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MAY-JUNE 1964 J. AIRCRAFT VOL. 1, NO. 3

Inertial Navigator Flight-Testing Experience with the Lockheed F-104

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In this paper a description is given of the flight profiles and courses flown, and the technique used for the reduction of data, during flight testing of a lightweight inertial navigator installed in the F-104 interceptor. Program objectives were to evaluate accuracy of navigator outputs and determine system reliability. Equipment requirements for system accuracy were established in terms of a statistical parameter, circular error probable. The major program effort was centered about the flight testing of inertial navigator systems in five F-104 airplanes. Navigator distance outputs were checked photographically against an independent reference, points on the earth's surface; a simple data-correction technique was used which obviated need for stabilization of the downward-looking camera. Problems were discovered in several areas. One of these, runaway distance outputs because of condensed moisture, was revealed only by flight tests. Because of the maneuverability of the F-104 and its extensive flight envelope, it was necessary to conduct inertial navigator tests under a wide variety of conditions.

Introduction

A REVIEW is presented of Lockheed experience during flight-test evaluation of a lightweight inertial navigator installed in the F-104 Super Starfighter airplane. This airplane, a derivative of the USAF "Starfighter," is capable of Mach 2 flight, interception of targets at high altitudes, and low-level ground attacks. The general arrangement of the F-104 is shown in Fig. 1. Highly maneuverable, the F-104 provides strenuous environmental conditions for all airplane systems, including avionics.

Inertial navigator tests commenced in a DC-3 electronics system test bed in July 1960. The first quantitative inertial navigator data from an F-104 systems installation were obtained in January 1961. Final data flights were conducted in August 1962. With the exception of high-humidity tests made from Eglin Air Force Base, Fla., all Lockheed-conducted inertial navigator flights were made from USAF Plant 42, Palmdale, Calif. The program objective was to determine whether the inertial navigation system installation was satisfactory, i.e., to insure that the accuracy of navigator and platform outputs was consistent with design objectives and that system reliability was sufficient to assure a high probability of mission success.

Description of System

The LN-3 inertial navigation system, manufactured by Litton Industries, was specified for the F-104 to provide accurate self-contained navigation information and roll angle, pitch angle, and vertical acceleration data from transducers mounted on the navigator stable platform. The distance and heading readout is provided by a Position and Homing Indicator (PHI) System, which is also used to display Tactical Air Navigation (TACAN) and dead-reckoning navigation computer output data. The PHI is manufactured by Computing Devices of Canada, Ltd. and features a 12-station selector unit (SSU) to facilitate navigation to preselected destinations.

The inertial navigator is a lightweight, fully automatic, self-contained navigation system. The heart of the system is a four-gimbal platform assembly aligned to the local vertical.

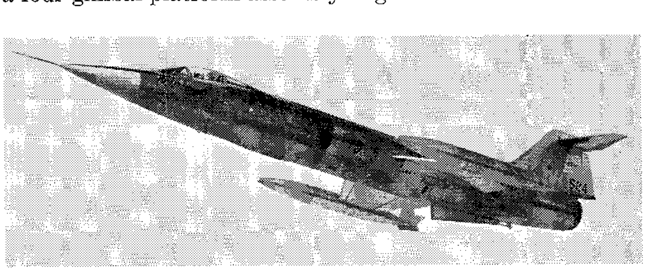

Fig. 1 Lockheed F-104 general arrangement.

This gimbal assembly mounts two floated gyros arranged in a dumbell configuration and three single-axis torque-balanced accelerometers with mutually perpendicular axes. Accelerations measured along the two axes tangent to the earth are used for navigation, whereas that measured along the local vertical is used by the autopilot for an inertial damping signal in the "altitude hold" mode.

Successive integrations are required to obtain ground velocity and position. When provided with manual inputs of initial and target or base position, the inertial navigator in conjunction with the PHI system continuously determines the position of the aircraft and indicates to the pilot the head-

Presented at the AIAA/AFFTC/NASA FRC Testing of Manned Flight Systems Conference, Edwards Air Force Base, Calif., December 4–6, 1963 (no preprint number; published in bound volume of preprints of the meeting); revision received March 17, 1964.

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ing and distance to the selected target or base. Figure 2 shows a schematic of the inertial navigation system.

