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STRAPDOWN COST TREND STUDY AND FORECAST

By A. J. Eberlein and P. G. Savage

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Minneapolis, Minnesota 55413

For

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

This report summarizes the results of a study performed to ascertain the potential cost advantages offered by advanced strapdown inertial technology in future commercial short-haul aircraft. Kinematic systems (attitude, rate, acceleration sensing) and inertial navigation systems were investigated in the study. Each type of system was mechanized in the traditional sense (using conventional sensors), and alternatively, using advanced strapdown technology (laser gyros and strapdown reference computers). The initial procurement cost and six year cost-of-ownership, which includes spares and direct maintenance cost were calculated for each system investigated such that traditional and strapdown mechanization costs could be compared.

Each system was mechanized assuming a fail-operational requirement. For the traditional systems, triple redundant sensors and electronics were assumed; for the strapdown systems, triple redundant electronics were assumed with skewed redundant strapdown sensors. In the case of the kinematic systems, the traditional system sensors were assumed to be standard flight control grade attitude/rate gyros and accelerometers; the strapdown sensors and attitude computers were sized for inertial navigation accuracy.

Cost results for the inertial navigation systems showed that initial costs and the cost of ownership for traditional triple redundant gimbaled inertial navigators are three times the cost of the equivalent skewed redundant strapdown inertial navigator. For the kinematic systems, the initial procurement cost of the strapdown system is fifty percent higher than

for the traditional system equivalent. However, on an overall cost-of-ownership basis, the strapdown system cost is twenty percent lower. The net cost advantage for the strapdown kinematic system is directly attributable to the fifty percent reduction in sensor count for strapdown compared to traditional kinematic systems with an associated reduction in sensor failures and repairs. In addition to the overall cost savings, the strapdown kinematic system has the added advantage of providing a fail-operational inertial navigation capability for no additional cost due to the use of inertial grade sensors and attitude reference computers.

INTRODUCTION

This report documents the results of a study performed for NASA Ames Research Laboratory by Honeywell Incorporated investigating cost comparisons and trends between traditional and advanced flight control and navigation systems in future commercial short-haul aircraft. Prior to this study, a comprehensive cost-of-ownership study did not exist that compared strapdown flight control and navigation systems with traditional flight control and navigation systems nor did a comprehensive cost-of-ownership study exist for comparing strapdown inertial navigation systems with gimbaled inertial navigation systems.

This study was initiated by NASA AMES Research Laboratory to determine the cost viability of strapdown systems in terms of current producible hardware and technology. The traditional systems were configured utilizing conventional sensors (momentum wheel rate gyros, vertical gyros, heading gyros, and gimbaled platforms); the advanced strapdown systems were configured utilizing strapdown laser gyros for the basic sensing element. Redundancy requirements for the traditional system sensors were implemented using traditional block level duplication for each aircraft axis independently. Redundancy requirements for the advanced strapdown systems were implemented using skewed sensor arrays. The computer configurations for the traditional and advanced strapdown systems were assumed comparable, based on identical state-of-the-art circuit technology.

Three systems configuration classes were considered in performing the cost analyses: kinematic systems that provide rate, acceleration, and attitude signal outputs, flight control systems that contain the kinematic system as an element and a flight control computer system to operate on the kinematic signals, and inertial navigation systems. In each case, the systems were configured to satisfy the fail-operational requirements of commercial short-haul aircraft.

Section I of the report gives a general description of the skewed redundant strapdown inertial systems and describes more specifically the hexad (six-axis) skewed sensor assembly and the computer configuration that formed the basis for the strapdown system mechanizations investigated in the study. Section II provides a detailed technical description of each of the particular advanced strapdown system configurations investigated in the study.

Section III described the method used to compute system cost-of-ownership estimates and presents initial procurement cost breakdowns for each system, resulting cost-of-ownership estimates, and cost comparisons with the equivalent traditionally mechanized systems. Also included is a projection of future costs for the advanced and traditional systems showing the impact of learning and inflation on future system costs. The appendixes contain detailed information supporting the individual sections of the report including a comparison of strapdown systems utilizing laser gyros and conventional floated rate integrating gyros.

The concluding section of the report summarizes the configurations investigated and the cost comparisons obtained for the traditional and advanced strapdown system configurations. A set of recommendations is outlined to extend the investigations leading to an advanced laser strapdown system that best satisfies commercial short-haul aircraft dispatch, redundancy, and cost-of-ownership constraints.

The equipment cost data presented in this document represents engineering estimates based on past experience for similar components. The cost figures were prepared for engineering tradeoff comparison purposes only.

SECTION I
SKEWED REDUNDANT STRAPDOWN INERTIAL SYSTEM – GENERAL CONFIGURATION

Strapdown Versus Gimbaled Inertial Navigation Systems

Inertial navigation systems represent a class of aircraft avionics equipment that compute position, velocity, and attitude using self-contained gyros and accelerometers as the primary sensing elements. In general, the gyros are used to determine the orientation of the accelerometers relative to earth. Accelerometer outputs are thereby interpreted relative to the earth referenced coordinates. Integration of the earth referenced acceleration data in a digital computer provides continuous measurements of aircraft velocity and position. Attitude data is provided as a by-product of the gyro reference.

Mechanization of the inertial navigation system is one of the most exacting electro-mechanical technologies in the aerospace industry. Gyro reference requirements, in particular, are most demanding. The gyro reference typically has to be accurate to 0.01-0.03 degrees per hour in the presence of aircraft rates that can be as high as several hundred degrees per second. This level of performance corresponds to a navigation accuracy of 1-3 nautical miles per hour, a typical user requirement. In general, two types of mechanization approaches are possible with inertial navigation systems: gimbaled and strapdown.

In the gimbaled approach, an orthogonal triad of gyro and accelerometer inertial instruments are mounted on the inner element of a gimbaled platform. The gimbal assembly contains torque motors about each gimbal shaft. The gyro outputs are used to command the gimbal torquers, thereby maintaining the inner element in a space-stable attitude. Commanded angular rates are applied to the stable inner element (platform) by electrically torquing the gyros. The gyro torquing rates are determined in a digital computer such that the platform will always be aligned to earth referenced coordinates (for example, north/east/vertical) as the aircraft cruises over the earth. The platform torquing rates represent the angular rate of the aircraft over the surface of the earth and include the effects of earth rate rotation and vehicle velocity relative to the earth. The torquing rates are determined in the system computer from vehicle velocity and position data which is computed by integrating the outputs of the platform accelerometers. Resolvers on the gimbal shafts provide aircraft attitude information as a secondary output.

In the strapdown approach, the inertial sensor triad (gyros and accelerometers) are mounted directly to the airframe. Both the gyro and accelerometer outputs are input directly to the system computer. The computer processes the gyro data to continuously determine aircraft attitude relative to earth referenced coordinates. The attitude data is used with the aircraft mounted accelerometer signals to compute the equivalent acceleration data in the earth referenced coordinate frame. Thus, the computer analytically simulates the function of the gimbal assembly in the gimbaled approach. The remainder of the computation to determine aircraft velocity, position, and reference torquing commands is identical to the gimbaled approach. The emergence of the strapdown system as a more practical and cost-effective system is due to the development of digital computers that are relatively inexpensive and that have the computational speeds necessary to perform the strapdown navigation computations rapidly.

The strapdown digital mechanization approach inherently avoids the problems encountered with gimbaled systems. By eliminating the complex mechanical gimbal assembly and associated motors, bearings, slip rings, resolvers, and electronics, strapdown systems offer lower procurement cost, improved reliability, and reduced maintenance costs. Also, significant improvements in reaction time, sensor reliability, and system cost are achievable because of the recent advent of strapdown laser gyro technology. The strapdown concept is compatible with recent trends toward large scale integration of digital avionics functions: the strapdown data format is inherently digital, and the total aircraft inertial state vector is available as a natural output for flight control usage (position, velocity, attitude, rate, and acceleration). Finally, low cost redundancy is achievable with a strapdown mechanization through use of skew aligned gyros and accelerometers.

Skewed sensor redundancy is a technique that enables a single inertial sensor (gyro or accelerometer) to replace any failed sensor regardless of its input axis orientation. The concept is to mount the sensors such that their input axes are nonorthogonal (skewed) relative to one another, with any set of three input axes nonplanar. With this arrangement, any set of three sensor outputs can be used to derive (in the system computer) the equivalent output of an orthogonal sensor triad. Thus, four skewed sensors would be capable of generating complete three-axis orthogonal output data with up to one sensor failure, and five skewed sensors would be capable of tolerating two failures. In a conventional redundancy approach, two sets of orthogonal triads (i. e., six sensors) would have the same fail/operational capability as four skewed sensors, and three orthogonal sets (nine sensors) would be equivalent to five skewed sensors. The hardware savings is substantial with the skewed approach as the redundancy requirement increases.

Hexad Skewed Redundant System Configuration

The strapdown skewed redundant system configurations investigated in this study combine six skewed redundant strapdown angular rate sensors and hexad accelerometers with a set of triple redundant computers programmed to perform the skewed redundant inertial navigation and attitude reference function, and for some configurations, to perform aircraft flight control computations. The hexad angular rate sensor used as a model for the study was the Honeywell GG1300 Laser Gyro (Figure 1). This advanced technology inertial component has demonstrated its suitability for precision inertial applications. The advantages projected for the laser gyro are fast reaction time, performance insensitivity to acceleration, vibration, and thermal environments, long term stability, high reliability, and low cost.

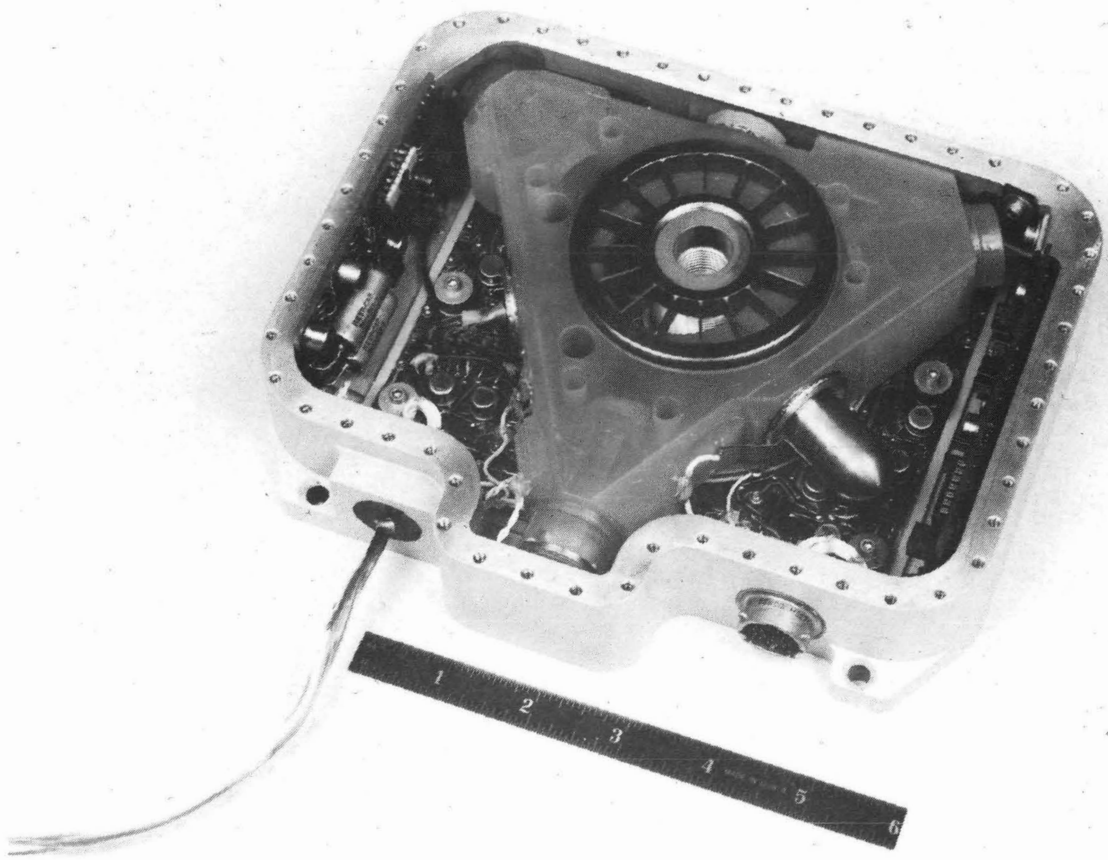


Figure 1. - Honeywell GG1300 Laser Gyro

Figure 2 is a block diagram showing the general configuration of the hexad/computer system. The internal and external signal, power, and synchronization interface between the system elements is identified. The hexad array is formed from three identical ISA's (inertial sensor assemblies), each containing two gyro/accelerometer pairs. The two angular rate and acceleration signals from each ISA are transmitted to each computer. Power supplies are contained in each computer to convert aircraft input power to regulated voltages for the computer electronics and to power one of the ISA's.

Other computer inputs generally include d-c signals, a-c signals, and discretes from other aircraft systems for the flight control computations, and mode control and latitude/longitude initialization data for the inertial computations from the aircraft control panel. Outputs from each computer, in general, are a-c, d-c, digital, and discrete outputs to the other aircraft systems and displays in addition to intercommunications (clock and data crossfeed) between the redundant computer channels for redundancy management.

The orientation of the input axes of one of the gyro/accelerometer pairs in each inertial sensor assembly box (two-axis ISA), as shown in Figure 2 is parallel to the long axis of the ISA (normal to the front face). The second gyro/accelerometer set is mounted with input axes perpendicular to the first set but skewed 54. 7 degrees (nonorthogonal) relative to the ISA base. The three two-axis ISA's are mounted to a common base, which is part of the aircraft rack structure, in precision alignment such that the long axis of the boxes are skewed relative to one another. This mounting arrangement is shown in Figure 3.

With the ISA's oriented this way, the gyro/accelerometer sets become aligned relative to one another such that the input axes of the four sensors (tetrad) formed from any two of the three sets of two ISA's are non-coplanar (i. e., they do not lie in a single plane). Under these conditions, software routines in the computer can operate on any one of the tetrad signal sets to analytically compute the equivalent roll, pitch, and yaw axis rate/acceleration data for computer operations. In addition, three of the four tetrad

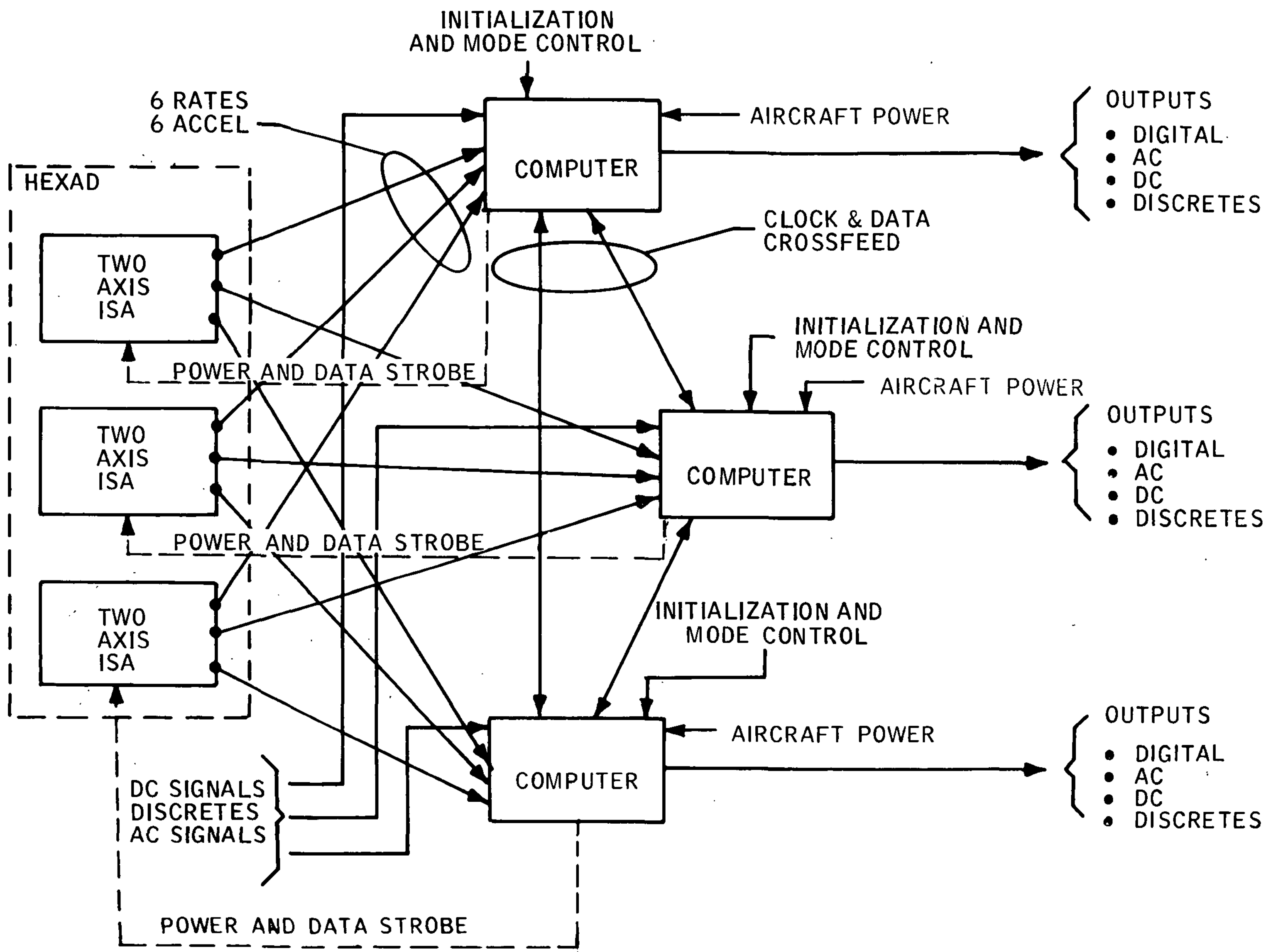


Figure 2. - General Skewed Redundant Hexad Strapdown System Configuration

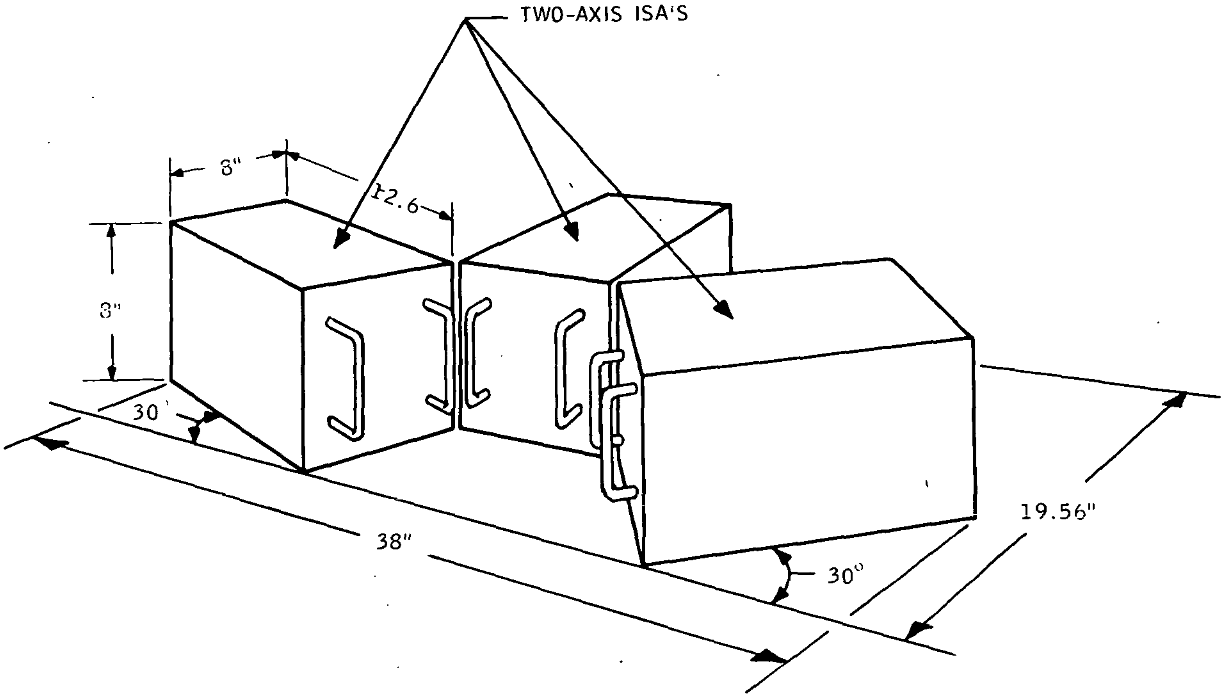


Figure 3. - Hexad Mounting Arrangement

gyro/accelerometer signals can be combined to analytically derive what the fourth sensor set is measuring. If the derived signals are unequal to the fourth set output (within prescribed tolerances), a failure has occurred in one of the tetrad sensors.

This logic provides the capability for assessing the functional integrity of each of the three tetrads. A single failure in the hexad (i. e., in one of the two-axis ISA's) will cause two tetrads to exhibit failures. The third tetrad will not exhibit failure, thereby isolating the failed ISA box to the unit not included in the functioning tetrad. Under these conditions, the identified functioning tetrad would be used to derive the roll/pitch/yaw axis data in the computer, thus allowing proper system operation with one failure (single-fail operational). Multiple failure occurrences can also be identified by this approach, but without a corresponding failure isolation. Under these conditions, the computer can be shut down safely (fail-safe) and the pilot will be notified of the shut down by the appropriate failure panel status lamp. Thus, the hexad geometry provides a single fail-operational/fail-safe capability.

Figure 4 illustrates the inertial computations in the system computers showing the hexad redundancy management and inertial calculations data flow. The ICS first compensates the input data from the three two-axis skewed gyro/accelerometer sets for known systematic errors in each instrument such as bias, scale factor, and misalignment. The compensated skewed gyro/accelerometer signals are then compared in the skewed voting algorithms for failure detection, isolation, and computation of equivalent three-axis orthogonal axis data (roll, pitch, yaw axis rate and acceleration) from a selected functional tetrad. In Appendix A the derivation of a representative set of skewed redundancy gyro voting equations and skew-to-orthogonal transformation equations that would be programmed into the system computer is given. Skewed accelerometer equations would be similar to those for the gyros in Appendix A.

The roll/pitch/yaw angular rate derived from the skewed gyro voting logic is then used in a three-axis attitude integration algorithm to compute

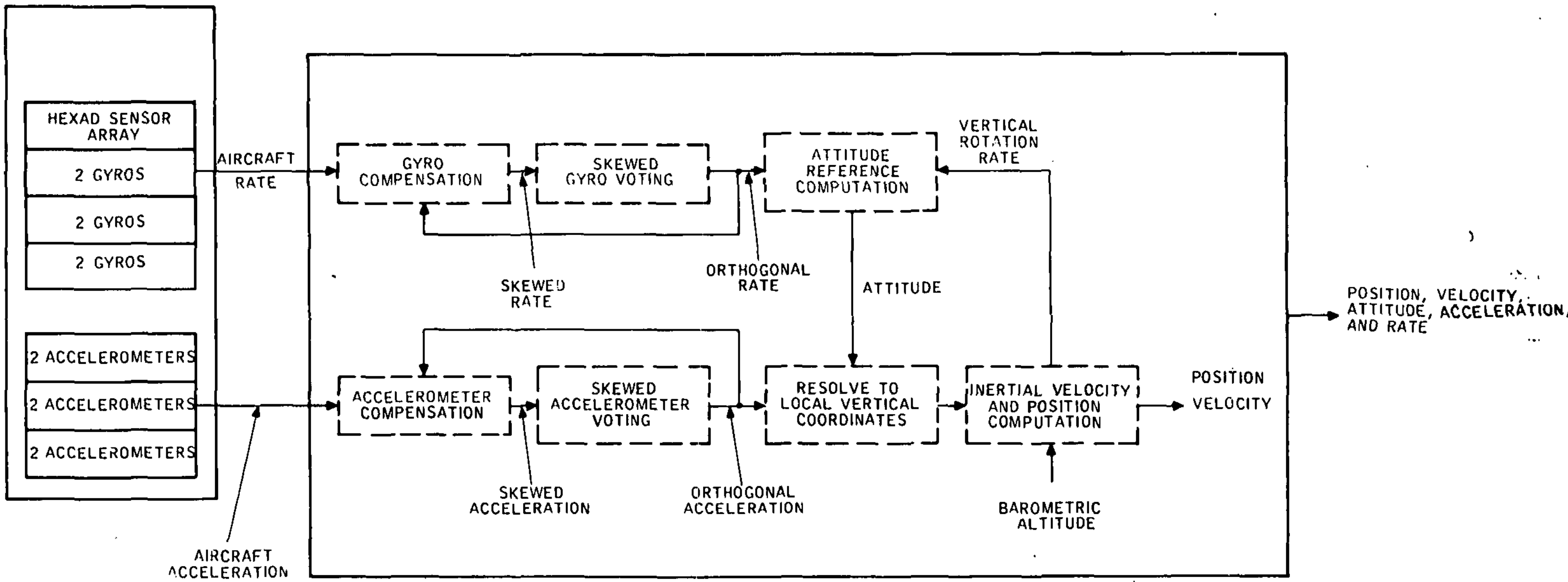


Figure 4. - Strapdown Skewed Inertial Computation

the attitude of the aircraft (more specifically, the accelerometer assembly) relative to local vertical/azimuth coordinates. The angular rate of the aircraft over the surface of the earth (due to earth's rotation and aircraft velocity) is included in this computation to account for the rotation rate of the local vertical.

The aircraft attitude data is used to resolve the roll/pitch/yaw aircraft axis acceleration vector data from the skewed accelerometer voting logic into the local vertical/azimuth coordinate frame. The computed horizontal/ vertical acceleration components are then integrated in an inertial velocity/ position computation algorithm to calculate aircraft horizontal velocity and latitude/longitude position. Barometric altitude is used in the inertial computation to stabilize the vertical channel.

Pentad Versus Hexad Configuration

The skewed sensor configuration chosen for the study uses a hexad (six-axis) sensor array to achieve fail-operational performance in general, and limited fail-operational performance. Theoretically, a pentad (five-axis) array could meet the fail-operational requirement with one less sensor and, therefore, less cost, but, as explained later in the report, this is not the case.

Pentad system description. - Figures 5 and 6 are block diagrams of a skewed redundant pentad inertial system showing the internal and external signal, power, and synchronization interface between the system assemblies. Each of the five ISA's in Figure 5 contains one skewed gyro/accelerometer pair. The angular rate and acceleration signals from each ISA are transmitted to each of the three redundant computers. Power supplies are contained in each computer to convert aircraft input power to regulated voltages for the computer electronics and to power three of the ISA's. Figure 6 defines the power interface.

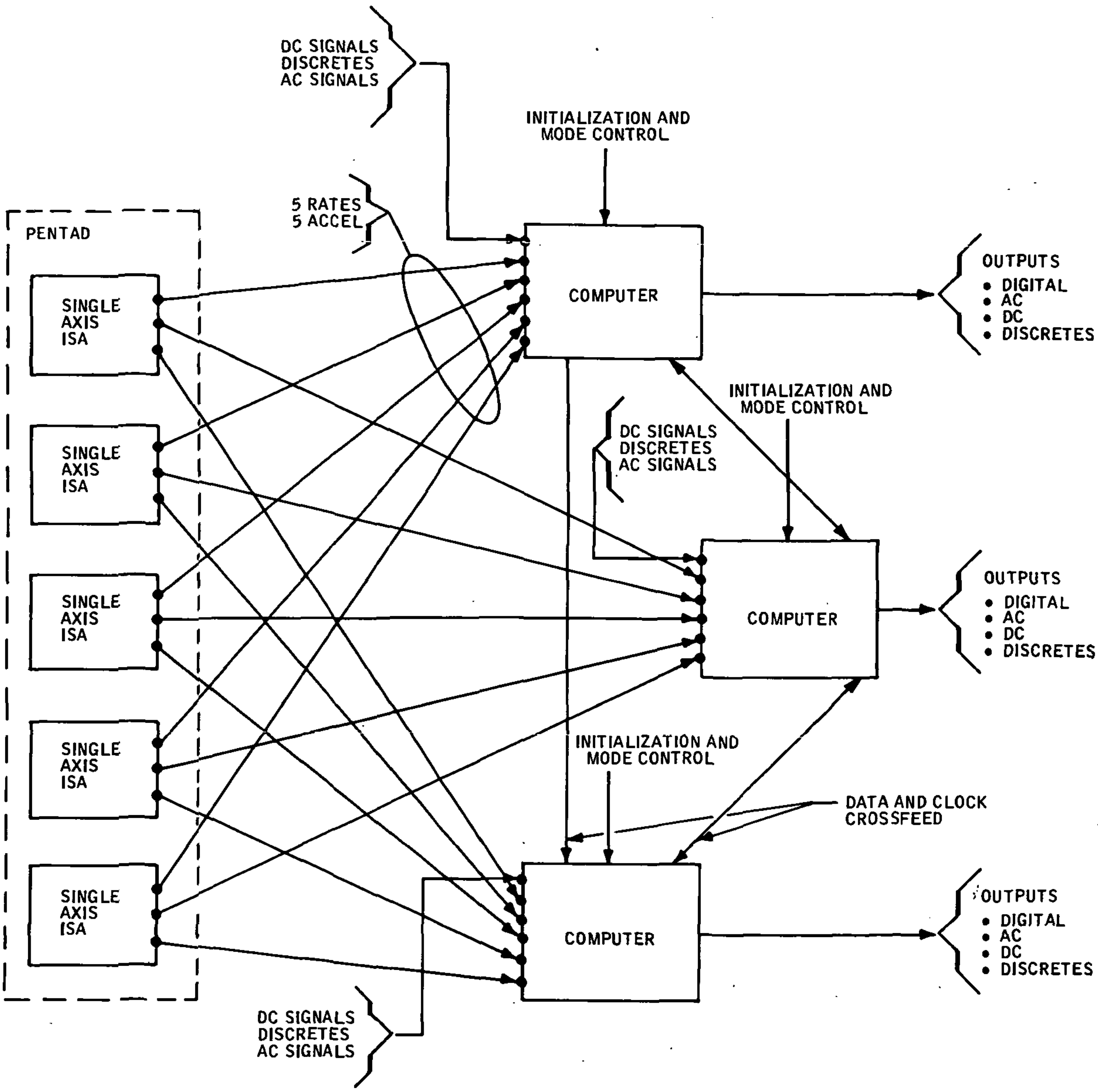


Figure 5. - General Skewed Redundant Pentad Strapdown System Configuration

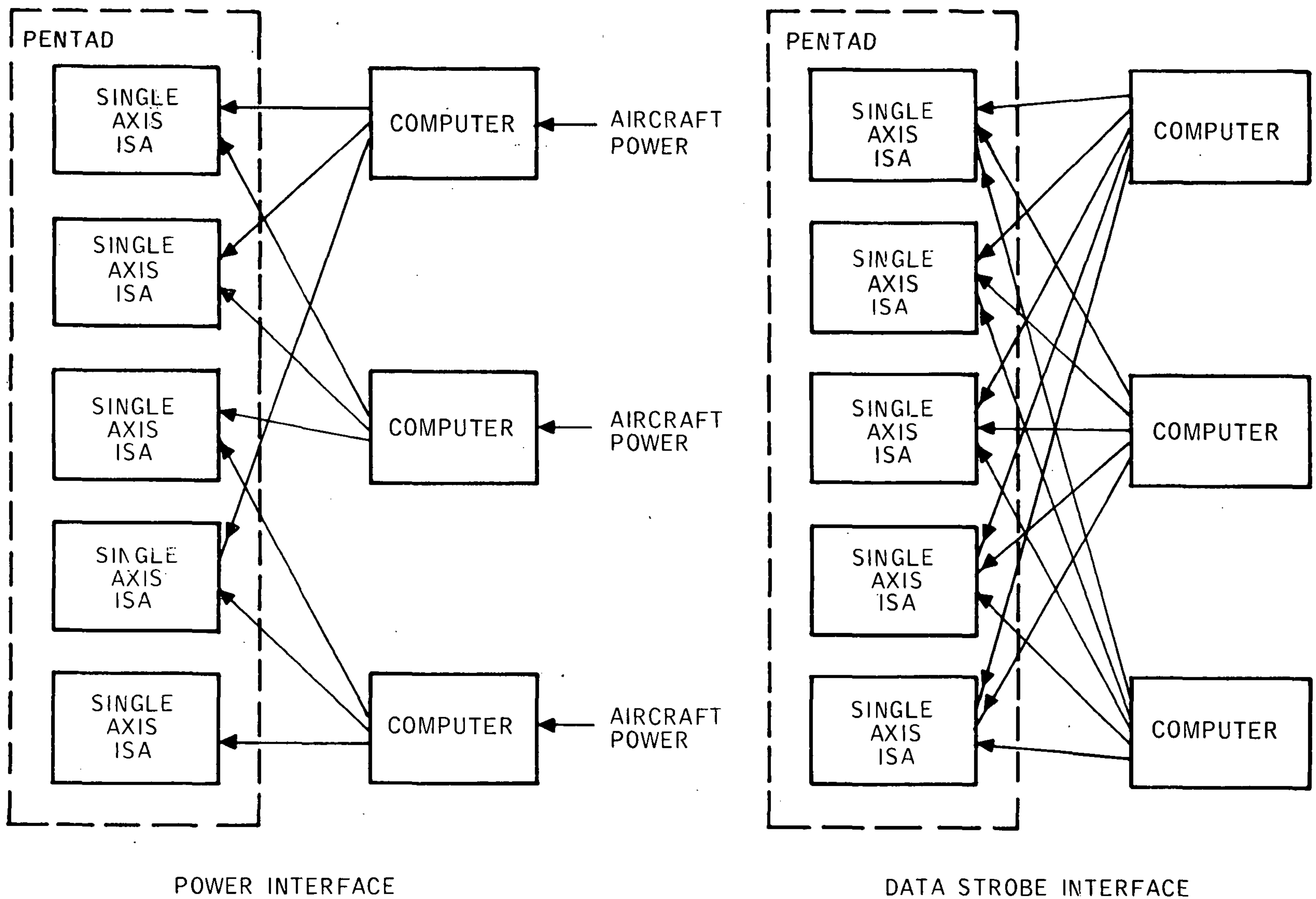


Figure 6. - Pentad System Power and Data Strobe Interface

The orientation of the input axes of the gyro/accelerometer pair in each inertial sensor assembly box (single-axis ISA) in Figure 5 is parallel to the front face of the ISA but skewed 54. 7 degrees relative to the ISA base. The five single-axis ISA's are mounted to a common base in precision alignment such that the long axis of the boxes are skewed relative to one another. Figure 7 illustrates the mounting orientation of the five ISAs.

