$ | 2H | 1 of 3 | $\phi,\theta/+z$ | 3 | ... | ... | |
| Precision sun sensor | 2 of 4 | $\psi/+X$ | | 1 of 2 | $\psi/+X$ | | 2 of 4 | $\theta,\psi/\pm X$ | |
| Coarse sun sensor | 3 of 6 | $\theta,\phi,\psi$ | | 2 of 4 | $\theta,\psi$ | | 2 of 4 | $\theta,\psi$ | |
| Accuracy, deg | Pitch | Roll | Yaw | Pitch | Roll | Yaw | Pitch | Roll | Yaw |
| Sensor system only (analysis, 3-$\sigma$) | 0.037 | 0.035 | 0.071 | 0.022 | 0.016 | 0.029 | 0.008 | 0.010 | 0.010 |
| Sensor system plus normal on-orbit control (simulation, 3 × rms) | 0.041 | 0.038 | 0.092 | 0.027 | 0.016 | 0.031 | 0.013 | 0.018 | 0.015 |
| Sensor system plus station-keeping control (simulation, 3 × rms) | 0.051 | 0.048 | 0.11 | 0.040 | 0.034 | 0.067 | 0.033 | 0.035 | 0.062 |
| Weight, kg | | | | | | | | | |
| Sensors and control logic | | 33.0 | | | 38.1 | | | 47.2 | |
| Wheels (including electronics) | | 19.0 | | | 19.0 | | | 19.0 | |
| *Total* | | 52.0 | | | 57.1 | | | 66.2 | |
| Operating power, W | | | | | | | | | |
| Sensors and control logic | | 29.5 | | | 39.4 | | | 37.8 | |
| Wheels | | 19.0 | | | 19.0 | | | 19.0 | |
| *Total* | | 48.5 | | | 58.4 | | | 56.8 | |
| Survival probability (10 yr) for sensors and control logic | | 0.966 | | | 0.948 | | | 0.948 | |
| Estimated cost, \$M | | 1.2 | | | 1.4 | | | 1.7 | |
| Development risk | | Low | | | Low | | | Medium | |

frequency is below 0.05 rad/s, the HF dropoff is not significant and can be safely eliminated. This removes the Kalman filter dynamics and produces the simple control loop shown in Fig. 2c.

Similarly, the roll axis of this concept can be simplified. In this case, a compensated earth sensor signal is available and can be used by the Kalman filter to estimate $\phi$. The estimate is used to drive a classical lead-lag control law. Since the cutoff frequency for the Kalman filter is much higher than the control loop bandwidth, the filter dynamics can be eliminated. The roll axis simplification can also be applied to the pitch axis with the exception that the orbital cross-coupling term must be deleted.

In addition to the above simplifications of the HF controller, the complexity in the LF calibration loop needs to be reduced. This was accomplished by comparing the a priori and a posteriori uncertainties of the error sources being calibrated by the discrete Kalman filter. Uncertainties not reduced significantly by calibration were then deleted from the LF error model. For the present concept, only the yaw gyro drift rate and the initial gyro integral can be effectively calibrated. A general treatment for the calibration filter is contained in Ref. 2.

### *Operational Requirements*

Attitude control system requirements vary in different modes of operation after injection into synchronous orbit. The calibration filter updates must be inhibited during all stationkeeping, momentum unloading, and offset pointing maneuvers. Since these operations are short compared to the calibration time-scales, the occasionally inhibited updates will not significantly reduce calibration accuracy.

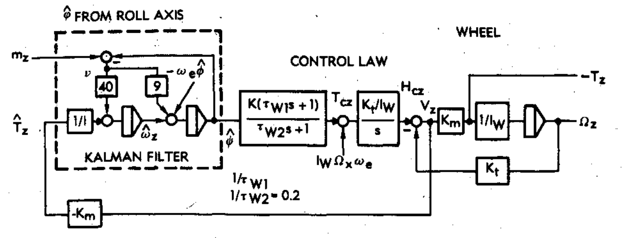
This concept uses the standard ATS 6-type acquisition sequence consisting of the steps of despin, sun acquisition, earth acquisition, and yaw correction followed by normal operation.

The normal operational mode uses the earth sensor for controlling roll and pitch, and the yaw gyro as the prime sensor for controlling yaw. Reaction wheels provide the control torque. After receiving the ephemeris data, the attitude control system (via the calibration filter) updates the yaw gyro output at half-hour intervals to maintain the orientation at specified accuracies. Yaw sun sensors are provided on the $+X$ face and $-X$ face of the spacecraft, allowing two update periods per orbit. Periodic updates of the ephemeris data are required from the ground.