The inertial navigator also provides the following information to the designated equipment. Pitch and roll angles: fire control system and attitude indicator. Pitch and roll angles, grid heading angle, and vertical acceleration: automatic flight control system. Grid heading: position and homing indicator. Figure 3 shows the inertial navigator control panel, and Fig. 4 shows the align control panel.

The PHI-IV consists of a small electromechanical navigation computer and associated readout indicator. In order to provide inertial mode readouts, the PHI navigates on a planar cartesian grid. East-West distances are measured along the X axis and North-South distances along the Y axis. The $X = 0$ line of the grid is aligned with true North at the reference or base point. Destination points are stored in a station selector (Fig. 5) in terms of X and Y. Provided with the instantaneous X and Y position of the airplane, the PHI computer, with reference to stored station coordinates, then determines and displays the range and bearing to the selected station, or to the base point, on the indicator shown in Fig. 6.

The LN-3 inertial navigation system is mechanized to provide position data relative to a pseudo-pole coordinate system. Any meridian of longitude may be selected as the base or reference meridian for this coordinate system. The navigator provides present airplane positions in terms of σ and μ, the grid horizontal and vertical coordinate axes variables. The σ and μ data are fed to the PHI computer, which

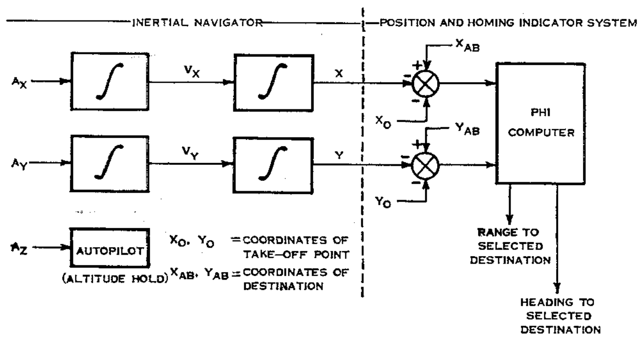

Fig. 2 Inertial navigation system schematic.

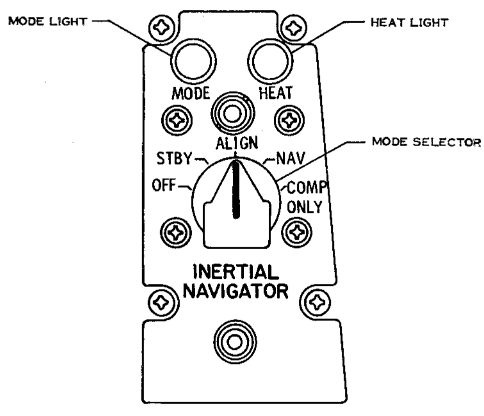

Fig. 3 Inertial navigator control panel.

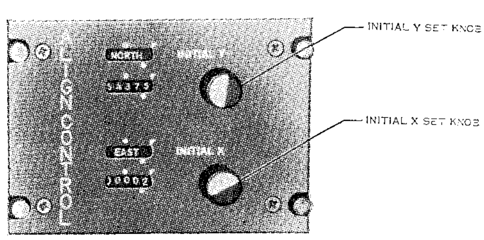

Fig. 4 Inertial navigator align-control panel.

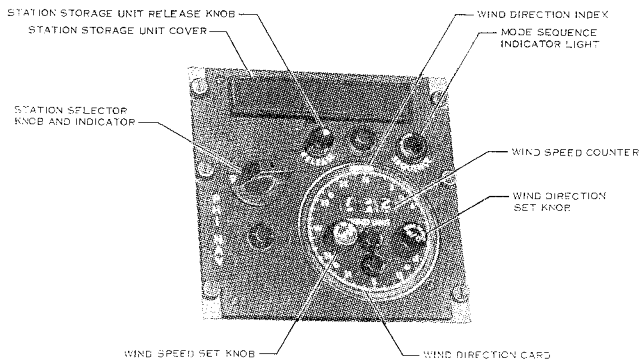

Fig. 5 PHI navigation control panel, showing station selector unit (SSU).

computes airplane position with respect to the selected destination by summing the σ and μ coordinates of the present position and those of the destination (which were set into the PHI station selector unit). The results are resolved into destination range and bearing and are displayed on the PHI system indicator.

