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RESEARCH IN ELECTRICALLY SUPPORTED VACUUM GYROSCOPE

VOLUME I - SUMMARY

November 1968

Prepared Under Contract NAS-12-542

HONEYWELL INC.
Systems & Research Division
Minneapolis, Minnesota
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA CR

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FOREWORD

This final report, consisting of five volumes, documents Research in Electrically Supported Vacuum Gyroscope (ESVG) performed under National Aeronautics and Space Administration Contract NAS 12-542 for NASA-ERC.

This investigation thoroughly reviewed and analyzed the performance characteristics, potential, and limitations of ESVG instruments for a general class of missions associated with NASA-ERC objectives. The scope of the investigation was generally limited to consideration of space missions and launch-vehicle guidance missions. The investigation was concerned with the following fundamental aspects of ESVG instruments:

1) Drift of the strapped-down ESVG
2) Suspension capability and suspension power consumption
3) Improvement of readout accuracy of the strapped-down ESVG

An extensive and intensive analysis of strapped-down ESVG drift showed that a number of terms in the math model describing drift are generally required for precise description and calibration of the instrument. The value of sum-of-squares types of suspension was evaluated. Generally, there is an improvement potential possible, but this is not an overriding consideration. The specific mission requirements must be analyzed to determine whether a sum-of-squares constraint is necessary or desirable.

The results of the suspension investigation showed that, in fundamental terms, improvement in power consumption is possible. However, the power consumption levels for applications other than low-g space applications will considerably exceed the 0.1 W requirement and will require a dual-mode circuit to accommodate both free-fall and booster-environment requirements.

The readout improvement investigation was limited to investigations of improvement of the current method of rotor-oriented pattern readout. It was concluded that substantial improvement could be effected in readout accuracy. Future development in the area of pattern application and improvement of line edge definition is required, in addition to optimization of the pattern and readout trigger circuits.

Honeywell Inc., Systems and Research Division, performed this research program under the technical direction of R. K. Phelps. Principal contributors to this effort were G. A. Matchett, principal investigator, and K. W. Exworthy and J. C. Wacker, associate investigators. Guidance and advice on the practical implementation of ESVG instruments was also contributed by D. F. Elwell, ESG Section Head of the Honeywell Inc., Aerospace Division.

Gratitude is extended to NASA-ERC for their technical guidance, under the program technical direction of Lawrence Sher of the NASA-ERC Guidance Laboratory.

CONTENTS

SECTION I

INTRODUCTION

The results of the research program, conducted under Contract NAS 12-542 for NASA-ERC, are documented in this final report. To present the material in the most logical and the most accessible manner, this final report is organized into five separate volumes.

VOLUME I - SUMMARY

Volume I presents an overview of the documentation and presents in summary form the results, intent, and recommendations of the research program.

VOLUME II - ELECTRIC TORQUE ON AN ESVG

A principal aim of the project was to develop in depth and detail the electric torque mechanism and the formulae which relate drift and the parameters associated with ESVG manufacture. This has been accomplished, and these results, together with the analysis methods employed, are the substance of the material presented in Volume II.

VOLUME III - ESVG SUSPENSION RESEARCH

The suspension mechanization of an ESVG was investigated from a number of standpoints. The main considerations were:

- Power Consumption (in particular, power consumption in a space environment)
- Suspension in a high-acceleration environment
- Dual-mode suspension systems (i.e., high-acceleration and low-acceleration mechanizations together with switching circuitry between the two modes)
- Interaction between parameters important to drift (e.g., rotor-electrode gap, sum-of-squares suspension) and suspension realizability

This program considered the suspension implementation in fundamental terms, rather than the innovation of specific circuits, to give results which have general applicability. The design of a specific suspension system is highly dependent on the particular application constraints (acceleration, power, drift, size, etc.). The material presented in Volume III is applicable to the estimation of various parameters which can be realized for a specific set of requirements.

VOLUME IV - ESVG READOUT - ACCURACY IMPROVEMENT RESEARCH

The error sources and means for improvement were investigated. The results of this investigation are contained in Volume IV. The effort was directed at the conventional and current readout approach of patterned rotors, with optical line-crossing detection considered the most promising approach for near-future application.

