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X-15 ANALOG AND DIGITAL INERTIAL SYSTEMS FLIGHT EXPERIENCE

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Flight Research Center
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SUMMARY

Two different types of inertial flight data systems, an analog system and a digital system, have been used during the X-15 program to provide primary flight information for the X-15 pilot. This use has afforded an opportunity to compare the two mechanization concepts in the same operating environment.

The two systems, although having basically different computers, use similar inertial measurement units. Equation mechanization is different primarily because of the difference in computers. The development problems on the analog system were considerably more complex than those with the digital system, inasmuch as the analog unit was the first of the miniature units conceived and thus was put into operation before it could be refined. These development problems ultimately brought about the redesign of the analog system and the utilization of the digital system.

The performance of the analog and digital systems has been adequate for X-15 requirements. The performance of the digital system has indicated that it is a highly accurate mechanization, with the only significant problem that of the computer susceptibility to power transients. The digital system also provides a more flexible mechanization than the analog system through the programing capabilities of the computer.

INTRODUCTION

The X-15 is a rocket-powered research airplane designed to be air launched from a B-52 carrier aircraft, fly a preplanned flight profile, and make horizontal landings on dry lakebeds (ref. 1). The X-15 flight envelope extends to speeds beyond Mach 6 and altitudes above 350,000 feet (106,680 meters). Thus, the original selection of an inertial flight data system over other types of flight data systems for the X-15 program was based on the requirement for precise position, velocity, and attitude information extending into planned X-15 flight regions where conventional pressure-measuring devices could not provide the necessary accuracy. Design and fabrication of a miniature inertial system for aircraft use started in June 1957 with a contract for six systems.

In 1957 an analog mechanization was the only feasible type of system available; digital systems for real-time airborne applications were some distance in the future. Even with an analog system, however, weight, power, reliability, and state of the art in inertial components posed formidable problems. It was decided that the mechanization could be accomplished through the use of solid-state electronics and the extensive use of electromechanical devices. Transistors, while still new to the designers, did, even then, offer sufficiently low power requirements at a relatively high reliability to warrant their use throughout the system.

From the start of the program, it was evident that the system requirements were slightly beyond the existing state-of-the-art capabilities. Performance of the original configuration of the analog system in the X-15 was marginal, both in accuracy and reliability. Although extensive efforts yielded reliable operation for about 1 year in late 1962 and early 1963, the performance more often than not failed to meet the design specifications. These specifications are shown in table I.

TABLE I

ANALOG-SYSTEM SPECIFICATIONS

		Range	Accuracy
Parameter	Total velocity V_t	0 to 7000 ft/sec (0 to 2134 m/sec)	±100 ft/sec (30 m/sec)
	Rate of climb	0 to 1000 ft/sec (0 to 305 m/sec)	±70 ft/sec (21 m/sec)
	Geometric height h	0 to 500,000 ft (152,400 m)	±5000 ft (1524 m) at 300 sec ±10,000 ft (3048 m) at 500 sec
Attitude	Pitch	360° (6.283 rad)	±0.5° (±0.009 rad)
	Roll	360° (6.283 rad)	±0.5° (±0.009 rad)
	Yaw	360° (6.283 rad)	±0.5° (±0.009 rad)

In November 1963, following continuous degradation of the system performance and reliability, efforts were initiated to procure a new system for X-15 use. Through the cancellation of the X-20 (Dyna-Soar) program, a digital inertial system was found to be available for use in the X-15. Even though this also was not a state-of-the-art system, since it used a computer which had been originally designed for another application in 1959, there were several advantages to be gained by its use. The decision was therefore made in April 1964 to modify the X-20 system to adapt it for use in the X-15 program.

At the same time, however, because of some degree of uncertainty about the outcome of the digital system, it was decided to proceed with a minimum redesign effort on the original analog system at the NASA Flight Research Center both to improve reliability and performance and to provide a backup system in the event of difficulties with the X-20 system.

In the fall of 1964, the digital system was installed in the X-15-1 airplane and the first checkout flight made. Subsequently, the digital system was also installed in the X-15-3 airplane. It is planned to continue flying with the redesigned analog system in the X-15-2 airplane so long as it is practical, based on both performance and reliability.

This paper compares these two different mechanizations, which perform essentially the same function in the same environment, on the basis of experience gained in the X-15 program. Areas of comparison include system integration, operational procedures, requirements, flexibility, and overall performance.

SYMBOLS

The units used for the physical quantities in this paper are given in U.S. Customary Units and, parenthetically, in the International System of Units (SI). Factors relating the two systems are presented in reference 2.

ΔE	change in east-west position (positive east), feet (meters)
g	acceleration due to gravity, feet/second^2 (meters/second^2)
h	geometric height, feet (meters)
$\dot{h}$	velocity along the vertical axis (analog system), feet/second (meters/second)
$\ddot{h}$	acceleration along the vertical axis, feet/second^2 (meters/second^2)
h_o	initial height position, feet (meters)
Δh	change in vertical position (positive up), feet (meters)
L	longitude, degrees (radians)
ΔL	change in longitude, degrees (radians)
ΔN	change in north-south position (positive north), feet (meters)
R	range axis, feet (meters)
$\dot{R}$	velocity along the range axis, feet/second (meters/second)
$\ddot{R}$	acceleration along the range axis, feet/second^2 (meters/second^2)
R_o	initial range position, feet (meters)
V_E	velocity along the east-west axis, positive east (digital system), feet/second (meters/second)
V_N	velocity along the north-south axis, positive north (digital system), feet/second (meters/second)
V_o	initial velocity, feet/second (meters/second)
V_t	total velocity, $\sqrt{\dot{R}^2 + \dot{X}^2 + \dot{h}^2}$, feet/second (meters/second)
V_v	vertical velocity (digital system), feet/second (meters/second)
ΔV	change in velocity component, feet/second (meters/second)
ΔV_E	change in east velocity component, feet/second (meters/second)
ΔV_N	change in north velocity component, feet/second (meters/second)

ΔV_V	change in vertical velocity, feet/second (meters/second)
X	cross-range axis, feet (meters)
$\dot{X}$	velocity along the cross-range axis, feet/second (meters/second)
$\ddot{X}$	acceleration along the cross-range axis, feet/second^2 (meters/second^2)
X_o	initial cross-range position, feet (meters)
λ	latitude, degrees (radians)
$\Delta\lambda$	change in latitude, degrees (radians)
Ω_e	rotational earth rate, degrees/second (radians/second)
σ	standard deviation
Subscript:	
u	uncorrected for coriolis or centrifugal acceleration

SYSTEM DESCRIPTION

General

The inertial flight data system (IFDS) supplies altitude, rate of climb, total velocity, and attitude information by measuring accelerations of the vehicle relative to inertial space and through subsequent integrations for velocity and position. The systems contain self-correction capabilities to compensate for some gyro drift terms, coriolis and centrifugal acceleration effects, as well as mass attraction and earth rotational rate.