Initial data to be calculated and set into the LN-3 and PHI systems include σ and μ coordinates of the takeoff point, destination σ and μ coordinates, grivation‡ at the takeoff point Γ, and enroute wind data for the dead-reckoning computer. Figure 7 shows problem geometry for a flight from a home base A on the reference meridian to a destination point B. Calculation of σ, μ, and Γ are covered in the following section.

Test Procedures

Inertial navigator flight testing procedures were relatively simple. The pilot was instructed to fly around a preset course under Visual Flying Rules (VFR) conditions. Airborne instrumentation (an oscillograph and automatic observer cameras) recorded system performance data. When over checkpoints, a downward-looking camera was activated and earth reference-point data were recorded for comparison with system outputs. Figure 8 shows a typical navigation course from Palmdale, Calif. to Hawthorne, Nev. Checkpoints were carefully chosen; it was necessary that they be on U. S. Coast and Geodetic Survey Maps, so that their exact latitude and longitude could be determined, and that they be readily identifiable from the air. Prior to adoption of a particular navigation test course, it was first surveyed from the air by the systems test engineer. Pictures of checkpoints and of approaches to checkpoints were taken for use in briefing the test pilots.

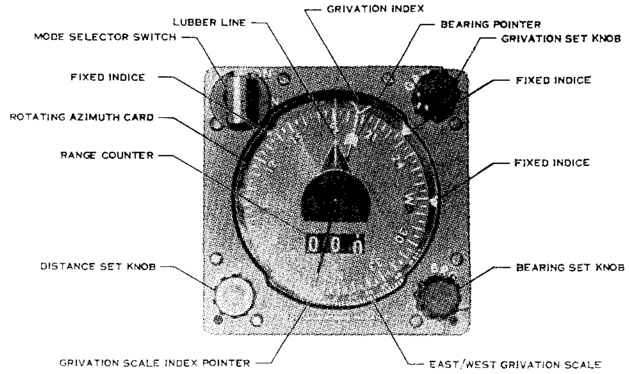

Fig. 6 PHI system indicator.

‡ Grivation Γ is grid variation from magnetic North, and it is equal to local magnetic variation ζ plus convergence γ of the pseudo-pole coordinate system at the same point.

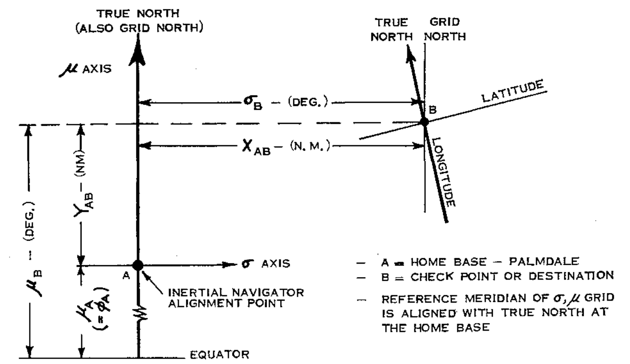

Fig. 7 Navigation problem geometry.

Several courses were laid out. North-South and East-West courses provided opportunity to obtain comparison data under special conditions for determination of possible mechanization and accelerometer errors. A "round-robin" course, such as in Fig. 9, provided a long-range simulated mission. Low- and high-altitude courses permitted system evaluation over widely separated portions of the airplane's operational envelope.

Once ground checkpoints were established, distance and bearing relationships from the reference or base point (Palmdale, Calif.) to these checkpoints were computed. These values were then used as the standard against which distance output information from the LN-3 and PHI were compared. X and Y distances were calculated from the LN-3 system equations of mechanization given below:

X_{AB} = x component of distance from A to B
X_{AB} = $60\sigma_B$ naut miles
Y_{AB} = y component of distance from A to B
Y_{AB} = $60(\mu_B - \mu_A)$ naut miles

where

σ_B = $\sin^{-1}(\cos\phi_B \sin\lambda)$
μ_A = latitude of reference base
μ_B = $\sin^{-1}(\sin\phi_B/\cos\sigma_B)$
ϕ_B = geographic latitude of point B
λ = latitude of point A minus latitude of point B

For convenience, the majority of tests were made with Palmdale as the reference base through which the base meridian (line of $\sigma = 0$) passed. Thus, the navigation system was aligned on the base meridian. Tests were satisfactorily conducted wherein navigator alignment was accomplished away from home base and the reference meridian. However, details of these tests will not be covered in this paper.

