DOPPLER-AIDED
STRAPDOWN INERTIAL FLIGHT TEST PROGRAM

1971

Vance H. Pearson
Richard E. Cleary
Leonard O. Hargrove

FOREWORD

This report encompasses the flight test of a strapdown inertial doppler aided system conducted from April 1971 through August 1971.

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Publication of this report does not constitute Air Force approval of the reports findings or conclusions. It is published only for the exchange and stimulation of ideas.

WILLIAM J. DELANEY
Lt Colonel, USAF
Chief, Navigation and Weapon
Delivery Division

ABSTRACT

This report is prepared as a requirement of Air Force Contract AF33615-71-C-1633, reference Contract CDRL Item A-003. The report encompasses preparation of the Honeywell H-429 (SIGN III Strapdown Inertial System; the design, checkout, and use of an interface unit for acquiring doppler radar and GEANS inertial navigation data; the modification of the analytical mechanization for the doppler aiding and Kalman filter techniques; the software preparation; and conduct of the test program, results and conclusions of the overall effort. The primary objectives to establish the output characteristics of the APN 193 Doppler Radar and to effect a data link between the H-429 system and the GEANS system were essentially accomplished. A demonstration of in-air alignment was not accomplished. However, a secondary objective to trim the velocity terms in the Kalman filter using a "zero velocity reset" technique was demonstrated.

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LIST OF ABBREVIATIONS AND SYMBOLS

H	Matrix of measurement residual sensitivity to the error state.
H^T	Transpose of H
L	Direction cosine transformation matrix - body frame to Earth referenced frame
L^*	Lower two rows of L
l_{ij}	ij^{th} element of L
n	Number of data points used for autocovariance calculation
P_{ij}	ij^{th} element of the error state covariance matrix
p	Number of data points comprising the lag in the autocovariance calculation
Q_{ij}	ij^{th} element of the matrix of noise driving the error state
q	Index in the autocovariance calculation
R^d_{ij}	ij^{th} element of the covariance matrix of doppler velocity error
R^p_x	Autocovariance of x at lag p
r_N	North position
r_E	East position
V^S_D or V_D	System velocity along a vertical axis - positive down
V^S_N or V_N	System North velocity
V^S_E or V_E	System East velocity

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

V_x^S	System velocity along x body axis
V_y^S	System velocity along y body axis
V_z^S	System velocity along z body axis
V_x^d	Doppler velocity along x body axis
V_y^d	Doppler velocity along y body axis
V_z^d	Doppler velocity along z body axis
V_u^G	GEANS velocity along a vertical axis - positive up
V_E^G	GEANS East velocity
V_N^G	GEANS North velocity
V_x^G	GEANS velocity along x body axis
V_y^G	GEANS velocity along y body axis
V_z^G	GEANS velocity along z body axis
α_y	Longitudinal doppler velocity scale factor correction.
ΔV_N	North component of velocity measurement residual
ΔV_E	East component of velocity measurement residual
θ_D	Misalignment angle about vertical axis - positive down
θ_N	Misalignment angle about North axis
θ_E	Misalignment angle about East axis

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

λ	Latitude
ρ	Earth radius
θ_x	Misalignment angle about x body axis(computer tab plots use PHI)
θz	Misalignment angle about z body axis(computer tab plots use PHI)
Ω_u	Vertical component of Earth rate
ω_x	System compensation rate about x body axis
ω_y	System compensation rate about y body axis
ω_z	System compensation rate about z body axis
DI	Doppler-Inertial
BOPS	"Basic Operating System" for the H-501 Computer
Chi Sq.	"Chi Square" distribution
C. P.	Check Point
Det	Determinant

SECTION I

INTRODUCTION

Prior to the program reported herein, a flight test was conducted under the auspices of the U.S. Air Force in 1970, wherein a Honeywell SIGN-III Strapdown Inertial Navigation System was flown with an Air Force APN 153 Doppler Radar. The objectives of that program were to develop and to demonstrate the techniques necessary to upgrade the individual navigation capability of each device when used in an "aided" configuration.

The program proved to be eminently successful in relation to the objectives. The Air Force report, AFSWC-TR-71-14, Final Report Flight Test of the SIGN-III Kalman Inertial Doppler System (SKIDS), dated April 1971, covering over 30 flights, fully documents the accomplishments of the program.

At the completion of the 1970 program, a number of factors pointed the way toward reestablishing a similar program. In summary, these were:

1. An additional test sample using a different type of doppler radar was deemed worthwhile in order to identify and evaluate radar-dependent results as distinguished from inertial system, or flight-related effects.

2. A flight test program was being formulated for another Honeywell system, the Gimbaled Electrostatic Gyro Aircraft Navigation System (GEANS), in which an Air Force APN 193 Doppler Radar was to be the auxiliary navigation device. An independent determination of the characteristics of this radar appeared highly desirable.

3. The possibility of flying both the GEANS and the SIGN-III systems simultaneously became apparent.

4. An opportunity to evaluate techniques of initializing a strapdown inertial system using a master reference system, i.e., GEANS, appeared pertinent and timely.

Consequently, a program was formulated which led to Air Force Contract AF33615-71-C-1633, having the objectives identified in the following sections of this report. The initial phases of this program occurred at Honeywell's St. Petersburg, Florida, facility, the site of the H-429 system and program personnel.

SECTION II

STATEMENT OF OBJECTIVES

The principal objectives below were defined at the outset of this program:

- Extend the doppler-aided strapdown inertial system data base from that accomplished during a similar program in 1970. Reference the final report for Contract AF29600-69-C-0021, Flight Test SIGN-III Kalman Inertial Doppler System - AFSWC-TR-71-14.

- Obtain data which will permit evaluating the output characteristics of the APN 193 Doppler Radar Set.

- Establish a data transmission link with the GEANS system to permit achieving the above objectives.

- Demonstrate a scheme for achieving in-air alignment of a strapdown inertial navigation system from an on-board master navigator (specifically, GEANS).

SECTION III

SUMMARY

Significant activities which occurred in the course of this program were:

- Refurbishment of the H-429 Strapdown System
- Design, fabrication, and checkout of the GEANS data interface unit
- Modification of the 1970 SKIDS doppler-aiding software
- Design of the in-air alignment software
- Interface testing with the GEANS system
- Field testing and installation of the H-429 in the KC-135 aircraft
- Support of the flight tests
- Maintaining hardware and software
- Data handling and coordination between field and in-plant operations
- Modification of data reduction software
- Reduction of flight data
- Analysis of processed data
- Reporting

The preparation phase of activity took place at Honeywell's St. Petersburg, Florida, facility. The first three and part of the fifth of the above activities were accomplished in the period of 12 April through 31 May 1971. The design of the in-air alignment software proceeded during the first six weeks of field test activity.

All of the foregoing functions were achieved as required. Seven flights were flown. Two of these flights produced sufficiently valuable data to warrant complete and formalized data processing and analysis. The remainder were analyzed from the quick-look data obtained during each flight. The field activity took place in the period of June 1971 through August 1971. Termination of the field program was keyed to contractual dates.

Essential accomplishments of the overall program are:

- Determination of the characteristics of the APN 193 Doppler Radar
- Completion of an in-air initialization software program
- Data transfer, in flight, between the GEANS system and the H-429 system
- Operation on seven aircraft flights
- Completion on schedule of all primary activity.

Sixteen flights were planned at the outset of the program. Twelve were to be doppler-aided inertial flights; four were to be in-air alignment tests. All of the seven flights flown were doppler-inertial. A variety of factors contributed to curtailment of the number of flights. Primarily the simultaneous coordination among two complex inertial systems and an aircraft was difficult to achieve in the three months available for the program. In addition, equipment failures, principally the H-429 computer and two gyros, occurred serially and consumed an inordinate amount of the schedule time.

SECTION IV

FIELD PROGRAM HISTORICAL DETAIL

The following describes the accomplishments, flight summary, detailed problems, and diary of the field activity on this program.

ACTIVITIES AND ACCOMPLISHMENTS

The SKIDS II Flight Test effort at Holloman AFB was terminated on 2 September 1971 and the equipment returned to St. Petersburg on 8 September 1971.

The program plan was to span 3-months with 16 flights and associated laboratory tests. The flights were to be made with two software configurations using a data link with the GEANS to obtain necessary information. The Doppler Radar/Kalman Filter program was to be used on 12 flights with the GEANS transferring doppler information to SKIDS. These tests were to obtain information on the APN 193 doppler radar. Four flights were to be used to develop a hand-off alignment program where the SKIDS would be aligned in flight using the GEANS as a reference.

The system experienced multiple hardware problems which prevented the successful completion of the program.

FLIGHT SUMMARY

Eight flights were attempted; one of these was aborted prior to takeoff. All flights were made with the Doppler Radar/Kalman Filter program.

Date	A. F. Ident	Run No.	Purpose	Results
29 June 71	SK2-001	2017	Installation Check-out	Discovered interface problems with GEANS and the altimeter and an aircraft power problem.
7 July 71	SK2-002	2021	Data Flight	Further interface problems with GEANS and the altimeter. No doppler data recorded.
8 July 71	SK2-003	2022	Data Flight	Doppler data was recorded. The Y gyro mass terms shifted causing poor pure inertial performance.
15 July 71	SK2-004	2030	Data Flight	Doppler data was recorded and the aided system operated correctly. The system malfunctioned after 4 hours of flight.
3 Aug 71	SK2-005	2043	Data Flight Holloman to MacDill	The system malfunctioned following takeoff. Suspect capacitor in accelerometer loop.
4 Aug 71	SK2-006	2044	Data Flight MacDill to Holloman	The system malfunctioned immediately before takeoff.
10 Aug 71	SK2-007	2048	Data Flight	Abort before takeoff. Unidentified computer or software problem.
1 Sept 71	SK2-008	2065	Data Flight	Y gyro shifted. GEANS interface was inoperative.

PROBLEMS

The following problems occurred during the field-test portion of the program.

1. Computer

a. The computer failed intermittently from the time the system arrived at Holloman until 1 July when the problem was isolated to the memory tray which was replaced.

b. The program/computer malfunctioned and was successfully restarted during run up for taxi tests on 9 August. The program was clobbered during run up for flight SK2-007 on 10 August and the flight was cancelled. The computer was returned to St. Petersburg and extensive troubleshooting revealed several noise sensitive flatpacks which were replaced.

2. Inertial Reference Unit

a. The "wet slug" tantalum capacitor in the Z accelerometer loop electronics shorted intermittently causing a large error in the rebalance torquing. This was the probable cause of the degraded performance in flights SK2-005 and SK2-006 to MacDill AFB and return. The capacitors in all three accelerometer loop electronics were replaced.

b. The fast reaction characteristics of the Z gyro changed and the compensation was recalculated. This was prior to the first flight.

c. The Z gyro fast reaction characteristics changed drastically on 21 August after the unit was returned to Holloman. The drift could not be compensated but came to a good value 30 minutes after turn on.

d. The Y gyro mass unbalances changed during or just prior to flight SK2-003 on 8 July causing a bad flight. The unit was successfully calibrated.

e. The Y gyro failed to start on 21 August after the unit was returned to Holloman. The gyro was started by applying a 50-volt signal with an external spin motor supply; however, a rattling noise was emitted when the motor started.

f. The Y gyro was replaced with a spare unit and static and dynamic calibrations were made. The gyro's performance determined continuously after installation and finally a 2.7 degree/hour change in drift rate was observed. A similar change was the probable cause of flight SK2-008 performance.

3. Interface

The discovery and resolution of the following interface problems were complicated due to lack of ground time on the aircraft.

a. The project altimeter was incorrectly connected due to incorrect Air Force documentation.

b. The camera pulse switch input was incorrectly connected to the system.

c. The aircraft 28 vdc power was routed through a switch which opened at power changeover.

d. A wire in the GEANS I/F unit (a SKIDS unit) was not soldered, causing an incorrect bit in the data.

e. A bit in the status word transmitted by the GEANS was incorrectly identified.

f. A software or GEANS I/F unit problem caused the first transmitted word to be loaded in two different memory locations.

4. Kleinschmidt Automatic Data Set (ADS)

Considerable time was expended in repairing and adjusting the ADS. Some portion of the unit was malfunctioning during all of the last two months at Holloman.

a. The tape reader began malfunctioning and was replaced when thorough adjustments per the ADS manual failed to fix the problem.

b. The new tape reader failed to operate correctly after installation and was completely adjusted to no avail.

c. The unit was returned to St. Petersburg for repair, but again failed after installation.

d. The tape reader required frequent adjustments and was marginal when the project finished.

e. The printer developed several problems which were successfully corrected by adjusting the unit per the ADS manual.

DETAILED FIELD CHRONOLOGY

The following is a chronological listing of the field activity from 19 July through 8 September when the system was returned to St. Petersburg.

19 July, Run 2031: (The computer programmer arrived at Holloman.) The system was run up to check out the Hand-Off Alignment program. Considerable time was expended adjusting the Kleinschmidt. Aircraft 371 is in "phase" inspection this week.

20 July, Run 2032: Developing Hand-Off Alignment program and working on Kleinschmidt.

21 July, Run 2033: Developing Hand-Off Alignment Program.

21 July, Run 2034: Static calibration. There was no significant change in the inertial component compensation values, but ADS problems prevented completion of the test.

22 July, Run 2035: Developing Hand-Off Alignment program. Completed the static calibration started in Run 2034. There was no significant change in compensation.

23 July, Run 2036: Developing Hand-Off Alignment program. Reduce data from previous runs.

26 July, Run 2037: Fast Reaction Test aborted due to ADS problems. Worked on the ADS and checked the flight program (Doppler-Inertial).

27 July, Run 2038: Check out and modify the flight program and work on the ADS.

28 July, Run 2039: Check out the Hand-Off Alignment program and work on the ADS.

29 July, Run 2040: Fast Reaction Test. Received a step acceleration input 1 hour 35 minutes after turn on. The run was restarted and no further problems occurred. The programmer returned to St. Petersburg.

30 July, Run 2041: Performance and functional checkout run before system installation in the aircraft. No problems.

2 August, Run 2042: The system was installed in aircraft 371. The system performance was good and functional tests indicated no discrepancies.