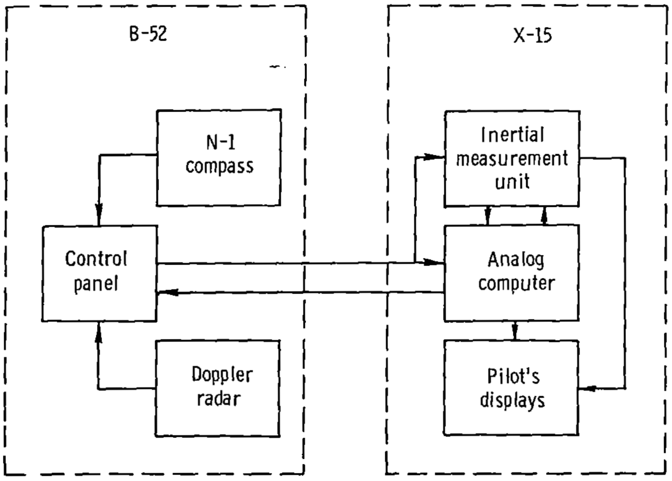

Figure 1.– Total analog system.

Analog

The total analog system is made up of two major units: the reference system, which is carried in the B-52 launch aircraft, and the IFDS, installed in the X-15. A further breakdown of the system is shown in figure 1.

The reference system in the B-52 consists of three major subsystems: an in-flight control panel, a Doppler radar, and a gyro-stabilized magnetic compass (N-1 compass). The Doppler radar furnishes ground velocity and drift angle to the in-flight control panel, and the N-1 compass furnishes magnetic heading. Using these parameters, the control-panel circuitry resolves the total radar velocity into range and cross-range components, which are required by the inertial computer for alinement and calibration of the system. The control panel also monitors the X-15 system performance by displaying X-15 position, velocity errors, and gyro drift rates to the control-panel operator in the B-52. Updated position data can be set into the computer through this panel before the X-15 launch.

The IFDS installed in the X-15 consists of an inertial measurement unit (IMU), an analog computer, and a set of pilot's displays (fig. 2). The design of the system is such that it operates free of any external references after the X-15 is launched from the B-52. Before the launch, however, the system is, in part, slaved to the control panel.

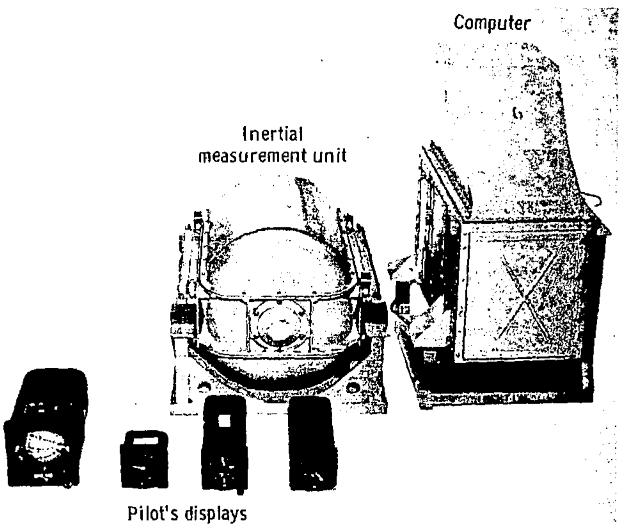

Figure 2.— Analog system.

The basic inertial reference in this system is a gyro-stabilized, four-gimbaled platform which maintains the orientation of three force rebalance accelerometers with respect to the gravity vertical and a predetermined azimuth throughout any orientation or attitude of the X-15. The performance specifications of the gyro sensors and the accelerometers that were initially used are presented in table II, along with the basic physical characteristics of the system. The associated stabilization electronics and the power supplies are also mounted within the IMU, using the gimbals and the case as heat sinks for the power transistors. The covers are designed to serve as heat exchangers, since the IMU is pressurized and there is no direct mix of instrument bay air with the air within the IMU.

TABLE II

SENSOR-PERFORMANCE SPECIFICATIONS

Parameter	Analog	Digital
Gyro		
Nonacceleration sensitive drift	1 deg/hr (0.017 rad/hr)	3.0 deg/hr (0.052 rad/hr)
Acceleration sensitive drift	0.1 deg/hr/g (0.0017 rad/hr/g)	0.5 deg/hr/g (0.0087 rad/hr/g)
Random drift	0.03 deg/hr rms (0.0005 rad/hr rms)	0.02 deg/hr (0.0003 rad/hr)
Anisoelastic drift	0.01 deg/hr/g^2 rms (0.0002 rad/hr/g^2 rms)	0.02 deg/hr/g^2 rms (0.0003 rad/hr/g^2 rms)
Accelerometer		
Range	±10g	±10g
Linearity	3×10^{-5} g or 0.01 percent (whichever is greater)	30×10^{-5} g or 0.03 percent (whichever is greater)
Threshold	$<1 \times 10^{-5}$ g	1×10^{-5} g
System		
Volume	6.03 ft^3 (1.71×10^5 cm^3)	5.29 ft^3 (1.50×10^5 cm^3)
Weight	176 lb (79.9 kg)	231 lb (104.8 kg)
Power	600 watts ac 56 watts dc	450 watts ac 10 watts dc

The analog computer converts the sensed inertial accelerations into appropriate output velocity and position about the three coordinate reference axes. It also furnishes torquing signals to the IMU, which continuously maintains the local vertical and azimuth orientation. This requires the use of the following functional units which are contained within the computer: position, velocity, and erection integrators, and the necessary power supplies. The three integrator packages, shown in figure 3, are of an electromechanical design, with each package containing an integrator for each axis of the coordinate system.

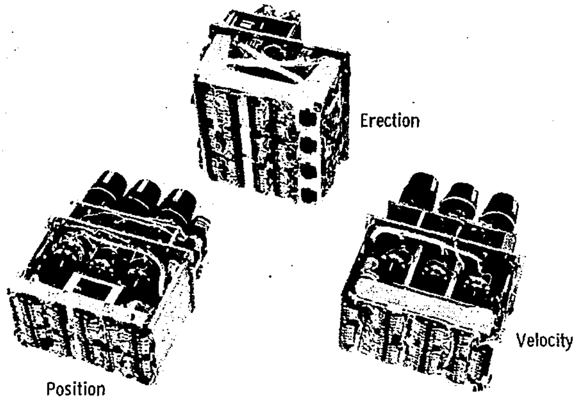

Figure 3.– Analog computer integrators.

The pilot's displays from the IFDS are pitch, roll, and heading, which are presented on a three-axis attitude indicator, total earth reference velocity, rate of climb, and geometric height. The attitude display is driven by synchro signals from the IMU, whereas the inertial-height display is driven by synchro signals originating in the computer. The pilot's total-velocity indicator performs the square-root-of-the-sum-of-the-squares computation necessary to convert the component velocities into total velocity, which is displayed through a servo followup circuit. The rate-of-climb indicator is a simple dc meter movement that receives its signal directly from the computer.

Digital

The digital IFDS consists of four subsystems: an IMU, a coupler electronics unit (CEU), a digital computer, and a set of pilot displays, as shown in figure 4. This system uses a gyrocompassing alinement technique and undergoes a complete erection and alinement cycle on the ground before B-52 taxi. Once alined, it remains in the inertial mode with the exception of the vertical loop, which is slaved to a pressure-altitude reference in the X-15 until launch from the B-52. With this system, there is no requirement for a reference system on board the B-52.

The inertial measurement unit is similar to that in the analog system, with the basic differences in the location of the IMU electronics. The electronics are mounted in the CEU rather than within the inertial platform. Also significant is the elimination of the need for special cooling, provided that the instrument-bay ambient temperature is maintained below 70° F (21° C). The performance specifications for the sensors used in this IMU are shown in table II. The gyros are similar to those used in the analog system, whereas the accelerometers are of an electromagnetically restrained floated pendulum design.