VOLUME V - NUMERICAL RESULTS (CONFIDENTIAL)

The numerical results of drift and readcut accuracy are presented in Volume V. Military Security requires that these results be classified; therefore, the results are published in a separate volume to free the relatively large amount of analysis and formulae from the constraints of security classification.

The numerical results illustrate the drift and readout magnitudes that can be obtained in realizable instruments. The results are presented in a way to permit scaling to specific numerical values of manufacturing imperfections.

SECTION II

STATEMENT OF WORK

The work reported in Volumes II, III, and IV correspond (together with the numerical results of Volume V) to the three main work statement items. The work statement is reproduced below (from NASA-ERC Contract NAS 12-542).

A. Objective

Research for the design and prototype development of an all attitude, electrically supported vacuum gyroscope for application in strapdown guidance systems for launch vehicle and deep space mission requirements.

The goals of this research program are to provide studies and analyses directed towards an instrument that can be operational through the boost phase of a mission, and perform the guidance function for a launch vehicle with an uncompensated drift rate of less than 10^{-3} deg/hr, consume less than 0.1 watts during free fall, requires no temperature control after start-up, and operate for three (3) years without performance degradation and five (5) years without failure.

The general areas of investigation to be pursued are minimization of drift torques, mechanization of the suspension, improvement of readout accuracy, and improvement of reliability.

The overall objective of Item 1 is to produce a definitive analysis which delineates in a cohesive and reasonably complete manner the magnitude of drift torques which can (and will) act on an ESVG as function of the constructional imperfections of the instrument. In addition the magnitudes of such torques will be estimated based upon state-of-art and projected-state-of-art of manufacture, environment, and mechanization of suspension and computer torque compensation schemes.

B. The contractor shall supply the necessary personnel, facilities, services, and material to accomplish the work set forth below:

Item 1 - a. The analytical model will be formulated in detail including the effects of:

(i) Rotor non-sphericity expressible by circular harmonics;

(ii) Electrode errors associated with mismatch of the hemispheric halves and with electrode non-sphericity; and

(iii) Rotor miscentering and the effects of dynamically varying rotor-electrode gap and voltages caused by a vibration environment.

The analytical model will include past work as well as the extensions of past work required for this study so that a cohesive model under one cover results.

The presently known results associated with magnetic fields, gas pressure gradient and run-down due to radial unbalance and gas pressure will be included for completeness.

b. The torque integrals will be calculated on a per unit basis of a given imperfection to permit classification of the torques as to type and magnitude. In many instances superposition will not hold, e.g. the effect of a rotor distorted by more than one harmonic will not necessarily be the sum of these taken individually. The analysis will consider this in sufficient detail for the accuracies of interest. A computer program will be written to facilitate the calculation of the torque integrals and will be for general purpose use in ESVG torque analysis.

c. The torque integrals will be summed for the various constraint conditions for the suspension voltages (or currents), constant preload, adaptive preload, sum of squares, and adaptive sum-of-squares ("energy control") to evaluate the relative effectiveness of these methods.

d. Electrode configurations will be evaluated. The well known hexahedral configuration is the most promising for a general purpose instrument; however, circular electrodes and non-orthogonal configurations will also be investigated as well as alternate hemispheric splits to evaluate the relative effectiveness of these methods.

e. The torques will be evaluated numerically, based on realizable state-of-the-art and projected state-of-the-art so that probable instrument performance can be projected.

f. Optimum configurations for the ESVG for the space applications envisioned will be recommended as well as delineation of developmental requirements and priorities. The recommendations will include such factors as the use of computer compensation of drift in the launch phase, optimum voltage constraints, electrode configurations, and suspension parameters necessary for minimization of vibration induced drift.

g. Recommend experimental tests to clarify the error model.

Item 2 - a. The ESVG suspension in several forms will be studied with respect to extending its dynamic acceleration ranges, in terms of the following:

1. Suspension Capability

   (a) Maintenance of suspension in a linear, vibration, and/or shock environment.

   (b) Minimization of rotor translation in a dynamic environment to minimize vibration-induced drift and readout errors.