3 August, Run 2043, SK2-005: Flight to MacDill AFB to pick up the number 2 GEANS. The pure inertial system malfunctioned shortly after take-off and caused the aided system to reject all doppler data. Later investigation indicated this problem was caused by an intermittent short in one of the tantalum (wet slug) capacitors in the accelerometer loops.

4 August, Run 2044, SK2-006: Return to Holloman AFB. The flight program was modified at MacDill AFB in an attempt to obtain usable data on this flight; however, the pure inertial system malfunctioned while taxiing before take-off. The computer memory data was recorded and returned to Engineering following the flight.

5 August, Run 2045: The system was moved to the lab for troubleshooting; however, no discrepancy was found.

6 August, Run 2046: Troubleshooting system when the capacitor in the Z accelerometer loop shorted causing a high east velocity.

9 August, Run 2047: Taxi tests -- the "wet slug" tantalum capacitors were replaced in all three accelerometer loops and the system was installed in the aircraft for taxi tests.

The system was run up and a taxi test performed with good pure inertial performance. The aided system malfunctioned 40 minutes after Nav entry but was good after restart following the taxi test. The cause of the problem was not found but 28 vdc power fluctuations occurred approximately 5 minutes before the problem was noted and may have affected the memory. No other problems occurred during the test series.

9 August, Run 2047B: The system was realigned and the second taxi test was performed. Each of these tests were exact simulations of the flight run ups including engine starting and power switch over. The GEANS was operating and transmitting data during the tests.

9 August, Run 2047C: The third taxi test included a high speed run on the runway with peak speed at 96 knots. No discrepancies occurred during these tests except as noted in Run 2047.

10 August, Run 2048, SK2-007: The system was run up for flight but the computer (or software) malfunctioned 11 minutes after Nav entry. The Clear to Send (CTS) light was off continuously and there was no response to control inputs. Attempts to restart the computer were unsuccessful. The System Control Unit (SCU) was moved to the aircraft but the Basic Operating Program (BOPS) program was clobbered preventing reloading of the flight program. The system was moved to the lab for troubleshooting so GEANS could complete the flight.

ADS problems prevented loading the program in the lab.

11 August, Run 2049: The ADS was adjusted and the flight program was loaded. The system was thoroughly tested with no discrepancies found.

12 August through 20 August: The computer and IRU were hand-carried to St. Petersburg and the computer was thoroughly tested. Several flatpacks in the processor and I/O unit were found to be noise sensitive and were replaced. Two of these were in the priority interrupt circuitry and may have caused a noise sensitivity problem which occurred when the system was in the aircraft. The computer and IRU were returned to Holloman on 20 August.

21 August, Run 2050: The IRU and computer were installed in the cradle and the system was run up. The initial run indicated a high north velocity during the align modes. (The Y gyro was north and the Z gyro was east.) The computer was restarted and the east velocity built up rapidly during the align mode. A clobbered memory was suspected at this point so after some problem with the tape reader the flight program was reloaded. The next run again resulted in a high east velocity. Troubleshooting of the hardware began at this time.

22 August, Run 2051: Troubleshooting revealed the Y gyro was not starting. An external spin motor supply was located and a 50 volt signal was applied across the spin motor with no results. The voltage was applied while the unit was moved from 5A horizontal to 5A vertical and the gyro emitted a rattling noise and started. The gyro was then started at 50 volts several times before it would start at the correct 36 volt input. The home office was informed of the problem.

23 August, Run 2052: The Y gyro spin motor was reconnected to the system power supply to investigate the hardware operation. The Y gyro constant torque had shifted by -0.05 degree/hour and the Z gyro exhibited an abnormally high drift rate during warmup which came to a good value approximately 30 minutes after turn on.

24 August, Run 2053: Further investigation of the gyro loops revealed no discrepancies. A short static calibration indicated no changes in the X and Z gyro parameters and only small changes in the Y gyro.

24 August, Run 2054: A replacement gyro was received from the home office. The Y gyro was removed from the system and the new gyro was installed. A function test was made and the system was set up to measure and adjust the misalignment angles.

25 August, Run 2054: The system was run up to check the Y gyro installation and adjust misalignment angles. The gyro required a very long warmup period and the drift rate was abnormally high at turn on. The shim and case alignment was accomplished to within 500 microradians.

26 August, Run 2055: The system was run up for Y gyro calibration and the abnormal fast heat characteristics were again noted.

The gyro scale factor was determined at approximately 3 degrees/second rate. The padding resistor across the signal generator was causing problems so this was replaced, and the loop operation was thoroughly checked with no discrepancies.

27 August, Run 2057: A static calibration was performed and the compensation parameters were calculated. The fast reaction characteristic curve was investigated.

28 August, Run 2058: Investigation of the Y gyro fast heat characteristics. The drift was in excess of 25 degrees/hour at turn on and settled out to 2 degrees/hour 3 hours later. The system was turned off and cooled down for 5 hours.

28 August, Run 2059: Fast reaction test on the Y gyro. The initial drift was again high and settled out at -0.9 degree/hour at three hours.

29 August, Run 2060: The system was moved to the Holloman Gyro Laboratory and set up on a rate table. Gyro scale factor versus rate data and misalignment data was taken. This data was given to Engineering via telecon for reduction and calculation of compensation parameters.

30 August, Run 2061: The system was returned to the Aircraft Test lab and set up for functional tests. A fast reaction test gave results similar to the above but the final value of the Y gyro drift was 1.8 degrees/hour.

30 August, Run 2062: Compensation parameters were received from Engineering. The flight program and compensation were loaded and a functional test performed with no discrepancies except the Y gyro random drift was large. Experiments indicated the Y gyro could be trimmed using the zero velocity fix capability in the aided system and the Kalman filter derived compensation could be loaded to correct the Y gyro compensation.

31 August, Run 2063: Investigation of the Y gyro loop during fast heat period established the electronics were working correctly and the gyro drift was changing as indicated by the computer in previous runs.

31 August, Run 2064: Checked the procedure for trimming the Y gyro using the Kalman filter and the zero velocity fix capability. The Wy filter parameters were changed and a 0.2 degree/hour drift was successfully compensated. The system was turned off for 5 minutes and run up and a 3 degree/hour shift occurred (Y gyro). The system was cycled off and on and the drift rate was 0.8 degree/hour different from the first value.

1 September, Run 2065, SK2-008: The system was run up for flight with a 4 hour warmup and the Y gyro was trimmed using the Kalman filter; however the gyro had a substantial shift before take-off. The system did not receive doppler data from GEANS so no significant data was recorded. The system was moved to the lab for testing when the aircraft returned.

2 September, Run 2066: The system was run up for testing the DISK CAL program. The system performance was monitored on a Sanborn Recorder. The system was on for approximately 3 hours when the Y gyro drift rate changed by 2.7 degrees/hour over a 28 second period. Engineering was contacted via telecon and it was agreed that no further flight testing was feasible. The AF personnel were informed and the operation was shutdown.

3 September: The system test setup was disassembled and packing was begun.

7 September: The system was packaged for return to St. Petersburg.

8 September: The system was transported to American Airlines, Air Freight Office in El Paso by Air Force truck and was sent to St. Petersburg.

SECTION V

DEVELOPMENT

HARDWARE

Baseline

The basic hardware used for this Doppler Inertial flight test is the H-429 strapdown system, the same as used under the previous Doppler Inertial flight test, Contract Number F29600-69-C-0021. This hardware, which consists of a SIGN-III IRU and computer, cradle, control indicator, interconnect cables and support equipment, was checked out prior to the start of any modifications for this doppler inertial flight test. (See Appendix I for a description of the principal H-429 equipment.) Several calibrations and static flight runs were performed to verify proper system operation and performance.

Modification

In order to obtain the data for the Doppler/Inertial flight test, an interface unit was constructed to transfer data between the GEANS computer and the SIGN-III computer. This interface unit was also planned to be used for the "Hand-off Alignment" portion of the flight test. The data on the GEANS interface bus available to be transferred across this interface is shown in Table I.

Every data word is divided into 32 bits, of which the 16 most significant bits are data, the next 8 bits are identification bits for the data, and the least significant 8 bits are for a data request function. The least significant 8 bits are not used in the SIGN-III - GEANS data transfer. The data required for the doppler inertial flight test are words 32, 46, and 47. Word number 47 is transferred across the interface as word 58. This is done because of the timing difficulty in taking two sequential words. The design of the interface unit is constrained so that successive transfers occur no more frequently than every other GEANS data word. This simplified the design of the interface unit. The doppler radar information received from the GEANS system is identical with that which has been transmitted from the APN 193 doppler radar system. The GEANS system receives the data from the doppler radar and retransmits the same data out of the computer data output bus.

TABLE I. AN/ASN-101 SERIAL DATA BUS FORMAT

DATA FROM COMPUTER (SODL)

SODL WORD NO.	DATA (16 BITS) MSB 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17	DATA OUT FUNCTION 16 15 14 13	DATA OUT UNIT 12 11 10 9	DATA REQUEST FUNCTION 8 7 6 5	DATA REQUEST UNIT 4 3 2 1 LSB
1	SPECIAL CODE 1 1 1 1 0 0 1 1 1 1 0 1 1 0 1 0	FRAME MKR 1 1 1 1	REC. SECT. 1 0 1 0 0	—— 1 1 1 1	CDU 0 0 1 1
2	⚠1 GMT_1	GMT_1 0 0 0 0	REC. SECT. 1 0 1 0 0	$\theta 1$ 0 1 0 0	EAU 0 0 0 1
3	⚠2 GMT_2 LSB = 2^{-13} sec.	GMT_2 0 0 0 1	REC. SECT. 1 0 1 0 0	$\theta 2$ 0 1 0 1	EAU 0 0 0 1
4	⚠1 $LATITUDE_1$	LATITUDE 0 0 1 0	REC. SECT. 1 0 1 0 0	$\theta 3$ 0 1 1 0	EAU 0 0 0 1
5	⚠2 $LATITUDE_2$ LSB = $2^{-30}\pi$ rad.	LATITUDE 0 0 1 1	REC. SECT. 1 0 1 0 0	$\theta 4$ 0 1 1 1	EAU 0 0 0 1
6	⚠1 $LONGITUDE_1$	LONGITUDE 0 1 0 0	REC. SECT. 1 0 1 0 0	$+\Delta V$ 0 0 0 1	EAU 0 0 0 1
7	⚠2 $LONGITUDE_2$ LSB = $2^{-30}\pi$ rad.	LONGITUDE 0 1 0 1	REC. SECT. 1 0 1 0 0	$-\Delta V$ 0 0 1 0	EAU 0 0 0 1
8	I.N.S. ALTITUDE LSB = 2^5 meters	I.N.S. ALT. 0 1 1 0	REC. SECT. 1 0 1 0 0	RAT. & ROT. SPD 0 0 1 1	EAU 0 0 0 1
9	⚠1 VERT. $VELOCITY_1$	I.N.S. V. VEL. 0 1 1 1	REC. SECT. 1 0 1 0 0	DOP. VEL. 0 0 1 0	DPU 0 0 1 0
10	⚠2 VERT. $VELOCITY_2$ LSB = 2^{-20} m/sec.	I.N.S. V. VEL. 1 0 0 0	REC. SECT. 1 0 1 0 0	ALT. DOP. S.S. 0 0 0 1	DPU 0 0 1 0
11	⚠1 EAST $VELOCITY_1$	I.N.S. E. VEL. 1 0 0 1	REC. SECT. 1 0 1 0 0	0 0 0 0 ↓	0 0 0 0 ↓
12	⚠2 EAST $VELOCITY_2$ LSB = 2^{-20} m/sec.	I.N.S. E. VEL. 1 0 1 0	REC. SECT. 1 0 1 0 0	↓	↓
13	⚠1 NORTH $VELOCITY_1$	I.N.S. N. VEL. 1 0 1 1	REC. SECT. 1 0 1 0 0	↓	↓
14	⚠2 NORTH $VELOCITY_2$ LSB = 2^{-20} m/sec.	I.N.S. N. VEL. 1 1 0 0	REC. SECT. 1 0 1 0 0	↓	↓
15	SPARE / ROTOR SPEED LSB = 1 R.P.S. / R R #2 / R R #1	ROTOR SPEED 1 1 0 1	REC. SECT. 1 0 1 0 0	↓	↓
16	RAT ST EN / RAT LSB = 977 µs / DOPPLER SIGNAL STRENGTH LSB = 19.53 mV.	RAT. & DOP. S.S. 1 1 1 0	REC. SECT. 1 0 1 0 0	↓	↓
17	$-\Delta V_X$ LSB = .039 ft/sec / $+\Delta V_X$ LSB = .039 ft/sec	$+ \& - \Delta V_X$ 0 0 0 0	REC. SECT. 2 0 1 0 1	↓	↓
18	$-\Delta V_Y$ LSB = .039 ft/sec / $+\Delta V_Y$ LSB = .039 ft/sec	$+ \& - \Delta V_Y$ 0 0 0 1	REC. SECT. 2 0 1 0 1	↓	↓
19	$-\Delta V_Z$ LSB = .039 ft/sec / $+\Delta V_Z$ LSB = .039 ft/sec	$+ \& - \Delta V_Z$ 0 0 1 0	REC. SECT. 2 0 1 0 1	↓	↓
20	θ1 BITE / θ1 - GIMBAL 1 RESOLVER LSB = $2^{-14}\pi$ rad.	θ1 0 0 1 1	REC. SECT. 2 0 1 0 1	↓	↓

⚠1 MOST SIGNIFICANT, DOUBLE PRECISION

⚠2 LEAST SIGNIFICANT, DOUBLE PRECISION

⚠3 SODL BIT 4 WILL BE "0" IN ASN 101 MECHANIZATION UNLESS OTHERWISE ASSIGNED BY SYSTEMS.