The CEU provides coupling and electrical interface between the IMU and the digital computer as well as the necessary power regulation, malfunction detection, gyro torquing, and accelerometer rebalancing for system operation.

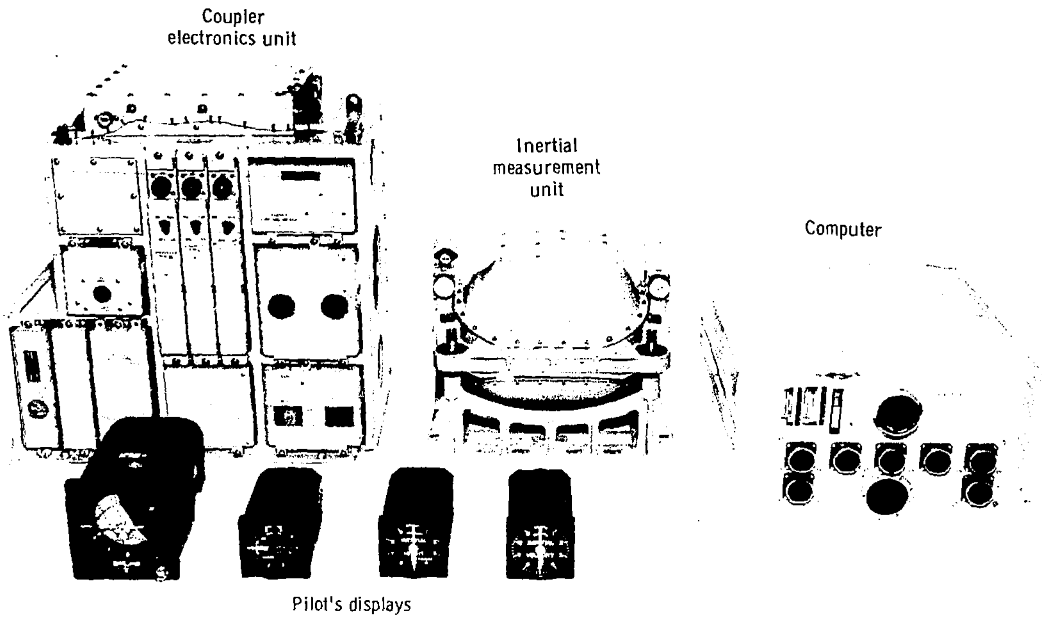

Figure 4.– Digital system.

The computer is a dual-function device consisting of a digital differential analyzer (DDA) section and a general purpose (GP) section with a drum memory of 1664 24-bit words. In the GP section, solutions of the complete guidance equations are performed, with each solution being largely independent of the previous solution. This arrangement is generally acceptable except in a real-time situation when uninterrupted solutions of a number of parameters are continuously required. Real-time computation in a rather slow GP instrument is accomplished by providing a section of integrators utilizing incremental computation techniques. The DDA section mechanizes the equation $dz = ydx$. Only increments of the variables x, y, and z are transferred from place to place within the DDA. The GP section maintains control over the DDA through its ability to address the DDA memory. Thus, through proper programing techniques, the combination provides an efficient computational capability with periodic solutions from the GP section and continuous updating from the DDA.

With the exception of the attitude display, the pilot's displays used with this system are mechanized somewhat differently from those used with the analog system. The total-velocity indicator, the rate-of-climb indicator, and the inertial-height indicator are all positioned through digital shaft encoder feedback.

EQUATION MECHANIZATION

The analog system is referenced to a line extending along the axis of the X-15 High Range (ref. 1), as shown in figure 5. This complicates the equations for earth rate corrections in the solution of the acceleration equations, since earth rate terms appear in all three coordinates and since a separate heading angle must be maintained in the

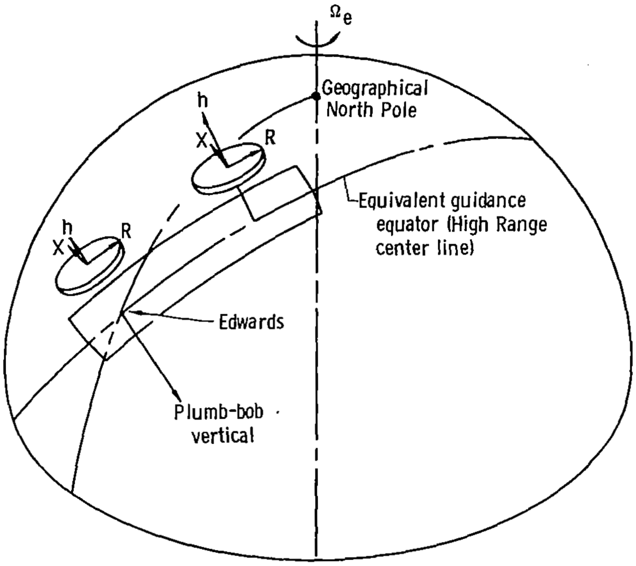

Figure 5.— Analog range orientation.

computer; however, at the same time, the mechanization is simplified as a result of the limited range restrictions.

The digital system is alined to true north and the geocentric vertical, thus its frame of reference is established in the north-east and vertical directions, whereas earth rate terms enter only in the north and vertical axes. Differences in mechanization of the equations between the two systems are shown in figures 6 and 7. The analog approach is a simple integration for velocity with a feedback for centrifugal- and coriolis-acceleration corrections and a second integration for position with the necessary mass-attraction feedback to the velocity integrators. In the digital system, the acceleration signals are converted to ΔV pulses by the pulse rebalance electronics mounted in the CEU. The ΔV pulses are continuously summed in the DDA section of the computer, which is updated every 3 seconds, with new direction cosines computed in the GP section of the computer. Position changes in the north, east, and vertical directions are similarly summed in the DDA along the direction cosines computed within the GP section.

DEVELOPMENT PROBLEMS

Analog

From its conception, the analog system was plagued with many developmental problems which remained throughout much of the X-15 program. Major resolutions of these problems were accomplished only when a redesign of the IMU was undertaken in 1964. Because of the excessive number of problems encountered, only the major ones are discussed, chronologically, in the following paragraphs.

The initial problem faced was that of providing proper cooling to the system so that a sufficiently long erection cycle could take place. The inertial system was designed to operate only when cooling air was supplied; consequently, because insufficient provision for storable coolant was provided, the system was turned on when an altitude of 33,000 feet was reached, at which time ram air was used for cooling. Turn-on was planned to occur about 30 minutes after takeoff or about 15 minutes before launch. Unfortunately, with this technique insufficient time was available for the system to erect properly. It was necessary, therefore, to add greater cooling capacity to the B-52 in the form of a liquid nitrogen (LN_2) tank so that the system could be erected continuously throughout the carrier flight.