2. Low Power Consumption

   (a) During acceleration or vibration.
   (b) During extended free fall missions.

3. Voltage Constraints

   In addition to supplying the voltages necessary for suspension, the system must also control the electrode voltages in accordance with some improved constraint to minimize drift.

   Suspension sets with a dynamic "G" range of the order of 12:1 have been built; the problems inherent in extending this range to 1000:1 will be considered. The study report will also include recommendations on techniques for switching or shifting the range of "G" capability if the total range from boost to free fall in space cannot be encompassed within the system constraints as specified.

b. (1) The section of the study devoted to suspension power consideration will include two principal areas - output stage power and bias circuit power losses.

(2) Different forms of output circuits will be studied and cataloged in terms of their relative power efficiency versus force requirements. The goal of reaching minimum bias power loss in the suspension set may be reached by the proposed study concept of scheduling the power supply voltage level.

c. The results of the analytical study above will be utilized to build a breadboard suspension output circuit and to test it on a dummy load which simulates the ESVG mechanical assembly. The output circuit judged to have optimum power efficiency should be evaluated to determine that all its parameters are compatible with the total ESVG function and performance.

Item 3 - Specific areas which have been selected for study as being of fundamental importance to defining realizability and readout limitations are:

a. Determination of the number and placement of pickoffs for maximum accuracy under static, vibration and angular rate/acceleration environments and the complexity-accuracy tradeoffs involved.

b. Study and delineation of the major error sources in pattern-readout systems and estimation of probability and realizable magnitudes.

c. Study of the processing of readout signals for maximum accuracy. This will include study of the system for closed-loop linear readout averaging.

SECTION III

PROGRAM DESCRIPTIONS

DRIFT
ELECTRIC TORQUE ANALYSIS

The drift producing torques which act on an ESVG can be categorized as follows:

- Electric Torques; i.e., those torques produced by the electric suspension field acting on the (nonspherical) rotor surface.
- Acceleration Torques; i.e., the mass unbalance torque which can exist even for a perfectly spherical rotor and the gravity gradient torque which is of only academic interest because of its small size.
- Magnetic Torques; i.e., the torques produced on a conductor spinning in a magnetic field.
- Gas Drag Torques; i.e., the torques which arise if there exists a pressure gradient over the spinning rotor surface.

The latter three torques are well understood and easily formulated analytically as to the magnitudes that can exist. Further, these torques are sufficiently small (assuming calibration and compensation for mass unbalance) in properly designed gyros so that drifts produced are not important contributions to the overall error.

The study, therefore, concentrated on the electric torques which are quite significant to the overall error for the strapped-down ESVG and to a somewhat lesser extent for the gimbaled ESVG.

The electric torque mechanism has been well understood for several years, and various analyses in past programs have been conducted to estimate the drift magnitudes. However, this past work is not in any sense complete, except for the gimbaled ESVG. Because the rotor spin axes orientation is fixed (or nearly so) symmetrically with respect to the suspension electrodes for the gimbaled gyro, the analysis is much simpler than for the strapped-down gyro; therefore, a sufficiently complete description of the drift mechanism and magnitudes, together with experimental verification, has existed for some time.

An analagous situation has not existed in the past for the strapped-down ESVG, either analytically or experimentally, because of the considerable complexity of both experimental verification and of the task of reducing the electric torque phenomena to tractable formulae. Past work has been confined to considerations of only the larger effects, such as the primary torques associated with elliptical and pear-shaped (i.e., third circular harmonic) distortion of the rotor. This work has largely omitted the class of secondary torques and the remaining primary torques associated with higher rotor harmonics.

It is important to have a complete description of the drift for two reasons. The first reason is to ensure a compatibility between design objectives and realizable manufacturing tolerances. The second reason, equally important, concerns the compensation and the calibration of the ESVG. To obtain unbiased estimates of drift coefficients for the purpose of gyro compensation under general conditions of acceleration and position on the earth, a sufficiently complete math model is required in the least squares regression (or equivalent process) of laboratory calibration data.