TABLE I. AN/ASN-101 SERIAL DATA BUS FORMAT (Continued)

DATA FROM COMPUTER (SODL)

SODL WORD NO.	DATA 16 BITS (MSB 32 ... 17)	DATA OUT FUNCTION (16 15 14 13)	DATA OUT UNIT (12 11 10 9)	DATA REQUEST FUNCTION (8 7 6 5)	DATA REQUEST UNIT (4 3 2 1, LSB)
21	θ2 BLUE; θ2 GIMBAL 2 RESOLVER LSB = $2^{-14}\pi$ rad.	θ2 0 1 0 0	REC. SECT. 2 0 1 0 1	0 0 0 0	0 0 0 0
22	θ3 BLUE; θ3 GIMBAL 3 RESOLVER LSB = $2^{-14}\pi$ rad	θ3 0 1 0 1	REC. SECT. 2 0 1 0 1		
23	θ4 BLUE; θ4 GIMBAL 4 RESOLVER LSB = $2^{-14}\pi$ rad.	θ4 0 1 1 0	REC. SECT. 2 0 1 0 1		
24	DIFFERENCE VELOCITY VERTICAL LSB = 2^{-6} M/sec	XDV 0 1 1 1	REC. SECT. 2 0 1 0 1		
25	DIFFERENCE VELOCITY CROSS TRACK LSB = 2^{-6} M/sec	Y DV 1 0 0 0	REC. SECT. 2 0 1 0 1		
26	DIFFERENCE VELOCITY ALONG TRACK LSB = 2^{-6} M/sec.	Z DV 1 0 0 1	REC. SECT. 2 0 1 0 1		
27	ΔLATITUDE (from Pos. fix) LSB = $2^{-24}\pi$ rad	ΔLAT. 1 0 1 0	REC. SECT. 2 0 1 0 1		
28	NAV ¦ TO BE ASSIGN. ¦ DATA SELECT SWITCH ¦ MODE SWITCH ¦ PRS TC TST ¦ PUSH-BUTTON SWITCHES	CDU SIDL 1 0 1 1	REC. SECT. 2 0 1 0 1		
29	OD1 ¦ OD2 ¦ OD3 ¦ OD4 ¦ OD5 ¦ OD6 ¦ OD7 ¦ OD8 ¦ OD9 ¦ OD10 ¦ OD11 ¦ OD12 ¦ OD13 ¦ OD14 ¦ OD15 ¦ OD16	DCU OUT. DISC 1 1 0 0	REC. SECT. 2 0 1 0 1		
30	Θ_1 ¦ Θ_2 ¦ Θ_3 ¦ Θ_4 ¦ ROT SPD ¦ RAT ¦ SPARE ¦ SPARE ¦ IMU O.T. ¦ SPARE ¦ EAU O.T. ¦ ROT O.T. ¦ VAC ¦ DCU O.T. ¦ PRE HT ¦ INV O.T.	BITE DATA 1 1 0 1	REC. SECT. 2 0 1 0 1		
31	R1 ¦ R2 ¦ BATT ¦ G1 ¦ G2 ¦ D & D SUP. ¦ ΔY ¦ SPARE ¦ +37 ¦ +35 #1 ¦ +35 #2 ¦ 37 − 35 ¦ DC PS ¦ IN. PWR MON ¦ INN ELE ¦ SPARE	BITE DATA 1 1 1 0	REC. SECT. 2 0 1 0 1		
32	BAROMETRIC ALTITUDE LSB = 78.125 ft ¦ DOP BITE GO ¦ DOP BITE TEST ¦ DOP REL ¦ DOP OFF ¦ TX ON ¦ BITE TEST	DOP DISC. BARO. ALT 0 1 0 1	DPU 0 0 1 0		
33	PITCH LSB = 1.0×10^{-4} rad	PITCH 0 0 0 1	DPU 0 0 1 0		
34	ROLL LSB = 1.0×10^{-4} rad.	ROLL 0 0 1 0	DPU 0 0 1 0		
35	HEADING LSB = 1.0×10^{-4} rad	HEADING 0 0 1 1	DPU 0 0 1 0		
36	TRACK ERROR LSB = 1.0×10^{-4} rad	TKE 0 1 0 0	DPU 0 0 1 0		
37	+/− ¦ GIMBAL #2 LSB = 1.2 oz.in ¦ −/+ ¦ GIMBAL #1 LSB = 1.2 oz.in. ¦ SPARE ¦ G1 RED SPN ¦ G2 RED SPN ¦ G1 TRM SPN ¦ G2 TRM SPN	TQ1 & TQ2 0 0 1 0	EAU 0 0 0 1		
38	+/− ¦ GIMBAL #4 LSB = 1.2 oz.in ¦ −/+ ¦ GIMBAL #3 LSB = 1.2 oz.in ¦ SPARE	TQ3 & TQ4 0 0 0 1	EAU 0 0 0 1		
39	SAME AS WORD NO. 8	EAU SPARE 0 0 0 0	EAU 0 0 0 1		
40	DS12 ¦ DS14 ¦ DS15 ¦ DS17	LCO 0 0 0 0	CDU 0 0 1 1	↓	↓

TABLE I. AN/ASN-101 SERIAL DATA BUS FORMAT (Continued)

DATA FROM COMPUTER (SODL)

SODL WORD NO.	DATA (16 BITS) MSB 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17	DATA OUT FUNCTION 16 15 14 13	DATA OUT UNIT 12 11 10 9	DATA REQUEST FUNCTION 8 7 6 5	DATA REQUEST UNIT 4 3 2 1 LSB
41	P.P. ELEC / DS7 / DS43 / DS16 / DS9 / DS10 / DS11	LC1 0001	CDU 0011	0000	0000
42	DS3 / DS5 / DS6 / DS8	LC2 0010	CDU 0011		
43	DS23 / DS24 / DS1 / DS2	LC3 0011	CDU 0011		
44	DS18 / DS19 / DS21 / DS22	LC4 0100	CDU 0011		
45	INS ALN NCT / ESG SYN COMR / PRS TC TST / ENTR / MARK / STRG IND / MALF / DATA CHK / MSG ALRT / DEL / DPLR / INIT / MEM / TK CHG / HOLD / TGT ST. / DSPLY	LC5 010	CDU 0011		
46	SIGN / DRIFT VEL. LSB = 3.05 KNOTS / HDG. VEL. LSB = 4 KNOTS	DOP. VEL. 0000	REC. SECT. 3 0110		
47	SPARE / SIGN / VERT. VEL. LSB = 78.1 FPM	DOP. VEL. 0001	REC. SECT. 3 0110		
48	ΔLONGITUDE (from Pos. Fix) LSB = 2^{-24} π rad.	ΔLON. 0010	REC. SECT. 3 0110		
49	A_{11} (A_{IJ} MATRIX) LSB = 2^{-15}	A_{11} 0011	REC. SECT. 3 0110		
50	A_{21} " "	A_{21} 0100	REC. SECT. 3 0110		
51	A_{31} " "	A_{31} 0101	REC. SECT. 3 0110		
52	A_{12} " "	A_{12} 0110	REC. SECT. 3 0110		
53	A_{22} " "	A_{22} 0111	REC. SECT. 3 0110		
54	A_{32} " "	A_{32} 1000	REC. SECT. 3 0110		
55	A_{13} " "	A_{13} 1001	REC. SECT. 3 0110		
56	A_{23} " "	A_{23} 1010	REC. SECT. 3 0110		
57	A_{33} (A_{IJ} MATRIX) LSB = 2^{-15}	A_{33} 1011	REC. SECT. 3 0110	0000	0000
58	SAME AS WORD No. 47	DOP VEL. 1100	REC. SECT 3 0110		
59	SPARE	1101	0110		
60	SAME AS WORD No. 5	LATITUDE 1110	REC SECT 3 0110		
61	SPARE	1111	REC SECT 3 0110		
62	SAME AS WORD No 7.	LONGITUDE 0000	REC. SECT 4 0111		
63	SPARE	0001	REC SECT 4 0111		

TABLE I. AN/ASN-101 SERIAL DATA BUS FORMAT (Continued)

DATA TO COMPUTER (SIDL)

SIDL WORD NO.	DATA REQUEST FUNCTION (MSB 32 31 30 29)	DATA REQUEST UNIT (28 27 26 25)	DATA (24 BITS) 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
—	— — — —	— — — —	NO DATA
1	——— 1 1 1 1	CDU 0 0 1 1	SPARE ¦ DATA SELECT SWITCH ¦ MODE SWITCH ¦ SPARE ¦ 1FPS TO TST. ¦ PUSH-BUTTON SWITCHES ¦ SPARE
2	θ1 0 1 0 0	EAU 0 0 0 1	BITE ¦ θ1 LSB = 2^{-14} π rad. ¦ R1 ② TMP ¦ R2 ① TMP ¦ BAT ① TMP ¦ G1 SP EN ¦ G2 SP WEX ¦ DED ¦ ΔV GATE ¦ SPARE
3	θ2 0 1 0 1	EAU 0 0 0 1	BITE ¦ θ2 LSB = 2^{-14} π rad. ¦ IMU U.T. ¦ SPARE ¦ EAU O.T. ¦ ROT. O.T. ¦ XAC SEN ¦ DCU O.T. ¦ RTR FREE HT. TH. ¦ IMU O.T.
4	θ3 0 1 1 0	EAU 0 0 0 1	BITE ¦ θ3 LSB = 2^{-14} π rad. ¦ +37 ¦ +35 #1 ¦ +35 #2 ¦ 37 − 35 ¦ DCPS ¦ INP. PWR MON. ¦ IN ELE ② TMP ¦ SPARE
5	θ4 0 1 1 1	EAU 0 0 0 1	BITE ¦ θ4 LSB = 2^{-14} π rad. ¦ SPARE
6	+ΔV 0 0 0 1	EAU 0 0 0 1	$+\Delta V_z$ LSB = .039 ft/sec ¦ $+\Delta V_y$ LSB = .039 ft/sec ¦ $+\Delta V_x$ LSB = .039 ft/sec
7	−ΔV 0 0 1 0	EAU 0 0 0 1	$-\Delta V_z$ LSB = .039 ft/sec ¦ $-\Delta V_y$ LSB = .039 ft/sec ¦ $-\Delta V_x$ LSB = .039 ft/sec
8	RAT. / ROT. SPD 0 0 1 1	EAU 0 0 0 1	R.S. BITE ¦ ROTOR SPEED LSB = 1 RPS ¦ RTR #2 ¦ RTR #1 ¦ SPARE ¦ RAT. BITE ¦ RAT SIGN ¦ RAT LSB = 977 μs
9	DOP. VEL. 0 0 1 0	DPU 0 0 1 0	SIGN ¦ VERT. VEL. LSB = 76.1 FPM ¦ SIGN ¦ DRIFT VEL. LSB = 30.05 KNOTS ¦ HEADING VEL. LSB = 4 KNOTS
10	DOPP. DISC. / PAR. ALT. 0 0 0 1	DPU 0 0 1 0	BAROMETRIC ALTITUDE LSB = 76.125 ft. ¦ SPARE ¦ BITE GO ¦ BITE TEST ¦ DOP REL. ¦ DOPPLER SIG. STR. LSB = 19.53 mv.

To simplify the interface, the Computer/ADS Buffer Unit (CABU) was eliminated and the function incorporated as part of the SIGN-III - GEANS interface unit. This buffer unit conditions data from the computer to the ADS (Kleinschmidt keyboard and printer) in punch tape format to provide on-line recording of data during flight. This provides the capability for quick-look data at the end of a flight.

A schematic and assembly layout of the SIGN-III - GEANS interface unit is shown in Figure 1a, b, c and d.

The interface unit receives one megacycle serial data from the GEANS computer and stores each word in a temporary holding register. When a word is loaded, a "word loaded" command is generated. In order to select a particular word, the SIGN-III computer generates a word corresponding to the "data out" code. This is an 8-bit word of the code shown in Table I. This "data out" word is loaded in a holding register and compared to the "data out" bits in the GEANS output wors. When a comparison is present at the same time as a "word loaded" command, an interrupt is sent to the SIGN-III computer and also the data portion of the GEANS word is loaded into a transfer holding register. The SIGN-III then responds to this interrupt and takes in the data from this holding register. This process is repeated to transfer the required words between the GEANS and SIGN-III computers.

Checkout

The SIGN-III - GEANS interface unit was mounted in the system cradle and interconnected with the SIGN-III computer. A sketch of the cradle is shown in Figure 2. The interface unit was connected to the GEANS computer telemetry output interface through 200 feet of twisted pair conductor. The interface was exercised and reliable data transfer was accomplished. Some timing problems were corrected to achieve a reliable interface.

During the checkout phase, noise problems were encountered in the computer. Some design improvements in the interrupt circuitry were incorporated in the computer. The computer was checked to see if any marginal conditions existed in its operation. The Automatic Data Set (ADS) was refurbished to improve operation.

The doppler/inertial software was checked out and several static navigation runs performed to verify system operation and performance prior to delivery to Holloman Air Force Base.

A complete calibration was performed to determine all drift rates, biases, scale factors and misalignments to enter in the compensation table.