When these cooling problems were overcome, it was found that other erection problems still existed because the dynamic conditions under which erection was taking place

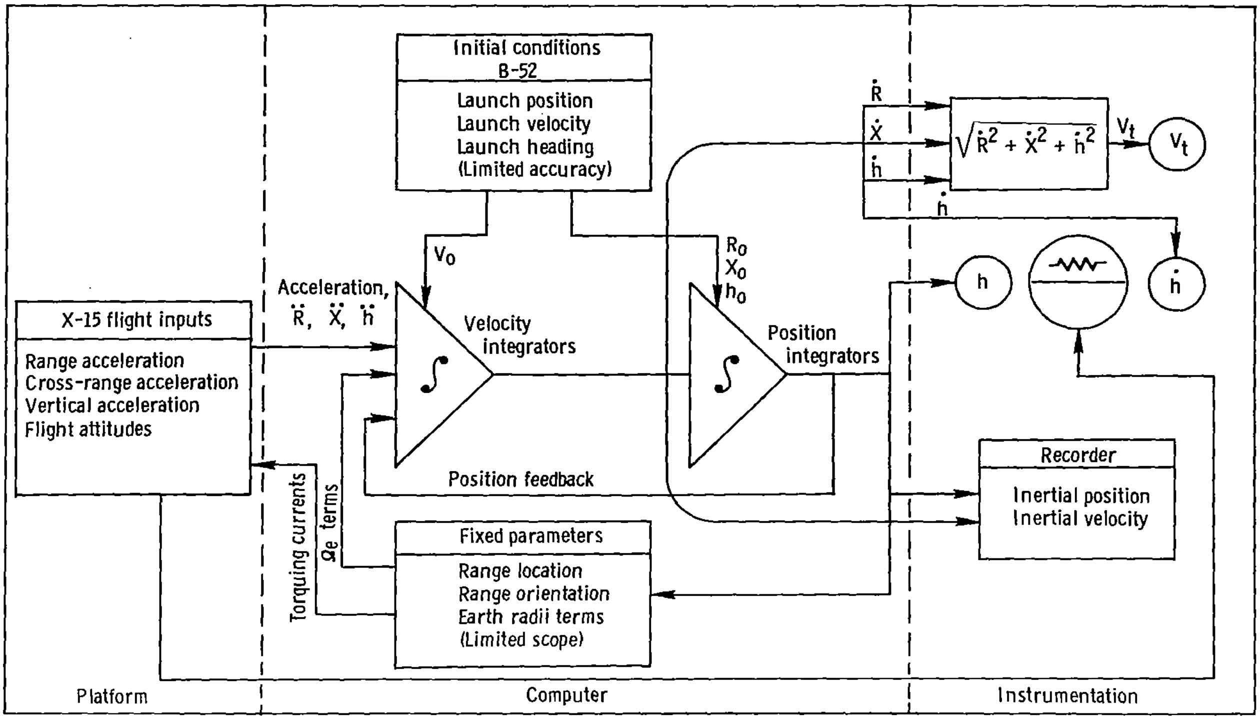

Figure 6.— Flow diagram of analog system.

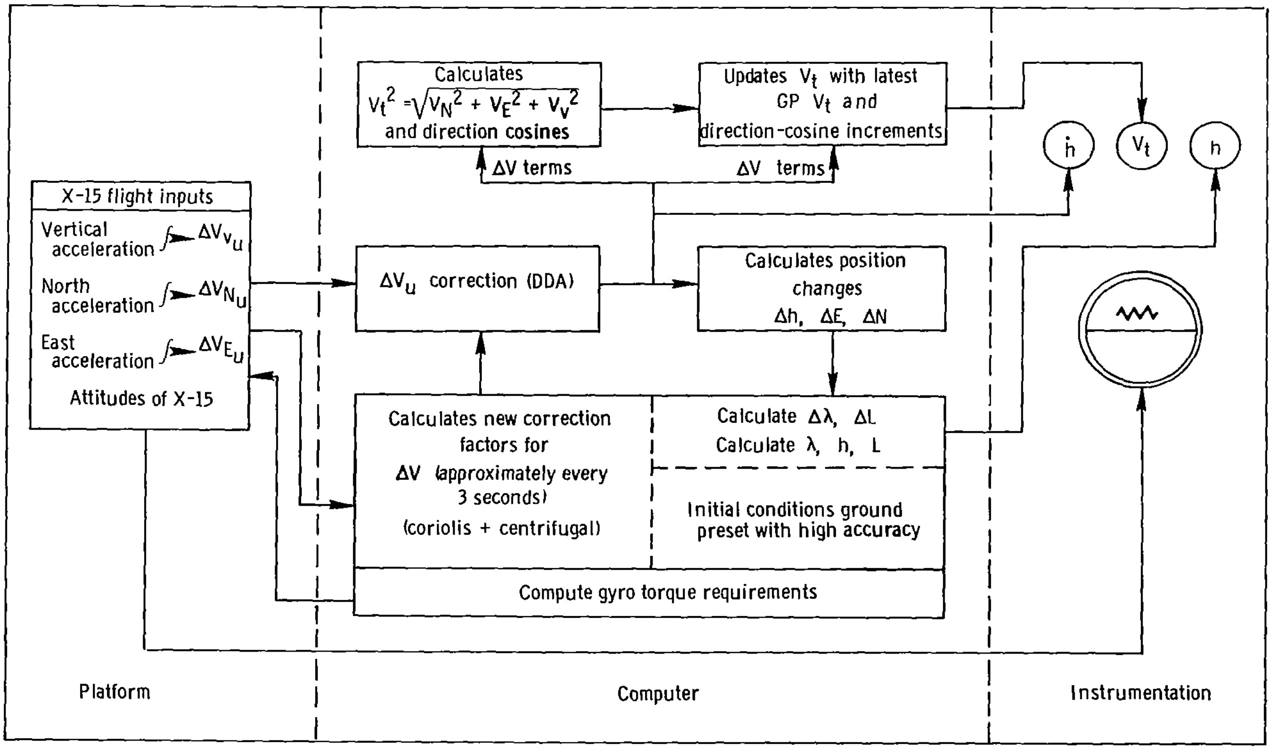

Figure 7.— Flow diagram of digital system.

were not compatible with the time constraints of the gyro drift compensation loops. This necessitated modifications to the compensation loops in an attempt to correct the problem. Shortly thereafter, it was decided that a more accurate calibration of gyro drift rate could be accomplished under static conditions on the ground, so the system was again modified to allow system turn-on, erection, and calibration in the service area prior to B-52 taxi. The modification allowed the gyro drift-rate potentiometers to be locked after ground erection and calibration. Compensation for variations in torquing rates required by horizontal and vertical position changes was then accomplished by trimming the basic drift term. After takeoff, the system received continuous updating in velocity and heading, as before, from the reference system and periodic updating in position from the control panel during the B-52 carrier flight.

This procedure, however, formulated new problems because of the ambient air that was introduced into the LN_2 cooling and pressurization system during ground operation. The temperature of the gasified nitrogen was approximately -40° F (-40° C), and when outside air was mixed in the system, moisture in it immediately condensed and froze. This condition produced frost, which collected in narrow passages in the cooling ducts or in the heat exchangers themselves. Frequently, the cooling airflow became completely blocked, causing the systems to overheat. This problem was finally resolved by delaying the system turn-on until after the pilot was in the X-15 and the canopy was closed in order to reduce the amount of moisture-laden air that was drawn into the cooling system. The feasibility of this procedure was further enhanced when it was found that gyro drift-rate stability and repeatability was sufficiently good to allow compensation to be performed on the day preceding a flight so that only system erection was necessary on the day of the flight. Finally, the elimination of various electrical "ground loops," that is, extraneous currents introduced into signal leads by improper grounding techniques, made it possible to shorten the ground erection cycle to less than 20 minutes, thereby allowing ground erection of the system with the pilot in the cockpit to become a standard procedure.