With the ISA's oriented this way, the gyro/accelerometer sets become aligned to one another such that the input axes of the four sensors formed from any of the four sets of five ISAs are non-coplanar. Under these conditions, software routines in the computer can operate on any one of the tetrad signal sets to analytically compute the equivalent roll, pitch, and yaw axis rate/acceleration data for computer operations. In addition, three of the four tetrad gyro/accelerometer signals can be combined to analytically derive what the fourth sensor set is measuring. If the derived signals are unequal to the fourth sensor set output (within prescribed tolerances), a failure has occurred in one of the tetrad sensors.

With this logic the functional integrity of each of the five tetrads can be assessed. A single failure in the pentad will cause four tetrads to exhibit failures. The fifth tetrad will not exhibit failure, thereby isolating the failed ISA box to the unit not included in the functioning tetrad. Under these conditions, the identified functioning tetrad would be used to derive the roll/pitch/yaw axis data in the computer, thereby allowing proper system operation with one failure. Multiple failure occurrences can also be identified by this approach, but without a corresponding failure isolation. Under these conditions, the computer can be shut down safely and the pilot will be notified of the failure by the appropriate failure status panel lamp. Thus, the pentad geometry provides single fail-operational/fail-safe capability.

Hexad versus pentad configuration. - The six-axis array was chosen for the study because the sensors can be divided into three two-axis packages with the hexad as opposed to five single-axis packages for the pentad. Decreased chassis costs result. Three ISA assemblies in the hexad provides

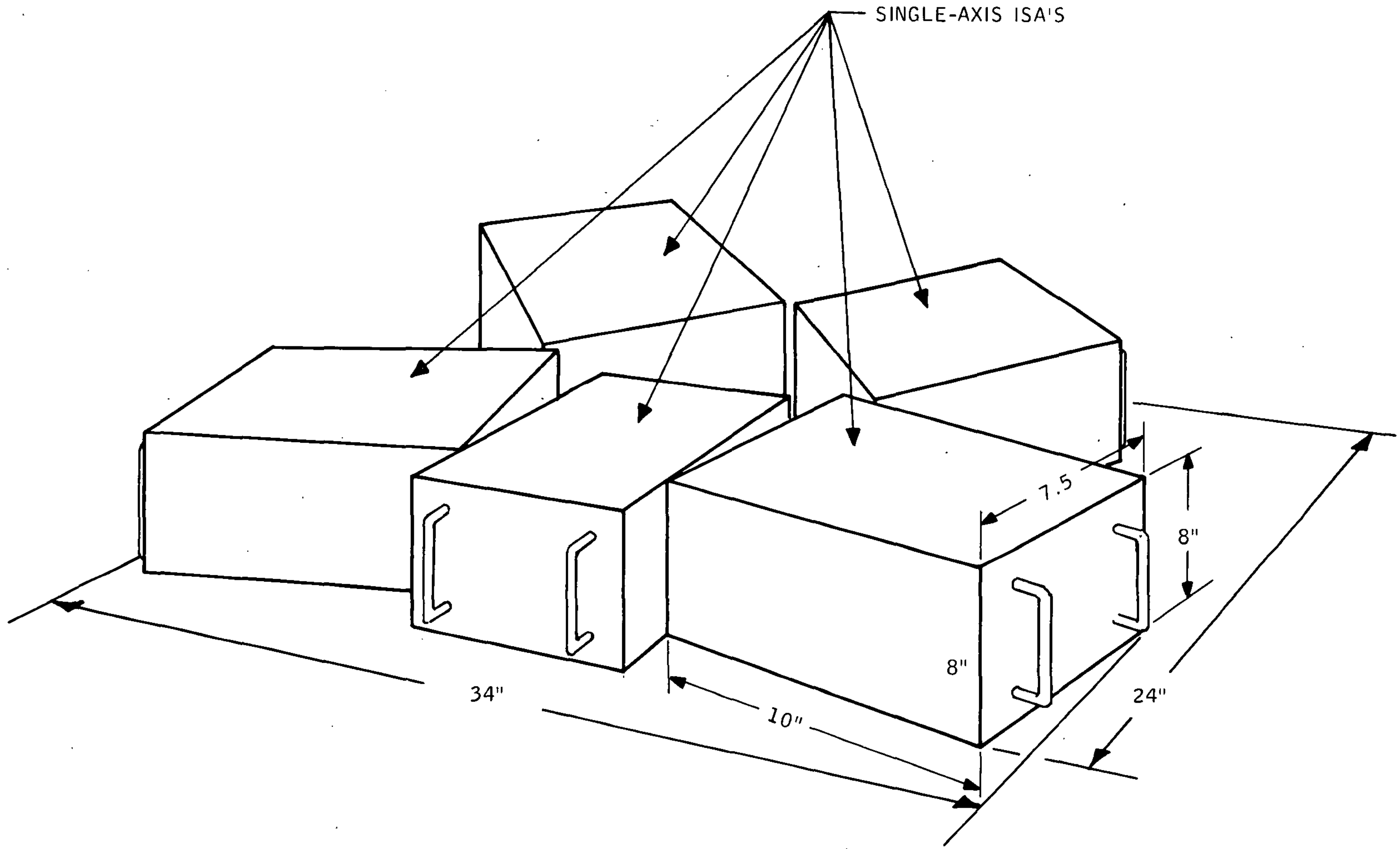


Figure 7. - Pentad Mounting Arrangement

a simple, single interface between any one ISA and one computer for power and data strobe (Figure 2). For the five ISA boxes in the pentad, the equivalent interface in each ISA requires redundancy voting on power and data strobe signals from the three computers (Figure 6). The skewed redundancy logic software for the hexad requires voting between three tetrads; the pentad software requires voting between five tetrads. These combined effects tend to nullify the cost penalty for one additional sensor set for the hexad as compared to the pentad.

The hexad has three technical advantages over the pentad. First, for the hexad, each ISA has one of its sensor axes in the horizontal plane normal to the front face; therefore, each of the three tetrads have two accelerometers nonaligned in the horizontal plane. The horizontal plane acceleration data for each tetrad (the most critical for the inertial computations), therefore, tends to be insensitive to accelerometer scale factor error (low level g's are input on the average in the horizontal plane). Performance is thereby improved for the hexad because not all of its axes are out of the horizontal plane and are not continuously exposed to nearly 1 g. The second advantage is the added redundancy provided by the hexad, which allows system operation with multiple failures in any one ISA. The third advantage is in the physical installation of the ISA boxes. As can be seen in Figure 3, the three interchangeable two-axis ISA boxes for the hexad can be easily installed or removed from one side of a side-wall mount. For the pentad (Figure 7), such an arrangement is not possible if the five single-axis ISA's are to be identical (interchangeable). The mounting arrangement for the pentad ISA's would require installation from all sides (or from the top) of a floor mount. Such an installation is very inconvenient.

Two-Axis Inertial Sensor Assembly (ISA)

Figure 8 is a functional block diagram of one of the three identical two-axis ISA's used in the hexad sensor array showing the data flow to the interface with the three redundant computers. Each ISA contains two

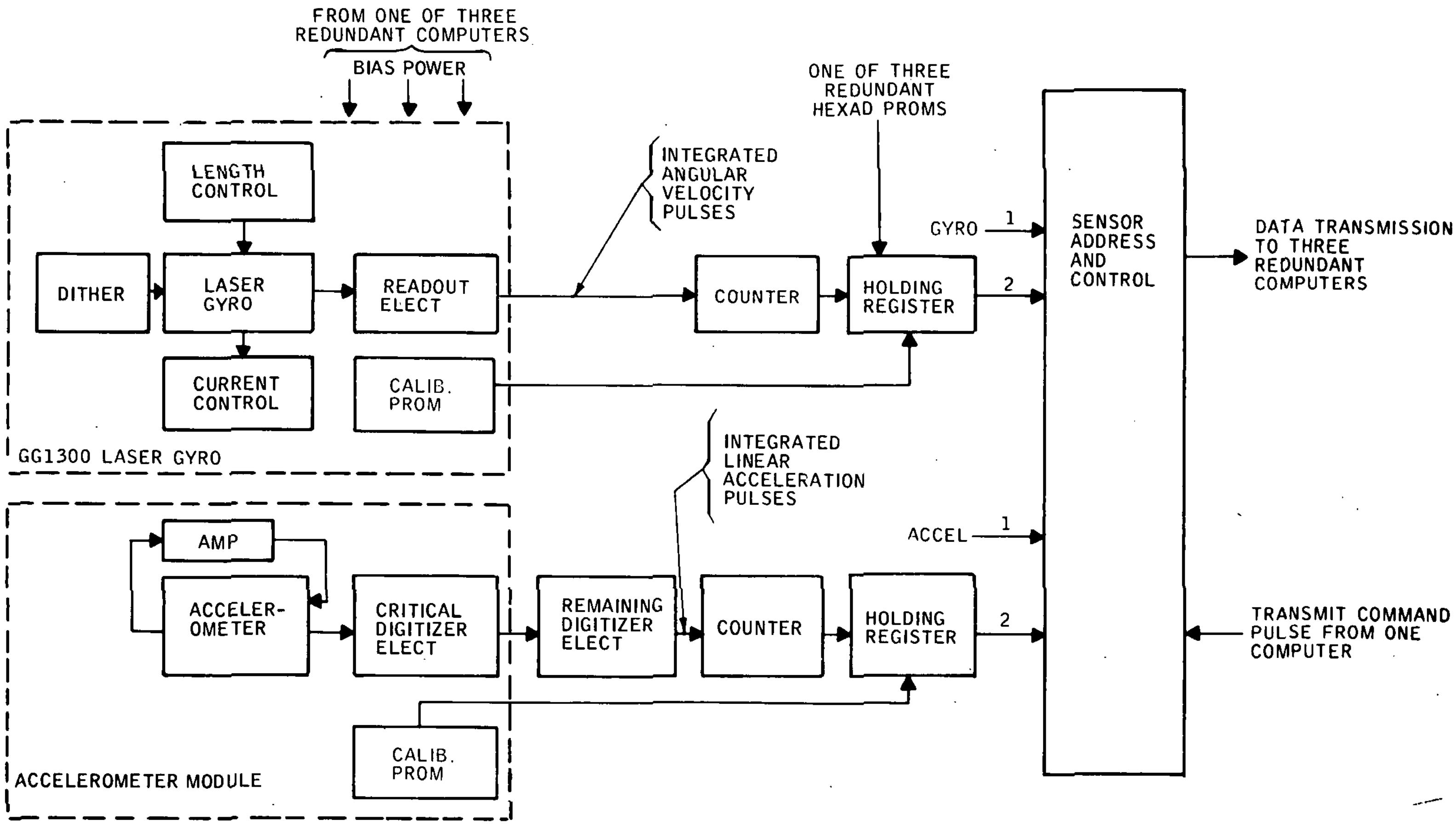


Figure 8. - Two-Axis ISA Functional Block Diagram

Honeywell GG1300 laser gyros, two accelerometer modules, pulse accumulator electronics for each channel, and computer interface electronics. Bias power for the ISA is provided by one of the three redundant computers (See Figure 2).

The laser gyros and accelerometer modules identified in Figure 8 are identical single-unit assemblies that are physically interchangeable in each of the two ISA axis channels and between ISA's. The output from the accelerometer contained in the accelerometer module is an electrical current proportional to sensed input axis linear acceleration. This signal is input to digitizer electronics within the accelerometer module to quantize the continuous analog electrical signal into digital incremental pulses. Each pulse represents the accumulation of a fixed increment of integrated linear acceleration. The output signals from the laser gyro are in a similar digital pulse format, each representing the accumulation of a fixed increment of integrated input axis angular rate.

Calibration data (fixed bias, scale factor error, and alignment errors) are included in each laser gyro and accelerometer module in a Programmable Read Only Memory (PROM) element for sensor input data compensation in the computer (See Figure 4). The PROM calibration data is read into each of the three redundant computers as part of normal preflight alignment procedures. Also read into each computer is calibration data from one of the three triple redundant PROM's attached to the hexad mounting plate containing known misalignments for the three ISA mounts. The PROM calibration concept provides a complete module interchangeable capability without accompanying software changes and without requiring sensors to be dedicated to particular mounting blocks or ISA's.

The pulses from each sensor are accumulated in an up-down counter for each channel. All counters are simultaneously strobed/cleared into holding registers at regular intervals by one of three redundant system computers (See Figure 2). Under computer clock control, the sensor address and control electronics then serially transmit the pulse counts from each sensor holding register into each of the three redundant computers simultaneously. The data transfer is repeated three times and completed before the next data strobe pulse is provided by the computer. During the data transfer period, sensor pulse counters accumulate data for the next data transfer to be initiated by the next computer strobe pulse. The three sequential transmissions are provided such that each of the three redundant computers can read the data from each of the three ISA's sequentially.

Figure 9 is a cutaway drawing illustrating the overall packaging arrangement for the two-axis ISA. The ISA consists of two GG1300 laser gyros, two accelerometer modules, a sensor module mounting block, a plug-in card assembly, and a chassis with associated wiring. The accelerometer module contains one accelerometer, and that portion of the digitizer electronics (Figure 8) that is performance calibrated to the particular accelerometer in that module. Estimated weight for the two-axis ISA is 35 pounds.

The laser gyros do not require temperature control,and perform satisfactorily mounted to the main mounting block structure. The accelerometer is chosen for compatibility with the laser gyro to perform within required inertial navigation accuracy specifications over the anticipated range of operating temperatures without temperature controls. Thus, the ISA does not require heaters, and warm-up delays normally associated with inertial systems are, thereby, eliminated. The low power (28 watts) dissipation within the ISA will permit satisfactory operation in commercial aircraft maximum temperature ambient environments (130°F) without special cooling provisions.

The ISA counter, holding register, address and control, and nonperformance critical accelerometer digitizer electronics (Figure 8) are mounted on plug-in cards. The interface wiring for the plug-in cards is through a wire-wrap baseplate.

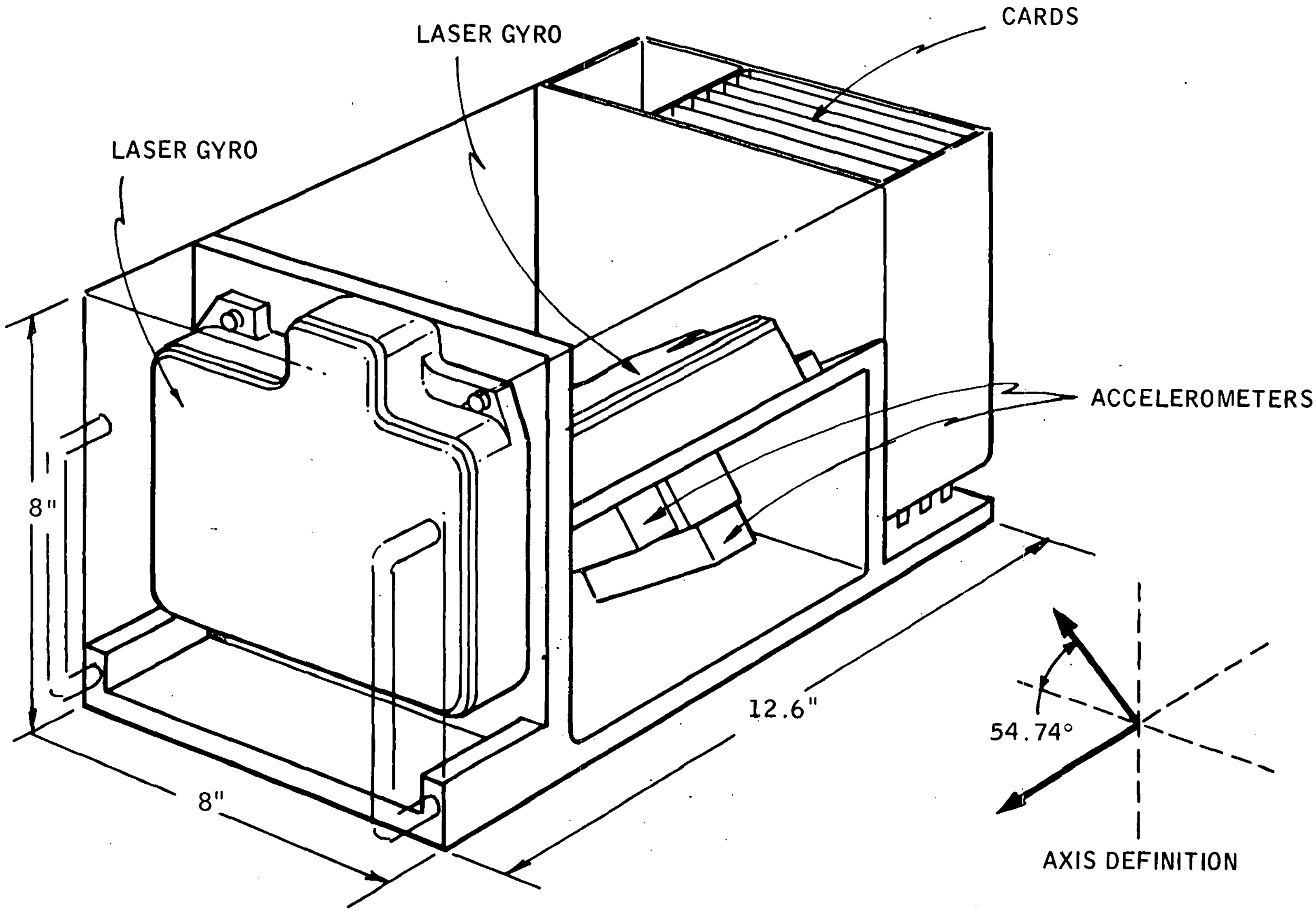


Figure 9. - Laser Two-Axis ISA

SECTION II
SYSTEM CONFIGURATIONS INVESTIGATED

Kinematic Systems

Kinematic System K-1. - The traditional kinematic system, K-1, investigated in the study supplies triple redundant heading, attitude (pitch and roll), orthogonal body rates (roll, pitch, and yaw), and orthogonal body acceleration signals to multiple flight control electronic packages and cockpit instruments. Figure 10 is a block diagram and pictorial drawing of System K-1. This system is considered to be generally applicable to short-haul aircraft.

The K-1 system contains triple redundant attitude gyros for pitch/roll attitude, compass systems (flux gate, directional gyro, and compass coupler) for heading, three-axis (roll, pitch, and yaw) rate gyros, and three-axis (longitudinal, lateral, and lift) accelerometers. The K-1 system in conjunction with a comparison voter located in the redundant aircraft flight control equipment, which is supplied with K-1 outputs, can be considered capable of satisfying a fail-operational/fail-safe redundancy requirement.

Kinematic System K-2. - The traditional fail-operational/fail-safe K-1 system can be replaced by a laser strapdown hexad (three two-axis ISA's) and three inertial calculation (IC) computers. This K-2 system supplies the same output signals (heading, attitude, body rate, and body acceleration) as does the traditional kinematic system, but the strapdown signals from K-2 are more accurate than those supplied by the traditional kinematic system. Also,aircraft velocity and position information is available, if desired, for navigational outputs.

Figure 11 is a general block diagram and pictorial drawing of the K-2 strapdown kinematic system. The details of hexad strapdown systems and their internal ISA/computer interfaces were described in Section I. The

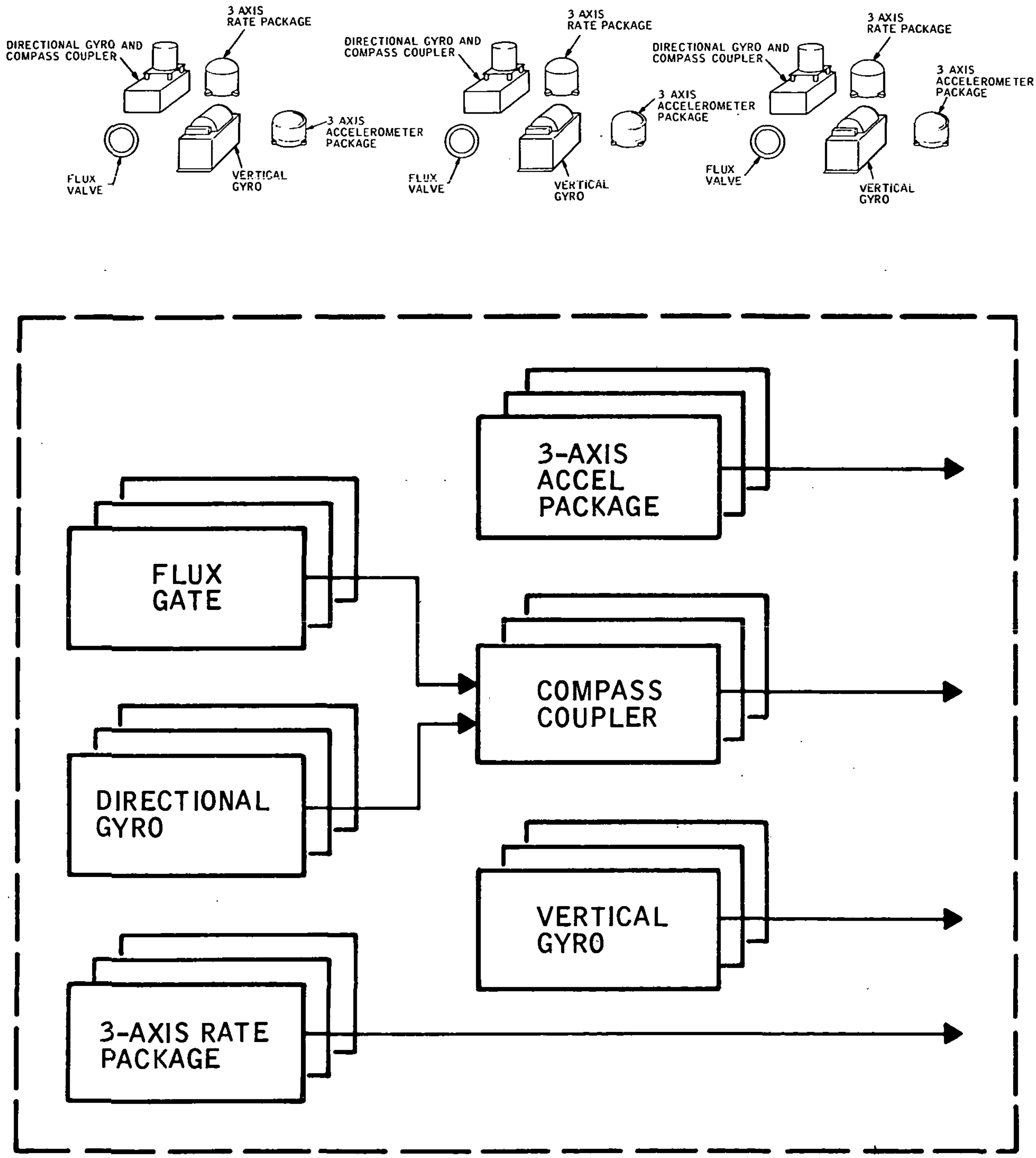


Figure 10. - Traditional Kinematic System

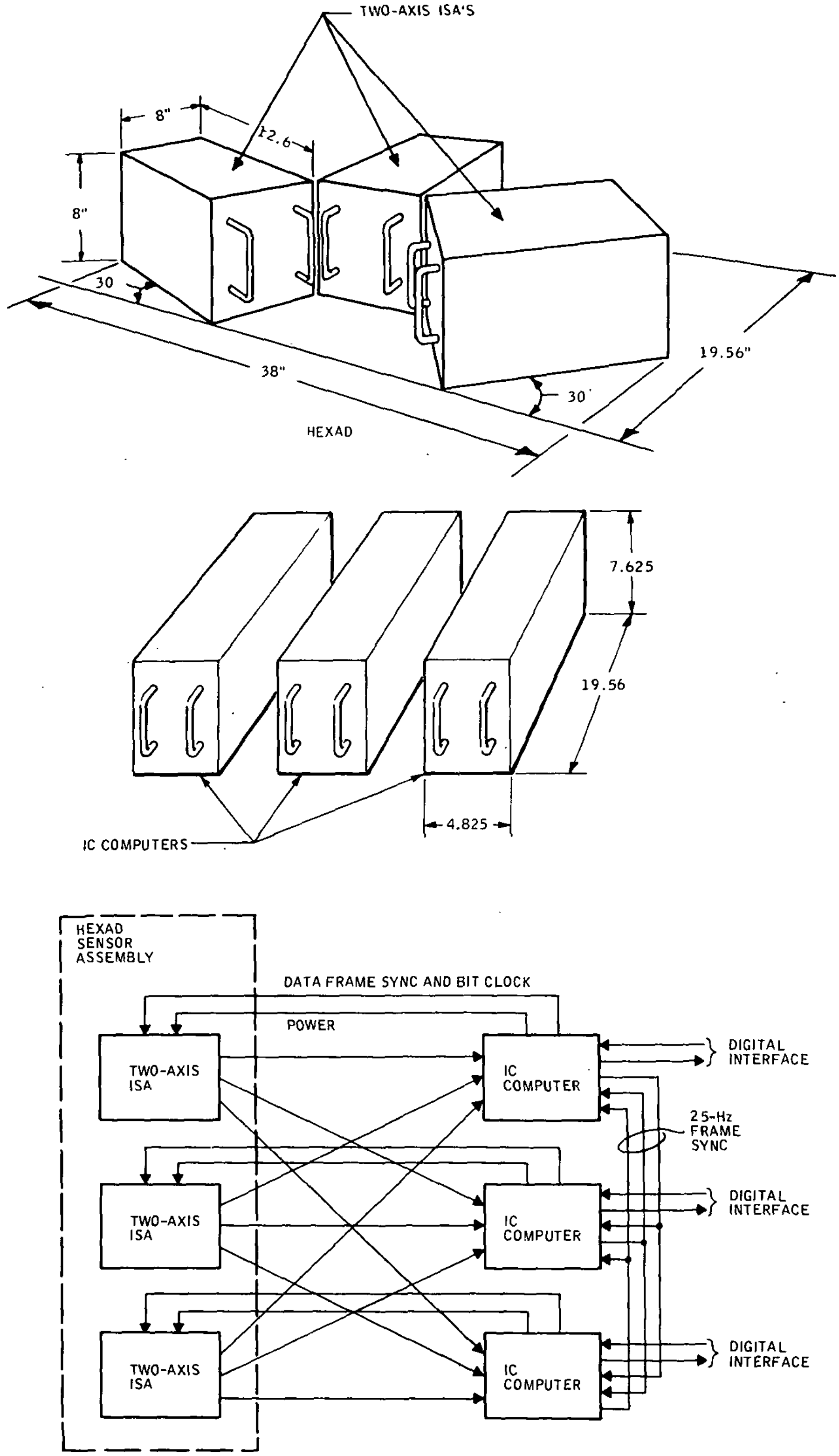


Figure 11. - K-2 Strapdown Kinematic System

particular strapdown K-2 System output interface to aircraft flight control systems is serial digital.

System K-2 computer: A functional block diagram of the System K-2 inertial calculations (IC) computer is given in Figure 12. The processing section of the computer was assumed to be mechanized with state-of-the-art MOS LSIC circuit technology; the Honeywell HDC-301 central processor unit and associated MOS semiconductor memory was used as a model for the processing section. One HDC-301 processor with 4000 words of memory (two HDC-301 memory cards) can perform the inertial computation function for System K-2. (Computation details were given in Section I.)

The Honeywell HDC-301 is a general purpose, medium speed, MOS LSIC digital processor designed for aircraft application. It is composed of 16 LSIC and 21 standard logic electronic piece parts mounted on a single 6.45-inch, plug-in, multilayer printed circuit board. Table 1 summarizes the salient characteristics of the HDC-301.

The principal I/O device for the System K-2 computer is a serial digital interface module that takes in serial data from the three two-axis ISA's under computer control. The computer ISA data control function provides a 200-Hz data sample strobe pulse and a 125-kHz clock to one of the three ISA's for serial data word transmission (see Figure 11). The serial digital interface module contains the logic to receive the data sets from each of the three ISA's (transmitted three times in succession), decode each sensor word for each ISA for one of the transmission times, and enter the word in memory. An additional function of the serial digital interface is to provide an interface with the pilot control panel for mode selection.

A timing and synchronization module is provided for overall I/O control/synchronization and for generating a 25-Hz real time clock for the computer. This clock is voted against similar clocks from the other two redundant computers to obtain a synchronized 25-Hz computation cycle clock, and 200-Hz and 125-kHz clocks are generated for the ISA interface synchronized to the 25-Hz synchronous clock.

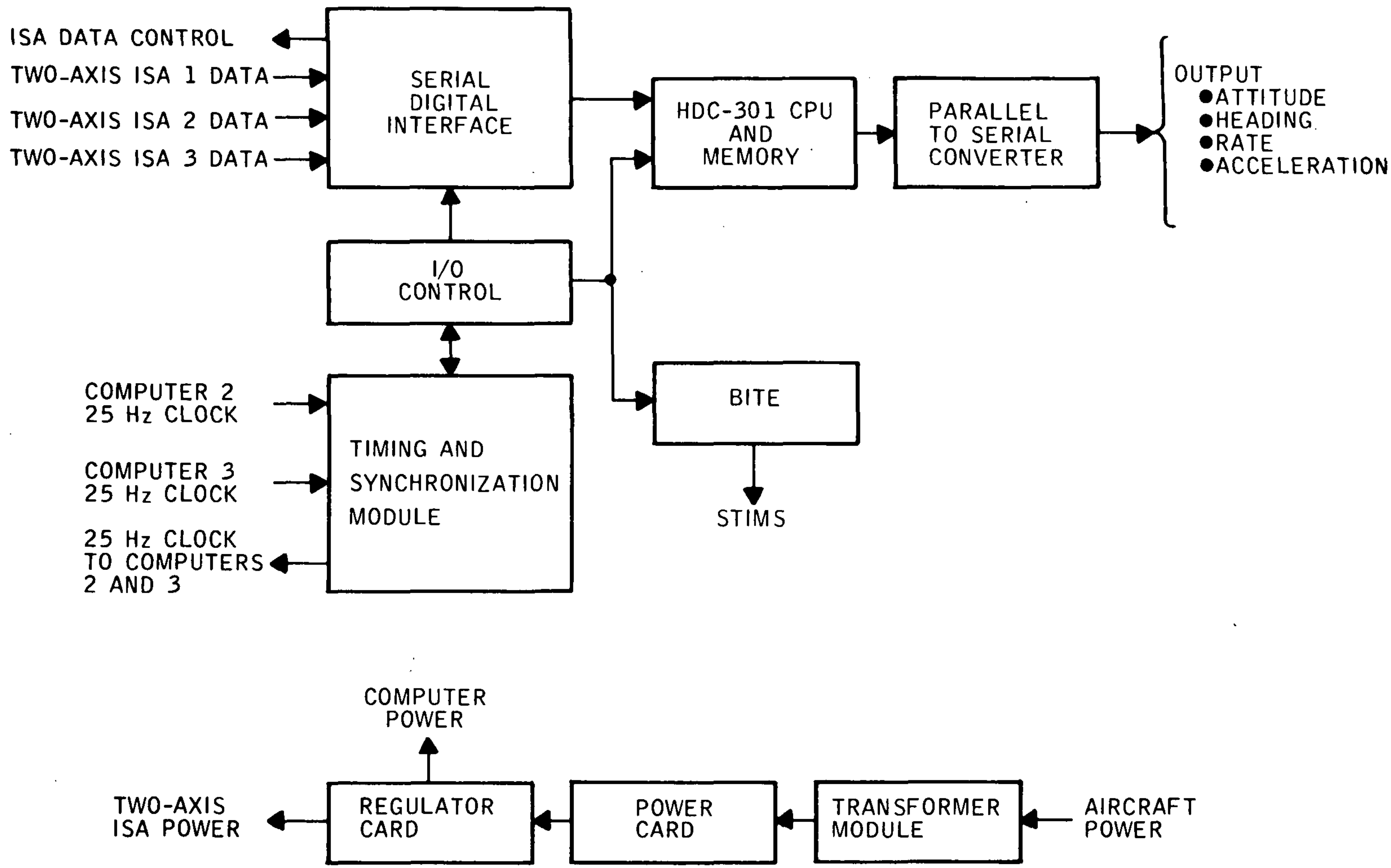


Figure 12. - K-2 System IC Computer

TABLE 1. - HDC-301 CHARACTERISTICS SUMMARY

Organization	• General purpose, stored program • 16 bit, parallel • Double precision arithmetic • 47 Instructions • One hardware index register
Circuits	• Custom two-phase dynamic P-MOS large scale integrated circuits (LSIC's)
Operational speeds	• 1-megahertz clock • Add - 5 microseconds • Multiply - 21 microseconds • Divide - 65 microseconds • Double precision add - 10 microseconds • Two-phase clocking
Input/output	• 16-bit parallel input • 16-bit parallel output • Discrete inputs and outputs • 1 system interrupt bus • 1 power recovery interrupt

An output module is provided to convert the computer digital outputs from a 16-bit parallel word to a 16-bit serial word for transmission to other devices over a minimum number of wires. A power supply consisting of a transformer module, power card, and regulator card converts aircraft unregulated input power to regulated voltages which are required by the computer electronics. The computer supply also provides regulated power to one of the three ISA's.