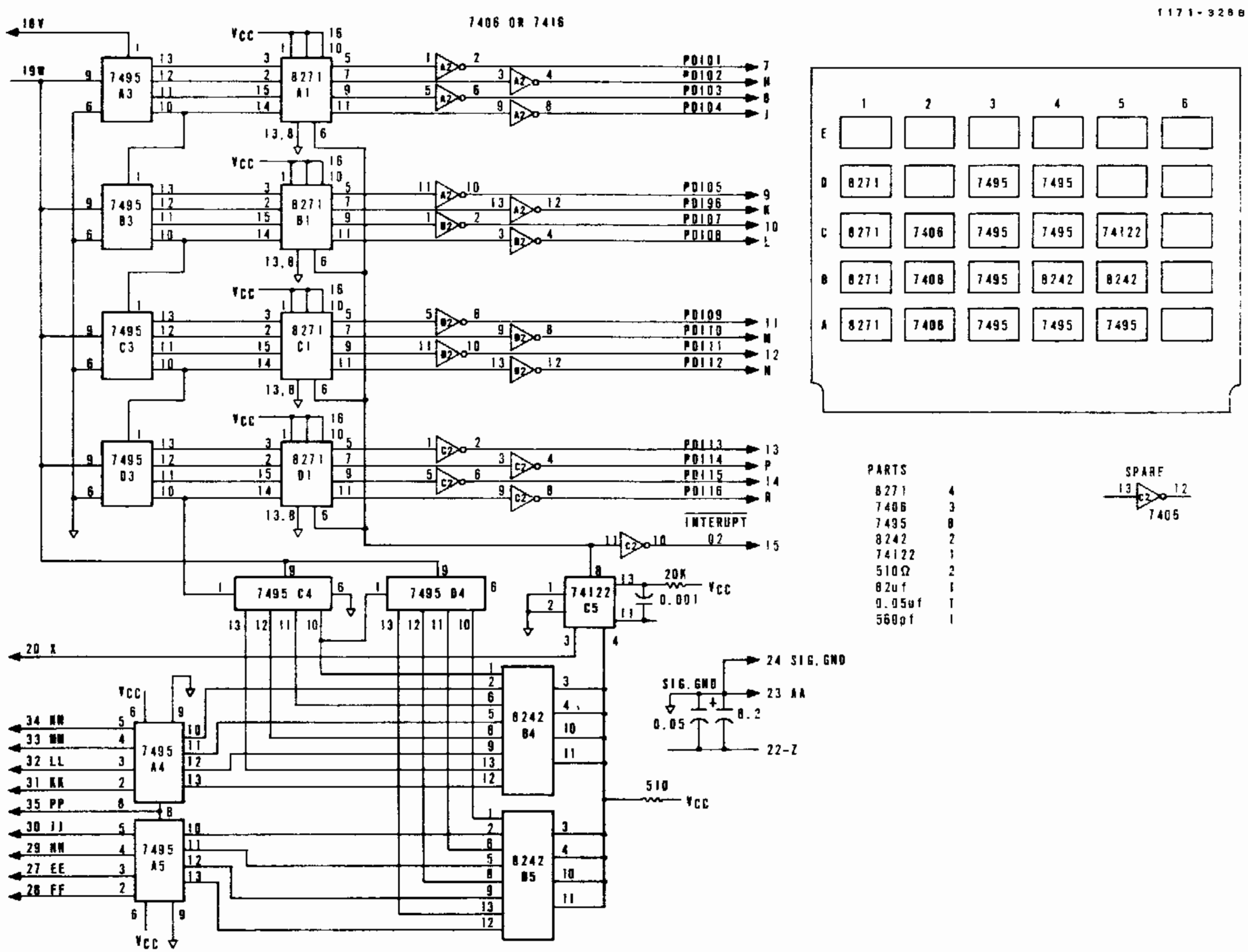


FIGURE 1a. SIGN-III - GEANS INTERFACE LAYOUT

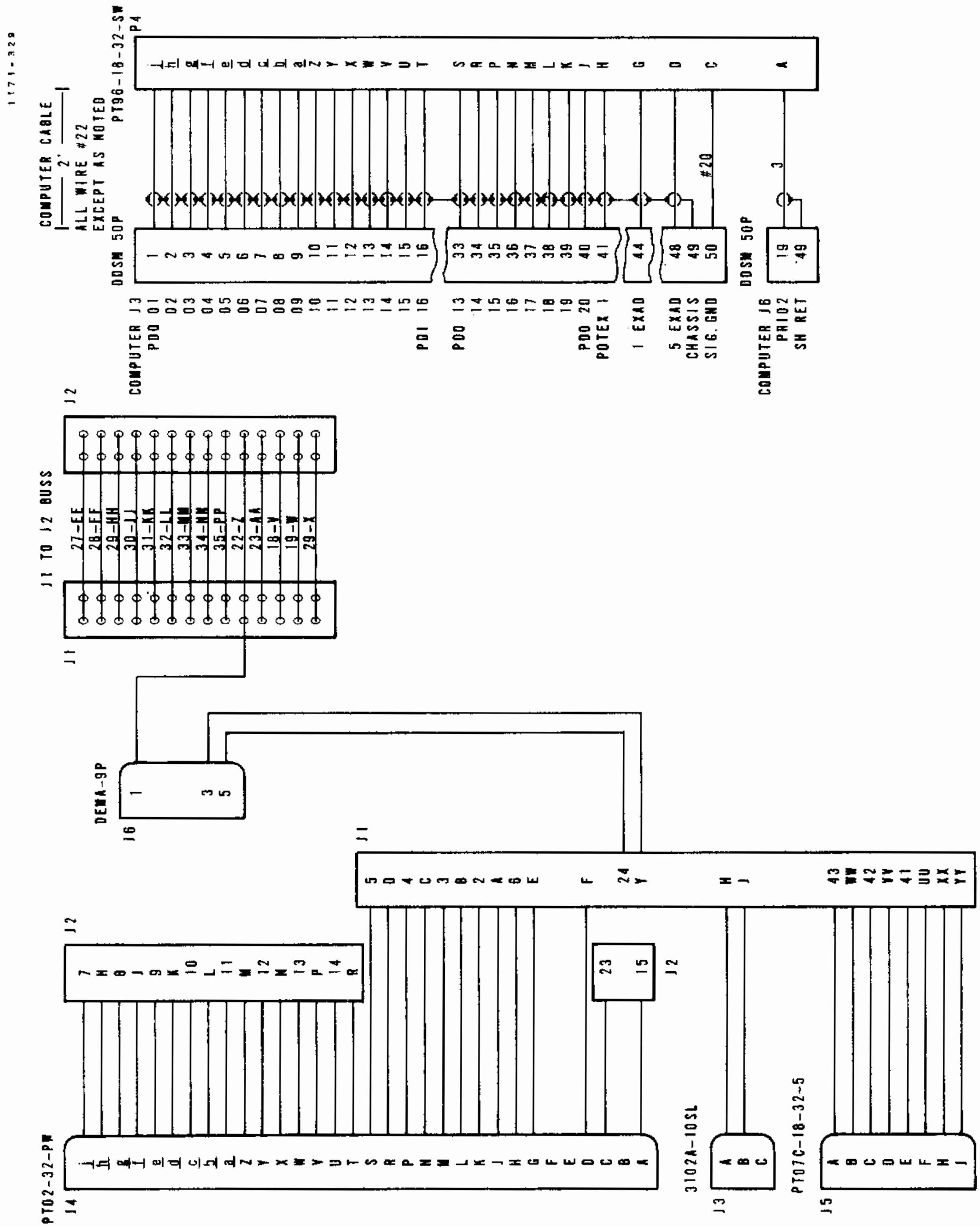


FIGURE 1b. SIGN-III - GEANS INTERFACE LAYOUT

1171-330C

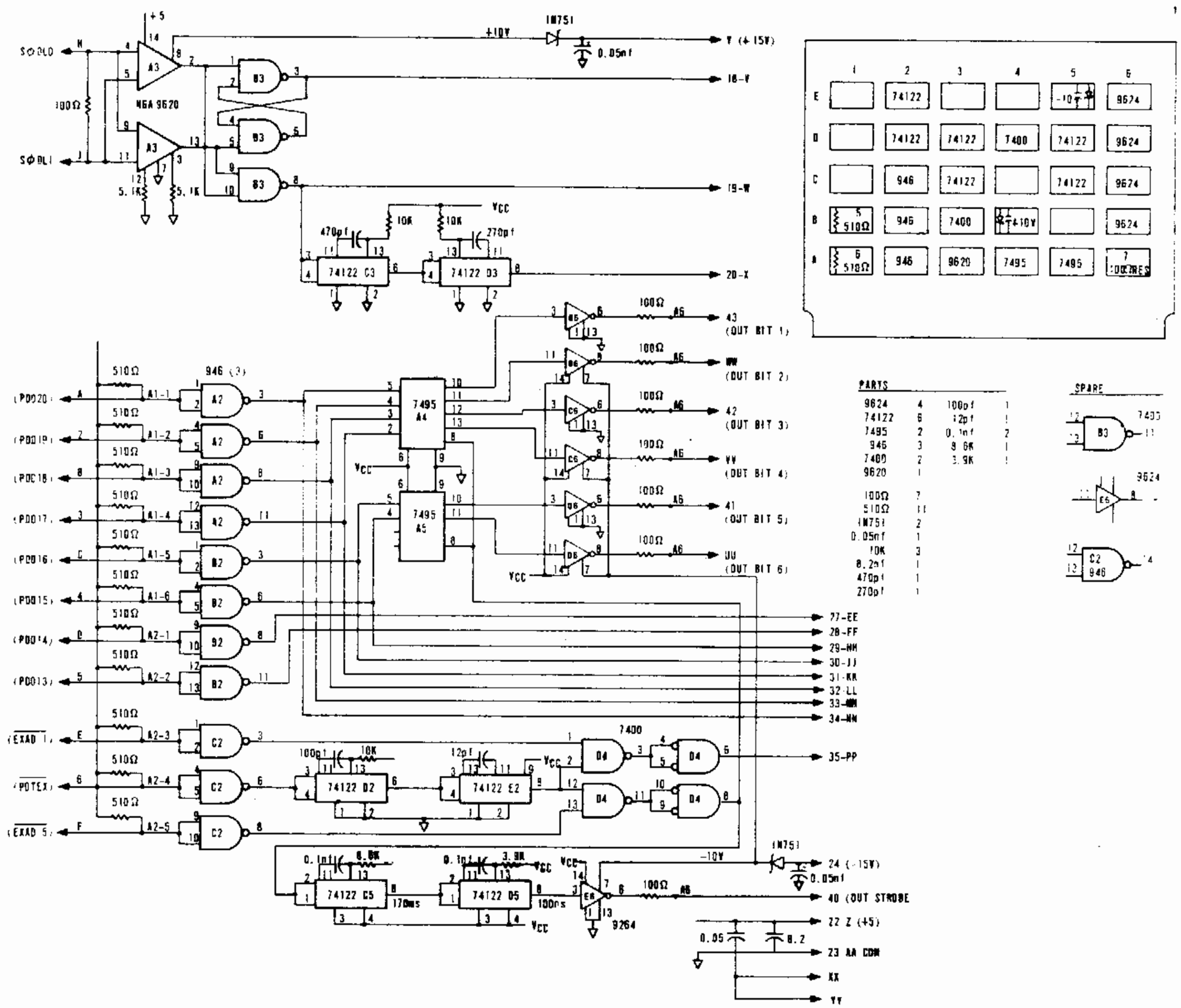


FIGURE 1c. SIGN-III - GEANS INTERFACE LAYOUT

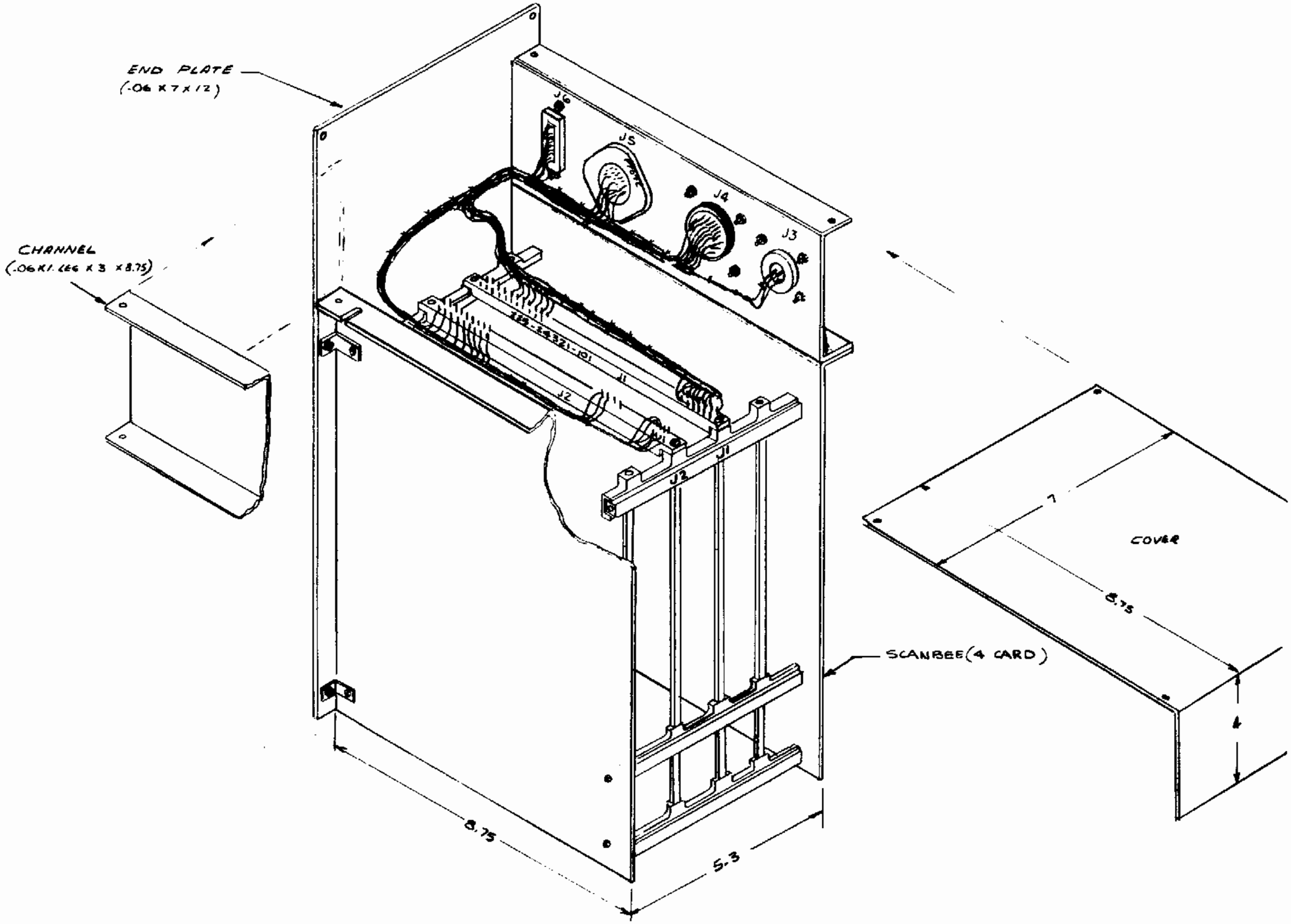


FIGURE 1d. SIGN-III - GEANS INTERFACE LAYOUT

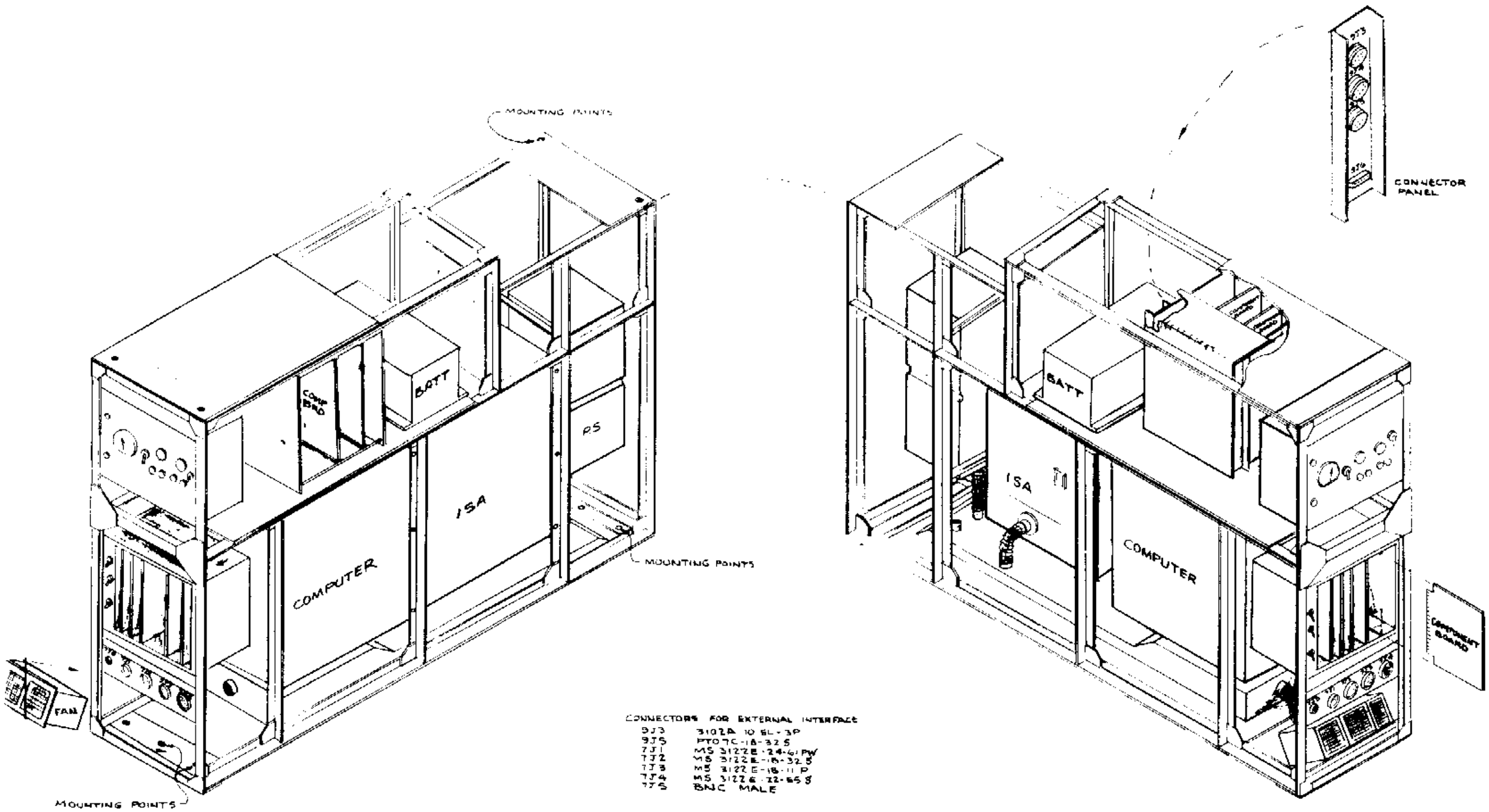


FIGURE 2. H-429 CONFIGURATION

ANALYSIS AND SOFTWARE

The most significant modification to the filter analytical mechanization between the 1970 and 1971 programs resulted from the change from the APN-153 to the APN-193 doppler system. This resulted in reformulation of the measurement processing to reflect body axis doppler velocity measurement, transformation of doppler velocity to the navigation frame (Down, North, and East) by means of the system direction cosine matrix at the measurement time, and formulation of the measurement residual in navigation coordinates according to

$$\begin{bmatrix} \Delta V_N \\ \\ \Delta V_E \end{bmatrix} = L^* \begin{bmatrix} V_x^d \\ V_y^d \\ V_z^d \end{bmatrix} - \begin{bmatrix} V_N^S \\ \\ V_E^S \end{bmatrix} \qquad (1)$$

where L* consists of the lower two rows of the system direction cosine matrix at measurement time.

The sensitivity matrix between measurement residual and the system error state was reformulated as

$$H^T = \begin{bmatrix} -\frac{V_d}{\rho} & -2\,\Omega_u \\ -\frac{V_E}{\rho}\tan\lambda + \Omega_u & -\frac{V_D}{\rho} - \frac{V_N}{\rho}\tan\lambda \\ -1 & 0 \\ 0 & -1 \\ V_E & V_N \\ 0 & V_D \\ -V_D & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -l_{22}\,V_y^d & -l_{32}\,V_y^d \\ -l_{22}\,V_z^d & -l_{32}\,V_z^d \\ l_{23}\,V_y^d & l_{33}\,V_y^d \end{bmatrix} \qquad (2)$$

As in the 1970 program, body axis doppler velocities were averaged over a 1 second period. A measurement was processed into an estimate of state error each 10 seconds and the result used to modify the state, provided a set of data valid criteria were met. These criteria were the same as those used in the earlier program except a body rate limit and a yaw velocity limit were added. The "doppler in memory signal" of the APN-153 was replaced by the "doppler off or unreliable" signal of the APN-193.

Again, as in the 1970 program, a 12-element state was used. This consisted of two position (r_N and r_E), two velocity (V_N and V_E), three attitude (θ_D, θ_N, θ_E), three drift (ω_x, ω_y, ω_z), doppler longitudinal scale factor (α_y), and doppler misalignment angle about the yaw axis (θ_x).

A second significant modification to the 1970 program resulted from the addition of a provision for "Zero Velocity Reset". This was a measurement to be used prior to take-off, anytime the aircraft was stopped and was initiated by the operator. The measurement was zero body velocity and was processed in the same manner as a doppler velocity measurement to yield an estimate of the error state.

The measurement residual for "Zero Velocity Reset" is given by Equation 1 with the measured velocity (V_x^d, V_y^d, V_z^d) set to zero. The sensitivity matrix is given by Equation 2 with the same velocity components again set to zero.

The software in existence at the end of the 1970 flight test series was used as the starting point in the development of the 1971 software. The following major changes were made to that software:

a. All software pertaining to the APN-153 radar and the land-sea option logic was removed.

b. A strong effort was made to reduce the memory requirements of the remaining software in preparation for the new program features.

c. A software/hardware interface concept with GEANS was developed and implemented to allow capture of telemetry, data from the H-601 computer. This interface was the source of both doppler and GEANS data. GEANS velocities were captured for post-flight doppler evaluation.

d. The switch from the roll stabilized APN-153 radar to the new three axis strapdown APN-193 introduced a new analytical mechanization of the filter. The major changes to the filter were:

    1. Development of new data collection techniques enabling a digital interface as opposed to the old analog method.

2. Formation of incremental summations in the body frame attitude correction as opposed to the old heading/cross course method.

3. Formation of measurement residuals in the strapdown navigation reference frame as opposed to the heading/cross course frame.

4. Reprogramming of the sensitivity matrix (H) relating the new measurement residual to the error state.

5. Compensation of doppler velocity in the body frame for scale factor, yaw misalignment, and the two remaining misalignment angles.

e. Modification of the quaternion attitude reference to include a third order term to evaluate any performance improvement over the previous second order approach.

f. Addition of zero velocity aiding, under operator option, to improve initial alignment and zero drift trim during quiescent preflight periods.

g. Development of new rejection criteria applicable to the new radar and GEANS interface. A checkpoint chi-square failure override was also implemented for improved operational capability.