The distance components X_{AB}, X_{AC}, X_{AD} . . . and Y_{AB}, Y_{AC}, Y_{AD} . . . were set into the SSU. Thus, to fly around the navigation test course the pilot needed only select suitable

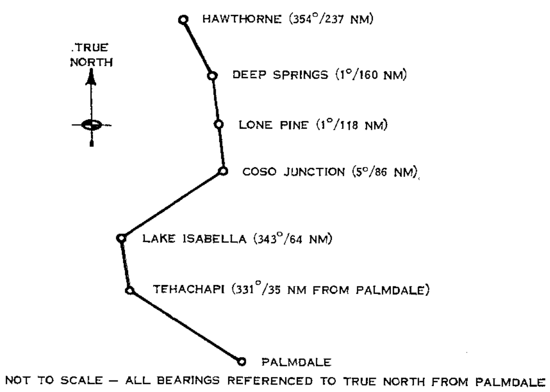

Fig. 8 Navigation test course—Palmdale, Calif. to Hawthorne, Nev.

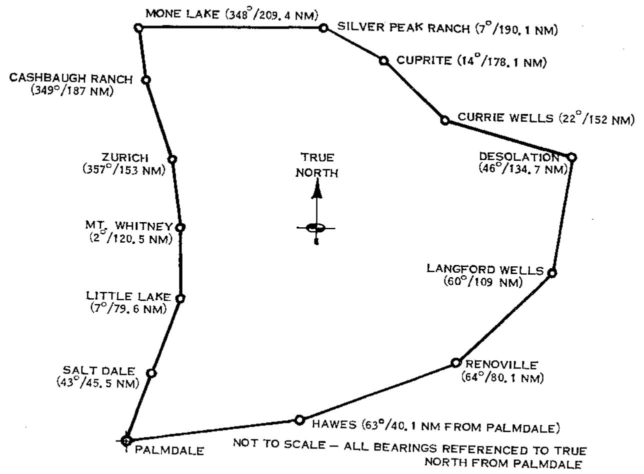

Fig. 9 "Round-robin" navigation test course.

SSU stations to obtain distance-to-go and heading information. The X and Y distance components are always measured from the reference station base to the destination of interest. Thus, since the reference station base is the origin of a coordinate axis system, X and Y distances may be either positive or negative.

Next, the inertial navigator must be "told" (prior to alignment) where its starting point is and that the base meridian passes through this point. This information is set into the LN-3 align control panel (Fig. 4) as "Initial X" and "Initial Y" in degrees and minutes. Initial X and initial Y are, of course, initials σ and μ. Since the base meridian passes through the home base, initial X = 00° 0.0 min and initial Y = ϕ_A, latitude of the home base (34° 37.2 min North for Palmdale).

Finally, the grivation Γ is calculated for insertion into the PHI indicator prior to system alignment. Grivation (grid variation from magnetic North) is local magnetic variation ζ plus convergence γ of the pseudo-pole coordinate system. That is, $\Gamma = \zeta + \gamma$ (degrees). The convergence at any point of the grid is given by

$$\gamma = \tan^{-1}(\tan\mu \sin\sigma)^\circ$$

With the reference meridian ($\sigma = 0$) passing through the home base, the convergence between true North and grid North is zero, and therefore grivation equals the local magnetic variation

$$\Gamma = \zeta = 16^\circ \text{ East, at Palmdale}$$

Figure 10 shows how to establish grivation at the home base.

Prior to each F-104 test flight, after navigator alignment had been achieved, the system was switched to "Navigate," which established the zero time reference point, and an Automatic Observer (AO) camera burst was taken of the instru-

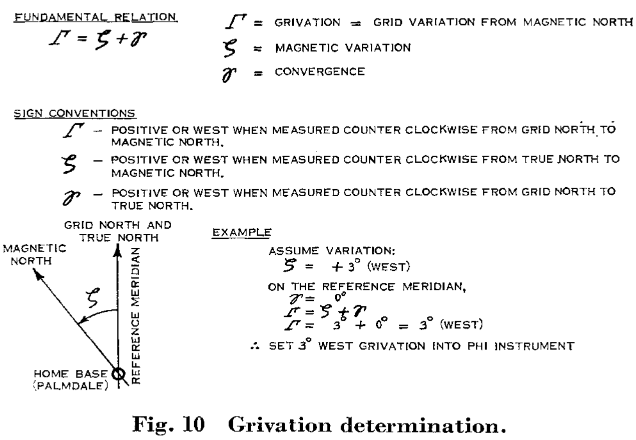

Fig. 10 Grivation determination.