The calculation of force and torque acting on the ESVG rotor is accomplished by evaluating the surface integrals:

$$F = \frac{\varepsilon_o}{2} \oiint_S \left| \vec{E} \right|^2 \hat{n} \, dS$$

$$T = \frac{\varepsilon_o}{2} \oiint_S \left| \vec{E} \right|^2 \vec{R} \times \hat{n} \, dS$$

where

$\hat{F}$ = electric force

$\vec{T}$ = electric torque about same center

$\hat{n}$ = outer normal to the surface S

$\vec{R}$ = radius vector from the center to S

ε_o = permitivity (8.85×10^{-12} Farad per meter, since a near vacuum exists)

S = outer surface of the rotor

$\vec{E}$ = electric intensity

The coordinates which are most convenient for computing the surface integrals are the electrode force axes coordinates $\hat{F}_x$, $\hat{F}_y$, $\hat{F}_z$. The suspension field, E, is produced between the rotor and electrode surfaces. Normally, the electrodes are arranged so that there are three orthogonal axes of suspension which correspond to the $\hat{F}_x$, $\hat{F}_y$, $\hat{F}_z$ coordinate system.

The torque integrals are evaluated piecewise over regions on the rotor surface, which are projections of the geometrical boundaries of the electrodes. Since both $\vec{E}$ and $\hat{n}$ depend on the rotor surface shape and $\vec{E}$ depends on the electrode geometry and the rotor-to-electrode gap, these factors must be specified in detail.

The following analysis is built-up in the following manner:

- The rotor shape is considered as a body of revolution described by circular harmonics:

  $$r(\theta) = r_o + \sum_{n=1}^{\infty} a_n \cos n\theta \qquad 0 < \theta < \pi$$

  where the a_n's represent the rotor nonsphericity. It is shown in Volume II that the actual rotor shape, which in general is not a figure of revolution and spins relative to the electrodes, can be described by a figure of revolution as described by circular harmonics. This average surface will produce the same results as an average of the integrals over a rotor revolution.

- The effect of rotor-to-electrode centering is introduced by a translation of the rotor center with respect to the electrode axes center in each of the three orthogonal directions.

- The effect of electrode errors is introduced by assuming two hemispheric halves for the electrode structure and by allowing a translation of one with respect to the other in two orthogonal directions in the plane of the boundary between the hemispheres. This is the most common manufacturing error and is more significant than other types of errors (viz., diametral differences between the two halves, area differences between electrodes, electrode edge effects, etc.).

Volume II discusses in depth the complex mathematical manipulation required to actually compute values of the integrals for specific parameters of rotor nonsphericity, miscentering, and electrode assembly errors. Considerable use is made of various symmetry properties to make the calculations tractable. Transformations of the integration variables are performed, which make the integration limits for one electrode look like any other electrode (Volume II, Section III).

Computer programs (described in Volume II, HEXINT, HC6INT) were written to facilitate the computations. A large number (approximately 200) of intermediate integral forms were computed, which, together with the various rules of combination deduced from the symmetry properties, permitted a complete model for the drift torque to be written. The methods employed, while somewhat intricate, enormously simplified the work as compared with a straightforward approach of direct calculation of each torque expression.

The torque expressions are written out in detail in Volume II. The expressions are complicated polynomial functions of the spin axis direction cosines, as expected for a strapped-down gyroscope.

The torque expressions are grouped and classified as follows.

Primary Torques

These are the largest torques in the strapped-down ESVG. These torques arise as a result of nonspherical rotor with perfect rotor-electrode centering and electrode structure. The results obtained are the same as previous results except that they have been extended to include rotor harmonics through the sixth.

These are tabulated in Volume II for each rotor harmonic, and have the following characteristics:

Even rotor harmonics. -- The torques are proportional to the product of a function of the spin axis-force axis direction cosines and a certain function of the electrode voltages.

The electrode voltage functions in all cases vanish identically under the constraint that the sum-of-squares of the voltages on opposite force axes electrodes is a constant. As a result, the torque also vanishes.

The direction cosine factors always contain a bilinear factor ($\alpha_o \beta_o$, $\alpha_o \gamma_o$, etc.), so that for a gimbaled gyro these torques always vanish also ($\alpha_o = 1, \beta_o = \gamma_o = 0$). The principal benefit of the gimbaled gyro is, therefore, the elimination of the largest torque sources which occur in the strapped-down gyro.