Data Reduction Process

The data reduction process was premised on minimum change from that developed for the 1970 program. All references to along-course and cross-course velocity were changed to reference longitudinal velocity and misalignment about the aircraft yaw axis. GEANS velocity (north, east, and up) were recorded for use as the standard, since range velocity was not expected to be available. Over 90 percent of the data recorded was intended as system-diagnostic information. The remainder was for use in study of the doppler characteristics.

The processing of data applicable to determination of the doppler characteristics proceeded as follows:

a. The quaternion recorded at the measurement time was used to generate a direction cosine matrix.

b. This was used to transform GEANS velocity (V_U^G, V_E^G, V_N^G) to system body coordinates to yield V_x^G, V_y^G, V_z^G.

c. System velocity was compared with GEANS velocity to yield yaw and pitch axis misalignment and longitudinal scale factor correction as follows:

$$\theta_x = \frac{V_z^G - V_z^S}{V_y^S}$$

$$\theta_z = \frac{V_x^S - V_x^G}{V_y^S}$$

$$\alpha_y = \frac{V_y^S - V_x^G}{V_y^S} - \theta_x \frac{V_z^S}{V_y^S} + \theta_z \frac{V_x^S}{V_y^S} \qquad (3)$$

d. The system parameters were listed and tab plotted against time.

e. The parameters θ_x and α_y were subjected to autocovariance analysis according to Equation 4 and the results tab plotted:

$$R_x^p = \frac{1}{m-p} \sum_{g=1}^{m-p} X_g X_{g+p} \qquad (4)$$

SECTION VI

RESULTS

ANALYTICAL AND SOFTWARE

Eight doppler/inertial flights were attempted. During the course of the program, two major software changes were made after delivery of the new DI software to Holloman:

- The GEANS interface electronics occasionally delivered extra interrupts to the computer for reasons as yet unknown. The software was modified to cope with the unplanned situation.
- A timing coincidence problem in the software allowed doppler data frames to be dropped from the incremental summations whenever certain keyboard entries upset the timing synchronization.

The only other software changes made at Holloman were numerical component and filter parameter values developed from test data. Some flight data was sufficiently good enough to warrant these changes, but final proof of their validity was not obtained.

Memory requirements for this new program were again tight. Two words out of the available 4096 were left after the final assembly. This does not include BOP's 192 words which are always retained for operational ease. The memory limitation did impede the development and checkout of the program, but the final version is quite acceptable for the intended purpose.

Two sets of numerical values of the filter parameters were used during the program. These are listed in Table II. The changes were due, in part, to flight test data reduction and, in part, to laboratory testing and, in part, to simple estimation. The parameter values of 28 June 1971 were used for tests SK2-001 through SK2-006. The values of 8 August 1971 were used for SK2-007 and SK2-008. Due to malfunction of the system hardware, neither of the latter two flights produced meaningful results and, therefore, the 8 August 1971 parameter set is essentially untried.

TABLE II. FILTER PARAMETERS

Name	Symbol	28 June 1971 Value	8 August 1971 Value
r_N Variance Initial Cond.	P°_{11}	2^{18} ft^2 = (512 ft)^2	Same as 28 June
r_E " " "	P°_{22}	2^{18} ft^2 = (512 ft)^2	"
V_N " " "	P°_{33}	2^0(ft/sec)^2	"
V_E " " "	P°_{44}	2^0(ft/sec)^2	"
θ_D " " "	P°_{55}	2^{-23}(rad)$^2 \simeq$(72 arc sec)^2	"
θ_N " " "	P°_{66}	2^{-26}(rad)$^2 \simeq$(25 arc sec)^2	"
θ_E " " "	P°_{77}	2^{-26}(rad)$^2 \simeq$(25 arc sec)^2	"
ω_x " " "	P°_{88}	2^{-43}(rad/sec)$^2 \simeq$(0.07 deg/hr)^2	"
ω_y " " "	P°_{99}	2^{-43}(rad/sec)$^2 \simeq$(0.07 deg/hr)^2	2^{-45}(rad/sec)$^2 \simeq$(0.035 deg/hr)^2
ω_z " " "	P°_{uu}	2^{-43}(rad/sec)$^2 \simeq$(0.07 deg/hr)^2	"
a_y " " "	P°_{vv}	$2^{-19} \simeq$ (0.14%)^2	Same as 28 June
θ_x " " "	P°_{ww}	2^{-19}(rad)$^2 \simeq$(1.38mr)^2	2^{-17}(rad)$^2 \simeq$(2.8mr)^2
r_N Driving Noise	Q_{11}	2^7 ft^2/sec	Same as 28 June
r_E " "	Q_{22}	2^7 ft^2/sec	"
V_N " "	Q_{33}	2^{-10}(ft/sec)^2/sec	"
V_E " "	Q_{44}	2^{-10}(ft/sec)^2/sec	"
θ_D " "	Q_{55}*		"
θ_N " "	Q_{66}*	$Q_{MAK}+(Q_{DYN}+Q_{HP})\sum \omega_i^2$	"
θ_E " "	Q_{77}*		"
ω_x " "	Q_{88}	2^{-53}(rad/sec)^2/sec	"
ω_y " "	Q_{99}	2^{-53}(rad/sec)^2/sec	2^{-55}(rad/sec)^2/sec
ω_z " "	Q_{uu}	2^{-53}(rad/sec)^2/sec	"
a_y " "	Q_{vv}	2^{-29}	Same as 28 June
θ_x " "	Q_{ww}	2^{-29}	2^{-26}
ω Characteristic Time	T_ω	2700 sec.	2^{11} = 2048 sec.
a_y " "	T_a	2^{11} = 2048 sec.	2^{11} = 2048 sec.
θ_x " "	T_{θ_x}	2^{11} = 2048 sec.	2^{10} = 1024 sec.
Attitude Constant Noise	Q_{MAK}	2^{-33} rad^2/sec	Same as 28 June
Attitude Dynamic Noise	Q_{DYN}	2^{-23}(rad^2/sec)/(rad/sec)^2	"
Attitude High Pulse Noise*	Q_{HP}*	2^{-23}(rad^2/sec)/(rad/sec)^2	"

* Q_{HP} is used only if a high scale rebalance pulse occurred at any time during the base 20 millisec. computation cycle.