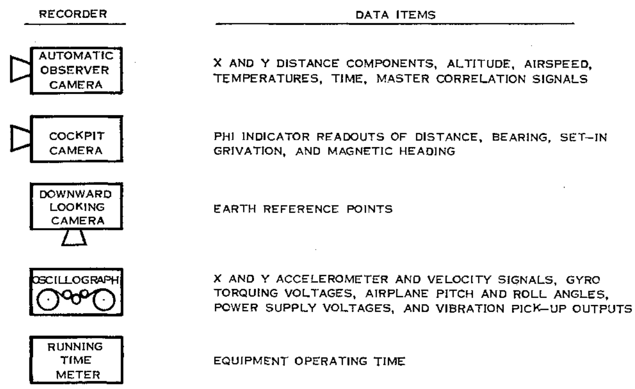

Fig. 11 Data acquisition system.

mentation panel; this recorded a chronometer reading and tare numbers on digital X and Y distance counters. SSU position 1 (home base) was selected and the PHI manual adjustment knob used to zero distance readouts in inertial and dead-reckoning navigation modes. Next, the pilot selected SSU position 2, the first checkpoint, and taxied out.

After takeoff, the pilot, while climbing to the scheduled flight altitude, steered toward the checkpoint by aligning the heading pointer with the grivation index on the PHI indicator. As the checkpoint is approached, the distance-to-go decreases. Three to five miles from the checkpoint, the pilot turned on the camera instrumentation and left it on during the level flight run, over and beyond the ground reference point. These cameras included the downward-looking camera, which photographed the ground track and checkpoint, the AO camera, and a cockpit camera that photographed the PHI indicator. This procedure was repeated over all checkpoints along the navigation course. When the flight was completed, the closure or terminal error was determined by flying over the takeoff point or by taking data at the ramp after the landing.

The pilot visually acquired each ground checkpoint and flew the airplane as best he could to pass directly over the checkpoint. The small "on-top" error as the airplane passed over the checkpoint was accounted for during data analysis.

When over the checkpoint, the pilot reported the distance-to-go and heading on the PHI; these data provided backup error information in the event an instrumentation malfunction occurred and also provided immediate "quick-look" accuracy data.

Flights were made with limited maneuvering and with combinations of maneuvers which would be encountered on tactical missions. The maneuvers, which were specified for certain flights, included left and right rolls, loops, Immelman turns, steep dives, rolling pullouts, turns with sustained high-load

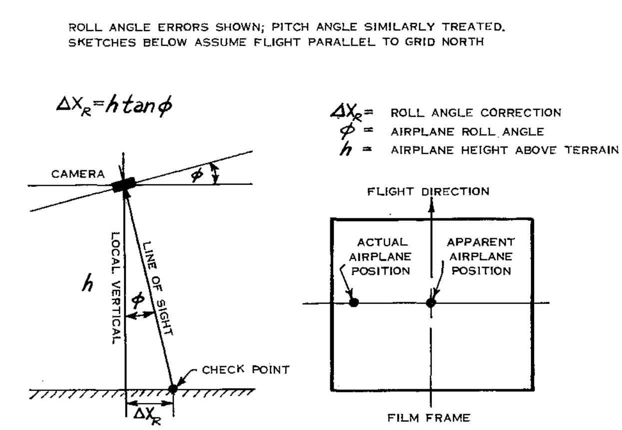

Fig. 12 Correction for roll angle to checkpoint position from downward-looking camera film.