BITE (Built-In-Test-Equipment) circuitry is provided in the IC computer to verify proper operation of computer functional elements through measured responses to stimuli applied to the I/O and through HDC-301 processor/memory operation checks.

The computer electronics circuits are packaged on plug-in circuit cards and/or on modules and are mounted in a standard one-half long ATR chassis. Each of the three redundant IC computers are identical and are interchangeable. System differences in the ISA interface would be implemented through the ISA/computer interface wiring. Each computer chassis contains 12 circuit cards and a power supply module.

System K-2 redundancy management concept: To provide the equivalent fail-operational/fail-safe redundancy capability as System K-1, System K-2 incorporates a redundancy management approach that encompasses three elements: power supply redundancy, ISA input data synchronization, and computation cycle synchronization.

The power supply redundancy management scheme is straightforward for the hexad configuration. The power supply in each computer also powers one of the two-axis ISA's. Therefore, a single power supply failure would affect one ISA and one computer, and the resulting degraded computer output would be detected and isolated by comparison monitors in the aircraft flight control equipment. The remaining two computers would still read all three ISA's, but would flag an ISA failure, reject the data from the failed ISA, and use the remaining two two-axis ISA's. A second power supply failure would affect a second ISA and computer channel. This would be detected by the flight control comparison monitor allowing safe shut-down of the flight control system.

Input data from the skew redundant sensor configuration is synchronized to ensure that each computer receives identical data. This allows each computer to make identical failure decisions, to select identical inputs for the inertial computations, and to provide identical outputs. All of the ISA output data is strobed into each computer at 200-Hz via a 125-kHz clock that is derived from a 2-Mhz oscillator located in each computer. The 200-kHz and 125-kHz clocks are synchronized between computers by means of their derivation from a 25-Hz clock that is vote synchronized between computers (See Appendix B for details).

Each computer strobes one ISA. When the ISA receives the 200-Hz data request strobe, it transmits its data three times to all three computers (at a 125-kHz bit transfer rate). Each computer, then, serially receives the data from the three ISA's sequentially during the three transmission periods. Because each computer inputs data from all three ISA's, identical data is received from the ISA's by each computer. The voted 25-Hz clock is used to synchronize the 200-Hz and 125-kHz data transfer pulse generators to prevent a continuing divergence between the 200-Hz data request strobes in each ISA.

Computer computation cycle synchronization consists of simultaneously restarting each computer at the 25-Hz computation cycle rate from a "halt" condition entered at the end of the previous computation cycle, using the 25-Hz synchronous clock.

Kinematic System K-3. - Kinematic System K-3 is functionally identical to System K-2; the only difference is in packaging. In System K-3, each computer and one of the two-axis ISA's is packaged in a single housing as opposed to separate housings as in System K-2. The interface is simplified and three ATR housings are eliminated.

A standard, long ATR chassis is required to house each of the System K-3 triple redundant two-axis ISA/IC computer assemblies. Figure 13 shows the resulting growth in mounting area that is required for the K-3 skewed orientation compared to the System K-2 skewed ISA's. The 19.56-inch installation dimension shown for the K-2 system ISA's is the maximum ATR chassis length and typical installation mounting depth permitted by ARINC. The 30-inch installation dimension shown for the K-3 system would require special mounting shelves. To maintain alignment between the two-axis ISA's, the skewed assemblies must remain rigid relative to each other. This is more difficult for the large System K-3 mounting area.

If the 19.56-inch maximum ARINC length standards are followed for the ATR installation racks, the height of each System K-3 chassis must be made larger to accommodate the required length decrease. This appears to be a more reasonable approach as the modification to the standard size electronic racks would, thereby, be minimized. Alternately, a vertical stacking mount could possibly be used with the 19.56-inch size K-3 assemblies to remain within a 19.56-inch installation mounting depth constraint. Further study is required to define configuration options and installation/packaging penalties associated with System K-3 compared to System K-2. The cost benefits (given in Section III) for System K-3 compared to K-2 must be weighed against these packaging penalties before a recommendation of the preferred configuration could be made.

Flight Control Systems

Figure 14 depicts the configuration of the traditional short-haul commercial aircraft flight control system assumed for the study. The dotted line outlines the System FC-1 flight control hardware assemblies analyzed in the study for cost comparisons to the equivalent strapdown mechanization. Items outside the dotted line are common to both alternatives. The System FC-1 configuration in Figure 14 interfaces a traditional K-1 kinematic system with a triple redundant flight control computer.

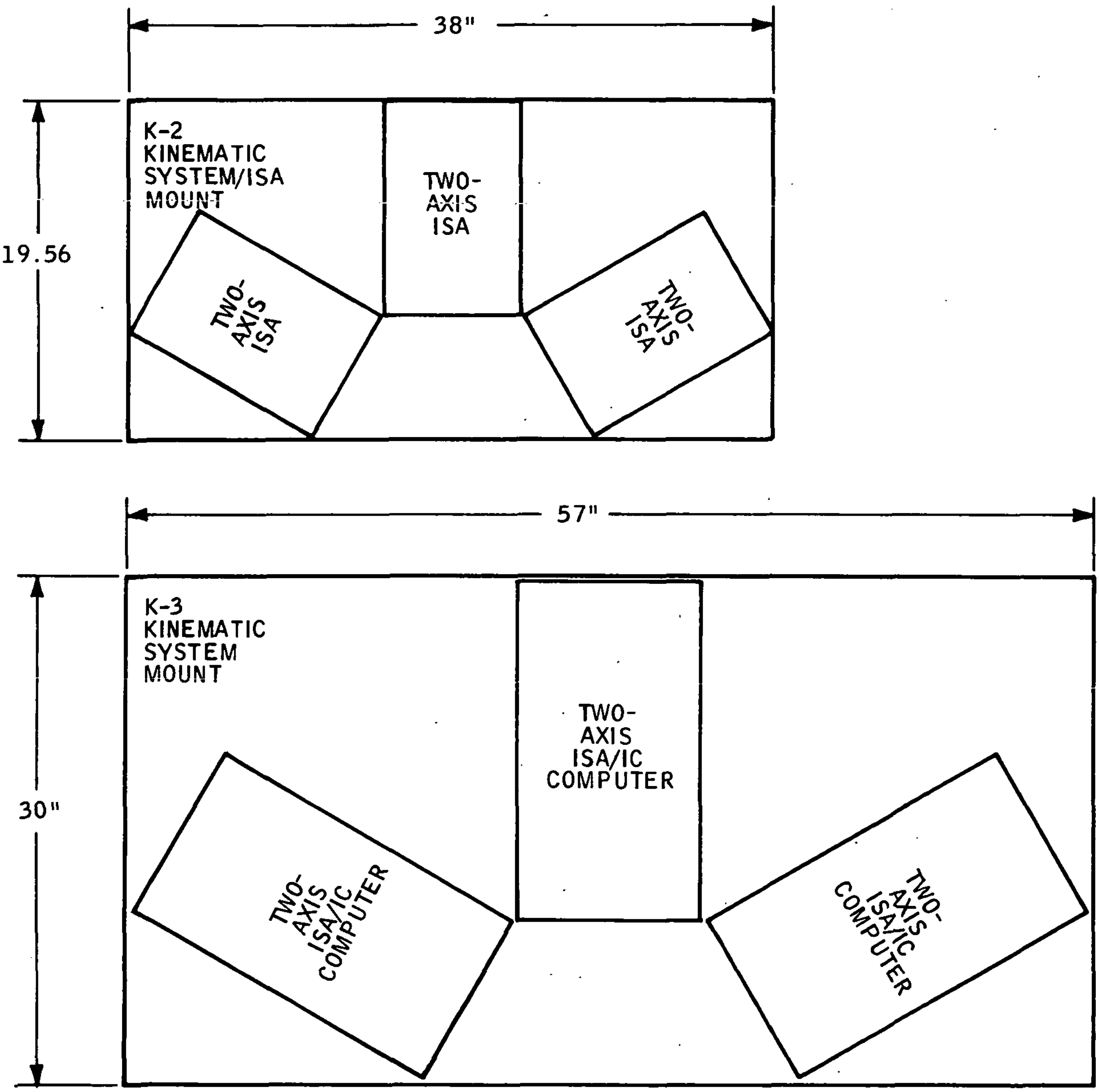


Figure 13. - K-3 Integrated ISA/Computer Skewed Mounting Requirements

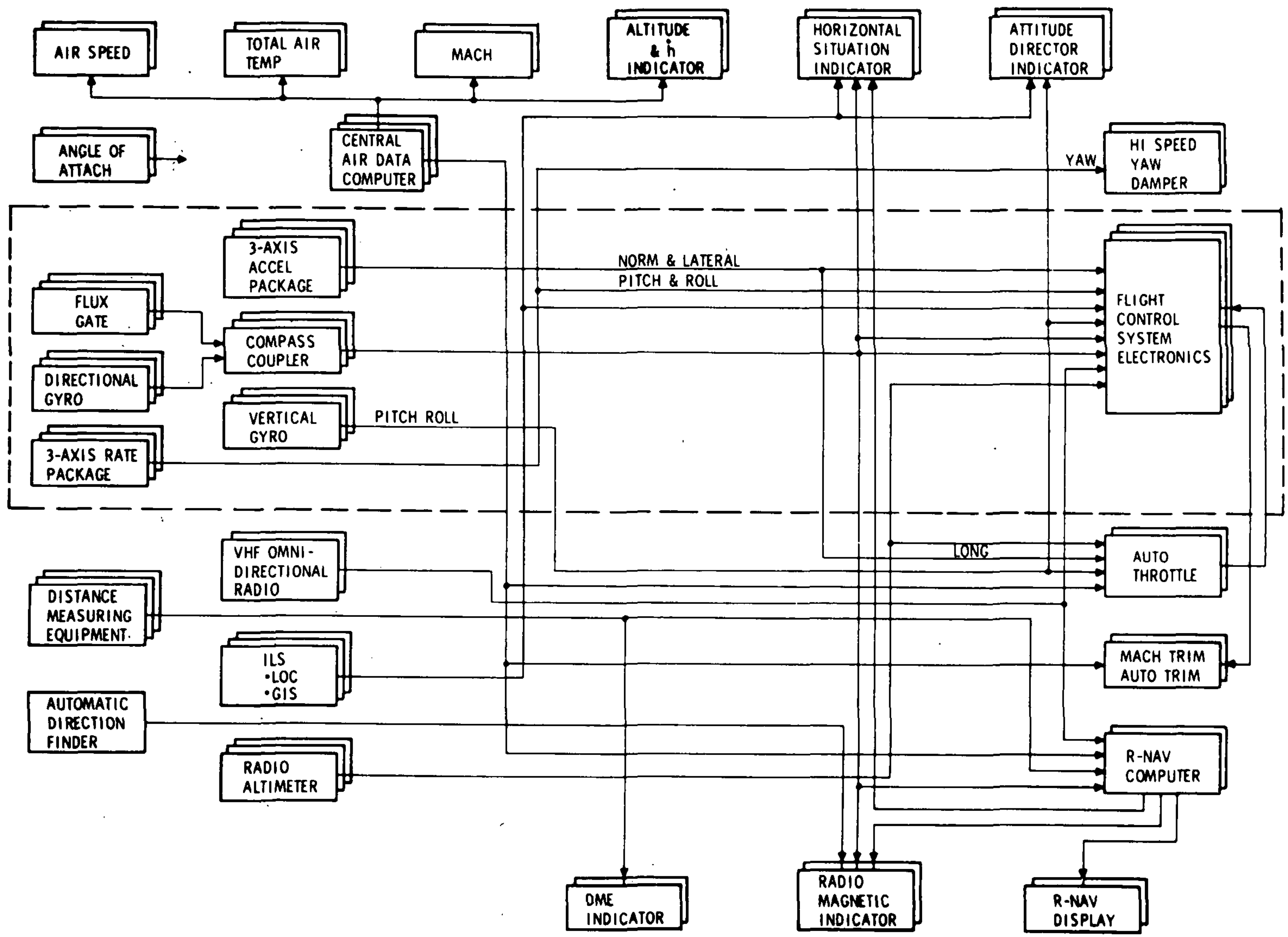


Figure 14. - Traditional Commercial Aircraft Flight Control System

Figure 15 shows the same basic flight control system using a strapdown skewed redundant mechanization for the outlined items. The system in Figure 15 contains a hexad ISA and associated triple redundant inertial computation (IC) computers to provide the required signals to the flight control computers. Three different versions (Systems FC-2, FC-3, and FC-4) of the outlined assemblies in Figure 15 were analyzed in the cost comparison to System FC-1. These three versions differ in where the inertial computations computer is housed: separately, with the flight control computer, or with the ISA's.

At present, there is no requirement for inertial navigation equipment on short-haul aircraft. The navigation function is normally handled by the radio-navigation computer and/or its related sensors. It should be noted, however, that inertial velocity and position information is available in the IC computer as part of normal attitude reference calculations and this information can be used, if desired, as an aid or, possibly, as a replacement for the R-Nav computer.

Flight control system FC-1. - The area within the dotted lines of Figure 14 is a hardware block diagram of the traditional flight control system FC-1 showing the signal interface between the system assemblies and external aircraft systems. The traditional kinematic system, K-1, is included as the sensing assembly in System FC-1.

System FC-1 computer: A functional block diagram of the FC-1 flight control (FC) computer is presented in Figure 16. Computer inputs are d-c signals, a-c signals, and discretes from the system sensors and other aircraft systems. Outputs from each computer are d-c control signals and discretes to other aircraft systems plus intercommunications (clock and data crossfeed) between the redundant computer channels for redundancy.

The redundancy management functions implemented in each computer are identical and are designed to ensure that each computer operates simultaneously on the same set of data. Deviations in the redundant computer

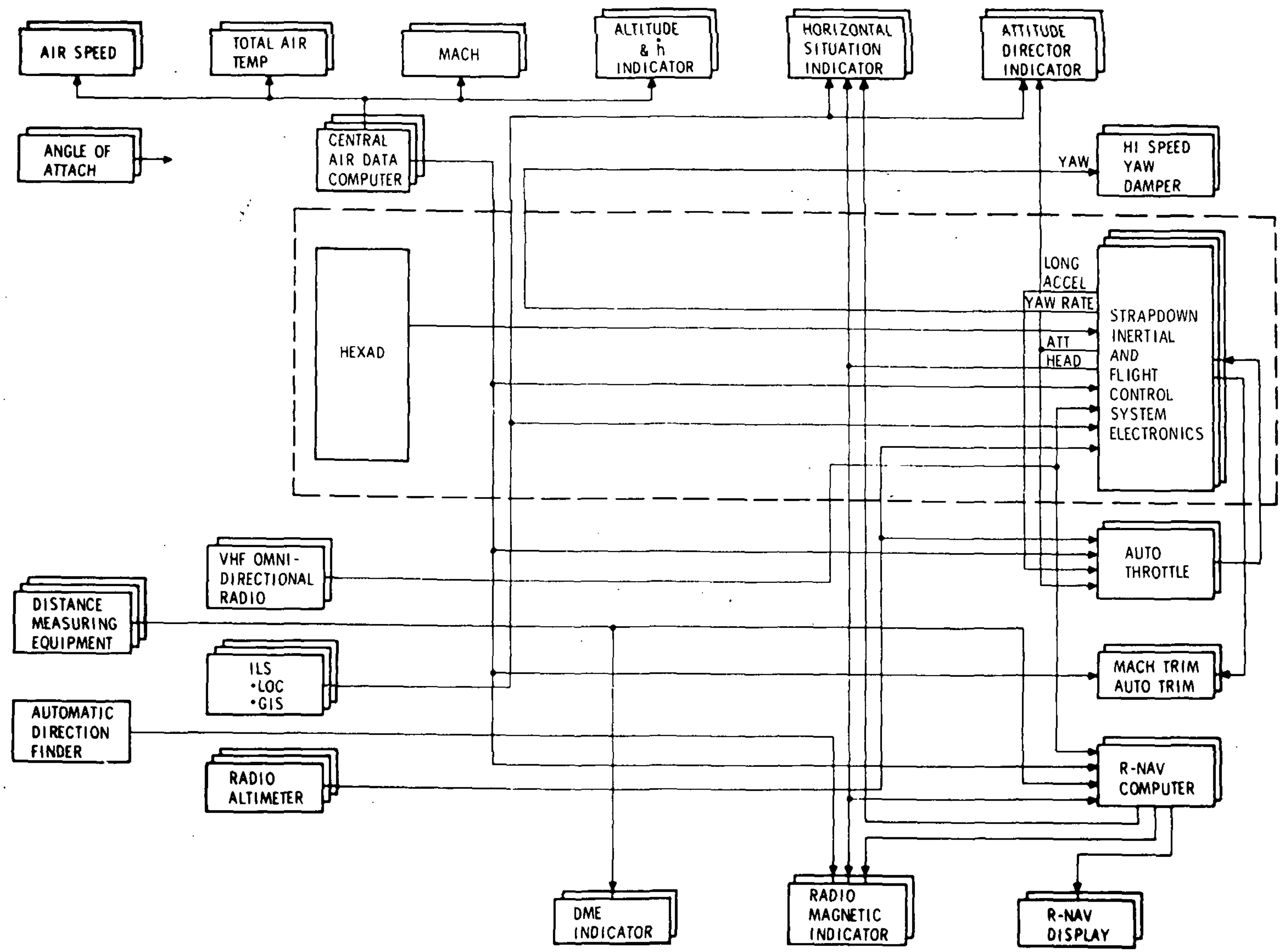


Figure 15. - Skewed Redundant Commercial Aircraft Flight Control System

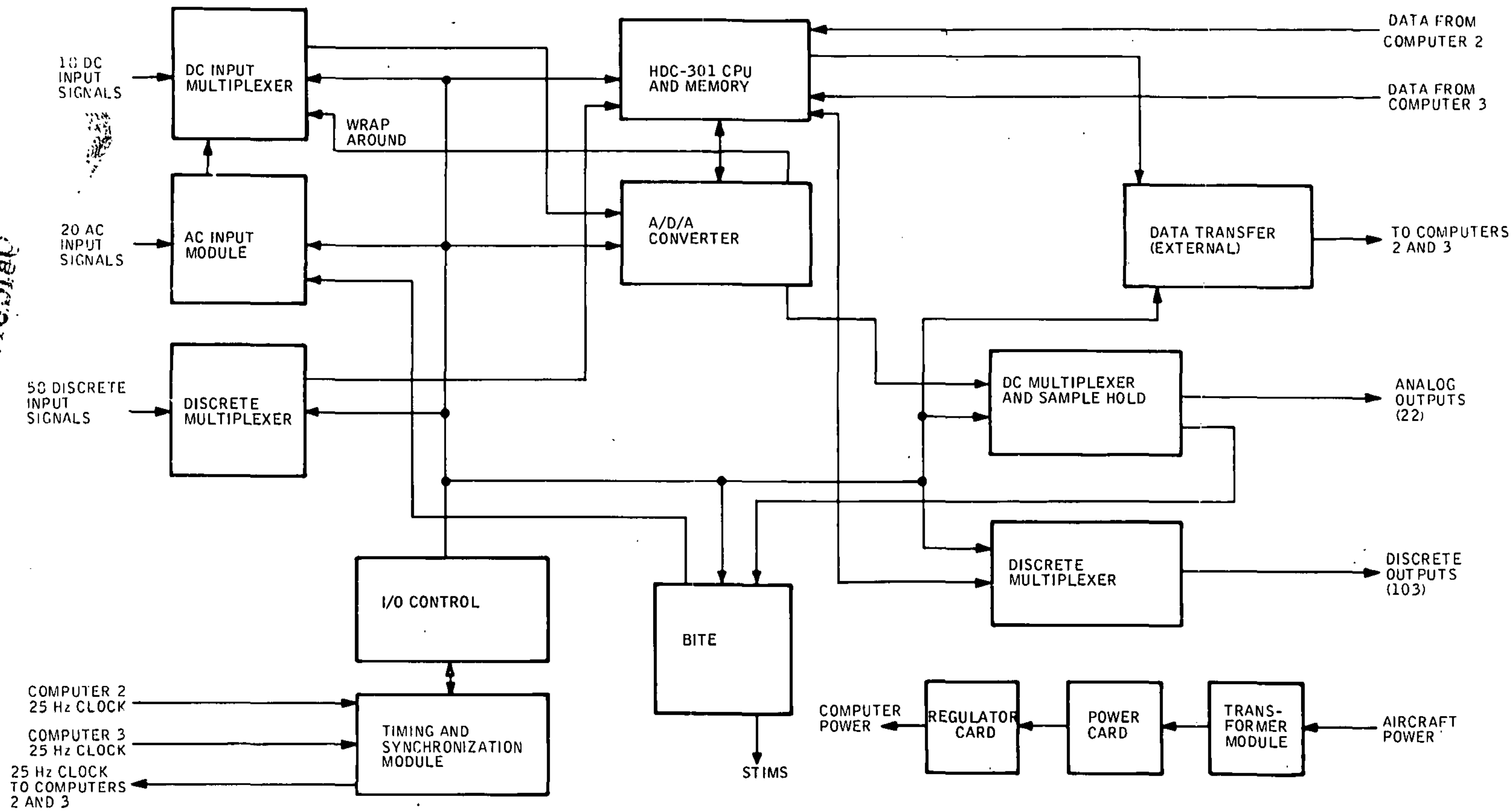


Figure 16. - FC-1 System FC Computer

outputs can, thereby, be clearly identified as computer failures. This is achieved by transferring the flight control signals from each computer to all computers and voting between these signals in each computer using a common voting law. An additional function of the redundancy management routine is to identify failures in redundant input signals by redundancy voting for output to the failure status panel.

The computer uses a Honeywell HDC-301 central processor with a MOS semiconductor memory. The flight control computations require approximately 8000 words of memory, which is approximately four HDC-301 memory cards.

Actual FC computer interface requirements will vary from aircraft to aircraft. An arbitrary group of input/output (I/O) modules have been assumed for costing purposes. These modules consist of a d-c input multiplexer, an a-c input module, and a discrete multiplexer for aircraft and sensor/computer input signals. For computer/aircraft output signals, they consist of a d-c multiplexer and sample hold, and a discrete multiplexer. These I/O devices all interface with the HDC-301 either directly or through an analog-to-digital-to-analog (A/D/A) converter module. The remaining I/O device is an external data transfer module that allows the exchange of data, taken in through I/O, between computer channels for redundancy voting (See Figure 16).

An I/O control module is included in the FC computer for overall I/O control and synchronization. A timing and synchronization module is provided for generating a 25-Hz real time clock for the computer and for voting this clock against similar clocks from the other two redundant computers to obtain a synchronized 25-Hz clock (See Appendix B for details). The 25-Hz synchronized clock is used through the I/O control module for initiating each 25-Hz computation iteration cycle. In this manner, all redundant computers are synchronized to the same time base every 40 μsec.

A power supply consisting of a transformer module, power card, and regulator card converts aircraft unregulated input power to regulated voltages which are required by the computer electronics. Built-in test equipment (BITE) circuitry is provided in the FC computer to verify proper operation of computer functional elements through measured responses to stimuli applied to the I/O and through HDC-301 processor/memory operation checks.

The FC computer electronics circuits are packaged on plug-in circuit cards and/or modules and are mounted in a standard three-fourths long ATR chassis. Each of the three redundant FC computers is identical and interchangeable. Each computer chassis has space for approximately 30 circuit cards plus a power supply module. The FC computer uses 22 circuit cards.

Flight Control System FC-2. - The FC-2 flight control system consists of a K-2 strapdown kinematic system interfaced with triple redundant flight control computers. The FC-2 flight control computer is almost identical to the computer in the FC-1 system. The difference is the added serial digital interface I/O in the FC-2 system, which takes in the digital kinematic sensor data, and the elimination of the a-c and d-c input signals previously assigned for traditional kinematic sensor inputs. Figure 17 depicts the FC-2 system FC computer.

Flight Control System FC-3. - System FC-3 is a packaging variation of System FC-2. For this configuration, each IC computer in the kinematic system has been packaged with one of the two-axis ISA's as described previously for System K-3. The flight control computer is identical to the computer used in System FC-2. Thus, System FC-3 is composed of a K-3 kinematic system in conjunction with triple redundant FC-2 flight control computers.

As discussed in the subsection on the K-3 kinematic system, the cost benefits of combining the IC computers and two-axis ISA's would have to be weighed against the problems associated with the resulting larger skewed assemblies before a recommendation could be made between the FC-2 and FC-3 flight control configurations.

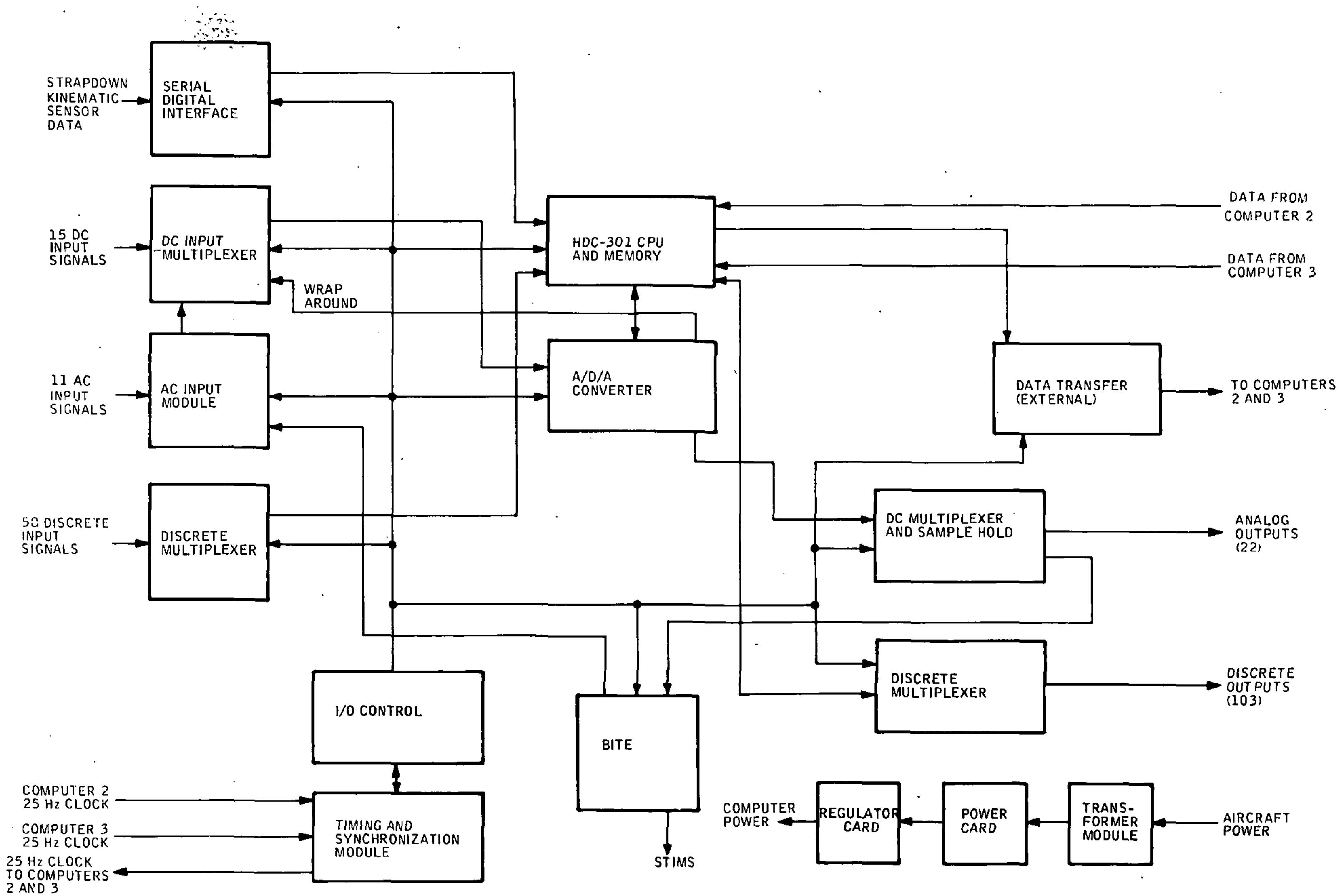


Figure 17. - FC-2 System FC Computer

Flight Control System FC-4. - System FC-4 is another packaging variation of System FC-2. In FC-4, each IC computer in the kinematic system is housed in a common chassis with one of the flight control computers. The hexad ISA's used with the integrated inertial calculations/flight control (IC/FC) computers are identical to the K-2 kinematic system ISA assemblies.

Kinematic systems are "dispatch critical"; that is, they must be operating to dispatch the aircraft. (Appendix C gives a definition of dispatch critical assignments for all flight control equipment considered in the study.) Flight control computers alone are not dispatch critical; however, they become dispatch critical when combined with the dispatch critical IC computers. Further cost studies would have to be made to determine if the cost savings for the FC-4 configuration compared to the FC-2 or FC-3 configurations is offset by delay costs incurred in servicing the dispatch critical IC/FC computer during normal flight operations.

System FC-4 computer: A functional block diagram of the integrated IC/FC computer used in System FC-4 is presented in Figure 18. The FC-4 computer is essentially a superposition of the FC-2 flight control (FC) computer (Figure 17) and the K-2 inertial calculations (IC) computer (Figure 12).

The FC-4 computer utilizes two Honeywell HDC-301 central processors, each with individually dedicated MOS semiconductor memories. A data transfer card is included between the 301 processors to enable interprocessor communications as an internal I/O function. One of the 301 processors is dedicated to the hexad inertial computation section (ICS) functions; the other 301 processor comprises the flight control computation section (FCCS). I/O and memory modules are dedicated to each of the 301 processors shown in Figure 18 to perform the ICS and FCCS functions.