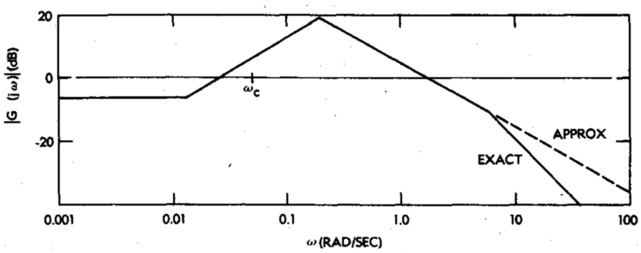
During stationkeeping, the integrating yaw gyro provides an attitude signal for the yaw axis, the earth sensor provides attitude information for roll and pitch, and the coarse sun sensor provides bandwidth augmentation. The jets are used as the control torquers with the wheels in a "hold-speed" mode. With this concept, stationkeeping is restricted to the noon and midnight orbit sectors. This corresponds to orbit node during the solstice seasons[5] but not during equinox seasons. After stationkeeping is completed, the ground commands a transition mode. This is the same as the normal operation mode with two exceptions: the gains are higher to damp stationkeeping disturbances and there are no control rolloff filters.

The operation of momentum unload is the same as stationkeeping except the stationkeeping jets are not fired. Instead, the speed setting of the wheel hold-speed circuit is reduced. As with stationkeeping, momentum unload is restricted to the noon and midnight sectors.

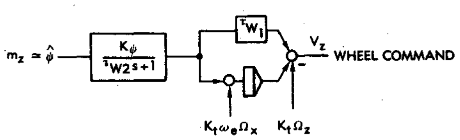
Offset pointing in roll and pitch can be accomplished by comparing the offset commands with the earth sensor output to establish the desired pointing. Offset angles are limited to the off-null accuracy range of the earth sensor.




**a) Optimal control law**




**b) Magnitude diagram, $G_z = T_z/m_z$.**




**c) Simplified control law.**

**Fig. 2 Control law simplification—concept I, yaw axis.**

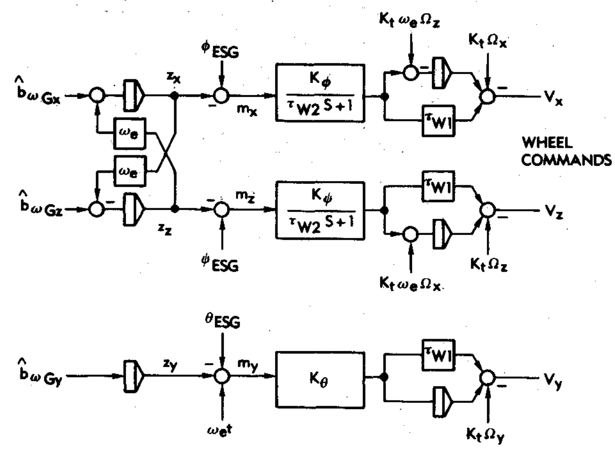



**Fig. 3 Control law simplification—concept III, pitch/roll/yaw axes.**

**Two-Axis Gyro Compassing (Concept II)**

*Concept Simplification*

This concept uses two class 2 gyros for roll and yaw, a sun sensor and a class 3 roll earth sensor for updating yaw and roll, and an earth sensor for pitch. The simplification procedure for this concept is analogous to the procedure for concept I. Roll, as well as yaw, is controlled by rate-integrating gyro outputs. (The earth sensor is used for calibrating only.)

The calibration filter for concept II was reduced by deleting the LF error sources which cannot be calibrated. Only four parameters, the initial gyro integrals and drift rates for the two gyros, are included in the calibration filter.

*Operation Requirements*

Sun acquisition is identical to that for concept I. During earth acquisition, the roll gyro can be used to measure and adjust roll rate before the earth enters the field of view of the earth sensor.

Normal operation uses the earth sensor to control pitch. Gyros provide the prime sensing function in roll and yaw; the digital sun sensor provides long-term sensing information in yaw, and the earth sensor in roll. Reaction wheels again provide the control torques. After receiving the ephemeris data from the ground, the control system updates the roll and yaw gyro outputs to maintain the specified attitude. Yaw sensors are available on the $+X$ face of the spacecraft, providing one update period per orbit. Periodic updates of the ephemeris data are required.