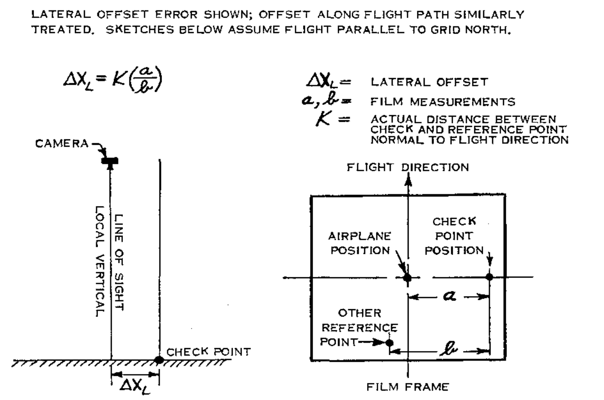

Fig. 13 Correction for lateral offset to checkpoint position from downward-looking camera film.

factors, and decelerations with speed brakes extended. In addition, navigation accuracy tests were made on flights during a portion of which the M-61 "Vulcan" gun was fired, to verify that navigator performance was not degraded because of the gun-firing vibration.

Instrumentation

As previously mentioned, a downward-looking camera was used to photograph the reference checkpoints, and a camera was mounted in the cockpit to record PHI readouts. The Automatic Observer (AO) camera recorded inertial navigator X and Y distance outputs (digital counters), airplane altitude and airspeed, free-air temperature, navigation system ambient and equipment temperatures, and timing and correlation data.

An oscillograph was carried in the airplane to record navigator variables, such as X and Y accelerometer and velocity outputs, gyro torquing voltages, system input voltages, etc. Airplane pitch and roll angles were also recorded on the oscillograph for correction of ground map camera data to account for airplane attitude changes. A running-time meter was used to obtain time between failures. Figure 11 shows the over-all data acquisition system for the inertial navigator tests.

Analysis

During the F-104 navigation flight-test program, accuracies of both the inertial navigator and PHI system were determined. Because inertial-mode data read from the PHI also included PHI errors, the inertial navigator X and Y outputs were intercepted and read out on digital counters in the AO panel. Thus, the inertial system accuracy could be analyzed independently. Since inertial navigator X and Y outputs were fed to the PHI system, both the input and output of the PHI system were available for accuracy analysis. This paper considers only the inertial navigator accuracy evaluation. As a matter of interest, PHI-system demonstrated accuracy in the inertial mode was better than that specified; average distance readout error from Lockheed flight-test data was approximately ± 1.4 naut miles, independent of range, and 90% of the bearing errors were less than $\pm 1.5°$.

When the pilot estimated that he was over a checkpoint, a signal was given to mark the records and provide a point at which to read the data. The corresponding ground map and AO film frames were located and identified and the corresponding point located on the oscillograph. The inertial navigator distance output from the Palmdale reference point to the checkpoint was then determined as follows:

$$X_1 = X_B - X_A$$
$$Y_1 = Y_B - Y_A$$

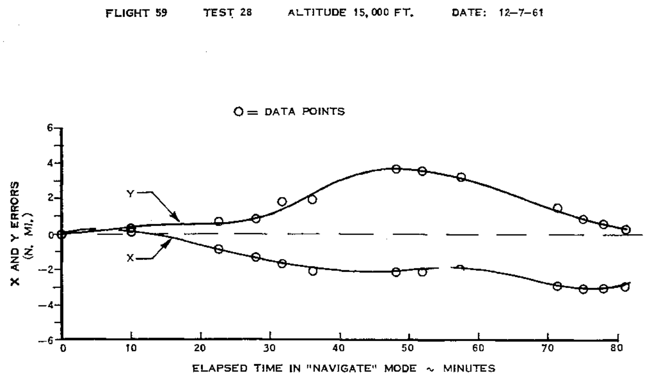

Fig. 14 Distance errors X and Y vs time.

where

X_A, Y_A = initial counter readings at zero navigate time (reference camera burst)

X_B, Y_B = distance counter readings over checkpoint (at pilot signal)

X_I, Y_I = inertial navigator distance components from the Palmdale, Calif. reference point to the selected checkpoint

When necessary, correction terms were calculated to account for errors in airplane position when reportedly over the checkpoint and to compensate for the effect on downward-looking camera data of airplane pitch and roll angles. The latter correction was made first.