The modifications described in the preceding paragraphs were made during late 1961 and early 1962 and were followed by a year of reasonably reliable inertial-system performance beginning about May 1962. However, the accuracy with which the system performed was still considerably less than desired. Little effort could be extended toward improvement of system performance because the number of X-15 flights being made was relatively high and all effort was directed toward meeting the flight schedule. In addition, the major requirements imposed on the system during the expansion of the X-15 flight envelope were for the presentation of vehicle attitudes throughout the flight and total velocity during the boost and reentry phases. Since these parameters were sufficiently reliable, no major effort was directed toward increasing their accuracy.

When an extensive X-15 follow-on program was approved, extending through 1967, it was decided that the requirements for precision data and reliability from the inertial system justified the procurement of a new inertial flight data system for the X-15. In addition, a desire for improvement of the analog system made it apparent that some interim design changes would be necessary to provide an adequate system during the period before a new system could be acquired and checked out. A preliminary analysis indicated that a redesign of most of the electronics in the system would be required, with priority being placed on the inertial measurement unit.

Initial efforts were directed toward the circuits and hardware in the accelerometer loops and in the power supplies. The accelerometers were replaced by a more advanced type with self-contained electronics; that is, rebalance loops and pick-off excitation were included as an integral part of the basic unit. This arrangement eliminated much existing hardware and greatly reduced the number of power supplies previously required. New power supplies were designed and constructed. Figure 8 shows the initial components and the replacement components.

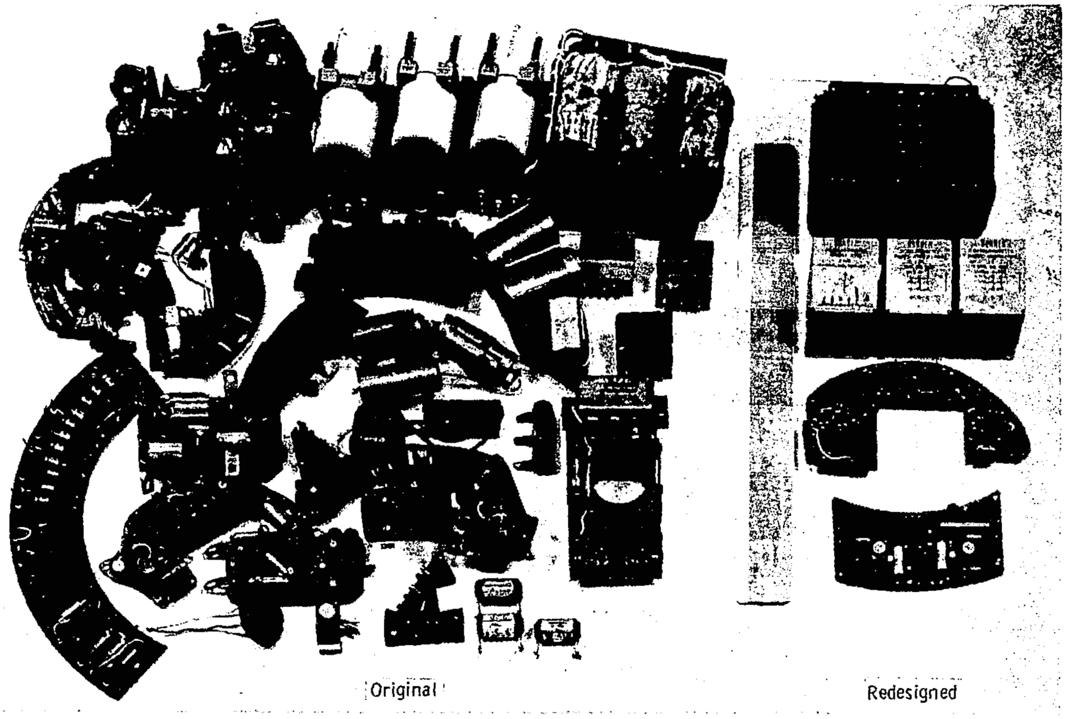

Figure 8.— Analog components.

This phase of the modification was completed on one IMU in July 1964. The effort proved so successful, with no major failures on the first 16 flights and with the accuracies meeting the original specifications, that the decision was made to modify another IMU with even more extensive redesign.

The next area of improvement was in the gyro-heater amplifiers. While this circuit had not caused any catastrophic system malfunctions, its operation was such that the heater cycling was reflected in voltages throughout the IMU B+ supply, causing variations in the output of the gimbal torque motors. This redesign was successfully completed, and further modification of the IMU design is now in progress.

In addition to the improved reliability and accuracy, another result of this modification program is the overall reduction in power dissipation within the IMU. Even though more than 50 percent of the cooling gas previously required by the IMU has been blocked off, heaters are required in the covers of the IMU to maintain its operating temperature.

As part of the system redesign, much effort was expended on the computer. Completely new amplifiers were procured for the integrators along with electromechanical choppers for these amplifiers. The original amplifiers operated Class A, which caused heat dissipation even with no signal because of high idling current in the transistors. The new amplifiers were designed for Class AB operation, thereby reducing the power dissipation by approximately 10 watts for each amplifier. The new design also provides a considerable improvement in overall computer performance through both change in class of operation and reduction in noise. The power supplies within the computer were also included in this redesign effort. The redesigned system has been completely tested in its various interim configurations. The flight results are reported in more detail in a subsequent section on PERFORMANCE. The requirements for both improved accuracy and reliability have been met with the redesigned configuration.

Digital

Considerable experience had been gained with the digital system before its introduction into the X-15 program. Much of the environmental testing was completed during the X-20 program. Also, a complete flight test program of 23 flights in an Air Force F-101 airplane was conducted on the system. The computer had also been used in other airborne applications. This amount of operational experience with the system plus the experience gained by Flight Research Center personnel with the analog system made the transition and integration of the digital system into the X-15 program relatively trouble free.

There were two major problems encountered in making the system operational in the X-15. The first problem concerned cooling of the computer. The system specifications required that the system operate in a temperature environment of 30° F (-1.1° C) to 70° F (21° C) at an ambient pressure of 14.7 psia to 3.5 psia. Blowers were attached to the inlet port and the exhaust port of the computer to circulate the instrument bay gas through the computer. It was found that when the temperature of the gas circulating through the computer dropped below 40° F (4.5° C) marginal operation occurred. Some computers would operate at lower temperatures while problems with the clock rate on others speeded up the computational rate in the DDA, which resulted in erroneous results. The simplest and most logical solution was to maintain the inlet temperature of the computer above 40° F (4.5° C). This was accomplished by baffling some of the exhaust gas to the inlet of the computer and by controlling the amount of liquid nitrogen put into the entire X-15 cooling system.

The second problem concerned the susceptibility of the computer to switching power transients. The computer has circuitry to provide protection to the memory at power shutdown or during power transients. It was found that on the computers in the program this circuitry did not operate properly at all times and numbers in the computer memory could be changed when large transients occurred. A wiring change was made in the computer to insure operation of the protection circuitry during power transfers. Additional power problems have been encountered on the X-15-1 because of large power transients on the main 400-hertz bus from the numerous experiments being carried on this aircraft. These problems are being investigated.