The stationkeeping mode is the same as that for concept I, except bandwidth augmentaiton is required only for pitch. This removes the noon/midnight orbit sector restrictions. Similarly, momentum unload does not have orbit sector restrictions.

During offset pointing, the ground commanded roll offset angle is compared to the integrated gyro output which has no off-null range limitations.

**Three-Axis Gyro Reference (Concept III)**

*Concept Simplification*

This concept uses three class 4 gyros (two 2-axis ESG's) with sun sensor update for pitch, roll, and yaw and does not need earth sensors. Sun line motion is exploited to achieve a final converged accuracy of 0.01 deg in all axes.

The simplified form of concept III is summarized in Fig. 3, which shows a reduced HF loop for pitch, roll, and yaw. Six parameters, gyro drift angles and drift rates along the three axes, are included in the calibration filter.

*Operational Requirements*

Since concept III does not have an earth sensor, the ESG's cannot be activated before a stable reference is attained; therefore, the operational sequences differ substantially from concepts I and II. The following steps are required after injection into synchronous orbit:

1) Sun Acquisition: After the apogee motor is fired and during nutation damping, the control sytem (except for the ESG's) is powered by ground commands. Despin of the vehicle is controlled by using the proper yaw jet to reduce the spin rate. In the absence of yaw rate gyro information, the rate is monitored by the spin sun sensor used in the transfer orbit. After despin, the solar panels are deployed by ground command and rotated (if necessary) to align the normal of the solar panel with the $X$-axis of the spacecraft.

The next ground command places the control system in the sun acquisition mode which uses coarse sun sensors with pseudo-rate to control the pitch and yaw axes with the reaction jet system. The roll axis is uncontrolled. Sun acquisition is completed when the $+X$ axis of the spacecraft is pointing toward the sun.

2) Wheel Spinup: In the next acquisition phase, the existing residual roll rate is damped by commanding a momentum bias in the pitch axis. Because of the pitch momentum, the existing roll rate will couple into the yaw axis and the yaw control loop can be used to remove the rate. The yaw control loop uses reaction jets to remove the major rate components and later transfers to reaction wheel control to provide a stable short-term platform for ESG spin-up.

3) ESG Spinup: When the roll rate has been reduced, the ground commands spin-up power to the two ESG's, followed by ESG damping permitting the rotor's axis of maximum inertia to become colinear with its angular momentum. Once rotor motion is damped, the ground commands the normal operation mode (without calibration). All three axes will be controlled by the ESG's using reaction wheels as torquers. The ground transmits ephemeris data to the spacecraft and maintains control on the ESG's for several days while monitoring sun sensor outputs to determine the roll angle. Proper roll, pitch, and yaw bias corrections place the

spacecraft near its nominal local vertical orientation. The ground also commands the solar panels to a sun tracking mode.

4) Normal Operation: The ground next commands the normal operational mode (with calibration) which allows the onboard system to converge to its final pointing accuracy. This mode consists of two ESG's, which provide sensing information in all axes with reaction wheels as torquers and sun sensors on the $+X$ and $-X$ faces for long-term calibration data.

5) Stationkeeping: If a stationkeeping maneuver is required, the ground commands the control system into the stationkeeping mode. All three axes are controlled by ESG attitude signals with pseudo-rate supplying the rate stabilization. The jets are used as control torquers with the wheels in a hold-speed mode. With this concept, stationkeeping at the nodes is possible at any time of the year. After stationkeeping is completed, the ground commands a transition mode in the same manner as concepts I and II.

6) Reacquisiton: If a failure cannot be attributed to the ESG's, the normal operational mode can be commanded without a transition to the sun acquisition mode after correcting the fault.

7) Momentum Unload: This is the same as for concepts I and II.

8) Offset Pointing: The ground-commanded offset angles in pitch and roll are compared with $m_y$ and $m_x$, respectively. Neither have off-null range limitations.

## Preliminary System Mechanizations

A preliminary system mechanization for each concept is presented including a functional block diagram; a redundancy diagram; and weight, power, and reliability predictions. Table 2 summarizes the weight, power, and survival probability of each sensing concept.[1,4]

Redundant components were assumed to achieve or exceed a 0.94 probability of success for a ten-year mission life. Standby units and switching elements were assumed to have zero failure rates. The sensing system functional block diagram for concept II is presented in Fig. 4, and the corresponding reliability redundancy model is presented in Fig. 5. The reliability model includes the component failure rate, the reliability prediction of the redundant units, and the overall system reliability prediction.