Odd rotor harmonics. -- The torques are proportional to the product of a function α_o, β_o, γ_o and a certain function of electrode voltages, which is proportional to the net suspension force. Hence, these torques are acceleration sensitive.

The direction cosine functions do not vanish if the gyro is gimbaled; however, most terms do vanish, which results in a much simplified expression. The remaining expression is merely an expression of the mass unbalance which is introduced artificially into the analysis since the rotor model was built-up from perturbations of perfect sphere using circular harmonics. It is clear that an odd harmonic expansion displaces the center of mass. Therefore, the results quoted must be corrected for this effect. With this qualification, all primary torques vanish for the gimbaled gyro.

Secondary Torques

There are three types of secondary torques which are considered. Secondary torques arise as the result of the distortion of the electrode-rotor electric field caused by electrode errors, miscentering, and the rotor shape itself. This distortion interacts with the rotor surface normal vector to produce a drift effect somewhat smaller than the primary torques which can be considered conceptually as the effect of a uniform electric field acting on the nonspherical rotor surface.

Self-interaction torques -- Self-interaction torques result from the distortion of the electric field due to the variation in rotor-electrode gap for a nonspherical rotor. The torque expressions are linear combinations of the primary torque forms as expected, but are smaller by the factor of a_n/d_o, where a_n is the rotor harmonic amplitude for the n^{th} harmonic and d_o is the nominal gap. These torques are only significant if very small values of d_o are used.

As an example, the value of the second harmonic interaction torque (T_{s22}) is given by

$$\vec{T}_{s22} = \frac{1}{4}\left(\frac{\vec{T}_{p4}}{a_4} + \frac{\vec{T}_{p2}}{a_2}\right) a_2 \left(\frac{a_2}{d_o}\right)$$

where T_{p2}, T_{p4} are the primary second and fourth harmonic torques, and a_2, a_4 are the harmonic amplitudes.

Rotor miscentering torques -- The torques arise as a result of the rotor center becoming displaced from the electrode array center. The even rotor harmonics give rise to acceleration sensitive drifts. The theory on expressions for these drifts is presented in Volume II for the second through sixth rotor harmonics.

The odd harmonics cause drifts which are proportional to the sum-of-squares of opposite electrode voltages, which may be either a constant or a constant plus an acceleration squared term. These torques do not vanish for the sum-of-squares equal to a constant constraint, as in the case of primary torques, and do not vanish for a gimbaled gyro.

This class of torques is the main source of vibration induced drift, since the rotor-electrode displacement is dependent on the gyro acceleration as well as static accuracy of the centering circuitry. Rectification will occur and produce drift torques of significant amplitude.

Electrode assembly error torques -- The electrode assembly is assumed to have an error which corresponds to a translation mismatch in two orthogonal directions in the plane of the split between two hemispheric electrode structures and in the torque expressions calculated for the second and third rotor harmonics.

The third harmonic produces an acceleration-sensitive torque, and the second harmonic produces a torque proportional to the sum-of-squares of electrode voltages. These torques also do not vanish for the gimbaled gyro and do not benefit from the sum-of-squares equal to a constant suspension constraint.

Numerical Results

Sample calculations of numerical values of electric torques are carried out in Volume V. It is found that for practical gyroscopes the torques are of significant magnitude for all rotor harmonics considered and should not be neglected in data analysis.

It is likely that if the calculations of seventh and higher harmonics were to be computed, they would also be significant. However, it becomes impractical to extend the results much further because of the considerable complexity of the torque expressions which would result and the attendant difficulty of utilizing such complicated models in the data analysis model. Another factor is the questionable merit of attaching physical significance to these higher harmonics in a practical case.

In Volume V the value of the sum-of-squares suspension constraint is discussed, particularly as applied to the primary torques where the apparent advantage is obvious. Since the constant sum-of-squares condition cannot be implemented without error, the advantage is not clear and depends very much on the particular application.