OPERATIONAL PROCEDURES

Extensive procedures are followed to assure that all systems are performing adequately prior to each X-15 flight. Both the analog and the digital inertial system are checked in the vehicle approximately 1 week before the scheduled flight. These checks have two major objectives: (1) to increase confidence in the system performance and (2) to calibrate the data-acquisition system.

The next check of the analog system is performed after the X-15 is mated to the B-52. This normally takes place on the day before the scheduled flight. During this check, all the connections between the IFDS in the X-15 and the control panel in the B-52 are confirmed. The computer is calibrated with the Doppler radar. The heading reference used is a precision synchrotransmitter that is set to the heading of the B-52 as determined from bench marks set into the preflight area. Following the system calibration, a simulated inertial run is made to determine the performance of the system under static conditions.

On the morning of a flight, the analog system is turned on and erected after the pilot is in the X-15. Since the gyro drift-compensation potentiometers were calibrated and locked previously, the erection cycle is fast, approximately 20 minutes. The system is then operated inertially until sufficient altitude, normally about 5000 feet (1524 meters), is reached for Doppler radar operation. Erection is then resumed, utilizing the reference systems on the B-52. This mode is normally followed until the X-15 is launched, at which time the system is operated in the inertial mode for the remainder of the flight.

The digital system is not turned on again after the check made in the vehicle approximately 1 week before the scheduled flight until the morning of the flight. Since flight tapes are loaded into the computer at the conclusion of the hangar tests, the requirement for the morning of the flight is for preheat and final alinement of the system. This is accomplished before and during pilot entry. Just before transfer from ground power to B-52 power, the system is switched to the flight mode and remains in this mode throughout the entire flight. The altitude loop is clamped to pressure altitude until 1 minute before launch when it is unclamped, and the entire system operates in the flight mode for the remainder of the flight.

SUPPORT REQUIREMENTS

The support required for an inertial flight data system in a research project such as the X-15 program is considerably different from that required in an operational vehicle, for several reasons. One reason, probably most outstanding, is the fact that the systems used are not produced in quantity but, rather, they are prototypes on which engineering evaluation was conducted while the systems were installed and performing in the research vehicle. As a result, far more extensive laboratory support was required in the field than would have been necessary for production systems.

Originally, it was planned to support the IFDS in the field with one technician, one NASA engineer, and one contractor field engineer. The level of maintenance accomplished was to be limited to simple module replacement and power-supply adjustment. The facility set up to handle this effort is depicted in figure 9. It was

Figure 9.— Original analog-system laboratory.

found that with only six systems available for the program and with the high component failure rate, this maintenance plan was inadequate. The number of people supporting the system was increased to five technicians and five engineers, and the level of maintenance was increased to cover complete computer rebuilding and IMU repairs, including gyro, accelerometer, and slip-ring replacement. This level of maintenance continued until the redesign of the analog system was completed.

With the arrival of the digital system the laboratory area had to be increased substantially to handle both systems test and component repair. A representative portion of the present laboratory, the digital system test area, is shown in figure 10. Manpower support requirements for these two systems increased so that the level is now six technicians and five engineers. This field support is augmented by in-plant support at the digital system contractor's facility consisting of a systems engineer, a computer programer, and other logistics support. It has been found that these levels of support are adequate for the X-15 program.

PERFORMANCE

The primary method for the evaluation of the performance of the inertial flight data system has been analysis of altitude recordings obtained from the system during flight.

Inertial height was selected for several reasons. The vertical loop which provides inertial height is divergent because of the gravitational effects; therefore, system errors are more magnified and apparent in this coordinate. The tracking radar stations used

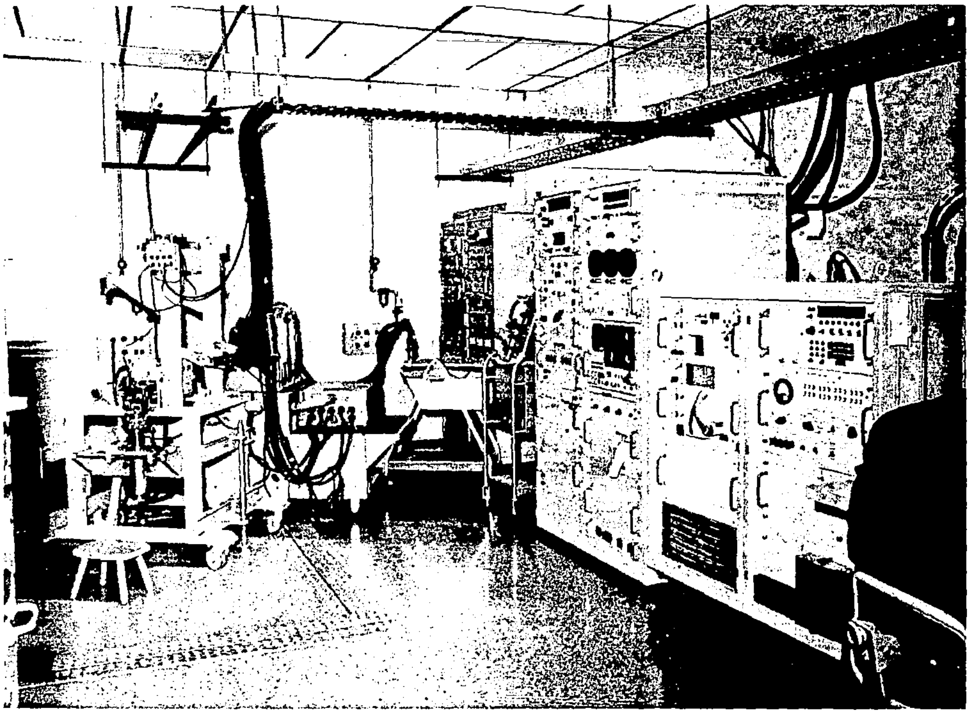

Figure 10.— Digital-system laboratory.

for reference directly read out range, azimuth, and elevation of the target. Finally, the altitude readout of the system after the completion of the flight can be directly related to the lakebed elevation, which is known precisely. However, since total velocity is a primary quantity for display to the pilot, a comparison of the IFDS total-velocity presentation is made with a faired reference curve for evaluation. The inertial-height data from the inertial system are in the form of a synchrotransmitter signal which is recorded optically on film with a servorecorder. The film is then read with a double magnification scale on a film reader and the data fitted to a calibration curve, which is made for each flight. The root-sum-square accuracy of this data is 335 feet (102.1 meters), established by assigning random errors of 140 feet (42.67 meters) to the altitude synchro, 280 feet (85.34 meters) to the servorecorder, and 120 feet (36.57 meters) to the reading of the film. The reference used for comparing the altitude of the inertial system is a faired curve obtained by weighing the tracking radar data, air data, and on-board acceleration data. The accuracy of this faired curve is estimated to be on the order of ±1000 feet (±304.8 meters) root mean square (ref. 3).

The mean of the altitude error as a function of time from launch for the 20 flights preceding redesign of the IMU is presented in figure 11. The standard deviation about each mean value is also shown. From this figure it can be seen that while the X-15 was under power, the inertial-height information from the inertial system was reasonably useful, i.e., the first 80 seconds of flight. However, as the flight progressed, the inertial height diverged, making the data essentially useless by the time the specification check point of 300 seconds was reached (see table I).