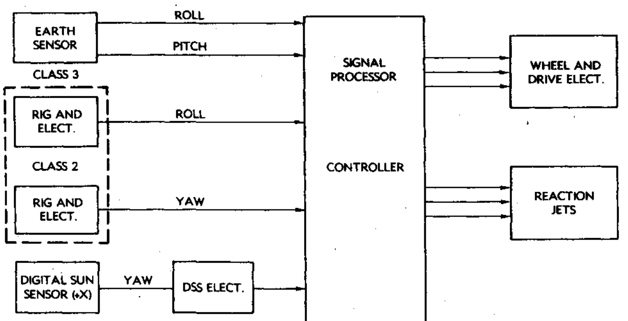



Fig. 4 Functional block diagram—concept II.

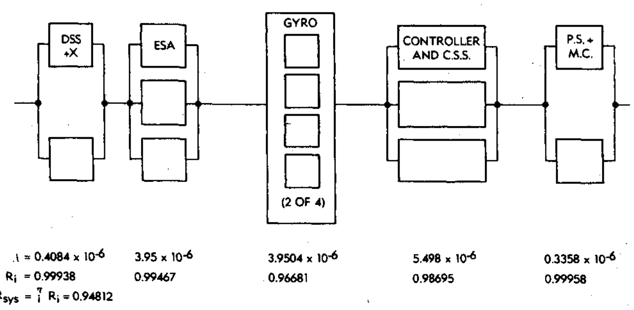



Fig. 5 Reliability block diagram—concept II.

## Concept Comparison

For comparison, the major features of the three attitude control concepts are summarized in Table 2, which lists the sensor complement of each concept and compares accuracy, weight, power, reliability, and cost/risk factors.

### Accuracy

Three different sets of performance numbers are shown in Table 2. The first set represents theoretical performance predictions for the sensing system which are 3-$\sigma$ statistics obtained by the analytical procedure previously described. The second set represents sensing system plus control errors exhibited in nonlinear simulation runs of normal on-orbit operation. The third set represents sensing system plus control error exhibited in the simulation runs of stationkeeping operation. In this case, the numbers are error values from worst-case simulation runs root-square-summed with the 3-$\sigma$ errors of normal on-orbit operation.

The theoretical predictions and simulation results agree quite well; the performance levels are consistent with the defined concept categories; and the control errors during stationkeeping dominate the error budget for concepts using the more accurate sensing systems.

### Weight, Power, Reliability, Cost, and Risk

As expected, weight, costs, and development risks of the three concepts increase directly with performance. Power deviates slightly from this trend because concept III does not require an earth sensor. Reliability numbers were forced to be consistent with the 0.94 survival probability through the use of redundancy. Concept I has the highest survival probability primarily because three redundant yaw gyros are needed to exceed 0.94.

### Operational Features

As described in the previous section, there are different procedures for the acquisition/reacquisition sequence, and different restrictions on stationkeeping, momentum unload and offset pointing operations, and special handling or operating requirements. No unusual requirements are foreseen for concepts I and II using conventional gas-bearing gyros. Concept III, on the other hand, will require special handling during integration and testing when the ESG's are in the spinning mode. This concept also requires considerably more ground participation and convergene time (15-30 days) to reach its final on-orbit pointing accuracy. However, pointing errors are within specifications after three or four days of calibration.

## Conclusions

Three promising attitude sensing concepts for gyro-based attitude control systems have been presented. These concepts combine high-quality gyros with earth sensors, sun sensors, and decentralized Kalman filter algorithms to achieve different levels of performance consistent with the defined concept categories.

The yaw gyro reference concept, whose performance just meets specifications, uses a class 2 gyro, a currently available earth sensor, and two yaw sun sensors. The two-gyro concept which corresponds to the two-axis orbital gyrocompassing, uses the same class of gyros, a sun sensor, and an earth sensor with fewer LF errors to improve accuracy. The performance of the three-gyro systems with sun sensors excels in all axes. Two ESG's (under development) and sun sensors on the $\pm X$

faces achieve 0.01 deg (3-$\sigma$) in all axes. With gyros of this quality, adding an earth sensor scarcely improves performance. This concept requires considerable ground participation and time to establish the desired orientation for normal operation. Since the control errors dominate the error budget for concept III, better control laws are necessary to effectively utilize three-gyro performance.

## Acknowledgment

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