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FINAL REPORT ON DEFINITION OF FIELD TESTS FOR SD-53 STRAPDOWN SYSTEM AND CORRECTION OF LABORATORY TEST PROGRAMS (U)

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1. INTRODUCTION

The purpose of this report is to document and summarize the results obtained under Contract Number NAS8-25971. The effort was an extension of work performed under Contract Number NAS8-21366 [5]*, and has resulted in (1) an initial specification of field tests on the SD-53 Strapdown Inertial Guidance System, (2) an increase in the laboratory system test capability, and (3) corrections to reports associated with the laboratory test program.

The major effort of the contract was to lay the groundwork and provide a basis for field evaluation of the SD-53 inertial system, both in a van and in an aircraft. Results of the study [8] are intended to be used in the preparation of the detailed test and data reduction procedures.

The laboratory system test capability, which was originally provided under the previous contract [1] through [6], was increased by providing an additional computer program to process data for estimating the PIGA internal misalignments and angular velocity scale factor error [7]. Also, corrections were made to one of the other programs (for estimating the SAP misalignments), thereby resolving differences in certain parameters as estimated by the Astrionics Lab. and DRC data reduction programs.

Corrections to the various reports associated with the laboratory test program were formalized in May 1969 [6]. Additional corrections have been made since that time, and a revised edition has been published [7].

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*Numbers in brackets [ ] correspond to references listed in Section 7.

These major areas of activity are discussed separately in the following four sections. This is followed by a listing of the major conclusions which were derived from this study.

2. SPECIFICATION OF FIELD TESTS

The study to generate an initial specification of the field test program was divided into the following six tasks:

- Define detailed objectives of the van and aircraft tests
- Establish a philosophy of the evaluation and an approach to fulfill the objectives
- Define an evaluation system configuration and approximate performance requirements
- Define possible tests to collect data required to fulfill the objectives
- Consider how the test data is to be reduced
- Provide an approximate estimate of the evaluation system precision

The results of a comprehensive study of each of the above tasks are presented in Ref. [8].

Included in the report are results of a preliminary survey of the literature relative to field testing of inertial systems. Also several recommendations are made concerning tests and analyses (related to but not involving the van or aircraft tests directly) that can make more efficient use of the field test time and make significant contributions in fulfilling the test objectives.

Preliminary analyses of the effect of certain calibration terms indicate that real time compensation most likely will be required. This appears to be particularly true for angular accelerations (vibrations) of the vehicle about the SAP OAs. Other terms for which compensation probably will be required included SAP and PIGA bias errors, misalignments, mass unbalance and coning.

Several preliminary analyses were performed concerning the use of Kalman filtering to (1) analytically align the strapdown system (before entering the navigate mode) and (2) to estimate the state of each significant error (or group of errors) as a function of time, using only position and/or velocity fixes. When velocity fixes are not available, the velocity error can be estimated by the filter. The studies indicate the degree of precision that may be expected, and this is shown to be quite adequate when compared to errors that may be expected from a nominal, state-of-the-art inertial navigation system (as determined by a separate analysis).

In conjunction with the analytical alignment technique, the following two significant improvements over other implementations are considered:

- Provide biasing of the East component of gyro drift* (thereby significantly improving the gyro compassing heading accuracy) by use of a 90° rotation of the inertial system about the nominal vertical during the alignment process.

- Significantly improve calibration of the vertical component of gyro drift (both by increasing accuracy and reducing test time) by use of heading error change measurement.

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*In addition to the North component

Further studies of both variations to the basic analytical alignment technique are recommended.

The study also considers techniques to evaluate the various computer algorithms required to perform the strapdown calculations, including compensation for significant errors.

3. PIGA ANGULAR VELOCITY SCALE FACTOR ERROR AND INTERNAL MISALIGNMENTS PROGRAM

The computer program which is described in [4] and [6] is designed to process data obtained from laboratory tests run with the inertial system mounted on a precision Goertz Test Stand. The test procedures are as specified in [2], and the data reduction equations are derived in [3].

The program can be run in two modes. In the first, the PIGA angular velocity scale factor errors are estimated (by least squares) for rates equal to 12, 10, 8, 6, 4 and 2°/sec, where 12°/sec occurs for a 1g input. To determine if there is a significant scale factor error, a regression line is determined by least squares and then tested statistically for linearity using both the F and Student's t tests. In the second mode, the PIGA internal misalignments* are determined in addition to the option of estimating angular velocity scale factor errors.