The two conditions, sum-of-squares equals a constant to one percent accuracy and sum-of-voltages equals a constant, produce equivalent results for primary torques when the gyro is operated in a 1-g field and has a 7-g maximum capability. For higher maximum-g capability, the sum-of-squares to one percent accuracy condition produces a larger error. Furthermore, the odd harmonic miscentering torques and even harmonic electrode error torques are increased by the constant sum-of-squares condition because of the larger average electric field strength.

Since the odd harmonic primary torques are independent of the suspension constraint used and are as large as the even harmonic primary torques, there are clearly no overwhelming benefits to improve constant sum-of-squares accuracy.

ESVG SUSPENSION

The suspension study was concerned primarily with two aspects:

- Low power consumption
- Dynamic range and suspension capability to provide for operation in a boost, stage separation, and zero-g environment

The motivation for low power consumption arises mainly from very long-term space missions and essentially zero-g operation. The ESVG, since it is a free gyro, can maintain highly accurate inertial reference with only the suspension circuitry operating. The readout system and the computer operations for attitude reference calculations can be shut down for long periods for many missions since the inertial reference data is not required continuously. Therefore, the steady power drain of the ESVG suspension is of considerable importance.

The acceleration requirements of an ESVG for the boost environment, and especially for the shock produced by stage separation, pose a difficult suspension problem. In this study it was assumed that the ESVG is to operate during the boost phase of the mission, either for guidance purposes or simply to maintain an inertial reference for other purposes. The approach of rotor levitation and spinup after boost is an alternative which relieves the suspension requirements. This study did not specifically consider this approach, but it has been considered in past studies.

To permit general assessments of current and projected capabilities,the suspension study program approached the problems of power consumption and suspension capability from a fundamental standpoint rather than from the approach of synthesis of various circuit possibilities. As in the case of the drift analysis portion of the study, it is quite clear that the choice of parameters and the realizable performance depends very much on the specific mission constraints.

Section II, Volume III discusses the various fundamental considerations governing the ESVG suspension for both square wave and sine wave suspensions. Both types of suspensions have been effectively implemented and each has advantages over the other.

Some of the general conclusions are:

- Square wave suspensions can provide higher static acceleration capability than sine wave systems because of the higher ratio of rms to peak value of the waveform. The ultimate capability is, of course, limited by the maximum breakdown voltage achievable, which is of the order of 1000 V per mil for reasonable rotor-to-electrode gaps (2 to 4 mils). Somewhat higher values are obtainable for very small gaps, but for reasons of drift performance these are not within the range of design parameters available.

- Square wave suspensions are more efficient from a power consumption standpoint for the larger (2 in. rotor dia) gyros and for high-acceleration operation. Sine wave suspensions tend to be more efficient for small and lightly loaded gyros.

- The implementation of an accurate sum-of-square voltage (or current) constraint is more easily achieved for sine wave systems. Several alternate schemes are outlined in Volume III, together with the advantages and disadvantages of each. Again, a specific requirement will dictate the particular form to be employed. The constraint can be mechanized as an outer loop so that circuit failures in the sum-of-square control will not effect the ability to maintain suspension, and the inner loop dynamic response is essentially unaffected. This approach is less accurate than a direct inner-loop implementation which is possible with a sine wave type of suspension. In this system, however, the circuit complexity in the inner loop is increased so that there is increased vulnerability to circuit failure.

The dynamic design considerations are discussed fully in Volume III. Basic lags for sample sine wave and square wave suspensions are tabulated together with the necessary parameters for, and the limitations of, stable suspension circuits.

In general, vibration isolation will be required to limit the rotor-electrode displacement to a design maximum of 200 μin. While a hypothetical system was considered which would not require isolation, this system required an unreasonably large suspension bandwidth (2800 Hz). Specifying a realizable 1000-Hz bandwidth leads to the requirement for second-order vibration isolation with a rolloff of 13 Hz and 12 db attenuation at 26 Hz.

The power consumption aspects of ESVG suspension systems are fully developed in Volume III. The losses in the output circuits are dominant and, therefore, received the most attention for both sine wave and square wave systems. There are two types of losses which are considered in detail:

- Exitation Losses; i.e., changing of the rotor-electrode capacitance.
- Circuit Losses; i.e., transformer and driver amplifier losses.