The I/O control module for the integrated IC/FC computer provides the overall I/O control and synchronization for both the ICS and FCCS. The I/O, memory timing, and synchronization implementation for the ICS and

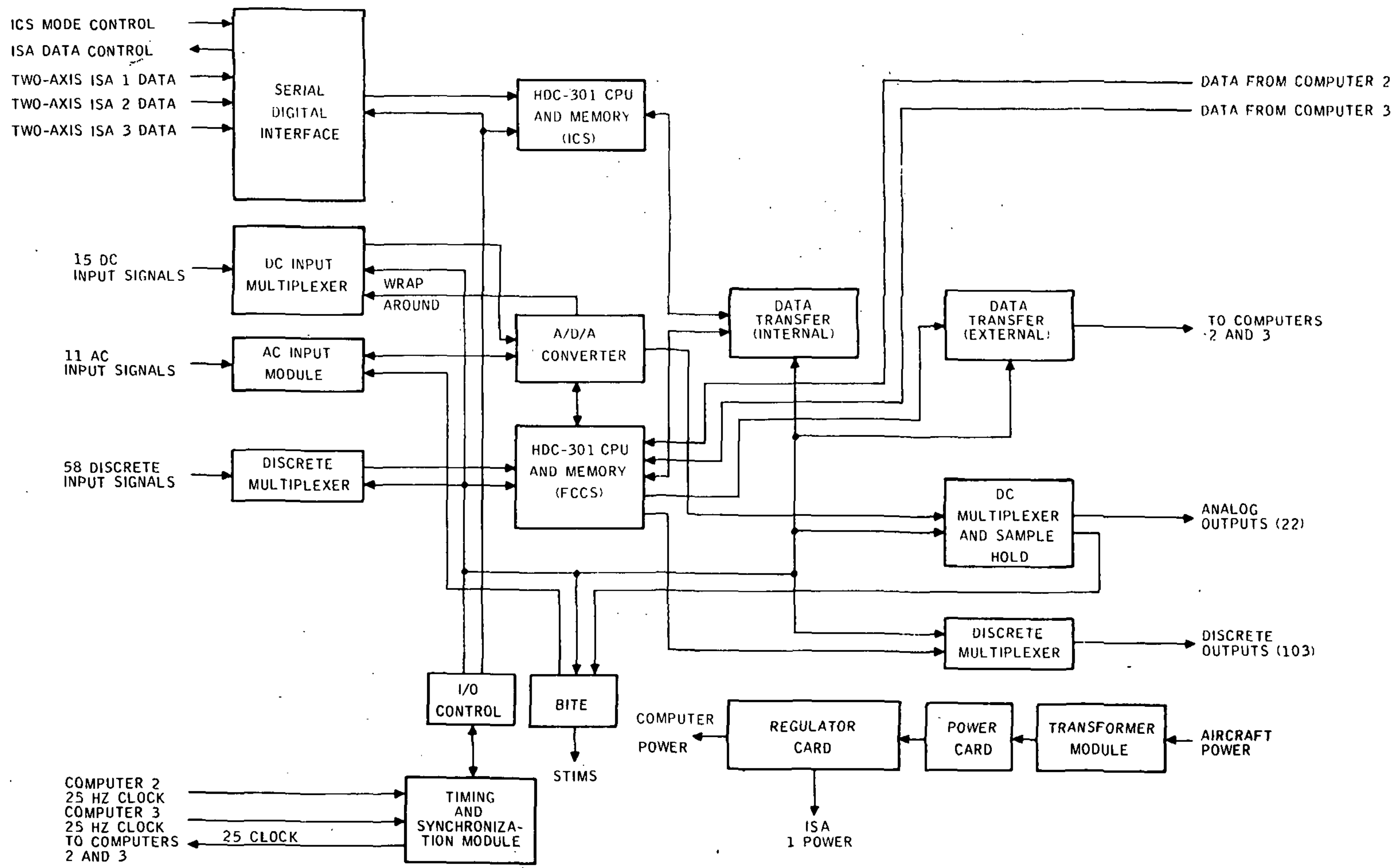


Figure 18. - FC-4 System IC/FC Computer

FCCS are identical to those functions described previously for the K-2 computer (for the ICS) and for the FC-2 flight control computer (for the FCCS). A single power supply consisting of a transformer module, power card, and regulator card converts aircraft unregulated input power to regulated voltages, which is required by all computer electronics. Thus, combining the IC and FC computers in a common housing eliminates one power supply. The computer supply also provides regulated power to one of the three ISA's.

BITE circuitry is provided in the IC/FC computer to verify proper operation of ICS and FCCS computer functional elements through measured responses to stimuli applied to the I/O and through the HDC-301 processor/memory operation checks.

Figure 19 is a cutaway drawing of a typical packaging arrangement for the IC/FC computer showing its construction and relative location of functions. The IC/FC computer electronics circuits are packaged on plug-in circuit cards and/or modules and are mounted in a standard full long ATR chassis. Each of the three redundant IC/FC computers are identical and interchangeable. System differences in the ISA interface would be implemented through the ISA/computer interface wiring. Each computer chassis has space for approximately 30 circuit cards plus a power supply module. The IC/FC computer uses 28 circuit cards.

Inertial Navigation Systems

Inertial Navigation System INAV-1. - An ARINC 561 gimbaled INS such as the CAROUSEL IV was selected as representative of a traditional commercial aircraft inertial navigation system. For the study, a triple redundant, fail-operational/fail-safe ARINC 561 INS configuration was investigated. Figure 20 summarizes its form factor, power, and weight.

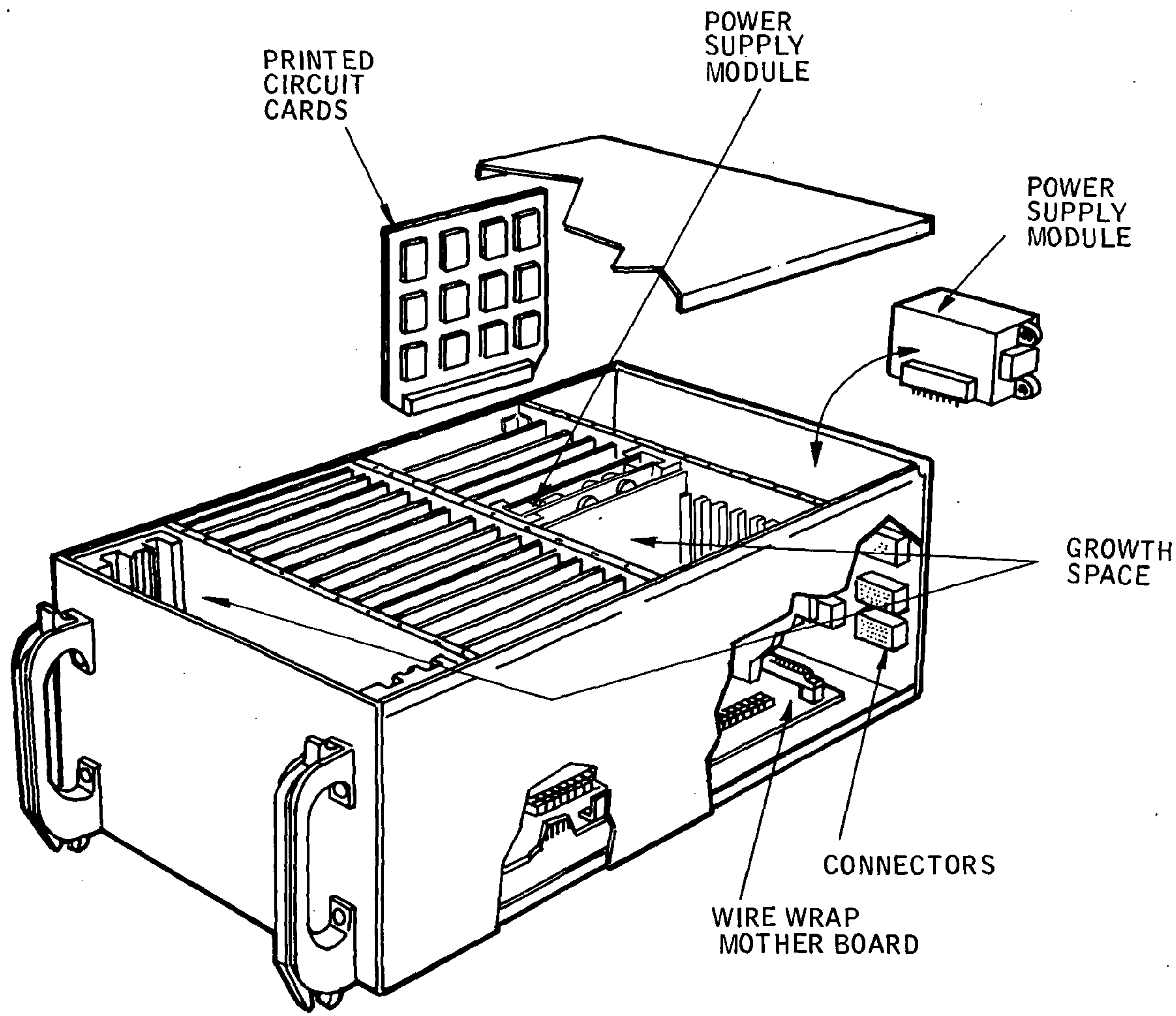
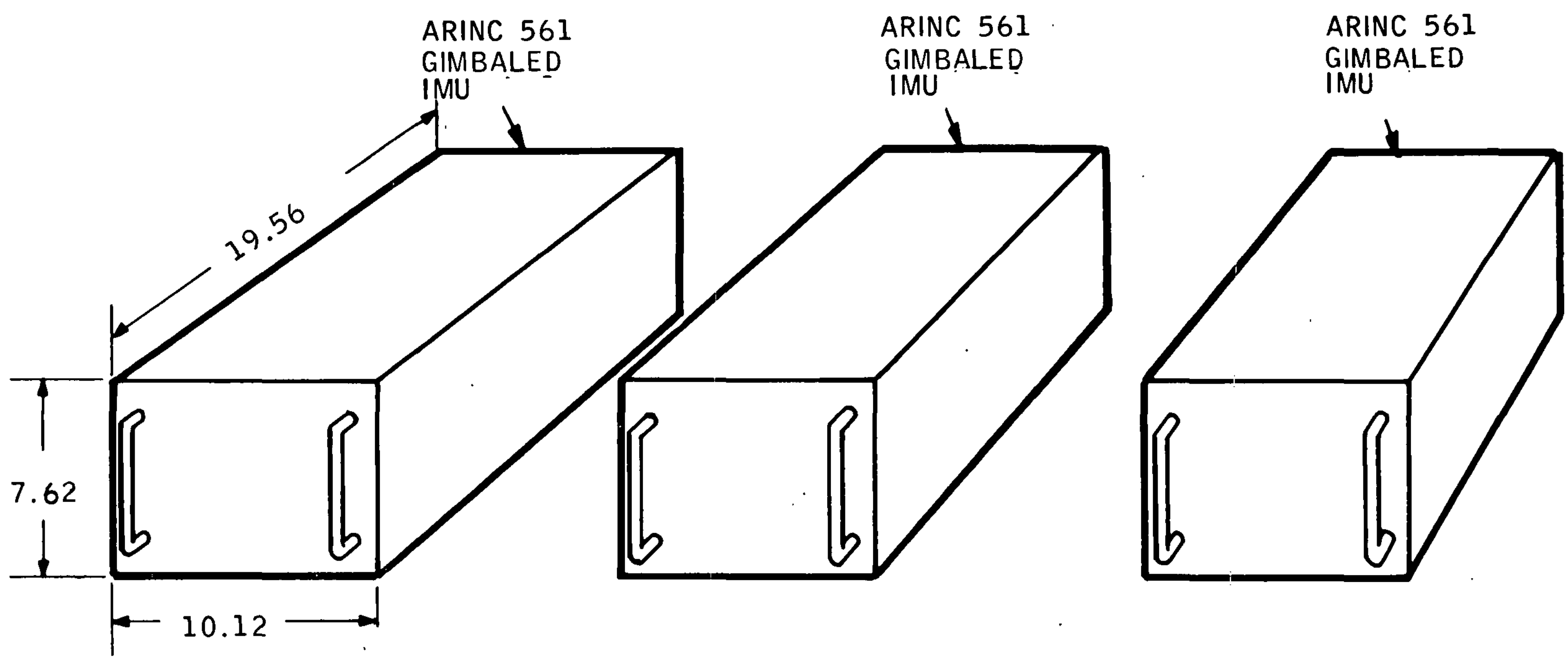


Figure 19. - Typical IC/FC Computer Packaging



ARINC 561	WEIGHT POUNDS	POWER WATTS*
GIMBALLED INS (3)	159	960/2400

* OPERATION/WARM-UP

Figure 20. - INAV-1 Traditional ARINC 561 Redundant Inertial Navigation System

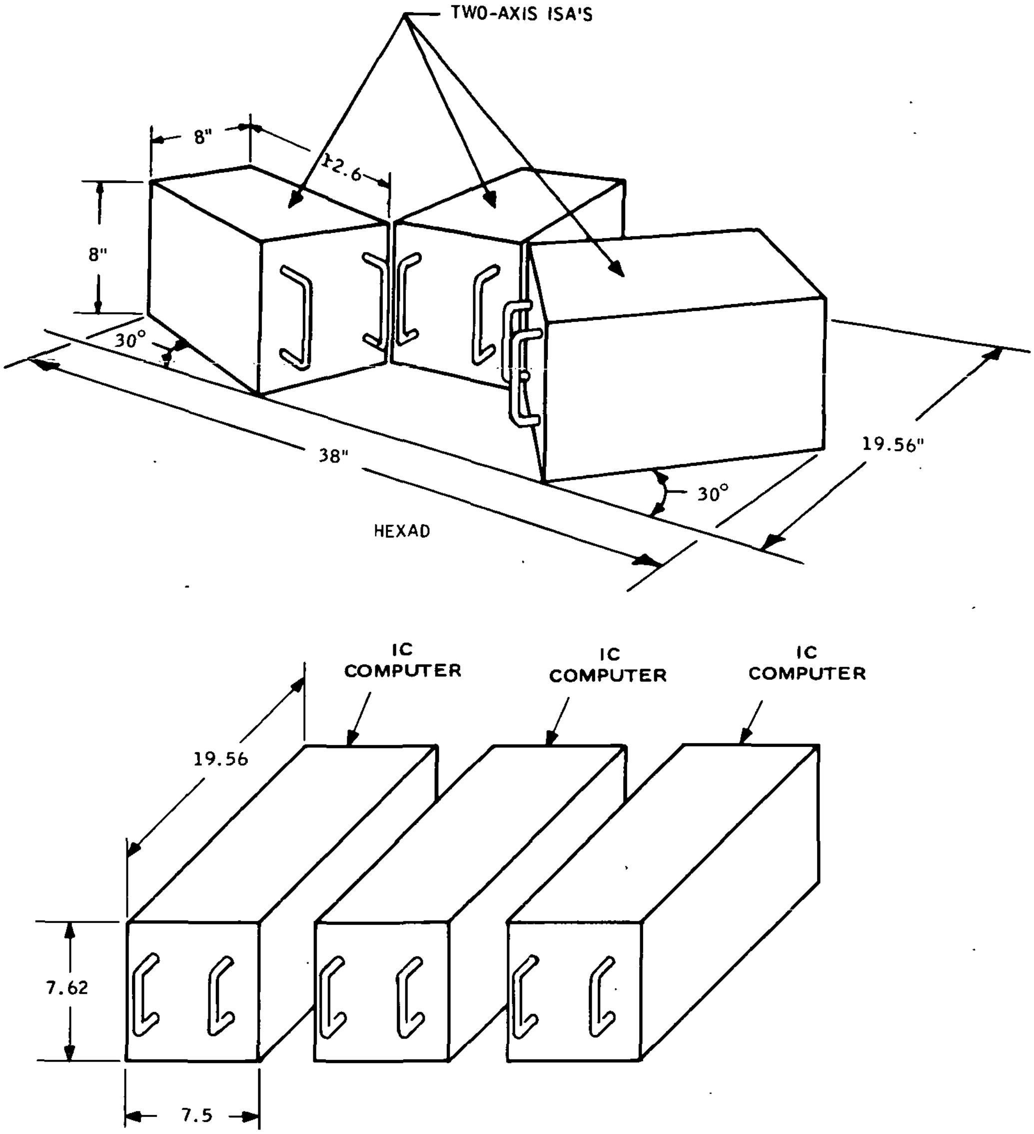
Inertial Navigation System INAV-2. - System INAV-2 is a strapdown equivalent of System INAV-1. It consists of a hexad inertial sensor assembly (three two-axis ISA's) and three IC computers with ARINC 561 I/O. Figure 21 summarizes the INAV-2 system form factor, weight, and power. The INAV-2 computer consists of 20 cards and a power supply module housed in a standard three-fourths long ATR chassis.

The INAV-2 computer, shown in the block diagram of Figure 22, is similar to the K-2 kinematic system computer described previously, differing only in the ARINC 561 I/O addition. The ARINC 561 I/O consists of nine interface cards (eight ARINC signal cards and one INS display interface card). The INS display interface card acts as the digital interface between the pilot display unit and the computer for system initialization and readout. The other seven cards are used to generate and/or receive synchro signals, discrete signals, d-c signals, and digital signals to meet the ARINC 561 output format.

Inertial Navigation System INAV-3. - System INAV-3 is functionally identical to the INAV-2 system; it differs in the combined packaging of each computer with one of the ISA's in a single standard full high long ATR chassis.

The resulting larger skewed sensor assemblies present the same mounting problems as described previously for the K-3 system. The advantage of the K-3 system over the INAV-2 system is reduced cost.

Inertial Navigation System INAV-4. - The INAV-4 system is the same as the K-2 kinematic system except for the addition of an INS display interface card and a digital serial-to-parallel I/O card for air data altitude inputs. The addition of these two cards converts the K-2 kinematic system into a full inertial navigator. The INAV-4 system was configured to show the cost benefits of an all-digital format for the strapdown navigator compared to the INAV-2 configuration with the more complex ARINC 561 interface.



ARINC 561	WEIGHT POUNDS	POWER* WATTS
TWO-AXIS ISA'S (3)	128.5	84
IC COMPUTERS (3)	80.1	379
TOTALS	208.6**	463

* NO WARM-UP REQUIRED
** INCLUDES 25 POUNDS FOR ADDITIONAL AIRCRAFT HEXAD INSTALLATION STRUCTURE

Figure 21. - INAV-2 Strapdown Redundant ARINC 561 Inertial Navigation System

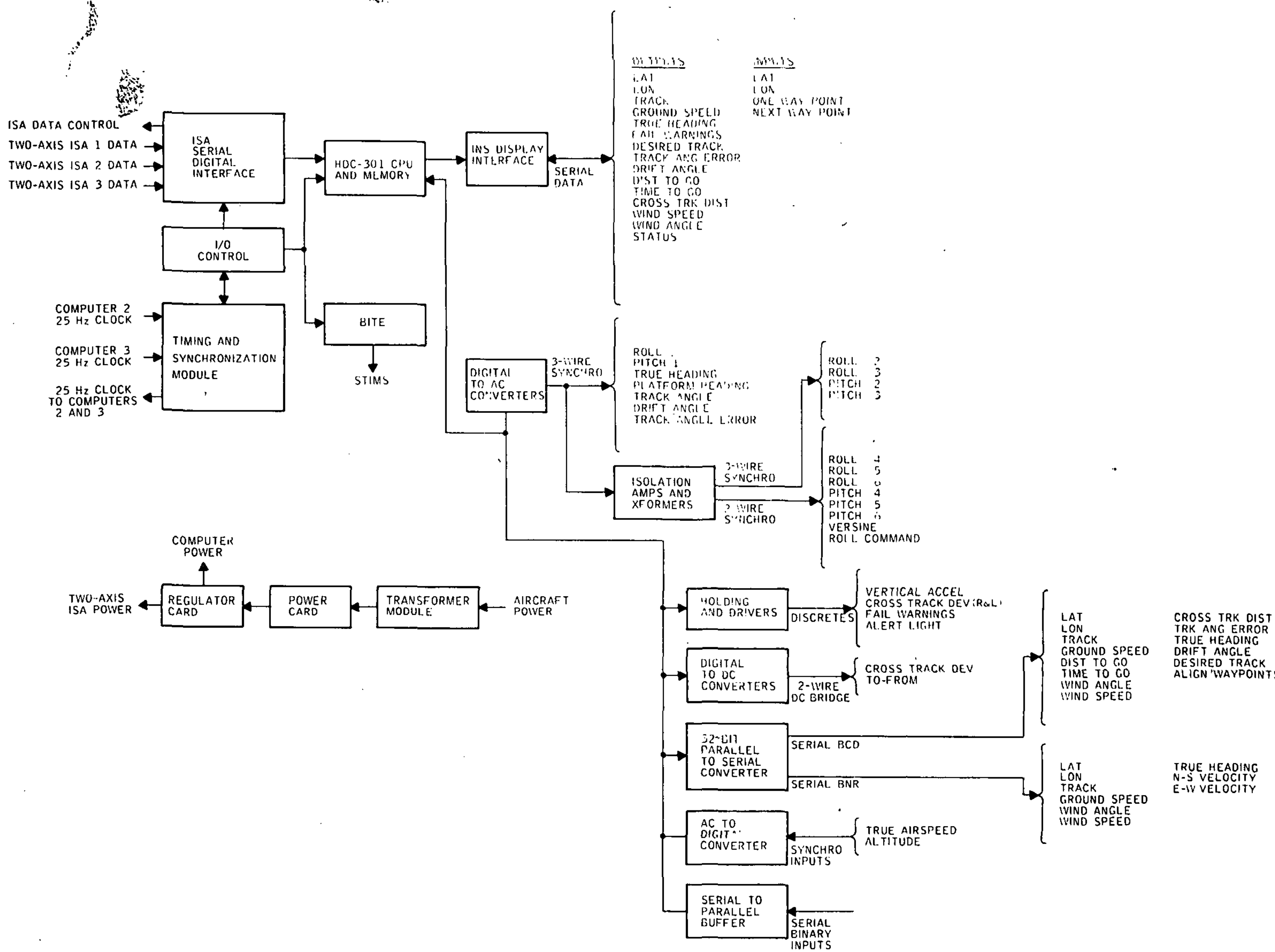


Figure 22. - INAV-2 System IC Computer

Inertial Navigation System INAV-5. - The INAV-5 system is the same as the K-2 kinematic system except for the addition of an INS display interface and digital serial-to-parallel I/O card. The resulting navigation system can be compared to System INAV-3 to assess the cost advantages of a digital interface compared to a standard ARINC 561 interface.

SECTION III
SYSTEM COST ANALYSES

In this section is described the method utilized to calculate cost of ownership in the study, and the cost results for the system configurations described in Section II are summarized. The detailed cost of ownership calculation computer run printouts for each system are contained in Appendix E. The cost of ownership calculations are based on an assumed 150 airplane fleet and a six-year amortization of initial hardware costs. The cost figures presented represent engineering estimates based on past experience for similar equipment assuming 1973-1974 labor and material rates. For the computer and strapdown hexad items, costs were based on the estimated average for an initial 500 system production run. The cost data shown was prepared for engineering tradeoff comparison purposes only.

Cost of Ownership Formula

The formula used to calculate system cost of ownership in the study was obtained by Honeywell from Boeing Commercial Airplane Co. and subsequently incorporated into a computer program. The cost of ownership formula is summarized below.

<u>Cost of Ownership (C_o ~ dollars/1000 flight hours).</u> -

$$C_o = C_{IP} + C_I + C_F + C_M \tag{1}$$

where:

C_{IP} = amortized initial hardware cost

C_I = amortized hardware spares cost

C_F = added fuel cost

C_M = hardware direct maintenance cost

Amortized initial hardware cost (C_{IP})

$$C_{IP} = \frac{B \times \alpha \times (C + C_{IN}) \times N \times \gamma \times 1000}{H \times D} \tag{2}$$

where:

B = borrowed money cost factor (B = 1.1)

α = amortization factor computed by fixed rate method. Based on six-year operation and 10-percent scrap value of C after six years (α = .15)

C = hardware purchase cost per unit

C_{IN} = unit installation cost

N = quantity of units per airplane

γ = annual parts pool cost factor (γ = 1.0)

H = average daily flight hours per airplane (H = 9)

D = airplane operating days per year (D = 365)

Amortized spares cost (C_I)

$$C_I = \frac{C \times \alpha \times B \times \gamma \times Q \times 1000}{A \times H \times D} \tag{3}$$

$$Q = \frac{A \times N \times H \times K \times T}{MTBF \times K_{F/R}} + r \times \sqrt{\frac{A \times N \times H \times K \times T}{MTBF \times K_{F/R}}}$$

where:

Q = quantity of hardware units required to replace those removed during the repair turn-around period

A = number of airplanes in fleet ($A = 150$)

K = ratio of hardware operating hours per flight hour ($K = 1.5$)

T = average repair turn-around time ($T = 7$ days)

MTBF = hardware unit mean time between failures

$K_{F/R}$ = hardware failure/removal ratio ($K_{F/R} = 0.5$)

r = risk factor ($r = 2$)

Added fuel cost (C_F)

$$C_F = \frac{P_F \times R_{F/t} \times W \times N \times 1000}{\gamma_F} \tag{4}$$

where:

P_F = fuel purchase price per gallon ($P_F = \$0.42$)

γ_F = pounds per gallon of fuel ($\gamma_F = 6.7$)

$R_{F/t}$ = ratio of added fuel per flight hour to added aircraft operating empty weight ($R_{F/t} = 0.133$)

W = hardware unit weight

Direct maintenance cost (C_M)

$$C_M = M_{RN} + C_L + C_S + C_B \tag{5}$$

where:

M_{RN} = failed module repair or replacement cost

C_L = line maintenance cost

C_S = shop repair cost

C_B = burden cost

Failed module repair (or replacement) and checkout cost (M_{RN})

$$M_{RN} = \frac{N \times K \times C_P \times 1000}{MTBF} \qquad (6)$$

where:

C_P = average parts cost per failure

Line maintenance cost (C_L)

$$C_L = \frac{N \times K \times t_L \times L_L \times 1000}{MTBF \times K_{F/R}} \qquad (7)$$

where:

t_L = average line maintenance time per removal (t_L = 0.5 hours)

L_L = line maintenance labor rate (L_L = \$9.52/hr)

Shop repair cost (C_S)

$$C_S = \frac{N \times K \times t_s \times L_s \times 1000}{MTBF \times K_{F/R}} \qquad (8)$$

where:

t_s = average shop repair hours per removal. Includes failed module replacement cost but not module repair (or new module purchase).

L_s = shop labor rate (L_s = \$8.14/hr)

Burden cost (C_B)

$$C_B = (1 + \frac{BR}{100}) \times (C_L + C_S) \tag{9}$$

where:

BR = burden rate (BR = 100%)

Figure 23 is a sample printout of a cost-of-ownership computer run that is representative of the equivalent runs for each system configuration contained in Appendix E.

The second line of the printout identifies the run number and computer run. In this case it was "RUN 1.2.3, 3 TWO-AXIS ISA'S LASER LIFE = 15,000 HOURS". The next eight lines list 16 cost-of-ownership variables given constant values for this study. The values used for these variables were supplied by Boeing as representative of typical commercial aircraft experience (except for the values included in "Line Hours Per Removal", "Fuel Costs", and "Average Turn-Around Time", which were Honeywell estimates).

The four lines beginning with the word "Enter" show the values given to the eight cost-of-ownership variables that were free to vary during the study. The fail-removal ratio variable was not allowed to vary but was set at 0.5 for all configurations.

DESCRIBE UNIT

! RUN 1.2.3 3 TWO-AXIS ISA'S LASER LIFE = 15,000 HRS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 3861., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 861., .5

\- -

SYSTEM COST	52230.00
NO. OF SPARE UNITS	31.41
ANNUAL FLEET REMOVALS	1148.60
ANNUAL PLANE REMOVALS	7.66
REMOVALS PER 1000 FLIGHT HRS	2.33

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	90243.61	601.62	183.14
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	494472.87	3296.49	1003.50
• LINE MAINTENANCE	5467.34	36.45	11.10
• SHOP MODULE REPLACEMT	65447.30	436.32	132.82
• BURDEN-SHOP AND LINE	70914.64	472.76	143.92
TOTAL COST OF OWNERSHIP	2494030.50	16626.87	5061.45
• DIRECT MAINT COST	636302.12	4242.01	1291.33

Figure 23. - Sample Cost-of-Ownership Computer Run

The output from the computer run begins below the dotted line. System cost is equal to the unit price multiplied by the number of units. The assumed number of spare units refers to the total system spares required to service an assumed 150 airplane fleet for the seven day shop turn-around period required for failed line replaceable unit (LRU) repairs. The next three lines list the probable LRU removals per fleet (150 planes) per year, per plane year, and per 1,000 flight hours.

Computed costs are shown in the printout on the basis of annual fleet costs, annual plane costs, and costs per 1,000 flight hours. Direct maintenance costs are a part of the total cost of ownership but are also shown separately on the last line.

Kinematic Systems Cost Analysis

Kinematic System K-1 cost. - Table 2 summarizes the direct maintenance and ownership costs for the K-1 kinematic system and line replaceable units (LRU's) as obtained in the study from the cost-of-ownership computer program. The detailed computer run printouts for the data are contained in Appendix E (Runs 1.1.1 - 1.1.6).

Table 3 identifies three sources of cost information for the K-1 equipment and the actual costs that were used for the study in the cost-of-ownership computer program. These costs are considered representative of the 1973-1974 costs for this class of equipment.

The wiring installation prices used in the computer runs were supplied by Boeing with the exception of the rate gyro. The rate gyro is usually packaged with the flight controls. A one-hundred dollar wiring price was arbitrarily allocated for the rate gyro.

The MTBF data utilized in the computer runs were obtained from a Battelle Report (NAS2-6889). This data was collected from July, 1971 to

TABLE 2. - K-1 KINEMATIC SYSTEM COST SUMMARY

K-1 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 vertical gyros	1, 000	18, 600	2. 84	4. 60
9 rate gyros	711	9, 000	. 86	1. 50
9 accelerometers	10, 787	9, 000	. 06	. 83
3 compass couplers	2, 834	12, 600	. 29	1. 38
3 directional gyros	2, 566	11, 400	. 77	1. 73
3 flux gates	60, 000	1, 800	. 02	. 29
K-1 system total	307	62, 400	4. 84	10. 33

TABLE 3. - SYSTEM K-2 LINE REPLACEABLE UNIT (LRU) COST IN DOLLARS

<table>
<tr><th>LRU</th><th>Boeing</th><th>Battelle[a]</th><th>Honeywell</th><th>Cost used in study</th></tr>
<tr><td>Rate gyro</td><td>600-1, 200</td><td>1, 000</td><td>1, 000</td><td>1, 000</td></tr>
<tr><td>Accelerometer</td><td>700</td><td>1, 000</td><td>1, 000</td><td>1, 000</td></tr>
<tr><td>Compass coupler</td><td>4, 200</td><td>4, 200</td><td>---</td><td>4, 200</td></tr>
<tr><td>Flux gate</td><td>600</td><td>600</td><td>---</td><td>600</td></tr>
<tr><td>Directional gyro</td><td rowspan="2">10, 000</td><td>3, 500</td><td>3, 800</td><td>3, 800</td></tr>
<tr><td>Vertical gyro</td><td>6, 000</td><td>6, 200</td><td>6, 200</td></tr>
</table>

[a] Listed as replacement or spares cost in Battelle Report prepared under Contract No. NAS2-6889.

June, 1973 on Air California aircraft. The average number of hours required to verify a failure in the shop is an estimate based on Honeywell experience. The assumed weights are typical for this type of equipment.

The average parts costs per failure used in the study were based on a percentage of initial cost as listed in Table 4.

TABLE 4. - SYSTEM K-1 AVERAGE LRU PARTS COST PER FAILURE

LRU	Cost basis
Vertical gyro	29% of initial cost
Rate gyro	34% of initial cost
Accelerometer	34% of initial cost
Compass coupler	$500 (cost of a typical card)
Directional gyro	34% of initial cost
Flux gate	100% of initial cost[a]

[a] The 180, 000 MTBF and low cost ($600) makes this item a throw-away unit.

Kinematic System K-2 cost. - Table 5 summarizes the K-2 kinematic system cost-of-ownership data detailed in the Appendix E Computer Runs 1. 2. 3 and 1. 2. 7. Tables 6 and 7 provide detailed breakouts of unit cost, MTBF, and average parts cost per failure for the two LRU's utilized in System K-2, which form the basis for equivalent data entries in the computer runs.

Wiring installation costs used in the computer runs for System K-2 LRU's are estimates obtained from Boeing. The shop hours per removal are Honeywell estimates and were made assuming that automatic test equipment will be used. Automatic test equipment enables the identification and replacement of an electronic assembly card in one-half hour. A seven-hour figure (considered conservative) was assumed for identification, replacement,

TABLE 5. - K-2 KINEMATIC SYSTEM COST SUMMARY

K-2 system LRU's	MTBF hrs	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA's	1287	52, 230	1. 29	5. 06
3 IC computers	1873	43, 440	. 38	3. 43
K-2 system total	763	95, 670	1. 67	8. 49

and checkout of assemblies containing laser gyros and accelerometers. Weight estimates were generated by Honeywell and are considered conservative.

An arbitrary fail-removal ratio of 0. 5 was assigned to all equipment. The 0. 5 ratio is considered realistic based on current airline experience. Strapdown digital configurations have the potential for a much higher ratio because of BITE and related failure identification.

The 15, 000-hour MTBF figure used for the laser gyros is a reliability estimate based on limited gyro test data, accelerated life tests, and experienced electronic piece-part failure rates (discussed in Appendix D). While it it felt that the 15, 000-hour MTBF figure is a realistic estimate, it is also recognized that a degree of uncertainty exists because of the limited amount of reliability data available on laser gyros utilizing current technology. Figure 24 was prepared to illustrate the sensitivity of the K-2 system cost of ownership to variations in laser gyro MTBF and is also representative of variations in cost of ownership for the general class of laser gyro strapdown systems investigated during the study. The data of Figure 24 is a plot of the Appendix E computer run printouts for System K-2 varying laser gyro MTBF as a parameter (Runs 1. 2. 1 - 1. 2. 6). Also shown in Figure 24 is the cost of ownership for traditional Kinematic System K-1, which indicates a lower cost for the strapdown system even for laser gyro MTBF's as low as 5, 000 hour, which is considered extremely pessimistic.