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*That is, the two components of the pendulous gyro IA misalignments relative to the PIGA rotation axis.

4. RESOLUTION OF DIFFERENCES IN LABORATORY DATA REDUCTION PROGRAMS

Several of the DRC programs delivered under the previous contract yielded estimates of certain parameters that were significantly different from those obtained using the Astrionics Laboratory programs. Specifically, the PIGA misalignment estimates for PIGAs 2 and 3 were different, as well as the bias and acceleration scale factor estimates for PIGA 2. In the case of the SAP misalignments, all estimates were quite different. One of the tasks in the present contract was to resolve these differences.

In the case of the bias and acceleration scale factor estimates for PIGA No. 2, the discrepancies were resolved by making several sign changes in the DRC computer program. The sign errors had been discovered following delivery of the program under the previous contract and after the Corrections Report [6] was issued on May 7, 1969. Although the corrections were forwarded to NASA, they were inadvertently not made on the computer cards used to process the test data. The computer cards have now been corrected.

The apparent discrepancies in all of the PIGA external misalignment terms merely reflected the different coordinate frames in which the IA misalignment components were expressed as defined on page 7 of [3] and corrected in [7]. Transformation from one frame into the other provides excellent agreement in all cases (within 1 $\widehat{\text{sec}}$), although all signs are now opposite (including the bias and acceleration scale factor error estimates) for all PIGAs. Since both the DRC and NASA Astrionics Lab. math models and derivations have been reviewed by DRC and found to be in complete agreement, the discrepancy in signs is believed to be due to different sign conventions used to express the PIGA pulse count output. To help NASA in the review of the sign conventions used in their program, we have prepared Appendix A which lists the SAP and PIGA sign conventions used by DRC. These conventions are believed to be compatible with those defined by the Astrionics Lab. [9]. The PIGA Misalignment, Bias and Accelerometer Scale Factor Program has been modified to print out the external misalignments in both DRC and NASA coordinates. The changes are documented in [7].

In the case of the SAP misalignment estimates, a sign reversal problem was found in the conversion between the NASA and DRC definitions of the SAP yoke angles (viz., $\beta_i' = \beta_i + (\phi_\beta)_i$ instead of $\beta_i' = \beta_i - (\phi_\beta)_i$, where β is the yoke angle and the prime indicates NASA coordinates).* Corrections for the sign reversal (as well as transformation into NASA coordinates) produced results that agreed completely with the NASA derived values for SAP No. 2.

In the case of SAPs No. 1 and 3, excellent agreement was reached only after compensation for very large SAP gyro bias errors was made. Since the NASA program provides estimates of the gyro biases, these values were used to correct the input data to the DRC data processing program. The DRC program assumes the gyro bias error effects are negligible (i.e., a 1°/hr bias error produces only 1 $\widehat{\text{sec}}$ error in

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*The relationships are further defined on page 7 of [3], and all corrections are documented in [7].

estimating the misalignments).* To accommodate abnormally large bias errors (which can be detected using the DRC SAP x-calibration program), the SAP misalignment program has been modified to accept gyro bias error as an input [7]. Normally, this should not be required and the value can be inputted as zero. The DRC program also now prints out the misalignment estimates in both DRC and NASA coordinates.

Although the sign reversal problem in the SAP misalignment tests could have been solved by respecifying the initial test conditions (viz., SAP head angles) as contained in [2], it was decided to redefine the data reduction equations in order to utilize all test data taken to date. In doing this, the equations were slightly altered to provide independent estimates of the cross-coupling effects due to SAP yoke zeroing errors. The detailed equations are documented in the corrections report [7].

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*In the case of SAP No. 2, the NASA estimated bias error was -.66°/hr, yet the NASA and DRC misalignment estimates agreed within .2 to 1.7 sec.

5. CORRECTIONS TO LABORATORY TEST REPORTS

On May 7, 1969, a report [6] was published which contained corrections, additions and clarifications to reports associated with the laboratory test program. Since that time, additional corrections have been made, including changes resulting from the work reported in Sections 3 and 4 above.

A revised edition of the original corrections report has been published [7] in order to summarize in one document all changes to all documents pertaining to the laboratory test program. The original corrections report contained no changes to the computer program documentation report [4] and so the revised edition is the first formal tabulation of the changes required.