TABLE II. FILTER PARAMETERS (Continued)

Name	Symbol	28 June 1971 Value	8 August 1971 Value
x Doppler Vel. Variance	R^d_{11}	$10^{-5}(V^d_y)^2 \simeq (0.3\%)^2$	$4 \times 10^{-6}(V^d_y)^2 \simeq (0.2\%)^2$
y Doppler Vel. Variance	R^d_{22}	"	"
z Doppler Vel. Variance	R^d_{33}	"	"
Check Point Variance	R^{CP}	$2^{18} ft^2 \simeq (512\ ft)^2$	$2^{20}\ ft^2 = (1024\ ft)^2$
Upper Chi. Sq. Limit		8.5	Same as 28 June
Lower Chi. Sq. Limit		$2^{-7}\ (10^{-2})$	"
Pitch Rate Max		0.175 rad/sec≃10 deg/sec	"
Roll Rate Max		"	"
Tilt Max (1_{11} max)		0.96593 ≃ cos 15 deg	"
Altitude Min.		500 ft.	"
V^d_x Doppler Vel. Max.		63 ft/sec	"
Min. Value P Diagonal		40_8	"
C. P. Fix Det. S Min.		$2^{36} ft^4 \simeq (512\ ft)^4$	"
Doppler Vel. Det. S Min.		$1\ (ft/sec)^4$	"
Zero Vel. Det. S Min.		"	"
Doppler Data Lag		≃ 0.5 sec.	"
Minimum R^d Diag.		$2^{-6} = (0.125)^2$	"
a_y Compensation Initial Cond.		0	+0.002
θ_x Compensation Initial Cond.		0	-2.5 mr
γ_x Doppler X Scale Factor		0.040394 ft/pulse	
γ_y Doppler Y Scale Factor		0.212052 ft/pulse	
γ_z Doppler Z Scale Factor		0.184413 ft/pulse	
θ_y Misalign. Compensation		0	Same as 28 June
θ_z Misalign. Compensation		0	+1.0 mr
Altimeter Scale Factor		16,000 ft/volt	Same as 28 June

DATA REDUCTION RESULTS

Data from two flights (SK2-004 and SK2-005) were judged of marginal quality to warrant reduction.

Flight SK2-004*

A tab plot of yaw misalignment, θ_x, and pitch misalignment, θ_z, is given in Figure 3. In general, yaw misalignment is indicated negative, 0.01 - 0.02 rad. Pitch misalignment is indicated very slightly positive.

A tab plot of the autocovariance of yaw misalignment angle is shown in Figure 4. Indicated parameters are:

Uncorrelated noise variance:	0.13×10^{-4} (rad)^2
Steady state correlated noise variance:	0.24×10^{-4} (rad)^2
Correlated noise characteristic time:	120 sec.

A tab plot of doppler longitudinal velocity scale factor, α_y, is given in Figure 5. As indicated earlier in this report, a timing problem allowed doppler information to be partially lost under certain conditions. The effect of this can readily be seen in Figure 5.

A tab plot of the autocovariance of α_y is given in Figure 6. The effect of the lost doppler information is apparent. Due to this, the autocovariance function was not analyzed further.

Flight SK2-005*

A tab plot of yaw misalignment, θ_x, and pitch misalignment, θ_z, is given in Figure 7. In general, the yaw misalignment settles at about negative 0.01-0.02 rad. Pitch misalignment settles at a very slight positive value. In both cases, the data supports that from SK2-004.

A tab plot of the autocovariance of yaw misalignment angle is shown in Figure 8. The oscillation (first half cycle only, shown) about the abscissa

* In all cases, the entire original plot is not shown, since it provides no usable additional information from that given.

indicates the presence of periodic terms in the data (probably oscillation of the GEANS velocities used as the standard). Ignoring this, the indicated parameters are

Uncorrelated noise variance:	0.19×10^{-4} (rad)^2
Steady state correlated noise variance:	0.36×10^{-4} (rad)^2
Correlated noise characteristic time:	470 sec.

This offers fair support of that of SK2-004.

A tab plot of longitudinal velocity scale factor, α_y, is given in Figure 9. The data again indicates the presence of oscillatory terms (probably, again, oscillation of the GEANS velocities used as the standard).

A tab plot of the autocovariance of α_y is given in Figure 10. The effect of oscillatory terms in the data is again apparent. Ignoring this, the indicated parameters are:

Uncorrected noise variance:	0.90×10^{-5}
Steady state correlated noise variance:	0.114×10^{-4}
Correlated noise characteristic time:	630 sec.

SYSTEM PERFORMANCE RESULTS

Navigation errors for flights 2 through 4 are shown in Figures 11 through 16. Data from the remaining flights is not meaningful due to various system/interface problems. All performance presented is based on quick-look data obtained in flight by the test team.

FIGURE 3. GRAPH OF PHI(X) AND PHI(Z)

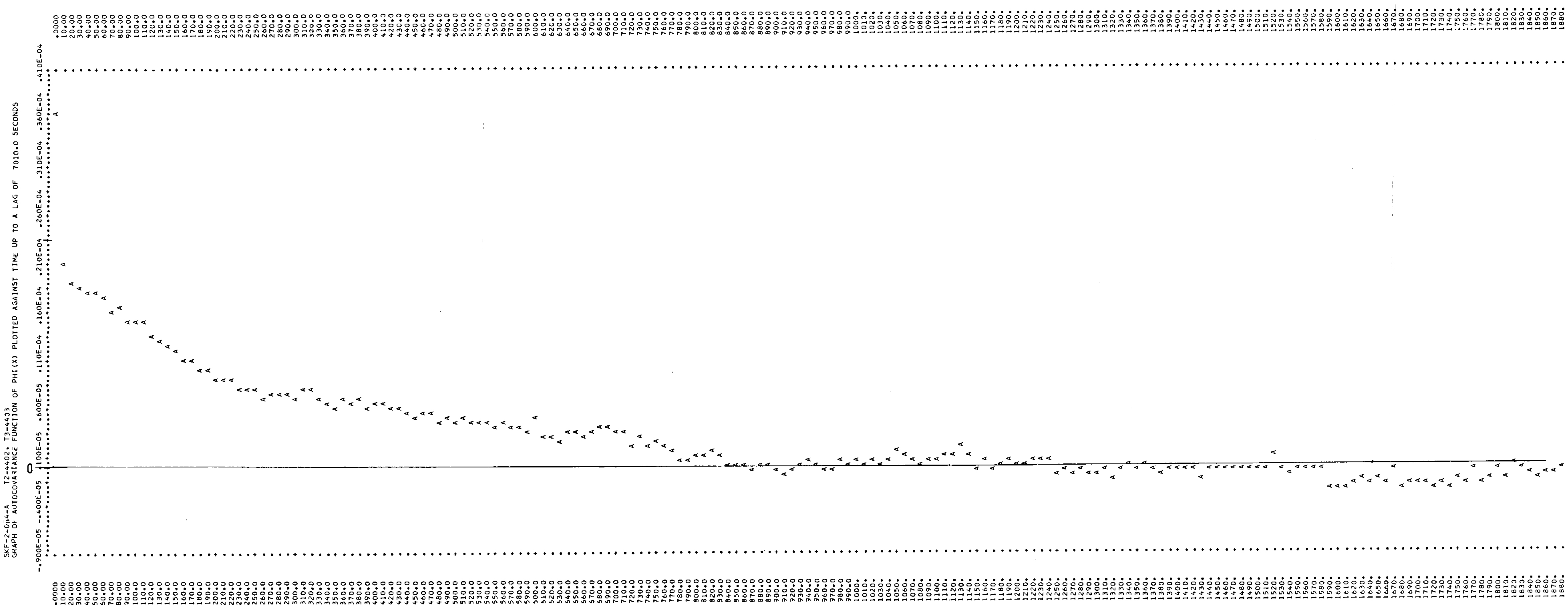


FIGURE 4. GRAPH OF AUTO-COVARIANCE FUNCTION OF PHI(X) PLOTTED AGAINST TIME UP TO A LAG OF 7010.0 SECONDS

1171-334R

FIGURE 5. GRAPH OF ALPHA(Y)