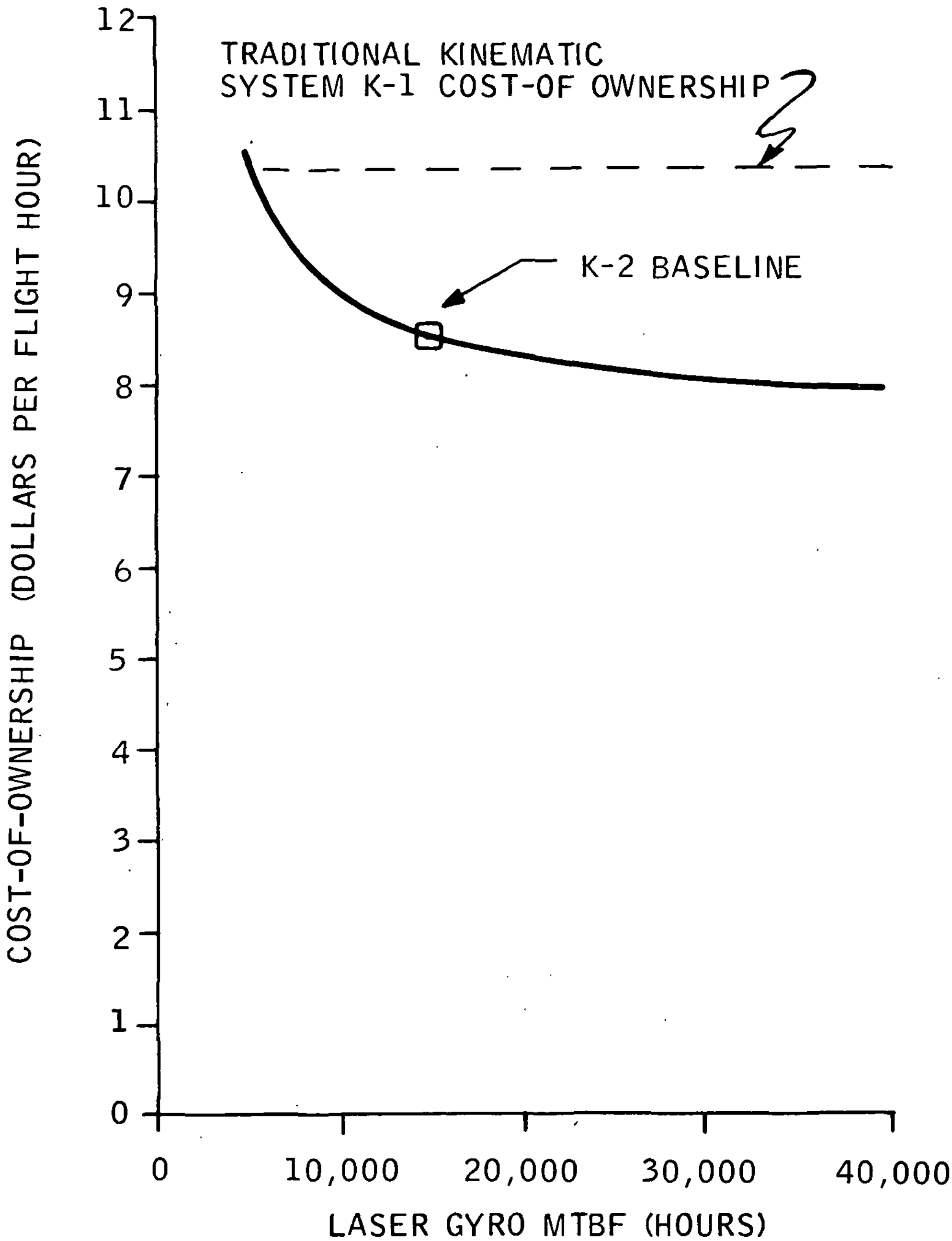


Figure 24. - Strapdown System Cost-of-Ownership Versus Laser Gyro Reliability

TABLE 6. - PART AND COST DETAIL FOR KINEMATIC SYSTEM K-2 TWO-AXIS ISA

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1,000 hr	Total failure rate, % per 1,000 hr	Parts cost dollars	Parts cost per hr
Up-down counter and storage cards	280	2	560	0.80	1.6	280	0.0045
Accelerometer pulse logic card	230	1	230	.80	.80	230	.0018
Control and transmit logic card	400	1	400	.80	.80	400	.0032
Control and output strobe	340	1	340	.80	.80	340	.0027
Accelerometer block	330	1	330	--	--	--	--
Laser gyro block	330	1	330	--	--	--	--
Chassis (including wiring and connectors)	2100	1	2100	.50	.50	300	.0015
Accelerometer and module electronics	1810	2	3620	4.0	8.0	625	.0484
Laser gyros[a]	4000	2	8000	6.7	13.4	1200	.1608
Assemble and test	1500	1	1500	--	--	--	--
LRU total			17,410		25.90	[b]861	0.2229

[a] Laser gyro - 15,000 hr MTBF

[b] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

TABLE 7. - PART AND COST DETAIL FOR KINEMATIC SYSTEM K-2 IC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1,000 hr	Total failure rate, % per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2.7	2.7	1000	0.0270
HDC-301 memory	2000	2	4000	2.0	4.0	400	.0160
301 buffer card	280	1	280	.70	.7	280	.0019
Timing and sync module	310	1	310	1.5	1.5	310	.0047
Bite card	320	1	320	1.0	1.0	320	.0032
Serial digital interface	280	2	560	.7	1.4	280	.0039
I/O control	340	2	680	.8	1.6	340	.0054
BCD and binary serial	290	1	290	.7	.7	290	.0020
Power supply regulator	310	1	310				
Power supply	1250	1	1250	3.2	3.2	350	.0112
Power transformer	90	1	90				
Chassis (wiring connectors, etc.)	2450	1	2450	1.0	1.0	300	.0030
Assemble and test	500	1	500				
LRU total			14,480		17.8	[a]440	0.0783

[a] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

Kinematic System K-3 cost. - Table 8 is a cost summary for the K-3 kinematic system obtained from the corresponding Appendix E detailed Computer Run 1. 3. 1. Table 9 presents the detail for the overall cost, MTBF, and parts repair cost used in the computer run for the integrated two-axis ISA/IC computer, the only LRU in the K-3 system. The rationale for the other variables in the computer run is the same as for the K-2 system.

TABLE 8. - K-3 KINEMATIC SYSTEM COST SUMMARY

K-3 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA/IC computers	819	86, 700	1. 76	7. 88
K-3 system total	819	86, 700	1. 76	7. 88

Flight Control Systems Cost Analysis

Flight Control System FC-1 cost. - Table 10 summarizes the FC-1 flight control system cost data detailed in the Appendix E Computer Runs 1. 1. 1 - 1. 1. 6 and 2. 1. 1. Table 11 provides the back-up detail for overall cost, MTBF, and parts repair cost utilized in the computer for the FC-1 FC computer (Run 2. 1. 1). The rationale for the remaining input variables for Run 2. 1. 1 parallels that described for the K-2 system. The remaining assembly in FC-1 is the K-1 traditional kinematic system (Appendix E Runs 1. 1. 1 - 1. 1. 6); cost elements for this system have been described previously.

Flight Control System FC-2 cost. - Table 12 summarizes the FC-2 flight control system cost data detailed in Appendix E Computer Runs 1. 2. 3, 1. 2. 7, and 2. 2. 1. Table 13 details the overall cost, MTBF, and parts repair costs for the FC computer in FC-2 used in the corresponding Appendix E Computer Run 2. 2. 1. The rationale for the remaining input variables for Run 2. 2. 1 parallels that described for the K-2 system. The remaining assembly in FC-2 is the K-2 kinematic system (Runs 1. 2. 3 and 1. 2. 7); cost elements for this system have been described previously.

TABLE 9. - PART AND COST DESCRIPTION FOR KINEMATIC SYSTEM K-3 INTEGRATED TWO-AXIS ISA/IC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1,000 hr	Total failure rate, % per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2.7	2.7	1000	0.0270
HDC-301 memory	2000	2	4000	2.0	4.0	400	.0160
301 buffer card	280	1	280	.70	.7	280	.0019
Timing module	310	1	310	1.5	1.5	310	.0047
Bite card	320	1	320	1.0	1.0	320	.0032
BCD and binary serial	290	1	290	.7	.7	290	.0020
Up-down counter and storage cards	380	2	560	.80	1.6	280	.0045
Accelerometer pulse logic card	230	1	230	.80	.80	230	.0018
I/O control	340	2	680	.80	1.6	340	.0054
Accelerometer block	330	1	330	--	--	--	--
Laser gyro block	330	1	330	--	--	--	--
Accelerometer and module electronics	1810	2	3620	4.0	8.0	625	.0484
Laser gyros	4000	2	8000	6.7	13.4	1200	.1608
Power supply regulator	310	1	310				
Power supply	1250	1	1250	3.2	3.2	350	.0112
Power transformer	90	1	90				
Chassis (wiring connectors, etc.)	2900	1	2900	1.5	1.5	300	.0045
Assemble and test	1900	1	1900				
LRU total			28,900		40.7	[a]716	0.2914

[a] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

TABLE 10. - FC-1 FLIGHT CONTROL SYSTEM COST SUMMARY

FC-1 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 vertical gyros	1,000	18,600	2.84	4.60
9 rate gyros	711	9,000	.86	1.50
9 accelerometers	10,787	9,000	.06	.83
3 compass couplers	2,834	12,600	.29	1.38
3 directional gyros	2,566	11,400	.77	1.73
3 flux gates	60,000	1,800	.02	.29
3 FC computers	899	65,700	.76	5.32
FC-1 system total	299	128,100	5.60	15.65

TABLE 11. - PART AND COST DESCRIPTION FOR FLIGHT CONTROL SYSTEM FC-1 FC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate,% per 1,000 hr	Total failure rate,% per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2.7	2.7	1000	0.0270
HDC-301 memory	2000	4	8000	2.0	8.0	400	.0320
301 buffer card	280	1	280	.70	.7	280	.2202
I/O control	340	2	680	.8	1.6	340	.0054
Data transfer card	280	1	280	.70	.70	380	.0019
A/D/A converter	360	1	360	1.50	1.50	360	.0054
Timing and sync card	340	1	340	1.50	1.50	340	.0051
AC analog input	530	2	1060	2.8	5.6	530	.0297
DC input multiplexer	380	1	380	.82	.82	380	.0031
Discrete input multiplexer	260	1	260	3.0	3.0	260	.0078
Discrete output	340	3	340	.85	2.55	340	.0087
Analog output	350	1	350	2.9	2.9	350	.0105
Bite	320	2	320	1.00	1.00	320	.0032
Power supply regulator	310	1	310				
Power supply components	1250	1	1250	3.2	3.2	350	.0112
Power supply transformer	90	1	90				
Chassis and mother board	3400		3400	1.3	1.3	300	.0039
Assemble and test	700		700				
LRU total			21,900		37.07	[a]423	0.1569

[a] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

TABLE 12. - FC-2 FLIGHT CONTROL SYSTEM COST SUMMARY

FC-2 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA's	1287	52, 230	1. 29	5. 06
3 IC computers	1873	43, 440	. 38	3. 43
3 FC computers	866	67, 380	. 78	5. 48
FC-2 system total	406	163, 050	2. 45	13. 97

TABLE 13. - PART AND COST DESCRIPTION FOR FC-2 SYSTEM FC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1, 000 hr	Total failure rate, % per 1, 000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2. 7	2. 7	1000	0. 0270
HDC-301 memory	2000	4	8000	2. 0	8. 0	400	. 0320
301 buffer card	280	1	280	. 70	. 7	280	. 2202
I/O control	340	2	680	. 8	1. 6	340	. 0054
Data transfer card	280	1	280	. 70	. 70	380	. 0019
A/D/A converter	360	1	360	1. 50	1. 50	360	. 0054
Timing and sync card	340	1	340	1. 50	1. 50	340	. 0051
AC analog input	530	2	1060	2. 8	5. 6	530	. 0297
DC input multiplexer	380	1	380	. 82	. 82	380	. 0031
Discrete input multiplexer	260	1	260	3. 0	3. 0	260	. 0078
Discrete output	340	3	340	. 85	2. 55	340	. 0087
Analog output	350	1	350	2. 9	2. 9	350	. 0105
Serial digital interface	280	2	560	. 7	1. 4	280	. 0039
Bite	320	2	320	1. 00	1. 00	320	. 0032
Power supply regulator	310	1	310				
Power supply components	1250	1	1250	3. 2	3. 2	350	. 0112
Power supply transformer	90	1	90				
Chassis and mother board	3400		3400	1. 3	1. 3	300	. 0039
Assemble and test	700		700				
LRU total			22, 460		38. 47	[a]418	0. 1608

[a] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

Flight Control System FC-3 cost. - Flight Control System FC-3 costs are the combination of the costs for Kinematic System K-3 (Appendix E Computer Run 1. 3. 1) and the FC-2 FC computer (Run 2. 1. 1). Table 14 summarizes the FC-3 System cost data.

TABLE 14. - FC-3 FLIGHT CONTROL SYSTEM COST SUMMARY

FC-3 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA/IC computers	819	86, 700	1. 76	7. 88
3 FC computers	866	67, 380	. 78	5. 48
FC-3 system total	421	154, 080	2. 54	13. 36

Flight Control System FC-4 cost. - Table 15 summarizes the FC-4 flight control system cost data detailed in Appendix E Computer Runs 1. 2. 3 and 2. 4. 1. Table 16 details the overall cost, MTBF, and parts repair costs for the IC/FC computer in System FC-4 used in the corresponding Appendix E Computer Run 2. 4. 1. The rationale for the remaining input variables for Run 2. 4. 1 parallels that described for System K-2. The remaining assembly in FC-4 is the hexad (three two-axis ISA's) utilized in the K-2 kinematic system; cost elements for this system have been described previously.

TABLE 15. - FC-4 FLIGHT CONTROL SYSTEM COST SUMMARY

FC-4 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA's	1287	52, 230	1. 29	5. 06
3 IC/FC computers	715	93, 030	. 98	7. 42
FC-4 system total	460	145, 260	2. 27	12. 48

TABLE 16. - PART AND COST DESCRIPTION FOR FLIGHT CONTROL SYSTEM FC-4 IC/FC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1,000 hr	Total failure rate, % per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	2	7000	2.7	5.4	1000	0.0540
HDC-301 memory	2000	6	12000	2.0	12	400	.0480
301 buffer card	280	2	560	.70	1.40	280	.0039
Serial digital interface	280	2	560	.70	1.40	280	.0039
I/O control	340	2	680	.8	1.6	340	.0054
Data transfer card	280	2	560	.70	1.4	280	.0038
A/D/A converter	360	1	360	1.50	1.50	360	.0054
Timing and sync card	340	1	340	1.50	1.50	340	.0051
AC analog input	530	1	530	2.8	2.8	530	.0148
DC output multiplexer	380	1	380	.82	.82	380	.0031
DC input multiplexer	380	1	380	.82	.82	380	.0031
Discrete input multiplexer	260	1	260	3.0	3.0	260	.0078
Discrete output	340	3	340	.85	2.55	340	.0087
Analog output	350	1	350	2.9	2.9	350	.0105
Bite	320	3	960	1.00	3.00	320	.0096
Power supply regulator	310	1	310				
Power supply components	1250	1	1250	3.2	3.2	350	.0112
Power supply transformer	90	1	90				
Chassis and mother board	3400		3400	1.3	1.3	300	.0039
Assemble and test	700		700	--	--	--	--
LRU total			31,010		46.59	[a]434	0.2022

[a] Average parts cost per failure is calculated by dividing parts cost per hour by failures per hour

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Inertial Navigation Systems Cost Analysis

Inertial Navigation System INAV-1 cost. - Table 17 summarizes the INAV-1 traditional ARINC 561 gimbaled inertial navigation system cost data detailed in the Appendix E Computer Run 3.1.1. The rationale for the input variables to the cost-of-ownership computer run is outlined below.

TABLE 17. - INAV-1 INERTIAL NAVIGATION SYSTEM COST SUMMARY

	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 gimbaled ARINC 561 nav units	600	285,000	7.50	25.39
INAV-1 system total	600	285,000	7.50	25.39

An ARINC 561 gimbaled navigation unit, such as the Carousel IV, is estimated to cost $95,000 in terms of 1973-1974 dollars. The weight of the Carousel IV navigation unit, which is 53 pounds, was used in the study for the INAV-1 LRU weight. The $2,000 cost assumed for wiring installation is an estimate supplied by Boeing and was identical for all I-Nav Systems in the study.

At the Joint Services Data Exchange for Inertial Systems (August 19-21, 1974), it was reported that the Delco Carousel IV Navigation Unit was achieving an 1,800-hour MTBF with a 0.5 failure-to-removal ratio (Jack Raia - Pan American) and that the Litton LTN-51 system was achieving an 1,881-hour MTBF (Ed Overxharper - Overseas National Airways). An 1,800-hour MTBF and a 0.5 failure-to-removal ratio was used in the study for the INAV-1 system gimbaled navigation unit.

The Battelle report gives the direct maintenance costs per installed INS as being $2.50 to $3.00 per hour. The 14 shop hours and $2,525 parts cost per failure were selected in the study to produce a $2. 50 per flight hour direct maintenance cost per LRU in the computer run.

Inertial Navigation System INAV-2 cost. - Table 18 summarizes the cost-of-ownership data for the INAV-2 inertial navigation system detailed in Appendix E Computer Runs 1. 2. 3 and 3. 2. 1. Details supporting the overall cost, MTBF, and parts cost for the INAV-2 IC computer (Run 3. 2. 1) are presented in Table 19. Rationale for the input variables for Run 3. 2. 1 parallel those for the K-2 kinematic system. The two-axis ISA utilized in INAV-2 is identical to the equivalent unit used in the K-2 kinematic system (Computer Run 1. 2. 3); cost detail for this system has been presented previously.

TABLE 18. - INAV-2 INERTIAL NAVIGATION SYSTEM COST SUMMARY

INAV-2 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA's	1287	52, 230	1. 29	5. 06
3 IC computers	1019	58, 440	. 68	4. 82
INAV-2 system total	569	110, 670	1. 97	9. 88

Inertial Navigation System INAV-3 cost. - Table 20 summarizes the cost of ownership for the INAV-3 inertial navigation system detailed in Appendix E Computer Run 3. 3. 1. Table 21 provides the overall cost, MTBF, and parts cost detail utilized in Run 3. 3. 1 for the only LRU in INAV-3, the integrated two-axis ISA/IC computer. Rationale for the other input variables for Run 3. 3. 1 parallels that for the K-2 kinematic system described previously.

Inertial Navigation System INAV-4 cost. - Table 22 summarizes the cost-of-ownership data for the INAV-4 system detailed in Appendix E, Runs 1. 2. 3 and 3. 4. 1. Cost detail for the IC computer (Run 3. 4. 1) for INAV-4 is presented in Table 23. Cost detail for the INAV-4 two-axis ISA (Run 1. 2. 3)

TABLE 19. - PART AND COST DESCRIPTION FOR INERTIAL NAVIGATION SYSTEM INAV-2 IC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1,000 hr	Total failure rate, % per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2.7	2.7	1000	0.0270
HDC-301 memory	2000	2	4000	2.0	4.0	400	.0160
301 buffer card	280	1	280	.70	.7	280	.0019
INS display interface card	240	1	240	.70	.7	240	.0017
Timing and sync module	310	1	310	1.5	1.5	310	.0047
Bite card	320	1	320	1.0	1.0	320	.0032
Serial digital interface	280	2	560	.7	1.4	280	.0039
I/O control	340	2	680	.8	1.6	340	.0054
ARINC							
Digital/synchro	430	7	3010	1.5	10.5	430	.0452
BCD and binary serial	290	1	290	.7	.7	290	.0020
Synchro/digital	430	1	430	1.5	1.5	430	.0065
Serial/parallel	290	1	290	.7	.7	290	.0020
Digital/analog converter	450	1	450	1.5	1.5	450	.0068
Power supply regulator	310	1	310				
Power supply	1250	1	1250	3.2	3.2	350	.0112
Power transformer	90	1	90				
Chassis (wiring connectors, etc.)	2900	1	2900	1.0	1.0	300	.0030
Assemble and test	600	1	600				
LRU total			19,480		32.7	[a]429	0.1405

[a] Average parts cost per failure calculated by dividing part costs per hour by failures per hour

TABLE 20. INAV-3 INERTIAL NAVIGATION SYSTEM COST SUMMARY

	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA/IC computers	600	101, 460	2. 20	9. 60
INAV-3 system total	600	101, 460	2. 20	9. 60

TABLE 21. - PART AND COST DESCRIPTION FOR INERTIAL NAVIGATION SYSTEM INAV-3 INTEGRATED TWO-AXIS ISA/IC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate,% per 1, 000 hr	Total failure rate,% per 1, 000 hr	Parts cost dollars	Parts cost per hr
HDC 301 CPU	3500	1	3500	2. 7	2. 7	1000	0. 0270
HDC 301 memory	2000	2	4000	2. 0	4. 0	400	. 0160
301 buffer card	280	1	280	. 70	. 7	280	. 0019
Timing module	310	1	310	1. 5	1. 5	310	. 0047
Bite card	320	1	320	1. 0	1. 0	320	. 0032
INS display interface card	240	1	240	. 70	. 7	240	. 0017
ARINC							
Digital/synchro	430	7	3010	1. 5	10. 5	430	. 0452
BCD and binary serial	290	1	290	. 7	. 7	290	. 0020
Synchro/digital	430	1	430	1. 5	1. 5	430	. 0065
Serial/parallel	290	1	290	. 7	. 7	290	. 0020
Digital/analog converter	450	1	450	1. 5	1. 5	450	. 0068
Up-down counter and storage cards	380	2	560	. 80	1. 6	280	. 0045
Accelerometer pulse logic card	230	1	230	. 80	. 80	230	. 0018
I/O control	340	2	680	. 80	1. 6	340	. 0054
Accelerometer block	330	1	330	--	--	--	--
Laser gyro block	330	1	330	--	--	--	--
Accelerometer and module electronics	1870	2	3620	4. 0	8. 0	625	. 0484
Laser gyros	4000	2	8000	6. 7	13. 4	1200	. 1608
Power supply regulator	310	1	310				
Power supply	1250	1	1250	3. 2	3. 2	350	. 0112
Power transformer	90	1	90				
Chassis (wiring connectors, etc.)	3300	1	3300	1. 5	1. 5	300	. 0045
Assemble and test	2000	1	2000				
LRU total			33, 820		55. 6	[a]634	0. 3536

[a] Parts cost per failure is calculated by dividing part costs per hour by failures per hour

TABLE 22. - INAV-4 INERTIAL NAVIGATION SYSTEM COST SUMMARY

INAV-4 system LRU's	MTBF (hrs)	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA's	1287	52, 230	1. 29	5. 06
3 IC computers	1736	45, 030	. 40	3. 56
INAV-4 system total	739	97, 260	1. 69	8. 62

TABLE 23. - PART AND COST DESCRIPTION FOR INERTIAL NAVIGATION SYSTEM INAV-4 IC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate,% per 1,000 hr	Total failure rate,% per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2.7	2.7	1000	0.0270
HDC-301 memory	2000	2	4000	2.0	4.0	400	.0160
301 buffer card	280	1	280	.70	.7	280	.0019
Timing module	310	1	310	1.5	1.5	310	.0047
Bite card	320	1	320	1.0	1.0	320	.0032
Serial digital interface	280	2	560	.7	1.4	280	.0039
INS display interface card	240	1	240	.7	.7	240	.0017
I/O control	340	2	680	.8	1.6	340	.0054
BCD and binary serial	290	1	290	.7	.7	290	.0020
Serial/parallel	290	1	290	.7	.7	290	.0020
Power supply regulator	310	1	310				
Power supply	1250	1	1250	3.2	3.2	350	.0112
Power transformer	90	1	90				
Chassis (wiring connectors, etc.)	2450	1	2450	1.0	1.0	300	.0030
Assemble and test	500	1	500				
LRU total			15,010		19.2	[a]427	0.0820

[a] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

is identical to that presented for the K-2 kinematic system. Rationale for the computer run input variables for INAV-4 parallels that for the K-2 kinematic system discussed previously.

Inertial Navigation System INAV-5 cost. - Table 24 summarizes the cost of ownership for the INAV-5 inertial navigation system detailed in Appendix E Computer Run 3. 5. 1. Table 25 provides the overall cost, MTBF, and part cost detail for the only LRU in INAV-5, the integrated two-axis ISA/IC computer. Rationale for the other input variables for Run 3. 5. 1 parallels that for the K-2 kinematic system described previously.

TABLE 24. - INAV-5 INERTIAL NAVIGATION SYSTEM COST SUMMARY

INAV-5 system LRU's	MTBF (hrs)	Initial cost (dollars/flight hr)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
3 two-axis ISA/IC computers	756	89, 250	1. 82	8. 15
INAV-5 system total	756	89, 250	1. 82	8. 15

Inertial Navigation System Cost Projections

Figure 25 illustrates the effect of inflation and learning on the gimbaled INAV-1 and strapdown INAV-2 inertial navigation systems from 1974 to 1975. The curve illustrates the impact of inflation on a mature inertial technology, INAV-1, compared to a new technology, INAV-2. Because INAV-1 is a mature production program, high learning rates have already been experienced and, therefore, there is no great potential for learning. For INAV-2, however, a new technology just entering production, high learning rates will be experienced between 1974 and 1978. The net effect is that the INAV-2 learning should offset the inflationary spiral between 1974 and 1985, while INAV-1 costs should rise at the inflation rate. This results in a widening of the cost advantage projected for strapdown over gimbaled systems during the next ten years. The plotted points of Figure 25 represent the average cost of 120 systems for the year shown.

TABLE 25. - PART AND COST DESCRIPTION FOR INERTIAL NAVIGATION SYSTEM INAV-5 INTEGRATED TWO-AXIS ISA/IC COMPUTER

LRU part	Item cost dollars	No. items	Cost total dollars	Failure rate, % per 1,000 hr	Total failure rate, % per 1,000 hr	Parts cost dollars	Parts cost per hr
HDC-301 CPU	3500	1	3500	2.7	2.7	1000	0.0270
HDC-301 memory	2000	2	4000	2.0	4.0	400	.0160
301 buffer card	280	1	280	.70	.7	280	.0019
Timing and sync module	310	1	310	1.5	1.5	310	.0047
Bite card	320	1	320	1.0	1.0	320	.0032
INS display interface card	240	1	240	.70	.7	240	.0017
BCD and binary serial	290	1	290	.7	.7	290	.0020
Serial/parallel	290	1	290	.7	.7	290	.0020
Up-down counter and storage cards	380	2	560	.80	1.6	280	.0045
Accelerometer pulse logic card	230	1	230	.80	.80	230	.0018
I/O control	340	2	680	.80	1.6	340	.0054
Accelerometer block	330	1	330	--	--	--	--
Laser gyro block	330	1	330	--	--	--	--
Accelerometer and module electronics	1810	2	3620	4.0	8.0	625	.0484
Laser gyros	4000	2	8000	6.7	13.4	1200	.1608
Power supply regulator	310	1	310				
Power supply	1250	1	1250	3.2	3.2	350	.0112
Power transformer	90	1	90				
Chassis (wiring connectors, etc.)	2900	1	2900	1.5	1.5	300	.0045
Assemble and test	1900	1	1900				
LRU total			29,750		44.1	[a]670	0.2951

[a] Average parts cost per failure is calculated by dividing part costs per hour by failures per hour

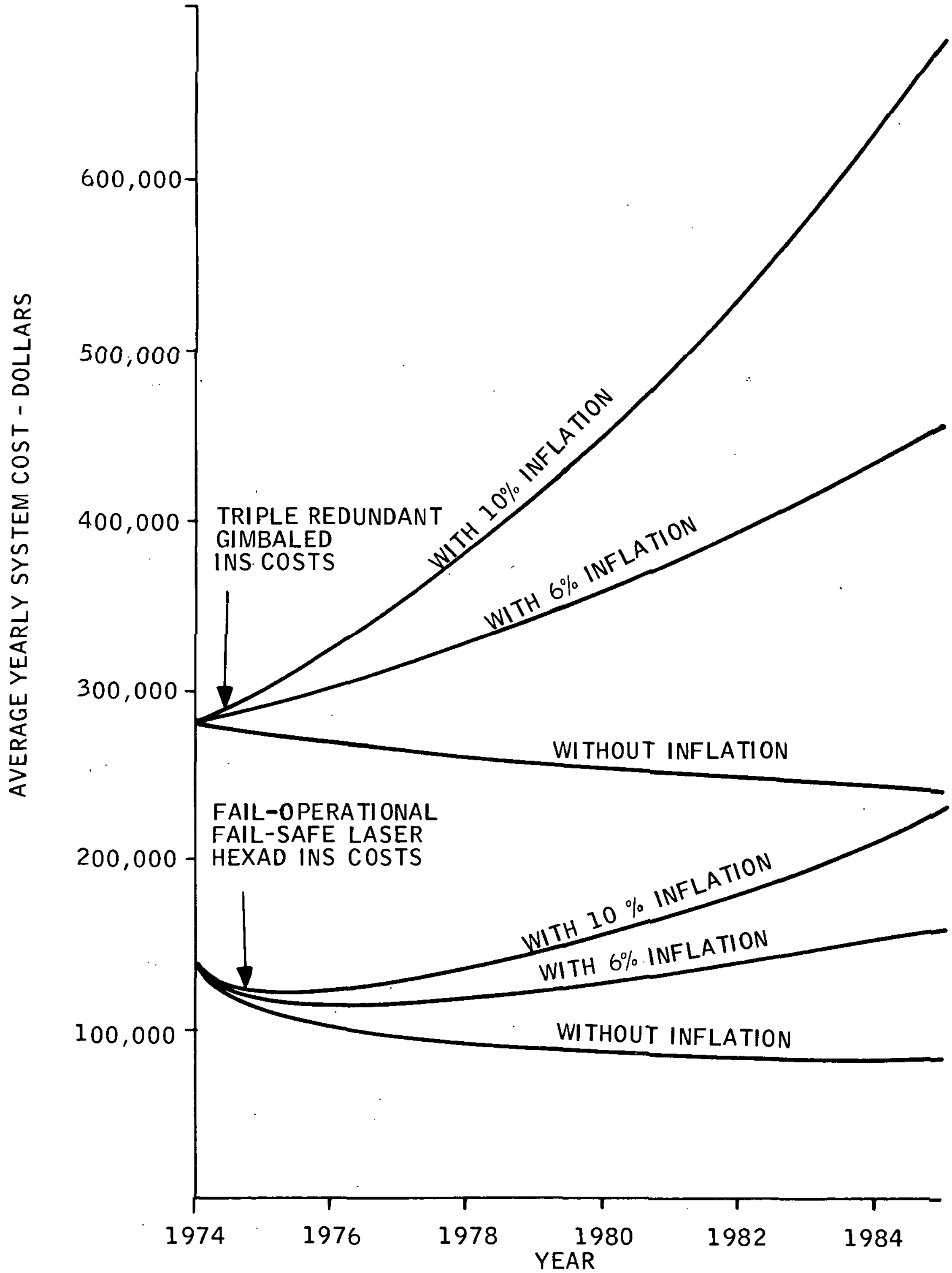


Figure 25. - Laser Strapdown Versus Gimbaled Redundant INS Cost Trends

Some assumptions applicable to the system cost projections were made. The production rate was assumed to be 10 systems (strapdown or gimbaled) per month over the 1974-1985 time period. The costs projected for the strapdown system are based on an average cost of $110,670 per system for the first 500 systems (INAV-2 system cost) and a 90-percent learning curve. The costs projected for the gimbaled system are based on the cost of the 2,000th unit in 1974 being $95,000 ($285,000 system cost). A 90-percent learning curve is assumed and cost projections begin with the 2,001st (667th system). This experience factor was selected as conservatively representative of current gimbaled navigation experience. As examples, Singer Kearfott has produced over 2,000 gimbaled KT-70 inertial navigation units, and Litton has produced over 10,000 gimbaled navigation units. Also, inflation rates of 6 percent and 10 percent per year were assumed.