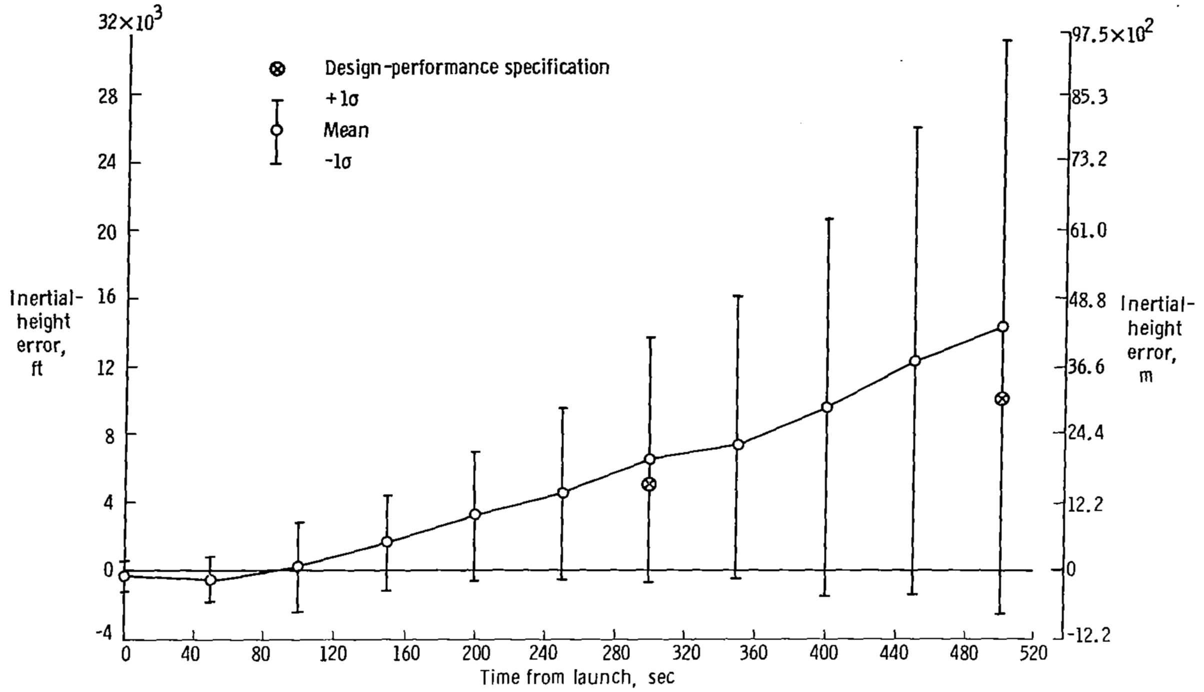

Figure 11.— Performance of original analog system (inertial height).

System operation on the ground differs from flight operation in that the ground operation is under static conditions and the flight operation is under dynamic conditions. Also, the environments of the two differ considerably in temperature, vibration, and electrical-power characteristics. With the analog system there is a third variable, in the erection of the system. During ground operation, the erection integrators use a zero velocity reference obtained by grounding the input for the range, cross range, and vertical axes and by using a precision synchro for the heading. During airborne operation, the reference velocity for range and cross range is the Doppler radar signal processed through the control panel, and the heading reference is taken from the N-1 compass.

Before the redesign of the analog system, there was very poor comparison between the performance of the system on the ground and in the air. The altitude error as a function of time for 20 ground operations performed during approximately the same period as the flights used for the data of figure 11 is presented in figure 12. A comparison of figures 11 and 12 indicates the impact of the flight environment on the performance of the system.

The altitude error as a function of time for the analog system with the redesigned IMU is presented in figure 13. The data are from the first 10 flights on the X-15-3 following the redesign effort. The performance of the system on 10 ground runs made during this same period is presented in figure 14. Although the air-ground differences are still large, the reduction in these differences may be attributed to the partial completion of the redesign effort. Comparison of the results presented in figure 11 with the data presented in figure 13 also indicates the improved performance achieved with the redesigned system. From this data, it can be concluded that the mean-value

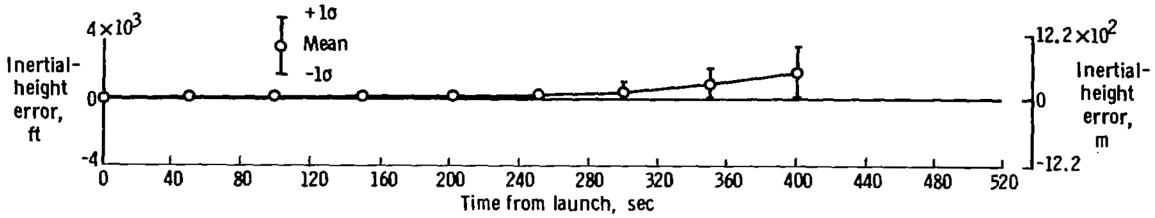

Figure 12.— Performance of original analog system (ground runs, inertial height).

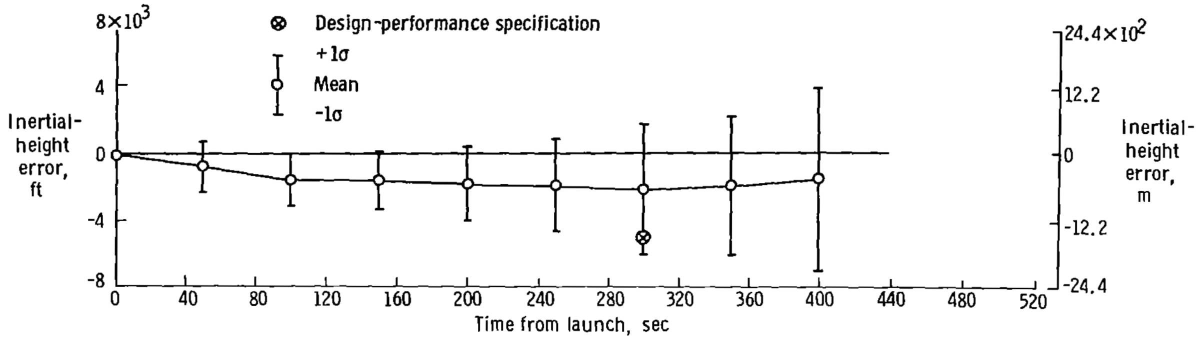

Figure 13.— Performance of interim analog system (inertial height).

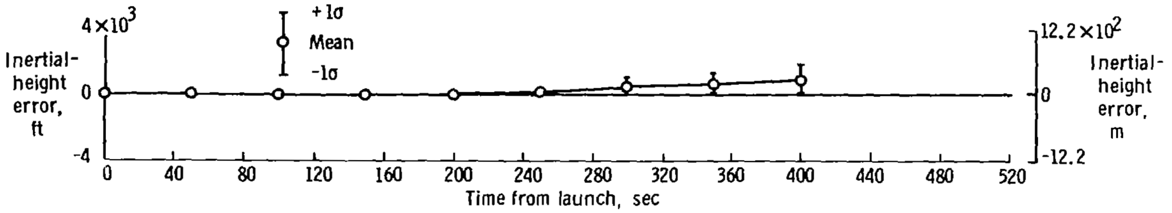

Figure 14.— Performance of interim analog system (ground runs, inertial height).

performance was within the original design specifications, whereas the standard deviations indicate that the performance was not consistent from flight to flight. The total-velocity performance of the system for these same flights is presented in figure 15.