1171-335R

FIGURE 6. GRAPH OF AUTO-COVARIANCE FUNCTION OF ALPHA(Y) PLOTTED AGAINST TIME UP TO A LAG OF 7010.0 SECONDS

FIGURE 7. GRAPH OF PHI(X) AND PHI(Z) FROM 9.84000 HOURS TO 12.09000 HOURS

FIGURE 8. GRAPH OF AUTO-COVARIANCE FUNCTION OF PHI(X) PLOTTED AGAINST TIME UP TO A LAG OF 5050.0 SECONDS

FIGURE 9. GRAPH OF ALPHA(Y) FROM 9.8400 HOURS TO 12.09000 HOURS

FIGURE 10. GRAPH OF AUTO-COVARIANCE FUNCTION OF ALPHA(Y) PLOTTED AGAINST TIME UP TO A LAG OF 6060.0 SECONDS

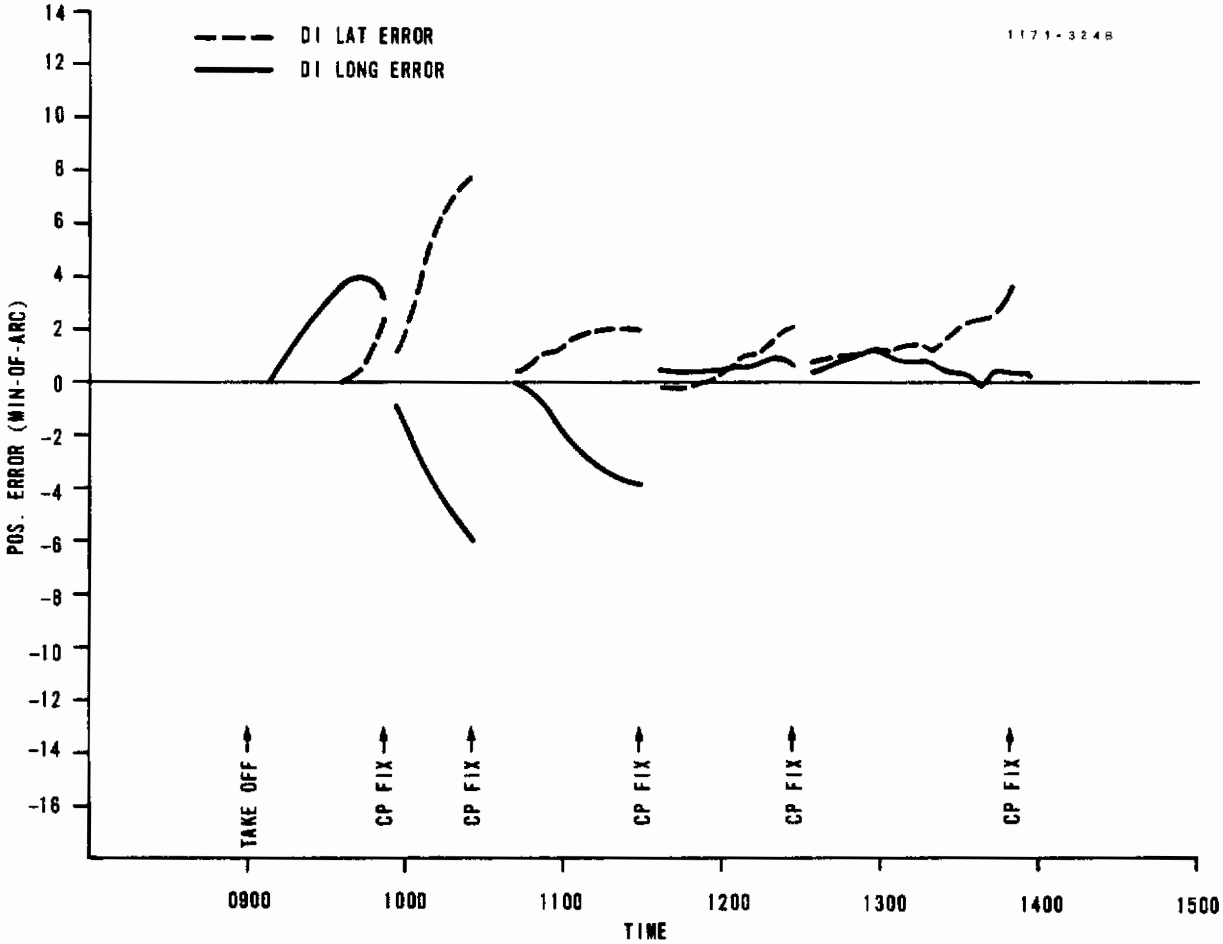


FIGURE 11. DI FLIGHT SK2-002

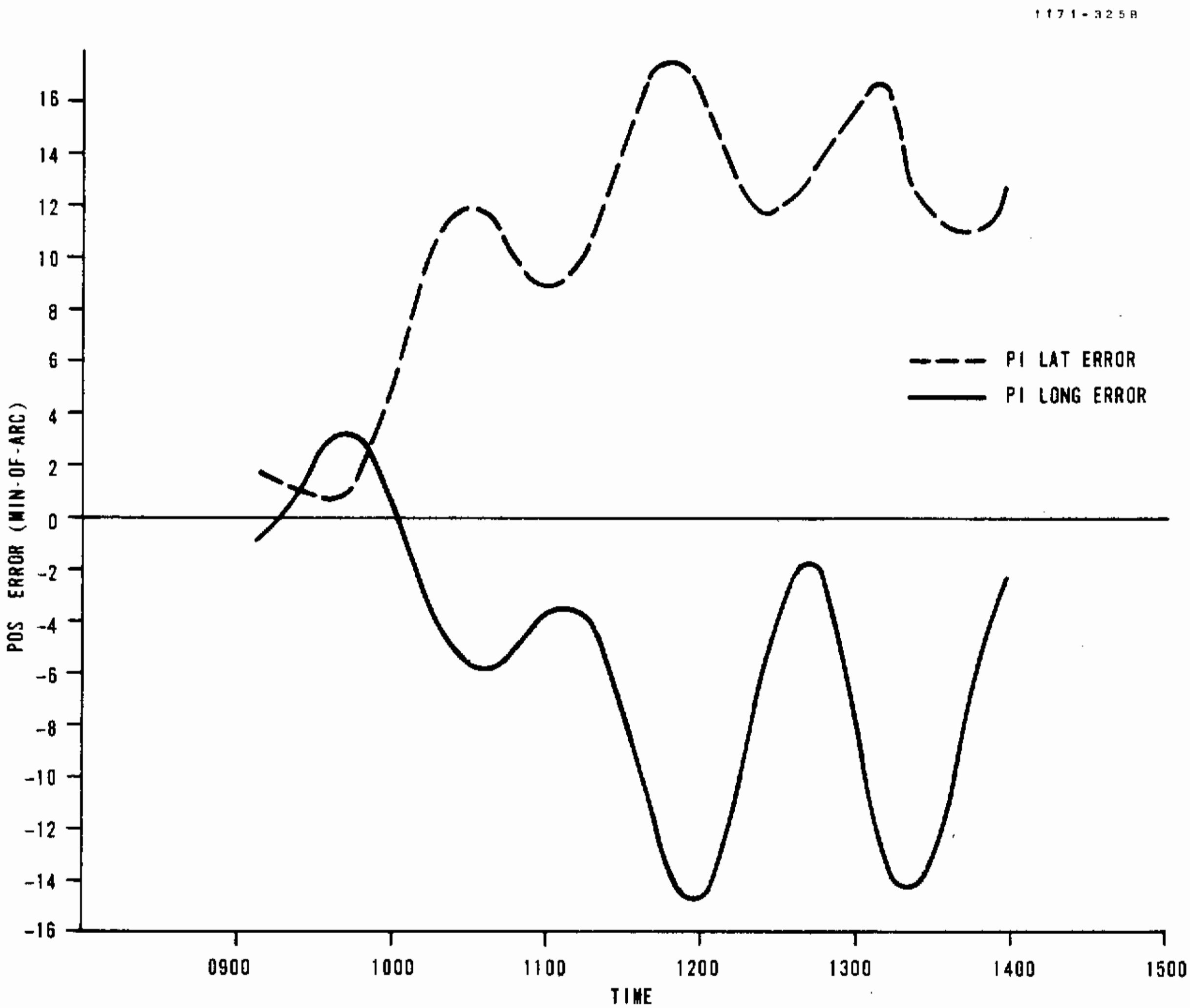


FIGURE 12. PI FLIGHT SK2-002

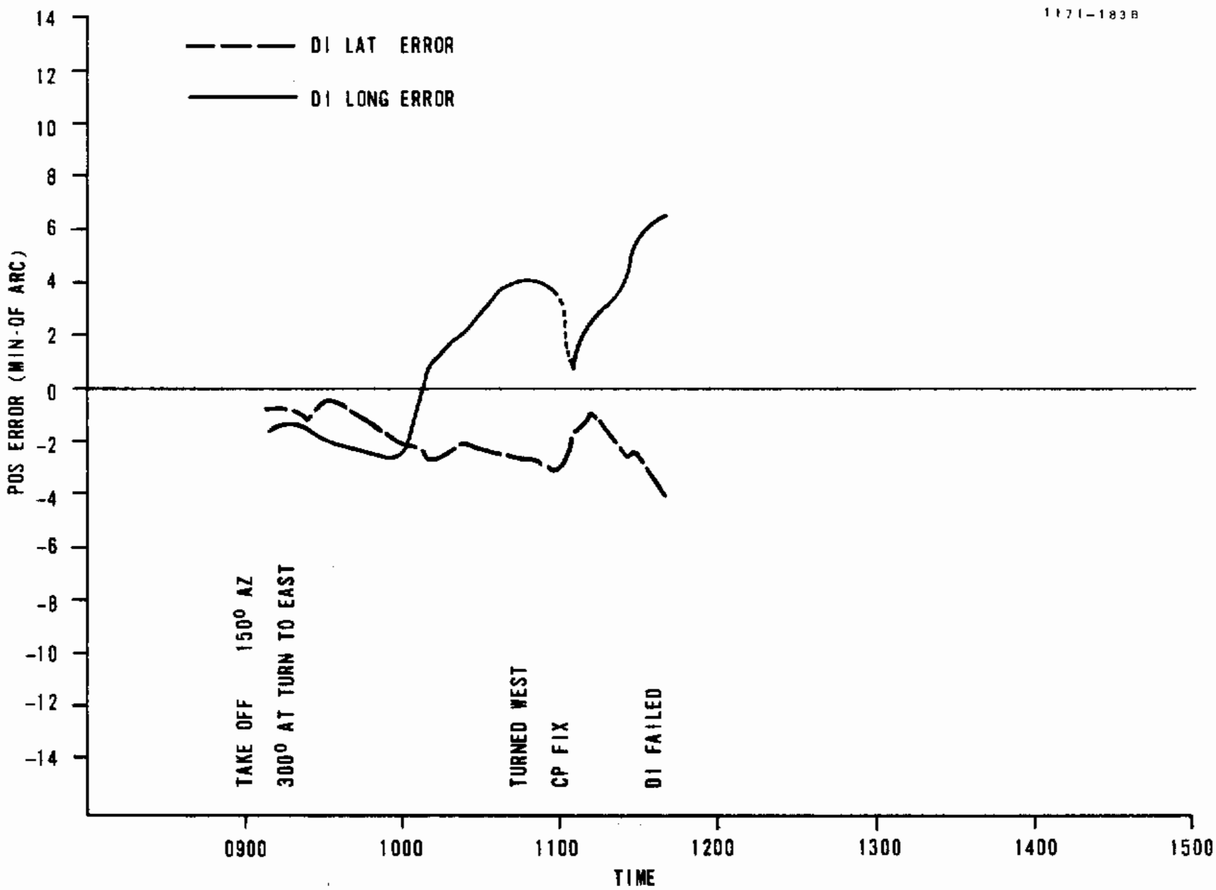


FIGURE 13. DI FLIGHT SK2-003

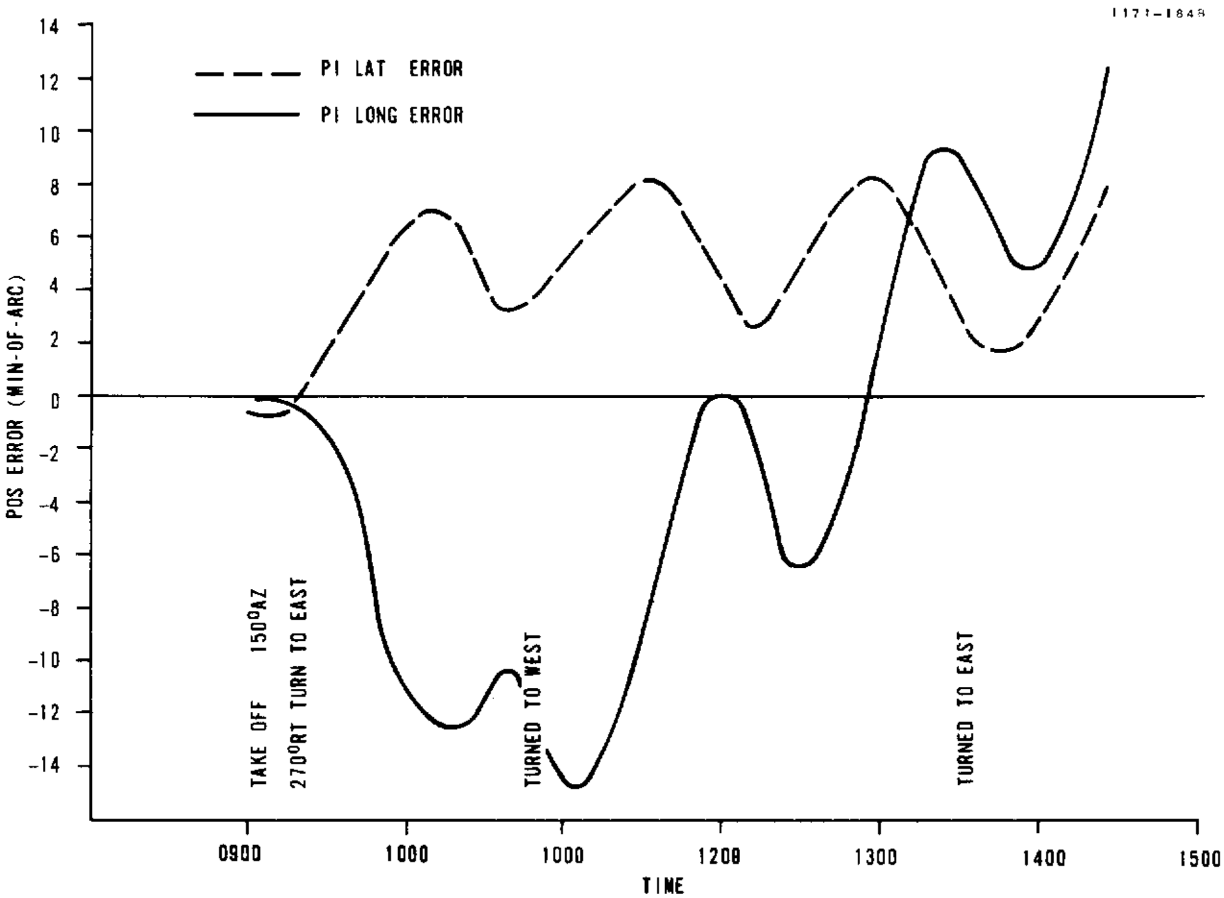


FIGURE 14. PI FLIGHT SK2-003

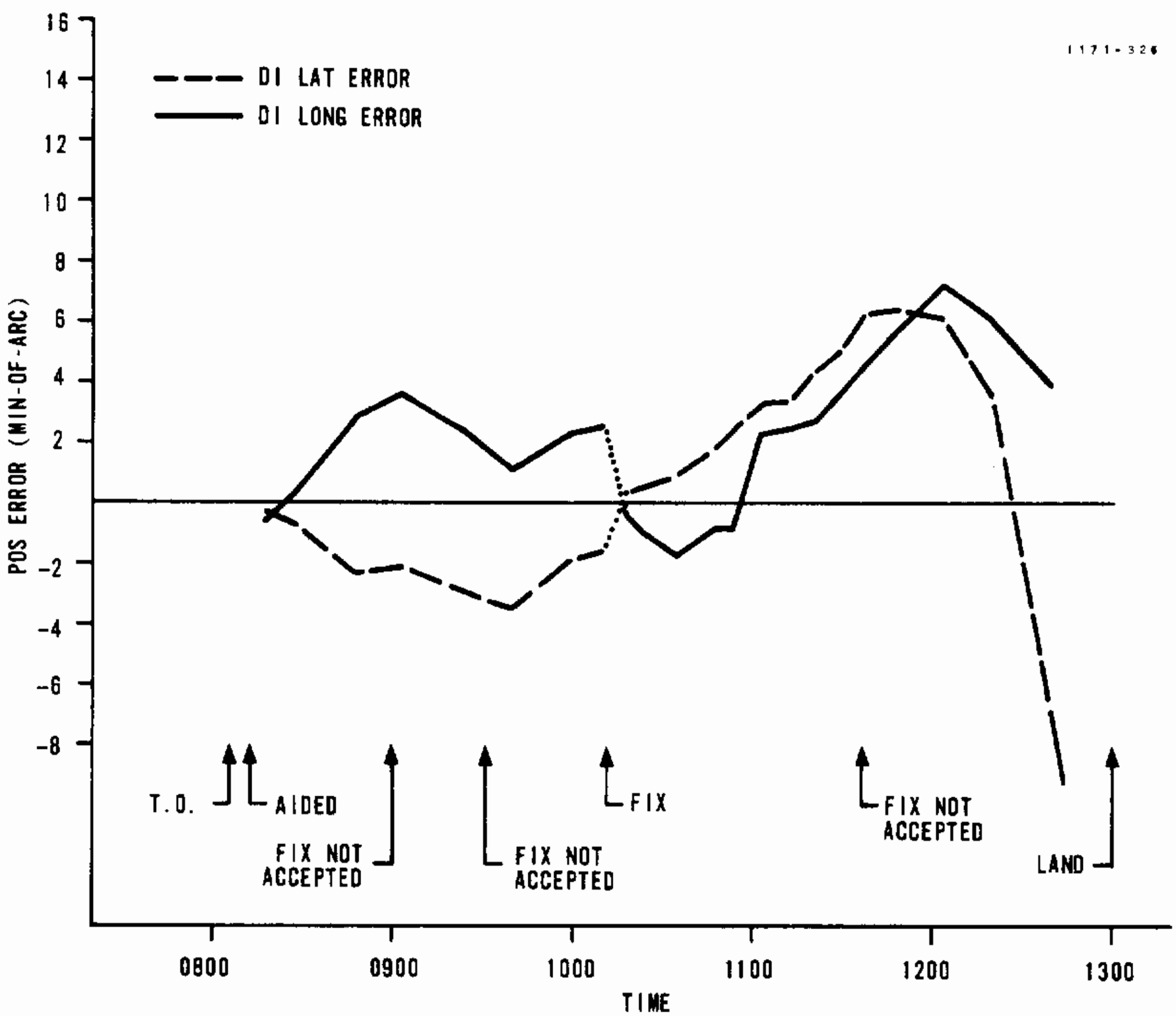


FIGURE 15. DI FLIGHT SK2-004

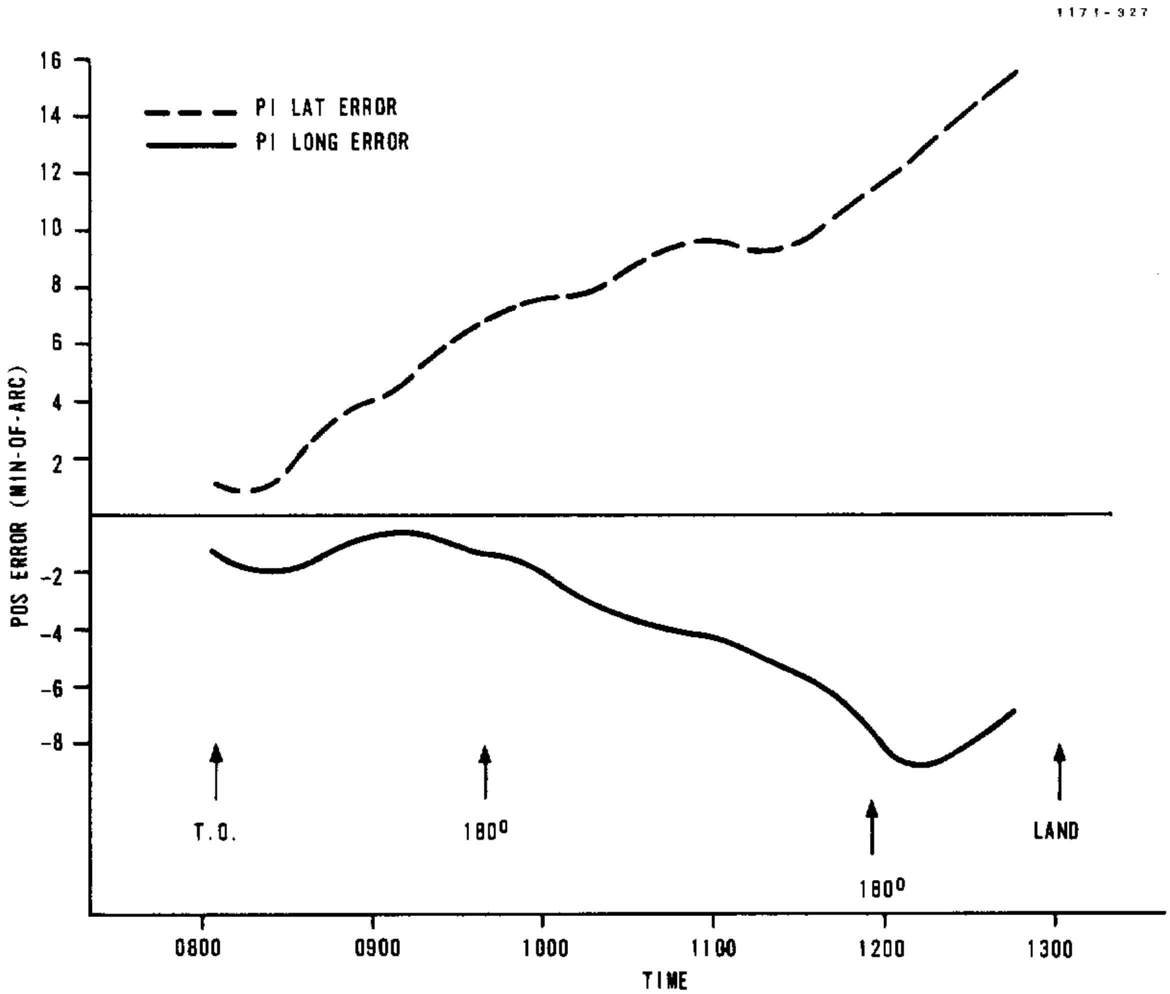


FIGURE 16. PI FLIGHT SK2-004

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

Two of the primary program objectives cited earlier in this report were essentially accomplished. The output characteristics of the APN 193 Doppler Radar were broadly established and are reported under the Results Section of this report. However, a greater sample (more flights) would be necessary to establish these characteristics conclusively. A data link to transmit doppler data and GEANS velocity data from GEANS to the H-429 system was designed, checked out, and used successfully. The objectives to extend the doppler-aided inertial data base and to demonstrate the in-air alignment of a strapdown inertial system were incomplete because of equipment and schedule problems.

One significant secondary objective was achieved. The trimming of the velocity terms in the Kalman filter was demonstrated by a "zero velocity reset" technique.

The objectives which were established at the start of this test program are still considered to be valid. However, a new program should be undertaken with a somewhat different slant. It is felt that the ability to improve inertial system performance was suitably proved in the 1970 flight test series. Full exploitation is recommended of the zero velocity initialization technique and the implicit cost benefits of combining inexpensive on-board aircraft navigation devices to achieve improved navigation performance. In addition, in-air alignment of air-launch missile inertial systems remains an open question. A program in the future to achieve these recommendations would be better accomplished on lower cost, less sophisticated hardware than that used. Ultimate lower cost is the underlying objective of both major elements of the flight test program reported herein.

Appendix I

H-429 SYSTEM DESCRIPTION

The H-429 consists of three major subassemblies:

- Inertial Reference Unit (IRU),
- SIGN-III Digital Computer, and
- Power Supply.

These units are complemented by a basic set of ground support equipment.

The heart of the IRU is a thermally controlled sensor block containing three GG334A gas bearing spin motor gyros for high stability and long term operation, and three GG177B17 accelerometers.

The gyro and accelerometer rebalance electronics use inertial component outputs proportional to angular rates and acceleration to generate precise current pulses with discrete energy levels to rebalance the gyros and accelerometers. These pulses are fed to the computer as incremental angle ($\Delta\theta$) and velocity (ΔV) information. The IRU was designed so that the gyro and accelerometer rebalance frequency and pulse weight can be tailored to fit several applications.

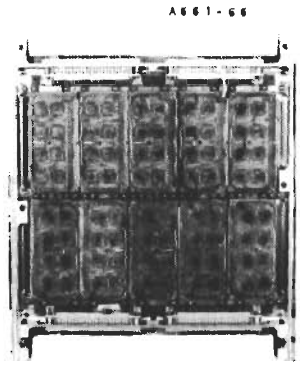
The power supply protects the system during excessive over/under voltage or power transient periods; likewise, it sends a "power off" interrupt to the computer to protect the memory during these abnormalities.

COMPUTER

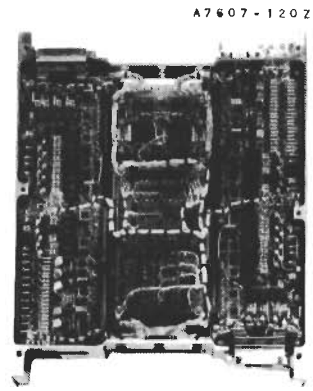
The SIGN-III computer is a stored program, general purpose, guidance and navigation computer that uses parallel, fixed-point, two's complement, binary arithmetic. It has an extensive instruction repertoire which includes double precision and half-word arithmetic instruction as well as four index registers to increase memory utilization efficiency and program flexibility.