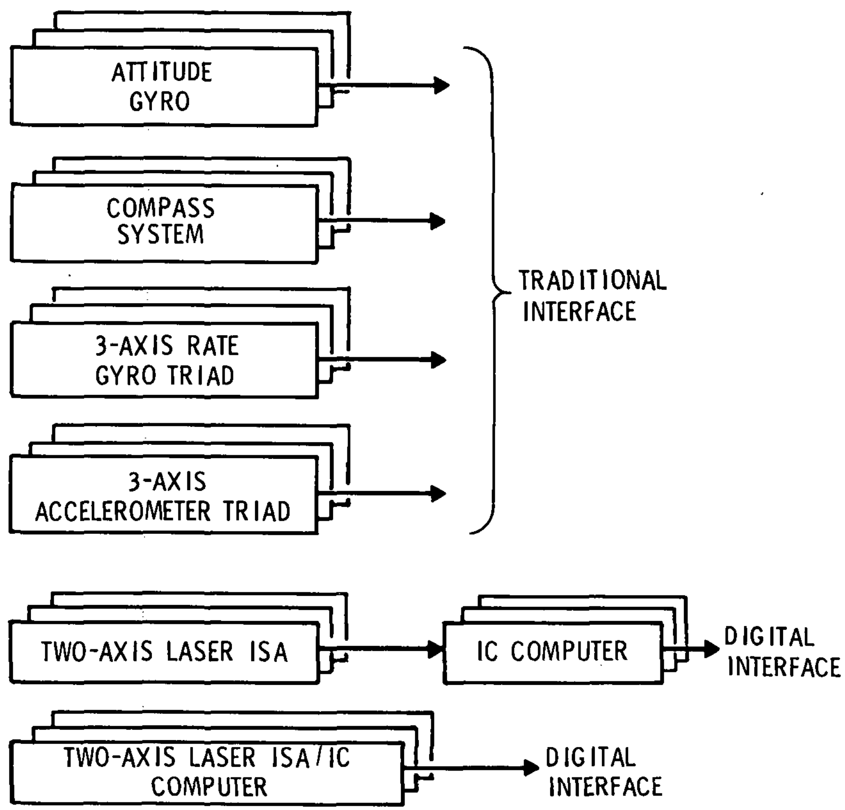
SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

Summary

Figures 26, 27,and 28 summarize the various kinematic, flight control, and inertial navigation systems investigated in the study, comparing the initial procurement cost, direct maintenance cost, and cost-of-ownership of these systems to the equivalent traditionally mechanized and strapdown laser gyro system configurations. The cost-of-ownership and direct maintenance cost formulas to derive the cost figures in Figures 26, 27, and 28 were based for the most part on inputs from Boeing Commercial Airplane Company.

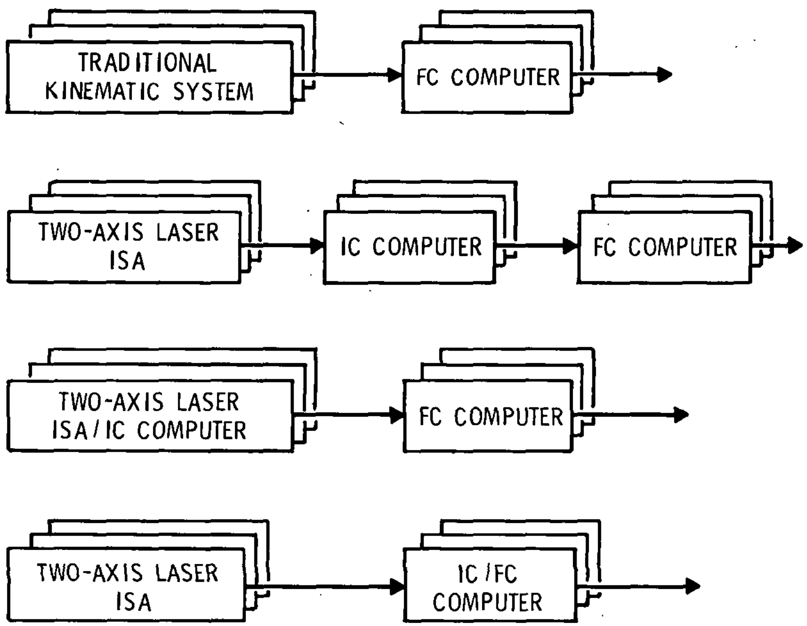
The initial costs for the laser systems are the estimated average prices for 500 systems assuming 1973-1974 labor and material rates and a 500 system initial buy; initial costs for the traditional systems were based on 1973-1974 prices for this equipment. Direct maintenance costs were based on an assumed fleet of 150 airplanes with nine flight hours per day per airplane, calculated or known failure rates and maintenance/repair costs. The cost of ownership figure includes the direct maintenance cost, a six-year amortization of the initial system procurement and aircraft installation cost including a borrowed money cost factor of 1. 1, and aircraft fuel costs associated with the equipment weight.

Throughout Figures 26, 27, and 28, the direct maintenance cost and cost of ownership for the laser strapdown systems are notably lower than the equivalent set of traditional equipment. For the kinematic and flight control systems (Figures 26 and 27), the strapdown cost savings results from the significant reduction in the number of inertial components per system (reduced from 24 in the traditional system to 12 in the strapdown system). For the inertial navigation systems (Figure 28), the savings results primarily from the elimination of the gimbal assemblies in the traditional systems.



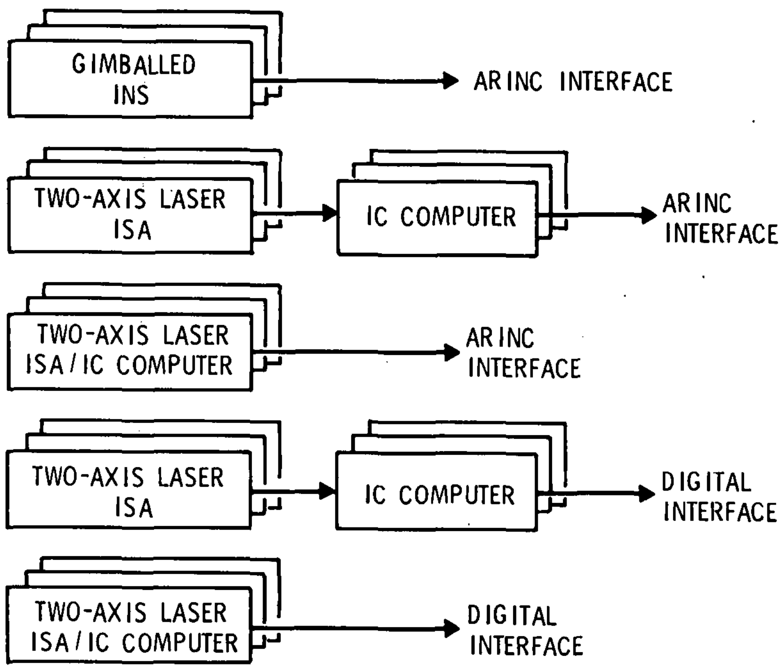
SYSTEM NUMBER	NUMBER OF SENSORS	SYSTEM MTBF HRS	INITIAL COST $	DIRECT MAINT COST $/FLT/HR	OWNER-SHIP COST $/FLT/HR
K-1	24	307	62,400	4.84	10.33
K-2	12	763	95,670	1.67	8.49
K-3	12	819	86,700	1.76	7.88

Figure 26. - Kinematic System Cost Comparisons



SYSTEM NUMBER	NUMBER OF SENSORS	SYSTEM MTBF HRS	INITIAL COST $	DIRECT MAINT COST $/FLT/HR	OWNER-SHIP COST $/FLT/HR
FC-1	24	229	128,100	5.60	15.65
FC-2	12	406	163,050	2.43	13.97
FC-3	12	421	154,080	2.54	13.36
FC-4	12	460	145,260	2.27	12.48

Figure 27. - Flight Control System Cost Comparisons



SYSTEM NUMBER	NUMBER OF SENSORS	SYSTEM MTBF HRS	INITIAL COST $	DIRECT MAINT COST $/FLT/HR	OWNER-SHIP COST $/FLT/HR
INAV-1	18	600	285,000	7.50	25.39
INAV-2	12	569	110,670	1.97	9.88
INAV-3	12	600	101,460	2.20	9.60
INAV-4	12	739	97,260	1.69	8.62
INAV-5	12	756	89,250	1.82	8.15

Figure 28. Inertial Navigation System Cost Comparisons

The traditional kinematic system for commercial aircraft (System K-1), as shown in Figure 26, consists of triple redundant attitude gyros, compass systems (heading gyro with flux valve), rate gyro triads (three orthogonal axes), and accelerometer triads. The equivalent redundant laser system (K-2 or K-3 in Figure 26) contains a skewed redundant hexad (ISA) inertial sensor assembly (three identical two-axis ISA's each containing two laser gyros and two accelerometers), and triple redundant inertial computation (IC) computers. The IC computers are separate assemblies, as in System K-2, or are individually integrated with each two-axis ISA, as in System K-3. The tradeoff between strapdown configurations K-2 and K-3 is lower cost for System K-2 versus a longer skewed ATR chassis in System K-3 and, hence, a more difficult skewed installation.

A cost comparison between the traditional and strapdown kinematic systems in Figure 26 shows a 20-percent cost-of-ownership savings for the strapdown system. A more significant fact is that the laser gyro strapdown kinematic system computer is mechanized assuming an INS attitude reference implementation. As such, the K-2 and K-3 system computers generate navigational position and velocity data as a normal part of the attitude reference calculations. Because the laser gyros utilized have INS accuracy capabilities, the additional navigation signals available in the triple redundant computers can be used to provide triple redundant inertial navigation outputs. The additional cost per system to utilize this capability is $1, 500 for additional I/O electronics.

The traditional flight control system in Figure 27 (System FC-1) consists of a triple redundant kinematic system interfaced with triple redundant fail-operational/fail-safe flight control computers. Three equivalent fail-operational/fail-safe strapdown laser flight control systems are shown in Figure 27. The FC-2 and FC-3 configurations interface the K-2 and K-3 kinematic systems with a triple redundant flight control computer; in the FC-4 configuration,the IC computer is integrated into the same housing as the FC computer. The tradeoff between the FC-2 and FC-3 configurations is similar to that between K-2 and K-3. The tradeoff between FC-4 and

FC-2 or FC-3 is lower cost versus the imposition of a dispatch critical requirement on the FC computer. The kinematic system is dispatch critical for commercial applications, the flight control computer normally is not. Incorporating part of the kinematic system into the FC computer makes this also a dispatch critical item.

A cost comparison between the traditional and strapdown flight control systems in Figure 27 shows the strapdown systems (FC-2 and FC-3) to have 13-percent lower cost of ownership. In the case of the FC-4 configuration, 20-percent savings results. In addition, triple redundant inertial navigation data can be obtained from either of the strapdown configurations for an added system cost of $1,500, as for the kinematic systems in Figure 26.

The traditional inertial navigation system shown in Figure 28, (System INAV-1) consists of a triple redundant ARINC 561 gimbaled INS. Four strapdown system types of equivalent redundancy level are illustrated in Figure 28: configurations INAV-2 and INAV-3 have the identical ARINC interface as INAV-1 but differ in where the IC computer is housed; configurations INAV-4 and INAV-5 are similar to INAV-2 and INAV-3 except that the ARINC interface is replaced by a simpler digital interface. The tradeoff between INAV-2 and INAV-4 and INAV-3 and INAV-5 is cost versus added skewed ATR length and associated installation constraints.

A comparison between the cost of ownership for the traditional and for the strapdown INS configuration in Figure 28 shows a dramatic 62-percent cost reduction for the strapdown systems with standard ARINC interface. For the strapdown systems with the simpler digital interface, the cost savings is 67 percent.

The strapdown system cost data summarized in Figures 26, 27, and 28 is based on an assumed laser gyro MTBF of 15,000 hours. Although this is considered to be a realistic estimate at the present time, it contains a degree of uncertainty because of the limited amount of reliability data currently available on recent technology laser gyros. Figure 29 illustrates the

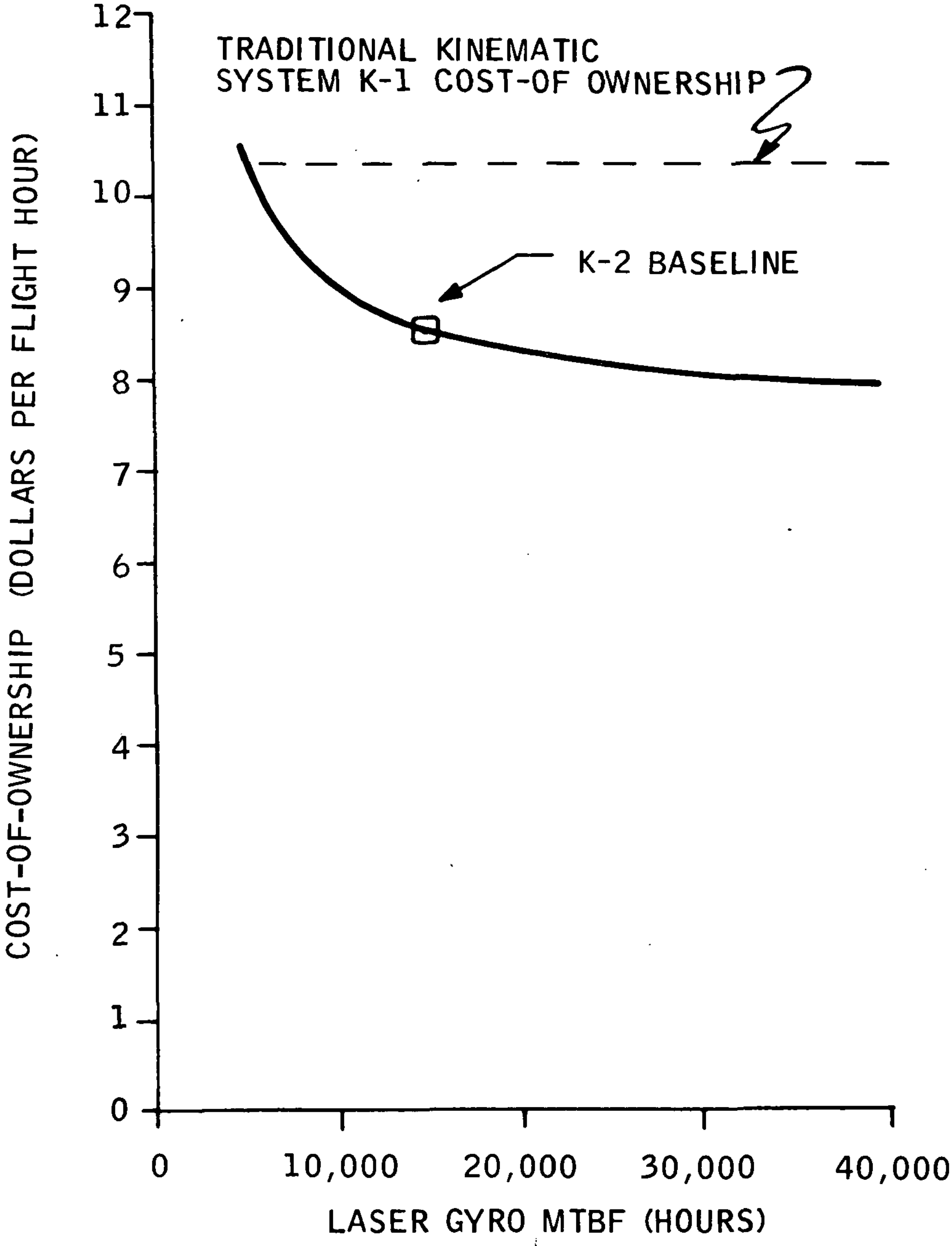


Figure 29. - Strapdown System Cost-of-Ownership versus Laser Gyro Reliability

sensitivity of the cost-of-ownership of strapdown system K-2, which is representative of the sensitivity of all strapdown systems evaluated in the study, to variations in laser gyro MTBF. Figure 29 shows that the strapdown system cost advantage over the traditional system, System K-1, is retained for laser gyro MTBF's as low as 5,000 hours, and this is considered unreasonably pessimistic.

Figure 30 illustrates the impact of six- and ten-percent inflation and 90-percent learning between 1974 and 1985 on initial procurement cost for redundant gimbaled (INAV-1 system) and strapdown (INAV-2 system) inertial navigation systems assuming a 10 system per month production rate. The curves show a widening of the strapdown cost advantage with time because of production learning. High rates of learning for the new strapdown technology are still to be experienced; mature gimbaled technology has been in production for several years and high learning rate periods are in the past. The new learning slope for the strapdown technology is steep enough between 1975 and 1978 to offset the effect of inflation. Because of the shallower learning slope for the gimbaled system, no such cancellation occurs and inflation results in an ever increasing procurement price.

From the study results it can be concluded that laser skewed redundant strapdown systems can provide significant advantages for future commercial aircraft in the areas of cost reduction and added performance capabilities. For basic redundant flight control systems and sensors, the strapdown approach is not only 15 to 20 percent lower in cost than traditional systems, but also can provide triple redundant inertial navigation data as an additional output for virtually no cost penalty. In the case of triple redundant inertial navigation systems, the strapdown skewed redundant system is one third the cost of the equivalent ARINC gimbaled triple redundant INS. If inflation and learning is taken into account, the strapdown INS cost advantage is even more dramatic. Strapdown systems are new and there is much to be learned about their production. The resulting steep learning slope for the strapdown technology over the next ten years will offset inflationary cost increases. For mature gimbaled technology, high learning rate periods are in the past, and

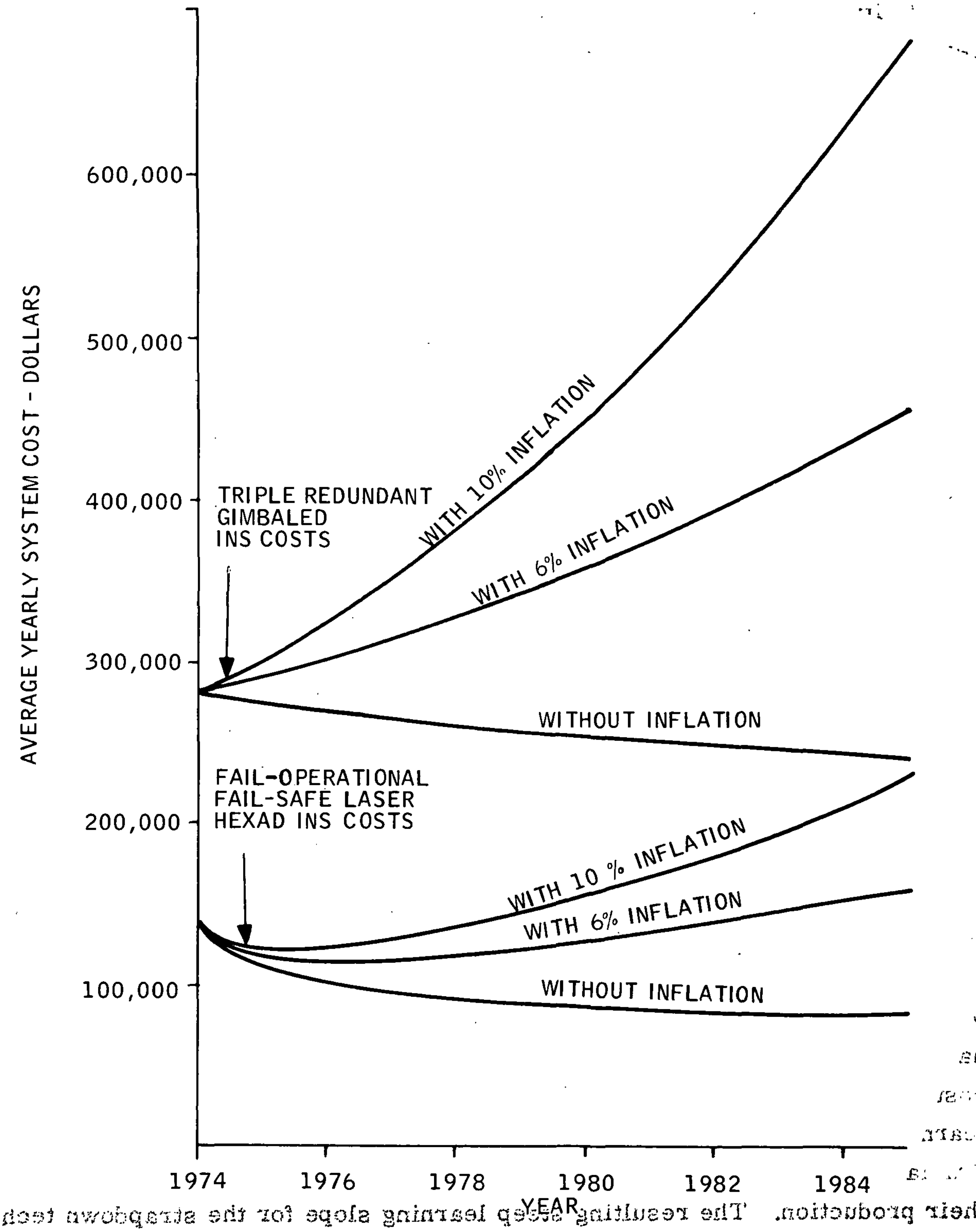


Figure 30. - Laser Strapdown Versus Gimbaled Redundant INS Cost Trends

inflation over the next ten years will result in continually increasing costs at the inflation rate.

Recommendations

For the study summarized in this report, several traditional and advanced strapdown configurations of kinematic, flight control, and inertial navigation systems were investigated for comparison on a cost-of-ownership basis. The study results have demonstrated that the strapdown skewed redundant configuration has significant cost and performance benefits over the equivalent traditional system. As a potential follow-on study, it is recommended that a strapdown configuration tradeoff be performed to define a single strapdown configuration that best satisfies overall requirements for commercial aircraft.

First, alternate system configurations would be defined for tradeoff evaluation. A kinematic system that includes the air data computation function interfaced with a set of remote air data transducers might be one configuration. Because air data is dispatch critical as is the kinematic system, this would be a logical combination of functions. Integrating the air data computation in the kinematic system computer would eliminate the air data computer ATR assembly normally contained in traditional flight control systems and it could then be replaced with a simpler, low cost remote transducer.

Tradeoff analyses would then be performed, entailing a review of all configurations investigated and the formulation of cost assumptions with commercial airline companies and aircraft manufacturers. Comments and recommendations would be solicited for preferences, changes, and configuration alternates. Questions concerning skewed ATR installation constraints that arose during this study would be answered. An additional question to be addressed would be how skewed ISA LRU's should be mounted in an aircraft such that necessary high alignment accuracies can be achieved between ISA's without requiring special installation alignment procedures.

The new configurations would then be costed and compared against the equivalent traditional system in the same manner as performed under the current study. In addition, a parameter variation study would be performed to assess the sensitivity of the system costs to uncertainties in the cost-of-ownership computer program input data. This was performed for the laser gyro MTBF in the current study, and could be performed for all other variables in the cost-of-ownership formula. The results could then be correlated with expected variations in the input parameters.

APPENDIX A

HEXAD SKEWED GYRO VOTING AND TRANSFORMATION EQUATIONS

Gyro Error Detection Equations

The derivation of a typical set of error equations to be used in the gyro error detection/isolation routines for the hexad system will be described in this subsection. It must be assumed that the three sets of orthogonal two-axis ISA's are placed such that each ISA has one input axis in the p and q (roll and pitch) plane, and the other axis rotated through an angle α with respect to the p and q plane as shown in Figure A-1. The p, q, and r (roll, pitch, yaw) coordinate frame was selected as the orthogonal reference triad. Figure A-2 shows the projection of the hexad input axes on the p and q plane.

The hexad input axes can be expressed in terms of the reference triad and configuration geometry by inspection as:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \\ \omega_5 \\ \omega_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -C\alpha & S\alpha \\ C_B & S_B & 0 \\ C\alpha\, CA & -C\alpha\, SA & S\alpha \\ CB & -SB & 0 \\ -C\alpha\, CA & -C\alpha\, SA & S\alpha \end{bmatrix} \begin{bmatrix} P \\ q \\ r \end{bmatrix}$$

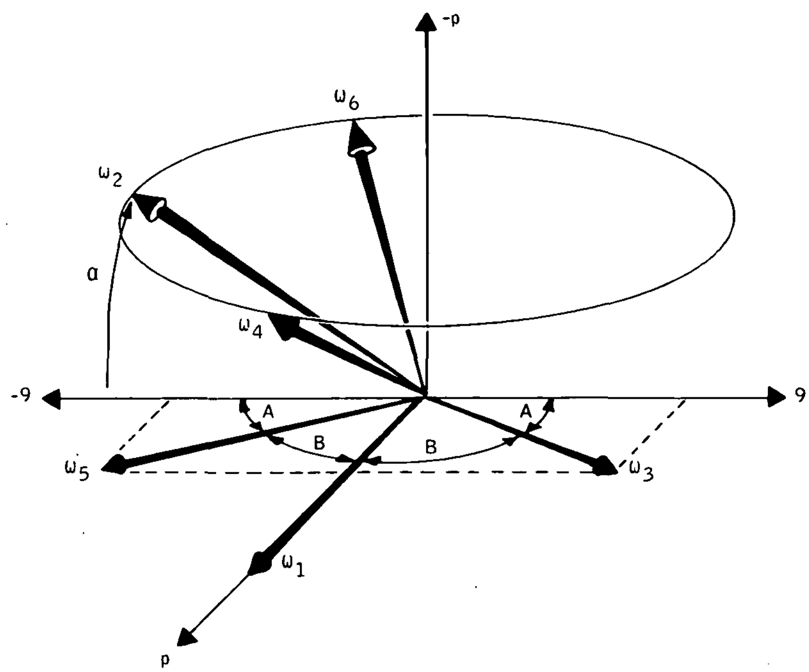


Figure A-1. - Hexad Geometry

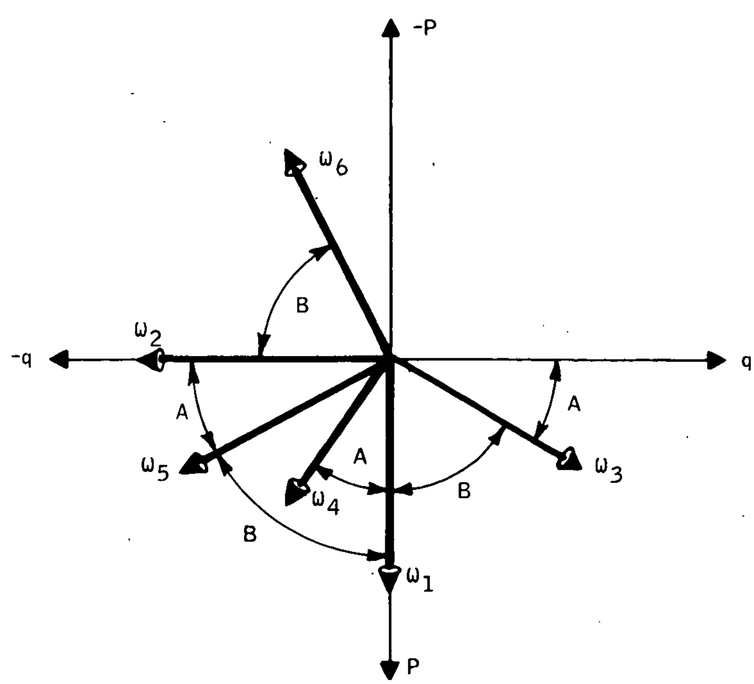


Figure A-2. - Projection of Hexad Input Axes into the q, p Plane

Where

ω_i	=	angular rate sensed by hexad gyro i
p, q, r	=	roll, pitch, yaw rates
α	=	45°
B	=	60°
A	=	30°
C	=	Cosine
S	=	Sine

The three sets of orthonormal two-axis ISA outputs are defined by ω_1, ω_2, ω_3, ω_4, ω_5, and ω_6. These sets, taken two at a time, result in three tetrad combinations:

$$\begin{array}{l} 1. \\ 2. \\ 3. \end{array} \left\{ \begin{array}{l} \omega_1, \omega_2, \omega_3, \omega_4 \\ \omega_1, \omega_2, \omega_5, \omega_6 \\ \omega_3, \omega_4, \omega_5, \omega_5 \end{array} \right\}$$

The associated error equations for each tetrad are sufficient to isolate a first failure to one two-axis ISA and to detect a second failure.

The tetrad error equations are derived by selecting pairs of triads from each of the tetrad combinations, such as:

$$\begin{array}{l} 1. \\ 2. \\ 3. \end{array} \left\{ \begin{array}{l} \omega_1, \omega_2, \omega_3 \\ \omega_1, \omega_2, \omega_5 \\ \omega_3, \omega_4, \omega_5 \end{array} \right\} \begin{array}{l} \text{and} \\ \text{and} \\ \text{and} \end{array} \left\{ \begin{array}{l} \omega_1, \omega_3, \omega_4 \\ \omega_1, \omega_2, \omega_6 \\ \omega_3, \omega_5, \omega_6 \end{array} \right\}$$

and solving for p, q, and r in terms of the three rowed submatrix inverses associated with each pair of triads. That is, for the selected pair of triads from the first tetrad,

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -C\alpha & -S\alpha \\ CB & SB & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$\begin{bmatrix} \omega_1 \\ \omega_3 \\ \omega_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ CB & -C\alpha & -S\alpha \\ CAC\alpha & -SAC\alpha & S\alpha \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

the second tetrad

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -C\alpha & S\alpha \\ CB & -SB & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -C\alpha & S\alpha \\ -C\alpha CA & -C\alpha SA & S\alpha \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

and the third tetrad,

$$\begin{bmatrix} \omega_3 \\ \omega_4 \\ \omega_5 \end{bmatrix} = \begin{bmatrix} CB & SB & 0 \\ C\alpha CA & -C\alpha SA & S\alpha \\ CB & -SB & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$\begin{bmatrix} \omega_3 \\ \omega_5 \\ \omega_6 \end{bmatrix} = \begin{bmatrix} CB & SB & 0 \\ CB & -SB & 0 \\ -C\alpha CA & -C\alpha SA & S\alpha \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

Taking inverses obtains for the first pair

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -\mathrm{Cot}B & 0 & \mathrm{Csc}(B) \\ -\mathrm{Cot}\alpha\,\mathrm{Cot}E & \mathrm{Csc}\,\alpha & \mathrm{Cot}\alpha\mathrm{C\,sc}(B) \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -\mathrm{Tan}A & \mathrm{Sec}A & 0 \\ -\mathrm{Cot}\alpha\,\mathrm{Sec}A & \mathrm{Tan}A\mathrm{Cot}\alpha & \mathrm{Csc}\alpha \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_4 \end{bmatrix}$$

for the second pair,

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \mathrm{Cot}B & 0 & -\mathrm{Csc}B \\ \mathrm{Cot}\alpha\,\mathrm{Cot}B & \mathrm{C}\quad\alpha & -\mathrm{Cot}\alpha\mathrm{C} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_5 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{CA}{(SA-1)} & \frac{1}{C\alpha(SA-1)} & \frac{1}{C\alpha(SA-1)} \\ \frac{CAC\alpha}{S\alpha(SA-1)} & \frac{SA}{S\alpha(SA-1)} & \frac{1}{S\alpha(SA-1)} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_6 \end{bmatrix}$$

and for the third pair,

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \frac{1}{CB} & 0 & \frac{1}{CB} \\ \frac{1}{SB} & 0 & -\frac{1}{SB} \\ \frac{C\alpha}{S\alpha}\frac{SA}{SB} - \frac{CA}{CB} & \frac{2}{S\alpha} & -\frac{C\alpha}{CB\,SB\,S\alpha} \end{bmatrix} \begin{bmatrix} \omega_3 \\ \omega_4 \\ \omega_5 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \frac{1}{CB} & \frac{1}{CB} & 0 \\ \frac{1}{CB} & -\frac{1}{SB} & 0 \\ \frac{C\alpha}{CB\,SBS\alpha} & -\frac{C\alpha}{S\alpha}\frac{SA}{SB} - \frac{CA}{CB} & \frac{2}{S\alpha} \end{bmatrix} \begin{bmatrix} \omega_3 \\ \omega_5 \\ \omega_6 \end{bmatrix}$$

In an ideal system, subtracting any two of the expressions for p, q, or r in each tetrad should yield zero. Nonzero values are indications of gyro (ω_i) failures. The difference equations can, therefore, be identified as error equations used to evaluate tetrad functional integrity. Subtracting the r terms for each tetrad yield the following equations:

$$E_1 = \mathrm{Cot}\alpha\ \mathrm{Sec}A\ (1-\mathrm{Sin}A)\ (\omega_3 + \omega_1)\ \mathrm{Csc}\alpha\ (\omega_2 - \omega_4)$$

$$E_2 = \mathrm{Cot}\alpha\ \mathrm{Csc}B\ (\omega_1 + \omega_5) + \frac{\mathrm{Csc}\alpha}{(\mathrm{Sin}A-1)}\ (\omega_6 - \omega_2)$$

$$E_3 = \mathrm{Cot}\alpha\ \mathrm{Cos}A\ \mathrm{Sec}B\ (\omega_3 + \omega_5) + \mathrm{C}\quad \alpha(\omega_4 - \omega_6)$$

---

1 Identical equations would be obtained (within a constant scale factor) if the p or q terms were subtracted and a nontrivial solution was produced (i. e., not a zero identity).