6. CONCLUSIONS

The following conclusions are drawn from the project:

6.1 INITIAL SPECIFICATION OF VAN AND AIRCRAFT TESTS

(1) Sufficient measurements can be made on the SD-53 Inertial System to adequately evaluate it in the field.

(2) Compensation most likely will be required for some of the calibration terms.

(3) Preliminary analyses and survey of the literature indicate that Kalman filtering can be used effectively (1) in the pre-navigate analytical alignment of the strapdown system, and (2) to estimate the state of each significant error as a function of time.

(4) Preliminary analyses indicate significant improvement in pre-navigate calibration and alignment is possible by rotating the inertial system 90° during alignment and by using heading error change measurements.

(5) Recordings of the inertial sensor outputs can be used effectively post-test time for a variety of off-line studies.

6.2 LABORATORY TEST DATA REDUCTION

(1) A full capability to calibrate the assembled SD-53 Inertial Sensing Unit on a laboratory test stand is provided by the PIGA Angular Velocity Scale Factor Error and Internal Misalignments Program, in conjunction with the four programs delivered under the previous contract.

(2) All discrepancies between results from the DRC and Astrionics Laboratory programs have been resolved and corrected, except the signs of all terms in one of the programs are opposite, as discussed in Section 4.

(3) Both the DRC and Astrionics Lab. math models and derivations have been reviewed and are in complete agreement.

7. REFERENCES

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2. Fincke, W. H., "SD-53 Strapdown Inertial Guidance System Laboratory Test Procedures", DRC Report E-1478U, Dynamics Research Corporation, Stoneham, Massachusetts, July 3, 1968.

3. Fincke, W. H., "Data Reduction Equations and Error Analysis for SD-53 Strapdown System Laboratory Tests", DRC Report E-1540U, Dynamics Research Corporation, September 27, 1968.

4. Jakimczyk, S., "Computer Program Documentation for SD-53 Strapdown System Laboratory Tests", DRC Report E-1556U, Dynamics Research Corporation, September 27, 1968.

5. Fincke, W. H., "Final Report on Development of Laboratory Test Data Reduction for SD-53 Strapdown System", DRC Report R-95U, Dynamics Research Corporation, September 30, 1968.

6. Fincke, W. H., "Corrections, Additions and Clarifications to Reports on Reduction of SD-53 Strapdown System Laboratory Test Data", DRC Report E-1778U, Dynamics Research Corp., Wilmington, Mass., May 7, 1969.

7. Fincke, W.H., "Revision A to Corrections, Additions and Clarifications to Reports on Reduction of SD-53 Strapdown System Laboratory Test Data", DRC Report E-2267U, Dynamics Research Corp., Wilmington, Mass. Nov. 5, 1970.

8. Fincke, W. H. and Benson, D. O. "Initial Specifications for Van Aircraft Testing of the SD-53 Strapdown System", DRC Report E-2266U, Dynamics Research Corp., Wilmington, Mass. Nov. 5, 1970.

9. Taylor, R.C., "SD-53 Inertial Sensor Polarity Definitions", NASA Astrionics Laboratory Report R-ASTR-G-WP-12-68; Mr. Taylor/876-3346, May 17, 1968.

APPENDIX A

COORDINATE AND SIGN CONVENTIONS

The following NASA coordinate and sign conventions expressed in nomenclature used in the DRC reports [1] through [7], are in accordance with those defined by the NASA Astrionics Laboratory [9]:

- IAs of SAPs and PIGAs point up, at equal angles to the vertical (nominally).
- A plus rate about the +IA of a SAP or PIGA (according to the right-hand rule) causes a minus indicated rate ($\dot{\beta}'$ = minus) for the SAP and a minus indicated acceleration (β' = minus) for the PIGA.
- When $\beta' = 0$, the +OAs of the SAPs and PIGAs are in a plane that is vertical, with a component of OA pointing up (nominally).
- The gyro coordinate frame is right-handed OA, SA, IA (x, y, z) with the +IA of the gyro nominally in the same direction as the +IA of the SAP (or PIGA).
- A plus acceleration along the +IA of a PIGA causes an increasing indicated velocity change ($\dot{\beta}'$ = plus).
- When a PIGA IA is pointing up, a plus acceleration is indicated ($\dot{\beta}'$ = plus).