The computer also contains a special purpose wired-program sequencer that performs a first order algorithm computation on the incremental $\Delta\theta$ and ΔV inputs from the H-429 IRU. The sequencer is essentially an electronic gimbal that changes body incremental attitude and velocity into a whole valued inertial frame attitude and velocity for use by the computer.

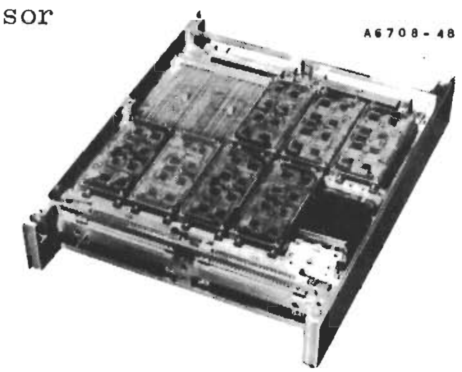
The SIGN-III computer consists of three trays:



Processor



Memory



Input/Output

OPERATIONAL CONSIDERATIONS

Navigation, guidance, control and initial alignment computations are performed by the computer. The software package includes:

- Basic Operating System
- Instruction Diagnostic
- Memory Diagnostic
- Basic Mathematical Subroutines
- Assembly System
- Initialization and Navigation

All the above routines are available on punched paper tape, and are documented by absolute and symbolic annotated listings.

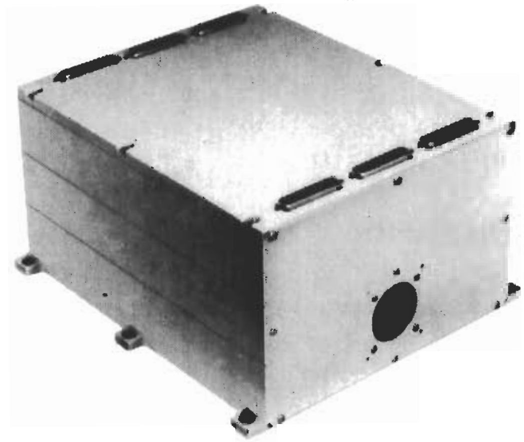
This software package provides complete system capabilities for both operation and maintenance.

MAINTENANCE CONSIDERATIONS

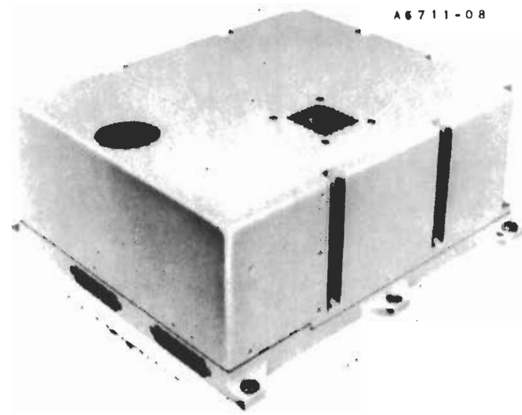
The H-429 uses proven, highly reliable DTL flatpacks and printed circuit boards which minimize maintenance and repair difficulty. The computer processor has two large interconnect boards and 35 small logic boards hinged and wired for easy access. Replacement using a conventional soldering iron provides reliability of hard wiring and maintainability of small plug-in modules.

The IRU packaging minimizes the effort required to replace gyros and accelerometers. The pulse rebalance loops and precision timing and voltage are packaged in individual plug-in trays for easy removal.

COMPUTER

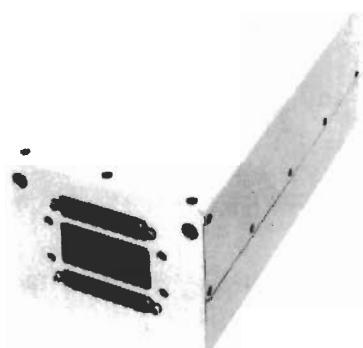


Size	10.12 by 6.5 by 12.75 inches
Weight	26 pounds
Power	90 watts nominal
Reliability	4650 hours MTBF
Memory Capacity	4096 words at 20 bits/word
Processor	Parallel, fixed point, two's complement
Add Time	4 microseconds
Multiply Time	24 microseconds
Index Registers	4
Clock Frequency	1 MHz single phase
Input/Output Capabilities	Discretes In/Out; Priority Interrupts; Parallel Data In/Out; Serial Register In/Out; Incremental Counters; A/D, D/A Conversion



H-429 IRU

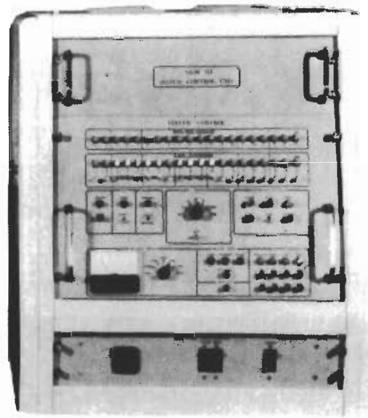
Size	10.12 by 5.10 by 12.75 inches
Weight	29 pounds
Power	90 watts
Acceleration Range and Scaling	±5.6 g's at 0.1 feet/second/pulse
Angular Rate and Scaling	±50 degrees/second at 12.6 arc-second/pulse
Gyro and Accelerometer Pulse Rate	1,800 pulses/second



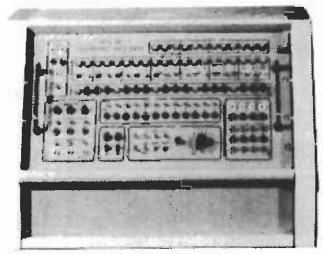
POWER SUPPLY	Integrated System	Brassboard Flight Test System
Size	4.0 x 5.0 x 9.5 In.	5.0 x 7.5 x 16.0 In.
Weight	15 pounds	23 pounds
Maximum Power Dissipation	50 watts	60 watts

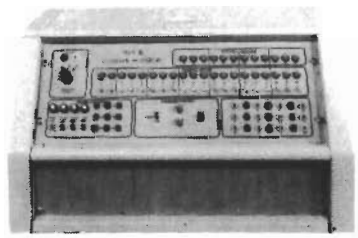
0267-102

System Control Unit



Interface Test Unit





Control and Display Unit

Automatic Data Set

H-429 GROUND SUPPORT EQUIPMENT

The H-429 system uses the following GSE:

- System Control Unit
- Automatic Data Set
- Interface Test Unit } Maintenance Test Equipment
- Control and Display Unit. } Maintenance Test Equipment

This GSE provides the following functions:

- Power and operation mode control
- Manual and/or automatic memory loading
- Data and mode display
- Local or remote operation interfacing
- Maintenance

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Security Classification

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13. ABSTRACT

This report is prepared as a requirement of Air Force Contract AF33615-71-C-1633, reference Contract CDRL Item A-003. The report encompasses preparation of the Honeywell H-429 (SIGN III) Strapdown Inertial System; the design, checkout, and use of an interface unit for acquiring doppler radar and GEANS inertial navigation data; the modification of the analytical mechanization for the doppler aiding and Kalman filter techniques; the software preparation; and conduct of the test program, results and conclusions of the overall effort.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Strapdown Inertial						
Doppler Radar						
H-429 or SIGN III (Honeywell Strapdown Inertial System)						
APN 193 (Military designation for a doppler radar)						
In-Air Alignment or						
Hand-Off Alignment						
Kalman Filter						
Flight Test						
GEANS (Gimbaled Electrostatic-gyro Aircraft Navigation System)						
Aided Inertial						
Pure Inertial						
Checkpoint fix						
Zero velocity reset						
Navigation						
Position or velocity errors						