And for the angles as previously specified,

$$E_1 = 0.58\ (\omega_1 + \omega_3) + 0.707\ (\omega_2 - \omega_4)$$

$$E_2 = -1.15\ (\omega_1 + \omega_5) + 1.414\ (\omega_2 - \omega_6)$$

$$E_3 = -1.73\ (\omega_3 + \omega_5) + 0.707\ (\omega_4 - \omega_6)$$

To minimize the software requirements, the equations would be scaled such that one of the coefficients in each error equation would become unity.

To be capable of discriminating low-level (soft) failures from normal input random noise, the E_i equations are first integrated and squared before comparison with an error tolerance equation for error detection. The error tolerance equation is a second-order polynomial and its coefficients represent statistical sensor output error tolerances. The tolerance equations are of the form:

$$T_i = A_i + B_i t + C_i t^2$$

where,

A = constant, based on the covariance of the scale factor and misalignment calibration uncertainties, input axis geometry, and worst case rates.

B = function of input axis geometry and random walk bias covariance.

C = function of input axis geometry and constant bias covariance.

If the inequality

$$E_i' = [\int_0^t E_i\, dt]^2 \geq A_i + B_i t + C_i t^2$$

exists, a failure is indicated in tetrad i.

These E_i' error equations are sufficient to isolate a first failure to one of the three sets of two-axis ISA boxes and to detect a second failure to enable subsystem shut-down. For example, if ω_1 or ω_2 failed, E_1' and E_2' would exceed the precomputed tolerance level, and E_3' would remain within tolerance. This isolates the failure to the $[\omega_1, \omega_2]$ ISA. An additional failure would cause all three error equations to exceed their tolerance levels.

When a sensor failure is indicated, the appropriate error flag is set for use by the error response/action routine in the computer.

Gyro Selection and Orthogonal Computations

Two of the three two-axis ISA's are selected from which to compute a best estimate of the components along the referenced triad (p, q, r). That is, the tetrad is selected based on the error flag status as determined in the error detection/isolation routine. If no failures are indicated, the tetrad formed by ω_1, ω_2, and ω_3, ω_4 is selected for processing. This approach minimizes the software memory and time requirements due to the resulting consistent form of the equations.

Assuming the variance of each gyro is the same and given four measurements, it can be shown that the best estimate of the reference triad components (p, q, r) can be found by assuming measurements ω_1, ω_2, ω_3, ω_4 are for this example,

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = (A^T A)^{-1} A^T \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}$$

where A is a constant matrix defined by the geometry of the hexad configuration. For this case,

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -C\alpha & S\alpha \\ CB & SB & 0 \\ C\alpha CA & -C\alpha SA & S\alpha \end{bmatrix}$$

If the indicated matrix operations are carried out, equations of the following form result:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} K \\ (3x4) \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}$$

The matrix K is computed for each of the three selected tetrads and are stored in constant memory. Selecting the corresponding four ω measurements results in three sets of equations for p, q, and r. The failure flags determine which set is to be used, and a subroutine is used to do the computations.

APPENDIX B
COMPUTER SYNCHRONIZATION

Figure B-1 is a block diagram of the computer hardware synchronization concept assumed for the study. A 2-MHz oscillator in each computer is used to generate a 125-kHz ISA data transfer pulse rate signal, a 200-Hz data strobe ISA input cycle pulse, and a 40-msec (25 Hz) clock pulse. The 40-msec clock pulse is compared with the equivalent clock pulses from the other computer channels to derive a 40-msec sync pulse used to synchronize the computers, to reset and start the ISA input data timing counters (200-Hz and 125-Hz clocks), and start the next 40-msec clock time count.

The 40-msec clock pulses are transferred between channels and subjected to the clock sync generator and failure detection logic shown in Figure B-2. This logic generates a valid sync pulse when two or three pulses from the individual 40-msec clocks occur within a prescribed time interval (τ), which is derived from the 2-MHz oscillators, and reset each time a pulse is received. If the time difference between the occurrence of the first and second or second and third pulse is greater than τ, failure discrete F_1 is generated. If no two pulses occur during time τ, two failure discretes (F_1 and F_2) are issued. In either case, a 40-msec clock sync pulse is generated that synchronizies the computers by releasing them from a "halt" condition entered at the end of each 25 - Hz computation cycle. The derived 40-msec clock sync pulse also synchronizes the 125- kHz, 200-Hz ISA data transfer timing signals and resets/starts the 40-msec clock timer to generate the next 40-msec pulse.

The above operations occur simultaneously in each computer such that all become synchronized to the same 40-msec clock.

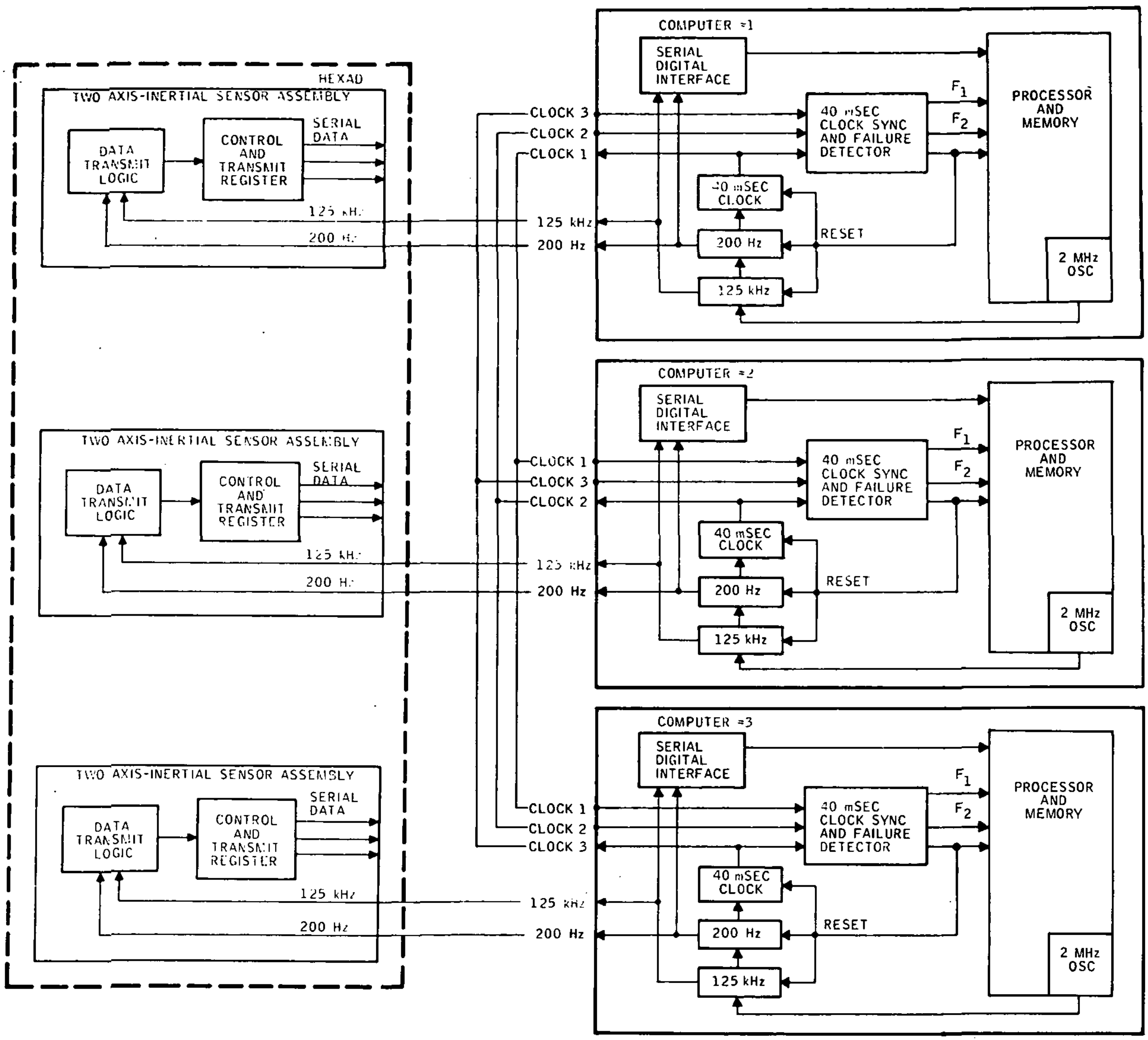


Figure B-1. - Computer Synchronization Concept

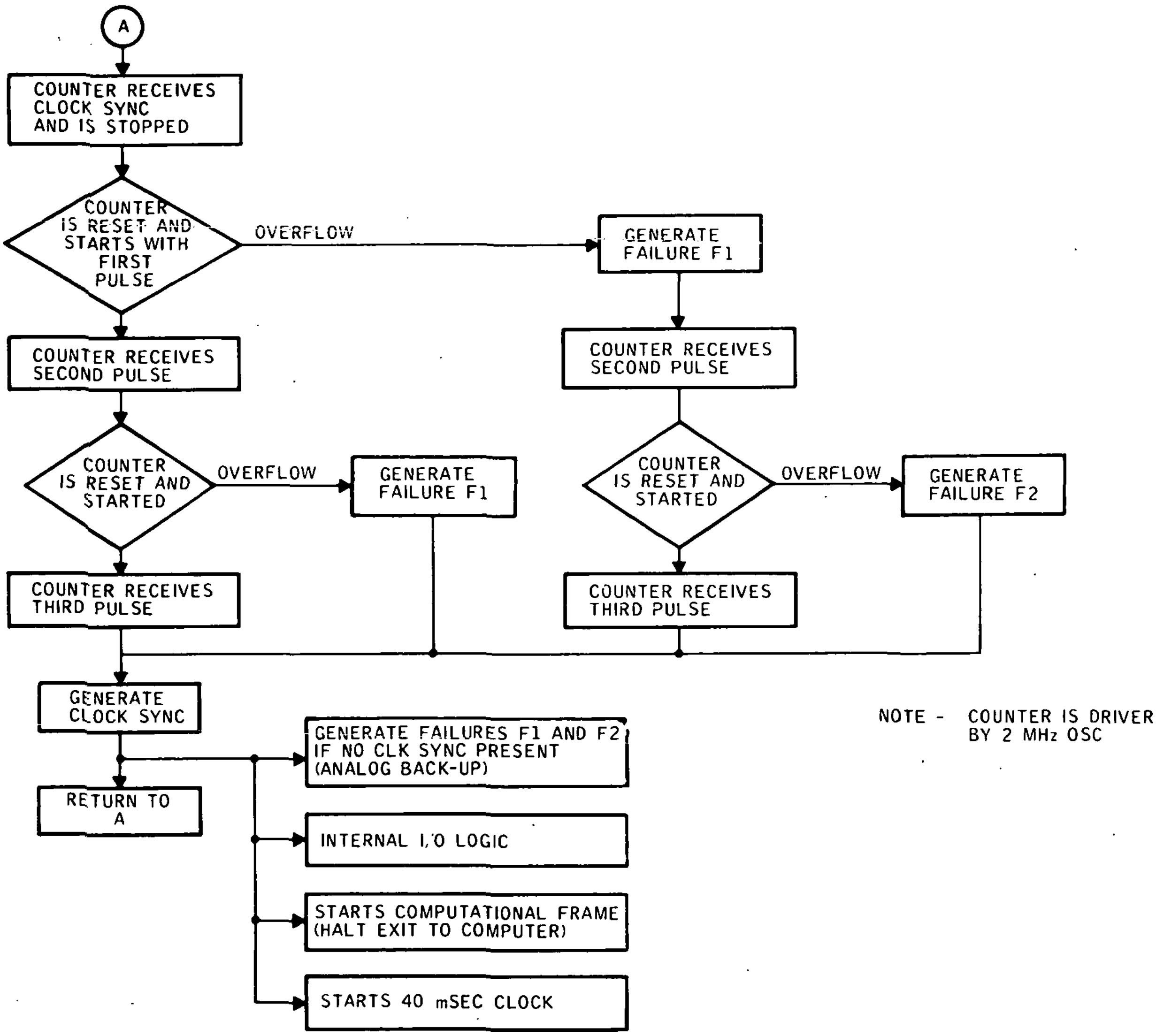


Figure B-2. - Sync Generator and Failure Detection Logic

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APPENDIX C

GENERAL SUBSYSTEM REQUIREMENTS FOR SHORT-HAUL AIRCRAFT

An operational requirement does not exist for inertial navigation (I-Nav) systems on short-haul aircraft because traditional attitude and area navigation (R-Nav) equipment will be satisfactory. I-Nav systems would have to be cost competitive with traditional attitude systems to be considered for short-haul aircraft. The cost of ownership of conventional gimbaled I-Nav systems has kept the I-Nav function from being seriously considered for short-haul applications even though there are realizable benefits in enroute and terminal navigation. Figure C-1 is a matrix relating general sensor output requirements for short-haul aircraft to the traditional computational boxes that use the sensor data and indicators for data display. The numbers shown in the matrix indicate redundancy levels required for boxes and indicators. The flight control mechanizations developed for the study as described in Section III were based on the Figure C-1 requirement summary.

Dispatch critical equipment refers to equipment that must be operating before the aircraft can leave. Airlines have multipage procedures governing the conditions for determining whether a particular piece of equipment is dispatch critical for a given flight. These procedures vary from airline to airline.

It is not believed that short-haul aircraft will be dispatched to a terminal at a time when landings must be under Category II or Category III weather conditions. Table C-1 shows probable dispatch critical assignments for traditional flight control equipment of the type described in Section III (Figure 14). Table C-2 shows probable dispatch critical assignments for a strapdown skewed redundant laser flight control system (Figure 15 of Section III). It should be noted that the hexad that replaces the three-axis accelerometer packages, flux gates, compass couplers, direction gyros, vertical gyros, and three-axis rate packages is considered a dispatch critical item as is most of the equipment it replaces.

Functions		Traditional computational boxes					Traditional flight indicators									
		High speed yaw damper	Flight control electronics	Auto throttle	Mach trim auto trim	R-Nav computer	Attitude and ḣ indicator	Horizontal situation indicator	Attitude director indicator	DME indicator	Radio magnetic indicator	R-NAV display	Mach	Total air temp	Air. speed
Attitute	Roll		3						2						
	Pitch		3	2					2						
	Heading		3			2		2			2				
Acceleration	Normal		3												
	Lateral		3			2									
	Longitudinal			2											
Rate	Roll		3												
	Pitch		3												
	Yaw	2	3												
Air data	Airspeed		2		2										2
	Airspeed Δ			2											
	Mach		2	2	2								2		
	Mach Δ														
	Altitude		2			2	2								
	Altitude Δ					2									
	Altitude rate		3			2	2								
	Total air temp													2	
Landing flight path	ILS		3					2	2						
Radio altimeter	Altitude		3	2											
Reference position	DME					2				2					
	VOR		2			2					2				
	ADF										2				
R-NAV output	Heading							2			2	2			
	position											2			

Figure C-1. - General Subsystem Requirements for Short-Haul Aircraft

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TABLE C-1. - TRADITIONAL FLIGHT CONTROL SYSTEM DISPATCH CRITICAL ASSIGNMENTS

No. of sensors	Type of Sensor	Dispatch critical
	Central air data computers	Yes
3	Angle of attack sensors	Yes
2	3-axis accelerometer package	Yes
3	Flux gates	Yes
3	Compass couplers	Yes
3	Directional gyros	Yes
3	Vertical gyros	Yes
3	3-axis rate packages	
	• 3 yaw rate sensors	Yes
	• 3 roll rate sensors	No
	• 3 pitch rate sensors	No
2	VHH omni-directional radio	Yes
2	Distance measuring equipment	Yes
3	Instrument landing systems	No
1	Automatic direction finder	Yes
3	Radio altimeters	No
No. of computational boxes	**Type of computation box**	**Dispatch critical**
2	High-speed yaw dampers	Yes
3	Flight control system electronics	No
2	Auto-throttle	No
2	Mach trim - auto trim	No
2	R-NAV computers	Route dependent
No. of displays	**Type of Display**	**Dispatch critical**
2	Airspeed	Yes
2	Total air temp	Yes
2	Mach	Yes
2	Altitude & $\dot{h}$ indicators	Yes
2	Horizontal situation indicators	Yes
2	Attitude director indicators	Yes
2	DME indicators	Yes
2	Radio Magnetic Indicators	Yes
2	R-NAV Displays	Route dependent

TABLE C-2. - STRAPDOWN LASER SKEWED REDUNDANT DISPATCH CRITICAL ASSIGNMENTS

No. of sensors	Type of sensor	Dispatch critical
3	Central air data computers	Yes
2	Angle of attack sensors	Yes
1	Hexad	Yes
2	VHH omni-directional radio	Yes
2	Distance measuring equipment	Yes
3	Instrument landing systems	Yes
1	Automatic direction finder	Yes
3	Radio altimeters	Yes
No. of computational boxes	**Type of computational box**	**Dispatch critical**
2	High-speed yaw dampers	Yes
3	Flight control system electronics	[a]Yes
2	Auto throttle	No
2	Mach trim auto trim	No
2	R-NAV computers	Route dependent
No. of displays	**Type of display**	**Dispatch critical**
2	Airspeed	Yes
2	Total air temp.	Yes
2	Mach	Yes
2	Altitude and $\dot{h}$ indicators	Yes
2	Horizontal situation indicators	Yes
2	Attitude director indicators	Yes
2	DME indicators	Yes
2	Radio magnetic indicators	Yes
2	R-NAV displays	Route dependent

[a] Those functions that are supplied to flight critical displays and the high-speed yaw damper are classified flight critical.

Airplane manufacturers are giving considerable attention to subsystem groupings to determine whether these groupings make sense from a dispatch critical point of view. For instance, the computer that is needed for the I-Nav calculations could also perform the air data calculations as both functions are dispatch critical.

APPENDIX D

LASER GYRO VERSUS FLOATED GYRO FOR STRAPDOWN INERTIAL SYSTEMS

Laser Gyro Versus Floated Gyro Performance

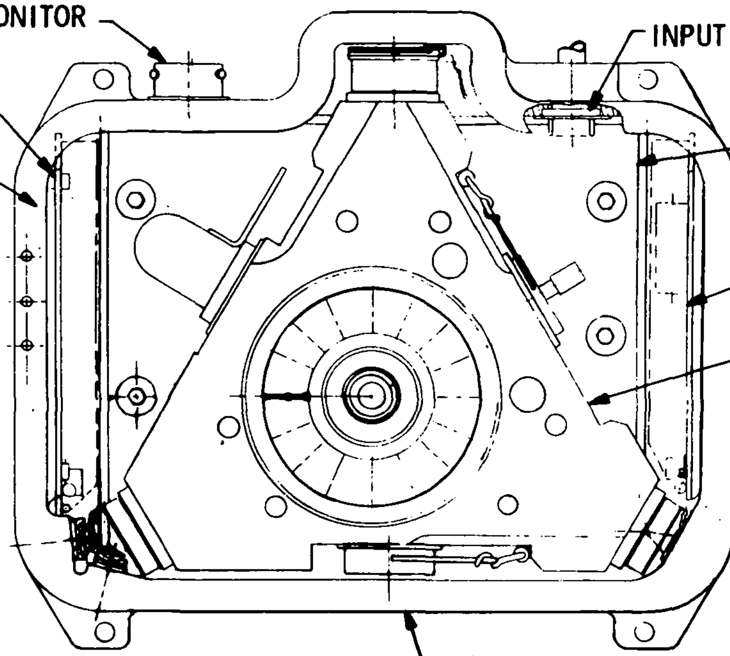
Figures D-1 depicts the Honeywell GG1300 laser gyro and Figure D-2 depicts the Honeywell GG1009H strapdown floated rate integrating gyro. Table D-1 summarizes their relative performance characteristics. The laser gyro has reaction time advantages because of its capability to achieve required performance levels without temperature control or frequent calibrations. For strapdown application, the performances of the floated gyro are marginal in scale factor accuracy; as such, its maneuver and flight path envelope is limited. The high scale factor accuracy capability of the laser gyro imposes no such restriction.

Laser Gyro Reliability Versus Floated Gyro Reliability

The MTBF for the laser gyro and its built-in electronics is projected at 15, 000 hours while the MTBF for the floated gyro and its support electronics is projected at 5, 700 hours.

The maintenance philosophy of airlines seldom provides for replacement and preventive maintenance on electronic equipment. Equipment is repaired and replaced only when it fails.

Figure D-3 shows a typical plot of device failure rate versus operating time. The shape of the plot is based upon both laboratory conducted tests and field observations. The curve is divided into three sections. Section A represents the failure rate during the infant mortality period. Infant morality failures are eliminated from operational considerations by burn-in tests. Section B of the curve is essentially flat representing a period where the failure rate is approximately constant. It is generally desired that this constant failure



SIZE:
7 BY 8 BY 2 INCHES

WEIGHT:
6.5 POUNDS

POWER:
6.0 WATTS NOMINAL, 8.0 WATTS MAX.

MAXIMUM INPUT RATE:
± 400 DEG/SEC

SCALE FACTOR:
2^{-17} RAD/PULSE 1.574 ARC-SEC/PULSE

PATH LENGTH:
43.13 CM (TOTAL); 5.66 INCHES PER LEG

NE LASER TRANSITION:
0.6328 MICRON

LOCK-IN COMPENSATION:
CAVITY ROTATIONAL DITHER

Figure D-1. - Honeywell GG1300 Laser Gyro Characteristics

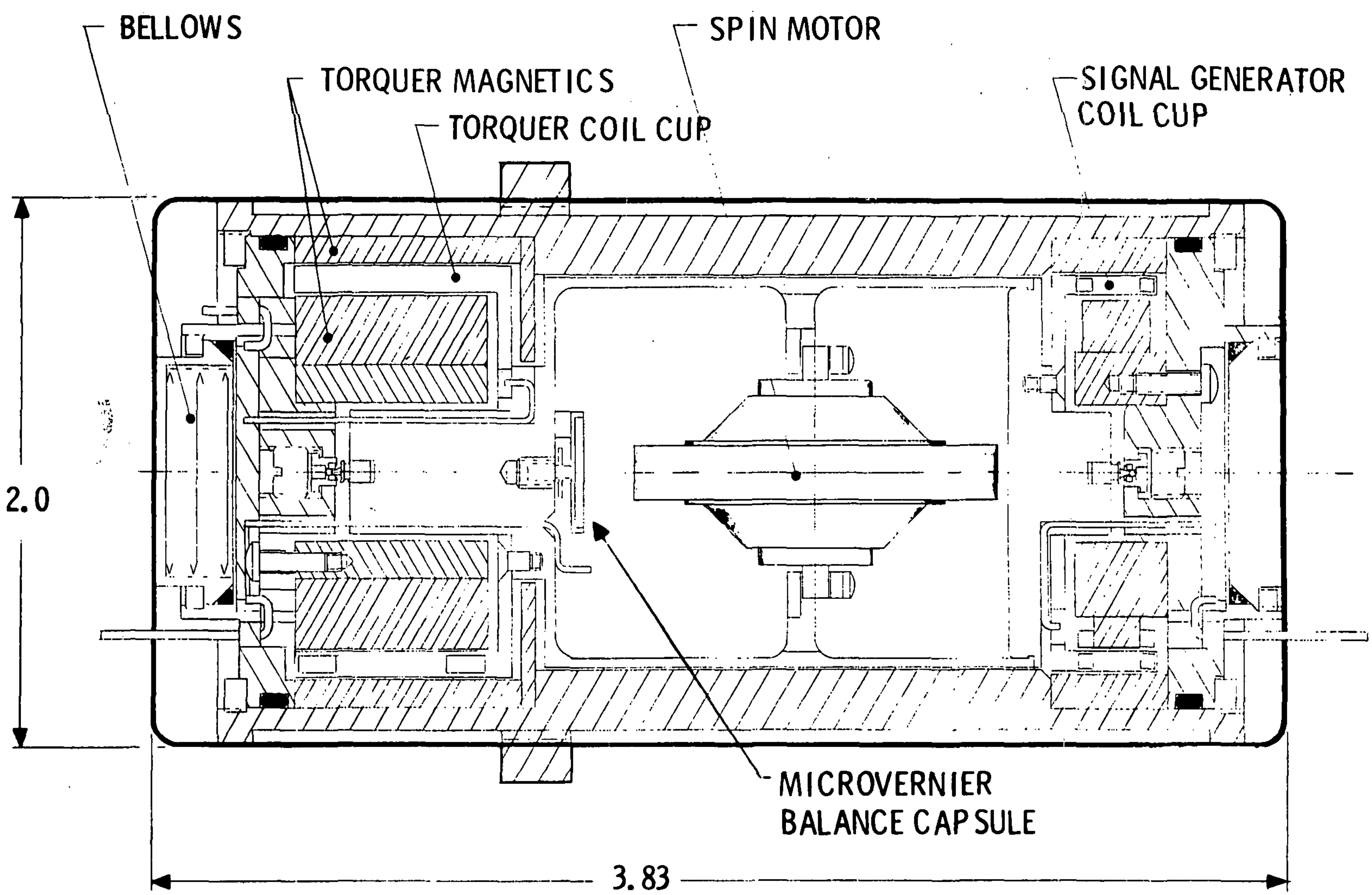


Figure D-2. - Honeywell GG1009H Strapdown Floated Rate Integrating Gyro

TABLE D-1. - LASER AND FLOATED GYRO STRAPDOWN PERFORMANCE SUMMARIES

Parameter	GG1300 Laser gyro	GG1009H Floated gyro
Bias	0.01-0.03 deg/hr	0.01-0.03 deg/hr
Scale factor error	0.001%	0.01%
Operating temp.	-65°F to 160°F	Controlled at 180°F
Warm-up time	0	10 min
Calibration time	0	5 min
Alignment time	2-5 min	2 min

portion of the curve be as long as possible. Section C of the curve represents long term wear-out phenomena of the device.

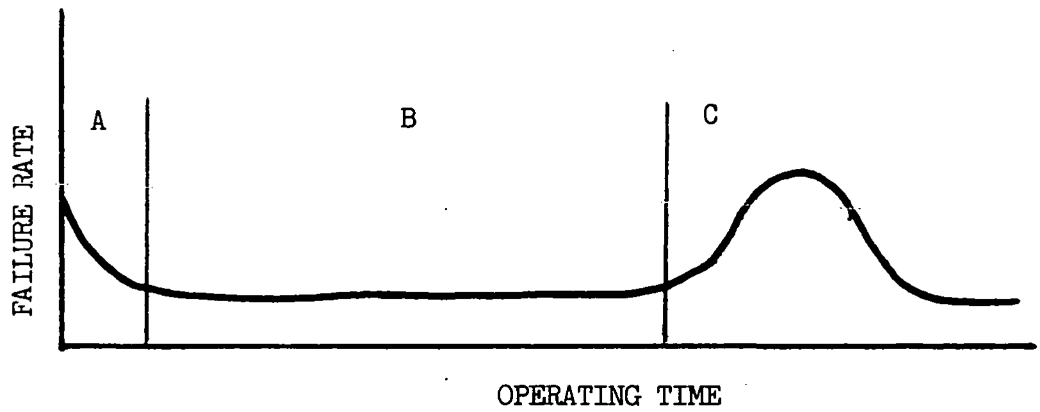


Figure D-3. - Device Failure Rate Versus Operating Time

Both the floated gyro and the laser gyro have a wear-out mechanism. The wear-out mechanism for the floated gyro centers on the ball bearings and results in a mean wear-out life of approximately 11, 000 hours. The wear-out mechanism that limits lifetime in the laser gyro is the gas pumping action of the cathode. To sustain the laser gas discharge, positive ions collide to provide electron emission. Some ions are trapped during this process and other gas atoms are buried by the sputtered cathode material. Thus, when the discharge is run, a small amount of helium and neon is pumped by the cathode. Over a period of time, this results in reduced gas pressure and eventual gyro failure. Based on accelerated life test results, estimates for the wear-out life due to cathode pumping of recent technology gyros is 30, 000 hours.

As both gyros have long term wear-out mechanisms, the Curve C failure rates shown in Tables D-2 and D-3 are applicable for the floated and laser gyros respectively.

TABLE D-2. - FLOATED GYRO FAILURE RATES

	Failure rate, %/1, 000 hrs	
	Section B	Section C
1 floated gyro	5. 0	11. 8
1 gyro digitizer	2. 8	2. 8
1 temp. control	1. 0	1. 0
1 gyro loop electronics	2. 0	2. 0
Applicable fail rate	10. 8	17. 6

TABLE D-3. - LASER GYRO FAILURE RATES

	Failure rate, %/1, 000 hrs	
	Section B	Section C
1 laser gryo and electronics	5. 1	6. 66
Applicable failure rate	5. 1	6. 66

An approximate equivalent MTBF for equipment having both a random and wear-out (normal) failure distribution can be computed using the following equation:

$$(\text{MTBF})_{\text{equivalent}} = \frac{1}{\lambda}\left(1-e^{-\lambda T}\right)$$

where

λ = random failure rate (Curve B)
T = mean in hours of wear-out distribution

Using 5 percent per 1,000 hours (random failure rate) and 11,000 hours (mean life) for the floated gyro yields the 11.8 percent per 1,000 hours failure rate for Section C (Table D-2). The floated gyro electronics are treated separately in Figure D-4.

Using 5.1 percent per 1,000 hours (random) and 30,000 hours (mean life) for the laser gyro yields the 6.66 percent per 1,000 hour failure rate for Curve C (Table D-3). The laser gyro electronics shown in Figure D-5 are included as part of the gyro.

If the gyros were replaced before they reached Section C of Figure D-3 (not normal airline maintenance philosophy), the Section B failures of Table D-2 and D-3 would apply.

Laser Gyro ISA Costs Compared To Floated Gyro ISA Costs

The cost of ownership of a hexad ISA mechanized with laser gyros is projected at 58 percent of the cost of a hexad ISA mechanized with floated gyros. The direct maintenance cost of a laser hexad ISA is 34 percent of the cost of a floated gyro hexad ISA.