Transformer designs were considered in sufficient detail to permit an evaluation of these losses for a wide range of design choices.

An output circuit based on the square wave approach was designed and tested to verify the calculations. The design data and test results are reported in Volume III, Section IV.

ESVG READOUT

The ESVG Readout Improvement Study Program (Volume IV) was primarily concerned with improvement utilizing the currently implemented concept; viz., optical readout of a patterned rotor and the associated data processing.

Substantial improvement in this method over the currently demonstrated results is possible and realizable in the foreseeable future.

Alternative methods are highly speculative in terms of producing accuracy improvement over the optically viewed, patterned-rotor method.

The readout study consisted of the following:

- A careful error analysis was conducted, which delineated all of the known error sources in the optical readout system. The values for the various error parameters were based on analysis and experimental results obtained from current systems. In addition, an error budget was prepared which shows an error allocation for an improved system and the areas where improvement is necessary and possible.

- The pattern geometry was studied in detail to determine if patterns more optimum than current practice were possible. It was concluded that a modification is desirable. This modification, in substance, is to increase the number of pattern lines by a factor of two to four; i.e., to provide a multiple pattern similar to the present patterns (direction cosine, great circle, etc) so that the pattern repeats two to four times per rotor revolution. A further increase leads to larger errors; therefore, the recommendation is a minimum-error situation.

  The pattern types were also investigated (great circle, direction cosine, colatitude), and it was concluded that the direction cosine pattern is the most accurate over the full range, assuming equal line edge uncertainties. The great circle is the least accurate under this assumption, but the planar nature of this pattern simplifies the application problem and results in smaller potential line edge error from the application process. The preferred pattern then depends on whether the observed line edge uncertainties are caused more by the pattern application process or by imperfections in the rotor surface finish.

- The use of an optical four-pickoff array rather than the conventional orthogonal triad of pickoffs was considered. In addition, the mode of operation of the three- and four-pickoff arrays was studied (i.e., the number of pickoffs used to determine the rotor attitude). Generally, two are sufficient, but over a portion of the readout range more than two are available.

  The specific configuration yielding the least error was found to depend on the preferred pattern type. In the case of the cosine pattern (and from a computational standpoint), it was concluded that the optimum configuration is a three-pickoff array utilizing data from all three pickoffs when available. A modest increase in pattern range to increase the availability of data from three pickoffs was found to be beneficial in reducing the overall error.

- The pattern edge errors were studied in detail, and certain recommendations for development required to improve this error were made (Section V, Volume IV). This is the largest error source inthe readout, and this is also an area where substantial improvement can be obtained. Significant errors result from the surface finish characteristics of the rotor material and from arc marks. Some amount of rotor-electrode arcing has always been present in practical ESVG mechanizations, resulting mainly from the initial levitation process. Improvement in this area is clearly required, together with a recommendation that the maximum voltage gradient be limited on gyros requiring high-precision readout. In addition, it is recommended that development work be conducted in rotor plating techniques to improve the rotor surface finish and to minimize the susceptibility to arcing (beryllium is particularly susceptible to surface damage by arcing). Plating of ESVG beryllium rotors is not a new concept and has been accomplished in experimental programs. However, since beryllium plating is particularly difficult, at least for the requirements imposed by the ESVG, none of these programs has been successful enough to warrant the use of plated rotors in the past. Additional development in this area is required.

- The readout data processing techniques were investigated briefly. A conclusion is drawn, on a judgment basis, that high-speed integrated circuits will be available to accomplish the pulse logic and counting required in the straightforward, time-difference technique. A phase lock loop approach was also investigated, but requires further study and breadboard testing. The main area of improvement required is in the trigger circuits [height insensitive trigger (HIT)] to precisely generate a pulse corresponding to the leading edge (or trailing edge or center) of the pattern. Particular problems are caused by the rotor surface background noise as well as the high-speed circuits themselves.

Generally, the results from the readout study state that a significant accuracy improvement is realizable if some additional development work is performed. The estimates of realizable accuracy are given in Volume V, as well as the relationship between this value and the design goal of one arcsec. The strapped-down ESVG readout performance figures and estimates are classified data.