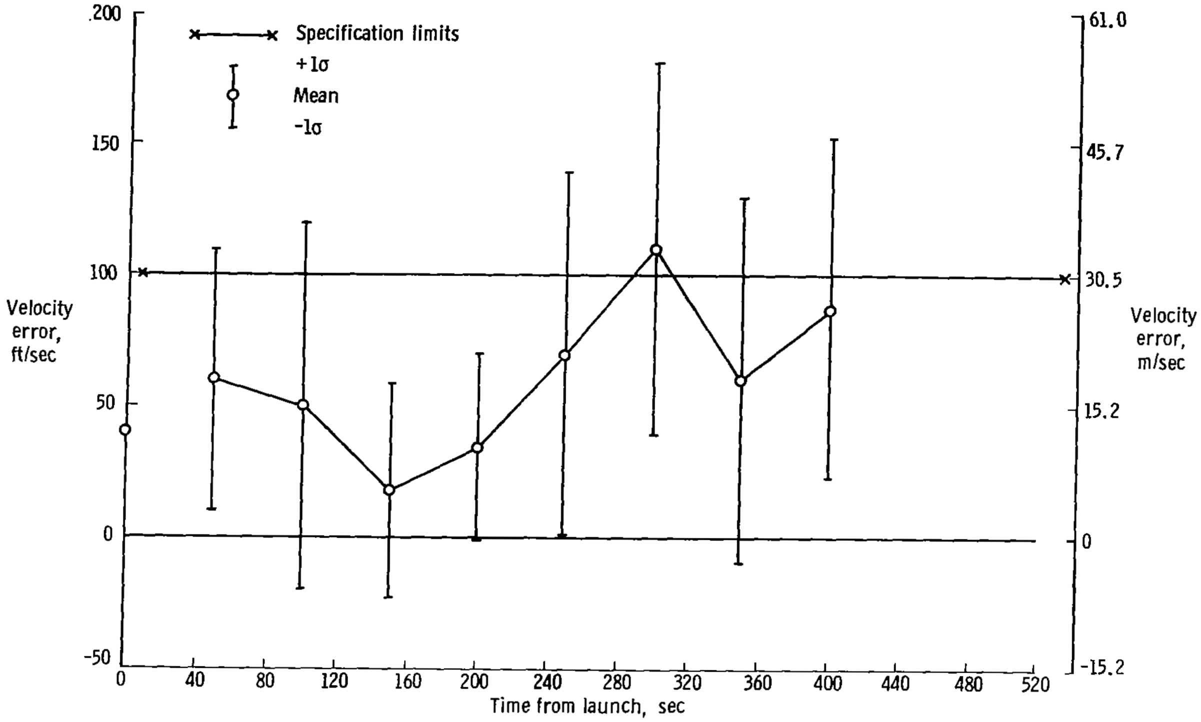

Figure 15.— Performance of interim analog system (velocity).

The performance results of the digital system are presented in the same manner as those of the analog system. Inertial height error is presented in figure 16, and velocity error is presented in figure 17. These results indicate the more consistent performance that has been demonstrated with the digital system.

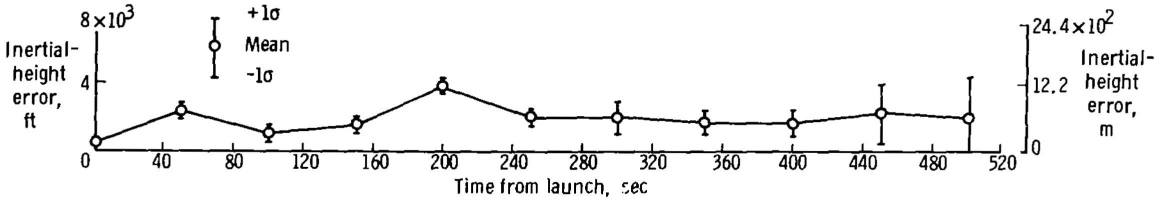

Figure 16.— Performance of digital system (inertial height).

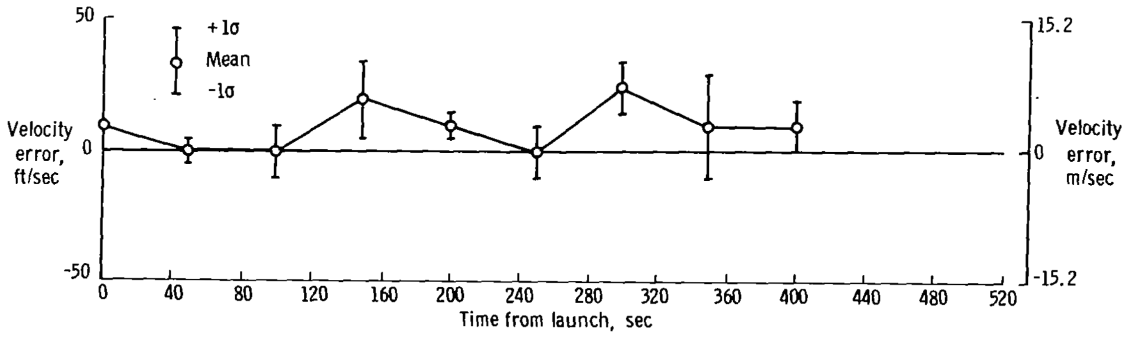

Figure 17.— Performance of digital system (velocity).

At this time, both the analog and the digital system meet the specifications in table I.

COMPARISON OF THE ANALOG AND DIGITAL SYSTEMS

On the basis of operational experiences with the analog and the digital inertial systems in the X-15 program, certain comparisons may be made. These comparisons must be tempered by several factors including the time period over which each of these systems was developed, the development costs of each system prior to integration into the X-15 aircraft, and the integration experience gained on the analog system that was subsequently used in integrating the digital system.

The design and development of the analog system started in June 1957, whereas the design and development of the digital system started in December 1960. Before integration of the analog system in the X-15, design and development costs were approximately 4.5 million dollars; these costs for the digital system amounted to approximately 28.3 million dollars. Modification of the digital system and computer programing for the X-15 cost 1.2 million dollars. No estimate has been made of the cost in materials and manpower of putting the analog system into the configuration on which these final performance data are based. Certainly, many of the original integration problems encountered with the analog system, such as the cooling problems, and the resolution of these problems eased the integration task for the digital system.

Comparing the performance results of the two systems (figs. 13 and 16), the digital system not only provides smaller mean errors but is also more repeatable in performance from flight to flight, as is indicated by the level of the standard deviations. Besides providing better performance, the digital system offers the advantage of flexibility through computer programing. Since equation mechanization in the analog computer is hardwired, there is very little flexibility.

Analog systems inherently have errors that are accumulative as a result of the tolerance errors of each component in the mechanization. This has necessitated the use of reference systems on board the B-52 to provide a continuous erection of the inertial system to the launch of the X-15. Degradation of the performance of these reference systems results in further degradation in the performance of the inertial system. The digital system has not been subject to these same error sources since, with the exception of the vertical loop, it is a self-contained navigation system.

In general, it is felt that the analog system is adequate to perform specific tasks, providing these tasks are not varied and do not require lengthy operating times. The digital system is more suited to handling a variety of tasks where high precision is required in the results.

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