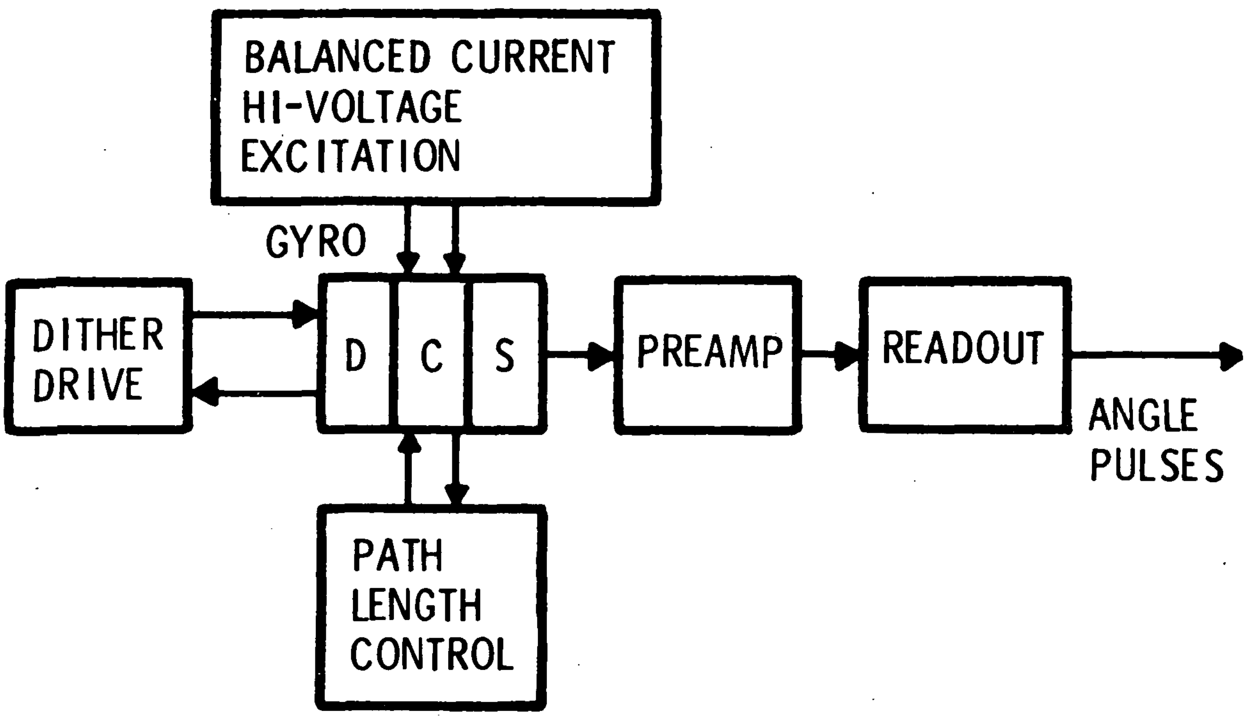


Figure D-4. - Laser Gyro Self-Contained Electronics

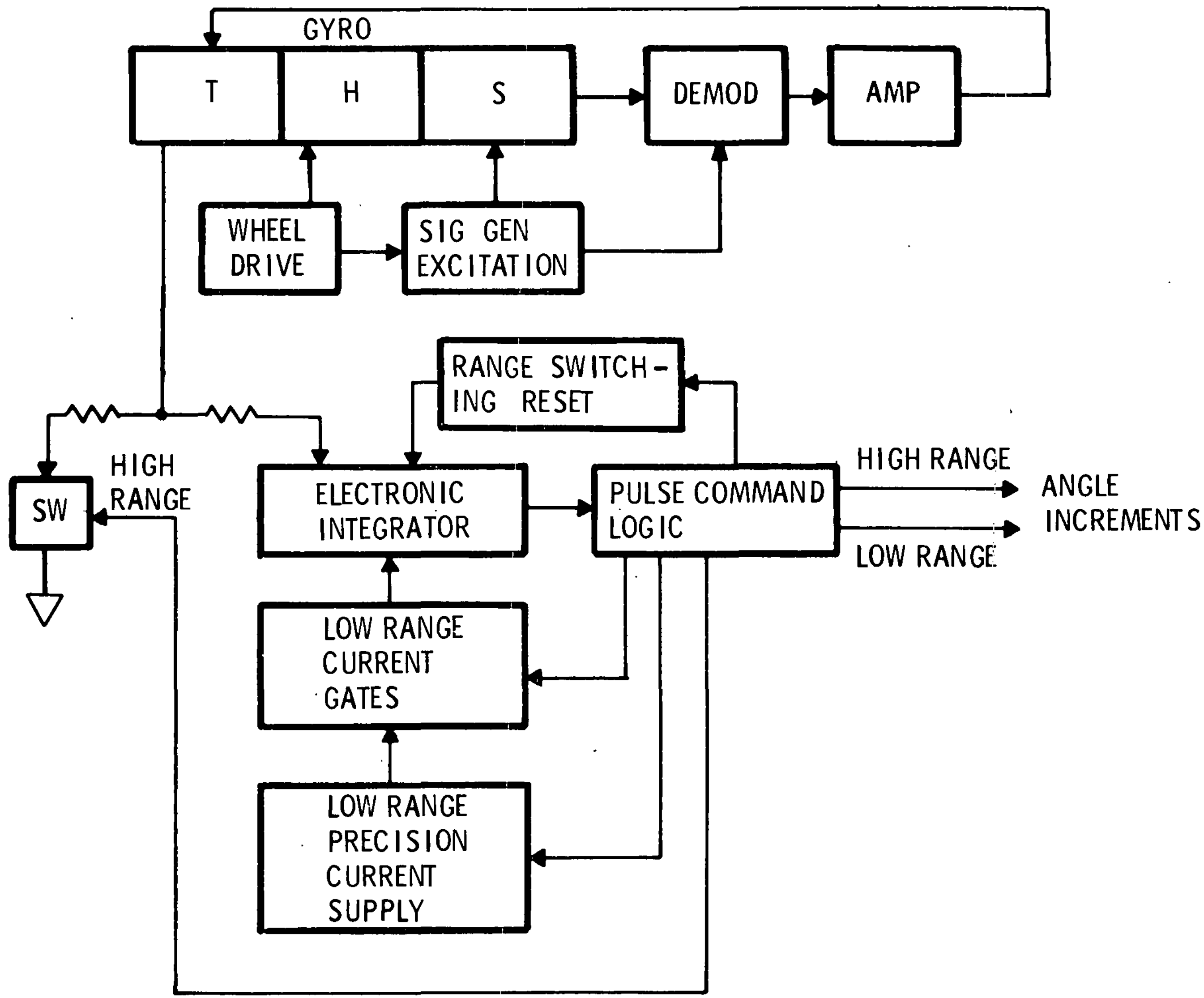


Figure D-5. - Floated Rate Integrating Gyro Strapdown Electronics

Tables D-4 and D-5 show how the MTBF and initial cost figures are calculated for laser and floated gyro two-axis ISA's. Table D-6 shows a cost summary for the two configirations based on Appendix E cost-of-ownership Computer Runs 4.1 and 1.2.3.

TABLE D-4. - MTBF CALCULATIONS FOR FLOATED GYRO TWO-AXIS ISA

ISA parts	Item cost	No. items	Cost total	MTBF, % per 1,000 hr	Total MTBF, % per 1,000 hr	Parts cost dollars	Parts cost per hr
Up-down counter and storage cards	380	2	560	.80	1.6	280	0.0045
Accelerometer pulse logic card	230	1	230	.80	.80	230	.0018
Gyro digitizer card	510	2	1020	2.8	5.6	510	.0286
Control and transmit logic card	400	1	400	.80	.80	400	.0032
Gyro temp. control card	320	1	320	2.0	2.0	320	.0064
Control and output strobe	340	1	340	.80	.80	340	.0027
Accelerometer block	330	1	330	---	---	---	---
Gyro block	330	1	330	---	---	---	---
Chassis (including wiring and connectors)	2100	1	2100	.50	.50	300	.0015
Accelerometer and module electronics	1810	2	3620	4.0	8.0	625	.0484
Gyro loop electronics card	380	2	760	2.0	4.0	380	.0152
Floated gyros	6000	2	12000	11.8	23.6	2400	.5664
Assemble and test	1700	1	1700	---	---	---	---
ISA total			23710		47.70	[a]1423	0.6787

[a] Parts costs per failure is calculated by dividing part costs per hour by failures per hour

TABLE D-5. - MTBF CALCULATIONS FOR LASER GYRO TWO-AXIS ISA

ISA parts	Item cost	No. items	Cost total	MTBF, % per 1,000 hr	Total MTBF, % per 1,000 hr	Parts cost dollars	Parts cost per hr
Up-down counter and storage cards	380	2	560	.80	1.6	280	0.0045
Accelerometer pulse logic card	230	1	230	.80	.80	230	.0018
Control and transmit logic card	400	1	400	.80	.80	400	.0032
Control and output strobe	340	1	340	.80	.80	340	.0027
Accelerometer block	330	1	330	--	--	--	--
Laser gyro block	330	1	330	--	--	--	--
Chassis (including wiring and connectors)	2100	1	2100	.50	.50	300	.0015
Accelerometer and module electronics	1810	2	3620	4.0	8.0	625	.0484
Laser gyros [a]	4000	2	8000	6.7	13.4	1200	.1608
Assemble and test	1500	1	1500	--	--	--	--
ISA total			17,410		25.90	[b]861	0.2229

[a] Laser gyro - 15,000 hr MTBF

[b] Parts costs per failure is calculated by dividing part costs per hour by failures per hour

TABLE D-6. - COST SUMMARY

	Initial cost (dollars)	Direct maintenance cost (dollars/flight hr)	Cost of ownership (dollars/flight hr)
Laser gyro hexad (3 two-axis ISA's)	$52,230	1.29	5.06
Floated gyro hexad (3 two-axis ISA's)	71,130	3.80	8.75

APPENDIX E
COST-OF-OWNERSHIP COMPUTER RUNS

1.0 Kinematic System Computer Runs

1.1 <u>Kinematic System K-1</u>

Run 1.1.1: 9 rate gyros

Run 1.1.2: 9 accelerometers

Run 1.1.3: 3 vertical gyros

Run 1.1.4: 3 directional gyros

Run 1.1.5: 3 compass couplers

Run 1.1.6: 3 flux gates

1.2 <u>Kinematic System K-2</u>

Run 1.2.1: 3 two-axis ISA's (laser life = 5,000 hours)

Run 1.2.2: 3 two-axis ISA's (laser life = 10,000 hours)

Run 1.2.3: 3 two-axis ISA's (laser life = 15,000 hours)

Run 1.2.4: 3 two-axis ISA's (laser life = 20,000 hours)

Run 1.2.5: 3 two-axis ISA's (laser life = 30,000 hours)

Run 1.2.6: 3 two-axis ISA's (laser life = 40,000 hours)

Run 1.2.7: 3 IC computers (kinematic-digital)

1.3 <u>Kinematic System K-3</u>

Run 1.3.1: 3 two-axis ISA/IC's (kinematic-digital)

2.0 Flight Control System Computer Runs

2.1 <u>Flight Control System FC-1</u>

Run 2.1.1: 3 FC computers (analog input)

Ref run: K-1 kinematic system (Runs 1.1.1 through 1.1.6)

2.2 <u>Flight Control System FC-2</u>

Run 2.2.1: 3 FC computers (digital input)

Ref run: 1.2.3 (3 two-axis-ISA's)

Ref run: 1.2.7 (3 IC computers)

2.3 <u>Flight Control System FC-3</u>

Ref run: 1.3.1 (3 two-axis ISA/IC's)

Ref run: 2.1.1 (3 FC computers)

2.4 <u>Flight Control System FC-4</u>

Run 2.4.1: 3 IC/FC computers

Ref run: 1.2.3 (3 two-axis ISA's)

3.0 Inertial Navigation System Computer Runs

3.1 <u>INAV-1 system</u>

Run 3.1.1: 3 gimbaled navigation boxes

3.2 <u>INAV-2 system</u>

Run 3.2.1: 3 IC computers (INAV-ARINC)

Ref run: 1.2.3 (3 two-axis ISA's)

3.3 <u>INAV-3 system</u>

Run 3.3.1: 3 two-axis ISA/IC's (INAV-ARINC)

3.4 <u>INAV-4 system</u>

Run 3.4.1: 3 IC computers (INAV-digital)

Ref run: 1.2.3 (3 two-axis ISA's)

3.5 <u>INAV-5 system</u>

Run 3.5.1: 3 two-axis ISA/IC (INAV-digital)

4.0 Hexad Inertial Sensor Assembly (Floated Gyros) Computer Run

4.1 <u>3 two-axis ISA's (floated gyros)</u>

DESCRIBE UNIT

! RUN 1.1.1 9 RATE GYROS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 1000., 100.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 6400., 1.5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 9., 1.67

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 340., .5

- -

SYSTEM COST	9000.00
NO. OF SPARE UNITS	52.50
ANNUAL FLEET REMOVALS	2078.79
ANNUAL PLANE REMOVALS	13.86
REMOVALS PER 1000 FLIGHT HRS	4.22

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	245024.97	1633.50	497.26
AMORTIZED SPARE COSTS	8661.72	57.74	17.58
FUEL COST	61885.66	412.57	125.59
DIRECT MAINTENANCE COST			
+ NEW MODULES OR REPAIR	353394.12	2355.96	717.19
+ LINE MAINTENANCE	9895.04	65.97	20.08
+ SHOP MODULE REPLACEMT	25382.01	169.21	51.51
+ BURDEN-SHOP AND LINE	35277.05	235.18	71.59
TOTAL COST OF OWNERSHIP	739520.62	4930.14	1500.80
+ DIRECT MAINT COST	423948.25	2826.32	860.37

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DESCRIBE UNIT

! RUN 1.1.2   9 ACCELEROMETERS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 1000., 625.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 96700., 1.5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 9., .5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 340., .5

- -

SYSTEM COST	9000.00
NO. OF SPARE UNITS	5.89
ANNUAL FLEET REMOVALS	137.58
ANNUAL PLANE REMOVALS	0.92
REMOVALS PER 1000 FLIGHT HRS	0.28

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	361968.69	2413.12	734.59
AMORTIZED SPARE COSTS	971.41	6.48	1.97
FUEL COST	18528.65	123.52	37.60
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	23389.07	155.93	47.47
• LINE MAINTENANCE	654.89	4.37	1.33
• SHOP MODULE REPLACEMT	1679.89	11.20	3.41
• BURDEN-SHOP AND LINE	2334.78	15.57	4.74
TOTAL COST OF OWNERSHIP	409527.25	2730.18	831.11
• DIRECT MAINT COST	28058.62	187.06	56.94

DESCRIBE UNIT

! RUN 1.1.3   3 VERTICAL GYROS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 6200., 1620.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 3000., 2.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 20.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 1811., .5

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SYSTEM COST	18600.00
NO. OF SPARE UNITS	39.00
ANNUAL FLEET REMOVALS	1478.25
ANNUAL PLANE REMOVALS	9.85
REMOVALS PER 1000 FLIGHT HRS	3.00

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	580634.87	3870.90	1178.36
AMORTIZED SPARE COSTS	39895.91	265.97	80.97
FUEL COST	247048.69	1646.99	501.37
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	1338555.50	8923.70	2716.50
◆ LINE MAINTENANCE	7036.47	46.91	14.28
◆ SHOP MODULE REPLACEMT	24065.91	160.44	48.84
◆ BURDEN-SHOP AND LINE	31102.38	207.35	63.12
TOTAL COST OF OWNERSHIP	2268340.00	15122.27	4603.43
◆ DIRECT MAINT COST	1400760.25	9338.40	2842.74

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DESCRIBE UNIT

! RUN 1.1.4   3 DIRECTIONAL GYROS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	9.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 3800., 50.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 7700., 2.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 14.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 1236., .5

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SYSTEM COST	11400.00
NO. OF SPARE UNITS	17.69
ANNUAL FLEET REMOVALS	575.94
ANNUAL PLANE REMOVALS	3.84
REMOVALS PER 1000 FLIGHT HRS	1.17

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	285862.44	1905.75	580.14
AMORTIZED SPARE COSTS	11093.13	73.95	22.51
FUEL COST	172934.00	1152.89	350.96
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	355931.87	2372.88	722.34
◆ LINE MAINTENANCE	2741.48	18.28	5.56
◆ SHOP MODULE REPLACEMT	9376.33	62.51	19.03
◆ BURDEN-SHOP AND LINE	12117.81	80.79	24.59
TOTAL COST OF OWNERSHIP	850057.12	5667.05	1725.13
◆ DIRECT MAINT COST	380167.50	2534.45	771.52

DESCRIBE UNIT

! RUN 1.1.5 3 COMPASS COUPLERS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 4200., 1415.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 8500., 1.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 8.6

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 500., .5

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SYSTEM COST	12600.00
NO. OF SPARE UNITS	16.33
ANNUAL FLEET REMOVALS	521.74
ANNUAL PLANE REMOVALS	3.48
REMOVALS PER 1000 FLIGHT HRS	1.06

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	416913.69	2779.42	846.10
AMORTIZED SPARE COSTS	11318.28	75.46	22.97
FUEL COST	106230.89	708.21	215.59
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	130433.31	869.56	264.71
• LINE MAINTENANCE	2483.46	16.56	5.04
• SHOP MODULE REPLACEMT	4246.92	28.31	8.62
• BURDEN-SHOP AND LINE	6730.38	44.87	13.66
TOTAL COST OF OWNERSHIP	678357.50	4522.38	1376.68
• DIRECT MAINT COST	143894.59	959.30	292.02

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DESCRIBE UNIT

! RUN 1.1.6 3 FLUX GATES

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 600., 900.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 180000., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 2.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 600., .5

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SYSTEM COST	1800.00
NO. OF SPARE UNITS	1.35
ANNUAL FLEET REMOVALS	24.64
ANNUAL PLANE REMOVALS	0.16
REMOVALS PER 1000 FLIGHT HRS	0.05

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	111374.98	742.50	226.03
AMORTIZED SPARE COSTS	182.88	1.22	0.37
FUEL COST	24704.86	164.70	50.14
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	7391.25	49.27	15.00
◆ LINE MAINTENANCE	117.27	0.78	0.24
◆ SHOP MODULE REPLACEMT	100.27	0.67	0.20
◆ BURDEN-SHOP AND LINE	217.55	1.45	0.44
TOTAL COST OF OWNERSHIP	144089.09	960.59	292.42
◆ DIRECT MAINT COST	7826.35	52.18	15.88

DESCRIBE UNIT

! RUN 1.2.1   3 TWO-AXIS ISA'S LASER LIFE = 5,000 HRS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 1904., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 1033., .5

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SYSTEM COST	52230.00
NO. OF SPARE UNITS	53.04
ANNUAL FLEET REMOVALS	2329.18
ANNUAL PLANE REMOVALS	15.53
REMOVALS PER 1000 FLIGHT HRS	4.73

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	166717.41	1111.45	338.34
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	1203019.00	8020.13	2441.44
• LINE MAINTENANCE	11086.87	73.91	22.50
• SHOP MODULE REPLACEMT	132716.41	884.78	269.34
• BURDEN-SHOP AND LINE	143803.28	958.69	291.84
TOTAL COST OF OWNERSHIP	3424828.00	22832.19	6950.44
• DIRECT MAINT COST	1490625.50	9937.50	3025.12

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DESCRIBE UNIT

! RUN 1.2.2   3 TWO-AXIS ISA'S   LASER LIFE - 10,000 HRS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 3077., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 930., .5

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SYSTEM COST	52230.00
NO. OF SPARE UNITS	33.16
ANNUAL FLEET REMOVALS	1441.26
ANNUAL PLANE REMOVALS	9.61
REMOVALS PER 1000 FLIGHT HRS	2.92

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	109607.14	730.71	222.44
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
* NEW MODULES OR REPAIR	670184.87	4467.90	1360.09
* LINE MAINTENANCE	6860.39	45.74	13.92
* SHOP MODULE REPLACEMT	82122.86	547.49	166.66
* BURDEN-SHOP AND LINE	88983.25	593.22	180.58
TOTAL COST OF OWNERSHIP	2725343.50	18168.29	5530.68
* DIRECT MAINT COST	848151.37	5654.34	1721.26

DESCRIBE UNIT

! RUN 1.2.3   3 TWO-AXIS ISA'S   LASER LIFE = 15,000 HRS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 3861., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 861., .5

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SYSTEM COST	52230.00
NO. OF SPARE UNITS	31.41
ANNUAL FLEET REMOVALS	1148.60
ANNUAL PLANE REMOVALS	7.66
REMOVALS PER 1000 FLIGHT HRS	2.33

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	90243.61	601.62	183.14
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
* NEW MODULES OR REPAIR	494472.87	3296.49	1003.50
* LINE MAINTENANCE	5467.34	36.45	11.10
* SHOP MODULE REPLACEMT	65447.30	436.32	132.82
* BURDEN-SHOP AND LINE	70914.64	472.76	143.92
TOTAL COST OF OWNERSHIP	2494030.50	16626.87	5061.45
* DIRECT MAINT COST	636302.12	4242.01	1291.33

DESCRIBE UNIT

! RUN 1.2.4   3 TWO-AXIS ISA'S LASER LIFE = 20,000

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 4444., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 809., .5

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SYSTEM COST	52230.00
NO. OF SPARE UNITS	27.89
ANNUAL FLEET REMOVALS	997.92
ANNUAL PLANE REMOVALS	6.65
REMOVALS PER 1000 FLIGHT HRS	2.03

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	80111.31	534.08	162.58
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	403658.06	2691.05	819.19
• LINE MAINTENANCE	4750.09	31.67	9.64
• SHOP MODULE REPLACEMT	56861.40	379.08	115.40
• BURDEN-SHOP AND LINE	61611.49	410.74	125.04
TOTAL COST OF OWNERSHIP	2374477.50	15829.85	4818.83
• **DIRECT MAINT COST**	526881.00	3512.54	1069.27

DESCRIBE UNIT

! RUN 1.2.5   3 TWO-AXIS ISA'S   LASER LIFE = 30,000 HRS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 5208., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 742., .5

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SYSTEM COST	52230.00
NO. OF SPARE UNITS	24.41
ANNUAL FLEET REMOVALS	851.53
ANNUAL PLANE REMOVALS	5.68
REMOVALS PER 1000 FLIGHT HRS	1.73

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	70129.66	467.53	142.32
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	315916.31	2106.11	641.13
• LINE MAINTENANCE	4053.27	27.02	8.23
• SHOP MODULE REPLACEMT	48519.98	323.47	98.47
• BURDEN-SHOP AND LINE	52573.24	350.49	106.69
TOTAL COST OF OWNERSHIP	2258677.50	15057.85	4583.82
• DIRECT MAINT COST	421062.81	2807.09	854.52

DESCRIBE UNIT

! RUN 1.2.6   3 TWO-AXIS ISA'S   LASER LIFE = 40,000 HRS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 17410., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 5714., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 698., .5

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SYSTEM COST	52230.00
NO. OF SPARE UNITS	22.60
ANNUAL FLEET REMOVALS	776.12
ANNUAL PLANE REMOVALS	5.17
REMOVALS PER 1000 FLIGHT HRS	1.58

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1341326.00	8942.17	2722.12
AMORTIZED SPARE COSTS	64923.54	432.82	131.76
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	270865.87	1805.77	549.70
• LINE MAINTENANCE	3694.33	24.63	7.50
• SHOP MODULE REPLACEMT	44223.31	294.82	89.75
• BURDEN-SHOP AND LINE	47917.64	319.45	97.25
TOTAL COST OF OWNERSHIP	2199109.50	14660.73	4462.93
• DIRECT MAINT COST	366701.19	2444.67	744.19

DESCRIBE UNIT

! RUN 1.2.7   3 IC COMPUTERS   (KINEMATIC-DIGITAL)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 14480., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 5620., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 18.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 440., .5

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SYSTEM COST	43440.00
NO. OF SPARE UNITS	22.91
ANNUAL FLEET REMOVALS	789.10
ANNUAL PLANE REMOVALS	5.26
REMOVALS PER 1000 FLIGHT HRS	1.60

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1223639.75	8157.60	2483.29
AMORTIZED SPARE COSTS	54745.63	364.97	111.10
FUEL COST	222343.81	1482.29	451.23
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	173602.28	1157.35	352.31
• LINE MAINTENANCE	3756.12	25.04	7.62
• SHOP MODULE REPLACEMT	3211.64	21.41	6.52
• BURDEN-SHOP AND LINE	6967.76	46.45	14.14
TOTAL COST OF OWNERSHIP	1688267.00	11255.11	3426.21
• DIRECT MAINT COST	187537.81	1250.25	380.59

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DESCRIBE UNIT

! RUN 1.3.1   3 TWO-AXIS ISA/IC'S   (KINEMATIC-DIGITAL)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 28900., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 2457., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 40.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 716., .5

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SYSTEM COST	86700.00
NO. OF SPARE UNITS	46.38
ANNUAL FLEET REMOVALS	1804.95
ANNUAL PLANE REMOVALS	12.03
REMOVALS PER 1000 FLIGHT HRS	3.66

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	2294324.50	15295.50	4656.16
AMORTIZED SPARE COSTS	221174.16	1474.49	448.86
FUEL COST	500273.56	3335.16	1015.27
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	646170.37	4307.80	1311.36
◆ LINE MAINTENANCE	8591.54	57.28	17.44
◆ SHOP MODULE REPLACEMT	102845.77	685.64	208.72
◆ BURDEN-SHOP AND LINE	111437.30	742.92	226.15
TOTAL COST OF OWNERSHIP	3884817.50	25898.79	7883.95
◆ DIRECT MAINT COST	869045.00	5793.63	1763.66

DESCRIBE UNIT

! RUN 2.1.1 3 FC COMPUTERS (ANALOG INPUTS)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 21900., 2100.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 2698., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 25.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 423., .5

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SYSTEM COST	65700.00
NO. OF SPARE UNITS	42.75
ANNUAL FLEET REMOVALS	1643.72
ANNUAL PLANE REMOVALS	10.96
REMOVALS PER 1000 FLIGHT HRS	3.34

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1781999.75	11880.00	3616.44
AMORTIZED SPARE COSTS	154486.06	1029.91	313.52
FUEL COST	308810.75	2058.74	626.71
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	347646.25	2317.64	705.52
◆ LINE MAINTENANCE	7824.09	52.16	15.88
◆ SHOP MODULE REPLACEMT	6689.93	44.60	13.58
◆ BURDEN-SHOP AND LINE	14514.03	96.76	29.46
TOTAL COST OF OWNERSHIP	2621971.00	17479.81	5321.10
◆ DIRECT MAINT COST	376674.31	2511.16	764.43

DESCRIBE UNIT

! RUN 2.2.1 3 FC COMPUTERS (DIGITAL INPUT)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 22460., 2100.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 2599., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 26.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 418., .5

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SYSTEM COST	67380.00
NO. OF SPARE UNITS	44.17
ANNUAL FLEET REMOVALS	1706.33
ANNUAL PLANE REMOVALS	11.38
REMOVALS PER 1000 FLIGHT HRS	3.46

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1823579.75	12157.20	3700.32
AMORTIZED SPARE COSTS	163671.50	1091.14	332.16
FUEL COST	327339.50	2182.26	664.31
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	356622.87	2377.49	723.74
• LINE MAINTENANCE	8122.13	54.15	16.48
• SHOP MODULE REPLACEMT	6944.76	46.30	14.09
• BURDEN-SHOP AND LINE	15066.89	100.45	30.58
TOTAL COST OF OWNERSHIP	2701348.00	18008.99	5482.19
• DIRECT MAINT COST	386756.62	2578.38	784.89

DESCRIBE UNIT

! RUN 2.4.1 3 IC/FC COMPUTERS

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 31010., 3000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 2146., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 30.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 434., .5

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SYSTEM COST	93030.00
NO. OF SPARE UNITS	52.22
ANNUAL FLEET REMOVALS	2066.52
ANNUAL PLANE REMOVALS	13.78
REMOVALS PER 1000 FLIGHT HRS	4.19

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	2525242.00	16834.95	5124.79
AMORTIZED SPARE COSTS	267204.94	1781.37	542.27
FUEL COST	376749.19	2511.66	764.58
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	448434.62	2989.56	910.07
◆ LINE MAINTENANCE	9836.63	65.58	19.96
◆ SHOP MODULE REPLACEMT	8410.73	56.07	17.07
◆ BURDEN-SHOP AND LINE	18247.36	121.65	37.03
TOTAL COST OF OWNERSHIP	3654125.00	24360.83	7415.78
◆ DIRECT MAINT COST	484929.37	3232.86	984.13

DESCRIBE UNIT

! RUN 3.1.1 3 GIMBALLED NAVIGATION BOXES

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 95000., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 1800., 14.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 53.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 2525., .5

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SYSTEM COST	285000.00
NO. OF SPARE UNITS	61.00
ANNUAL FLEET REMOVALS	2463.75
ANNUAL PLANE REMOVALS	16.42
REMOVALS PER 1000 FLIGHT HRS	5.00

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	7202249.00	48014.99	14616.44
AMORTIZED SPARE COSTS	956139.12	6374.26	1940.41
FUEL COST	654679.00	4364.53	1328.62
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	3110484.50	20736.56	6312.50
◆ LINE MAINTENANCE	11727.45	78.18	23.80
◆ SHOP MODULE REPLACEMT	280768.94	1871.79	569.80
◆ BURDEN-SHOP AND LINE	292496.37	1949.98	593.60
TOTAL COST OF OWNERSHIP	12508544.00	83390.30	25385.18
◆ DIRECT MAINT COST	**3695477.50**	**24636.52**	**7499.70**

DESCRIBE UNIT

! RUN 3.2.1   3 IC COMPUTERS   <INAV-ARINC>

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 19480., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 3058., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 26.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 429., .5

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SYSTEM COST	58440.00
NO. OF SPARE UNITS	38.36
ANNUAL FLEET REMOVALS	1450.21
ANNUAL PLANE REMOVALS	9.67
REMOVALS PER 1000 FLIGHT HRS	2.94

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1594889.75	10632.60	3236.71
AMORTIZED SPARE COSTS	123295.95	821.97	250.22
FUEL COST	321163.25	2141.09	651.78
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	311070.62	2073.80	631.30
◆ LINE MAINTENANCE	6903.01	46.02	14.01
◆ SHOP MODULE REPLACEMT	5902.36	39.35	11.98
◆ BURDEN-SHOP AND LINE	12805.37	85.37	25.99
TOTAL COST OF OWNERSHIP	2376030.50	15840.21	4821.98
◆ DIRECT MAINT COST	336681.37	2244.54	683.27

DESCRIBE UNIT

! RUN 3.3.1   3 TWO-AXIS ISA/IC'S   (INAV-ARINC)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	9.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 33820., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 1799., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 52.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 634., .5

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SYSTEM COST	101460.00
NO. OF SPARE UNITS	61.03
ANNUAL FLEET REMOVALS	2465.12
ANNUAL PLANE REMOVALS	16.43
REMOVALS PER 1000 FLIGHT HRS	5.00

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	2659634.50	17730.90	5397.53
AMORTIZED SPARE COSTS	340553.44	2270.36	691.13
FUEL COST	642326.50	4282.18	1303.55
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	781442.87	5209.62	1585.88
◆ LINE MAINTENANCE	11733.97	78.23	23.81
◆ SHOP MODULE REPLACEMT	140462.50	936.42	285.06
◆ BURDEN-SHOP AND LINE	152196.47	1014.64	308.87
TOTAL COST OF OWNERSHIP	4728350.00	31522.33	9595.84
◆ DIRECT MAINT COST	1085835.75	7238.91	2203.62

DESCRIBE UNIT

! RUN 3.4.1   3 IC COMPUTERS   (INAV-DIGITAL)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 15010., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 5208., .5

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 19.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 427., .5

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SYSTEM COST	45030.00
NO. OF SPARE UNITS	24.41
ANNUAL FLEET REMOVALS	851.53
ANNUAL PLANE REMOVALS	5.68
REMOVALS PER 1000 FLIGHT HRS	1.73

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1262992.25	8419.95	2563.15
AMORTIZED SPARE COSTS	60462.16	403.08	122.70
FUEL COST	234696.25	1564.64	476.30
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	181800.91	1212.01	368.95
◆ LINE MAINTENANCE	4053.27	27.02	8.23
◆ SHOP MODULE REPLACEMT	3465.71	23.10	7.03
◆ BURDEN-SHOP AND LINE	7518.98	50.13	15.26
TOTAL COST OF OWNERSHIP	1754989.75	11699.93	3561.62
◆ DIRECT MAINT COST	196838.87	1312.26	399.47

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DESCRIBE UNIT

! RUN 3.5.1 3 TWO-AXIS ISA/IC'S (INAV-DIGITAL)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 29750., 2000.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 2267., 7.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 42.

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 670., .5

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SYSTEM COST	89250.00
NO. OF SPARE UNITS	49.77
ANNUAL FLEET REMOVALS	1956.22
ANNUAL PLANE REMOVALS	13.04
REMOVALS PER 1000 FLIGHT HRS	3.97

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	2357437.00	15716.25	4784.25
AMORTIZED SPARE COSTS	244292.16	1628.61	495.77
FUEL COST	518802.12	3458.68	1052.87
DIRECT MAINTENANCE COST			
◆ NEW MODULES OR REPAIR	655333.50	4368.89	1329.95
◆ LINE MAINTENANCE	9311.60	62.08	18.90
◆ SHOP MODULE REPLACEMT	111465.39	743.10	226.21
◆ BURDEN-SHOP AND LINE	120777.00	805.18	245.11
TOTAL COST OF OWNERSHIP	4017418.50	26782.79	8153.06
◆ DIRECT MAINT COST	896887.50	5979.25	1820.17

DESCRIBE UNIT

! RUN 4.1   3 TWO-AXIS ISA'S   (FLOATED GYROS)

AMORIZATION FACTOR	0.15	BORROWED MONEY COST	1.10
PARTS POOL COST	1.00	DAILY FLIGHT HOURS	9.00
OP. HRS TO FLT HRS	1.50	FUEL PRICE PER GALLON	0.42
RISK FACTOR	2.00	OP. DAYS PER YEAR	365.00
HR RATE FOR LINE	9.52	HR RATE FOR SHOP	8.14
LINE HRS PER REMOVAL	0.50	DAYS TO REPAIR	7.00
LBS PER GAL FUEL	6.70	RATIO ADDED FUEL	0.1333
S-L BURDEN PER CENT	100.00	NO. OF AIRPLANES	150.00

ENTER UNIT PRICE, INSTALLATION PRICE! 23710., 655.

ENTER HRS BETWEEN FAILURE, SHOP HRS PER REMOVAL! 2096., 10.

ENTER UNITS PER AIRPLANE, UNIT WEIGHT! 3., 34.5

ENTER AV. PARTS COST PER FAILURE, FAIL-REMOVAL RATIO! 1423., .5

- -

SYSTEM COST	71130.00
NO. OF SPARE UNITS	53.32
ANNUAL FLEET REMOVALS	2115.82
ANNUAL PLANE REMOVALS	14.11
REMOVALS PER 1000 FLIGHT HRS	4.29

	ANNUAL FLEET COSTS	ANNUAL PLANE COSTS	1000 FLT HRS COSTS
AMORTIZED INITIAL COST	1809101.00	12060.67	3671.44
AMORTIZED SPARE COSTS	208585.44	1390.57	423.31
FUEL COST	426158.87	2841.06	864.86
DIRECT MAINTENANCE COST			
• NEW MODULES OR REPAIR	1505403.00	10036.02	3055.10
• LINE MAINTENANCE	10071.28	67.14	20.44
• SHOP MODULE REPLACEMENT	172227.37	1148.18	349.52
• BURDEN-SHOP AND LINE	182298.66	1215.32	369.96
TOTAL COST OF OWNERSHIP	4313846.00	28758.97	8754.63
• [illegible]	1870000.25	12466.67	3795.03

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