Correction to Checkpoint Position for Effects of Pitch and Roll

The downward-looking camera was mounted so that its optical axis was normal to the airplane fuselage reference line in the plane of symmetry. Consequently, roll and/or pitch angles would cause apparent displacement of the checkpoint image on the film frame, as shown in Fig. 12. Local terrain height at the checkpoint was subtracted from airplane altitude above mean sea level to obtain airplane height above terrain h. Roll and pitch angles were determined from the oscillograph in conjunction with bearing, and correction terms ΔX and ΔY calculated. Figure 12 illustrates a simplified case; corrections for effects of simultaneous roll and pitch angles and resolution through the bearing angle are straightforward and will not be developed here. These corrections were easily accomplished where needed and obviated need for space stabilizing the downward-looking camera installation.

Correction to Checkpoint Position for Effects of Path Offset

Allowance was made for the on-top error as the airplane passed over the checkpoint; these errors were usually negligible at low altitude but were necessary to consider when flying the navigation course at high altitudes, such as 30,000 ft. As Fig. 13 shows, the distance error was calculated by multiplying a ratio of measurements from the film frame by the known distance between two points on the Coast and Geodetic Survey maps. The on-top error was then resolved into X and Y components.

On occasion the checkpoint was outside the downward-looking camera's field of view. In this case a distinctive object or landmark on the film record was located on the Coast and Geodetic Survey map for the area, and the radial miss distance was scaled directly from the map.

The previously determined distance components from Palmdale to the checkpoint (X_{AB} and Y_{AB}) were corrected to the actual airplane position relative to the checkpoint, the corrections accounting for camera pitch and/or roll and airplane offset from the checkpoint. The navigator error was thus determined as follows:

$$X_e = X_{AB} + \Delta X - X_I$$
$$Y_e = Y_{AB} + \Delta Y - Y_I$$

where

X_e, Y_e = inertial navigator error components

X_{AB}, Y_{AB} = computer grid distance components to checkpoint

ΔX, ΔY = corrections to computed distances X_{AB}, Y_{AB} to account for airplane on-top error

X_I, Y_I = inertial navigator distance component outputs

X_e and Y_e errors were then plotted vs time in the "navigate" mode for each individual flight. In addition, the combination of X_e and Y_e into radial error was accomplished and radial error plotted for each flight. Figure 14 shows a typical variation of the X and Y errors with time; Fig. 15 shows the corresponding radial distance error time history.

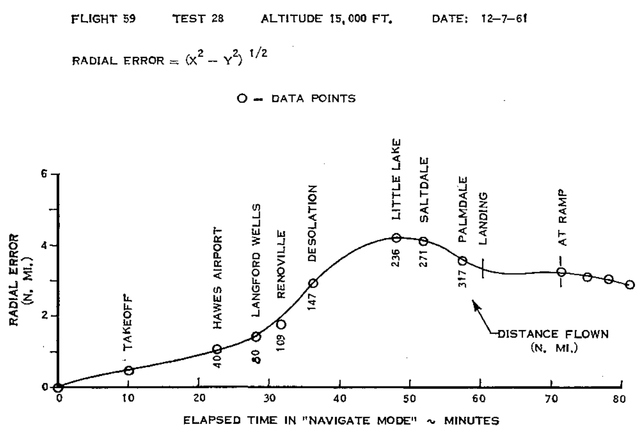

Fig. 15 Radial distance error vs time.

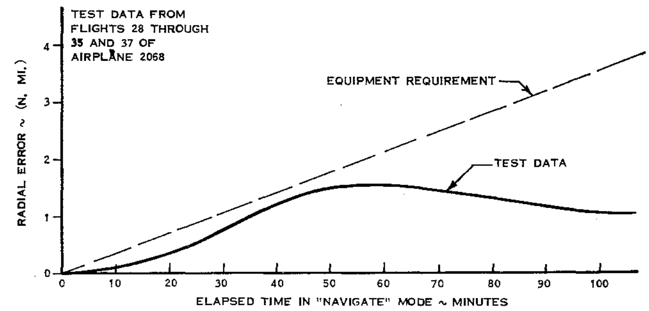

Fig. 16 Inertial navigator CEP vs time.

Discussion of Results

After a number of flights had been made, the radial error data were processed statistically to determine Circular Error Probable (CEP). Figure 16 shows a typical variation of CEP with time; the circular error probable will not be exceeded 50% of the time. CEP is often stated alternately as that point above or below which errors may lie with equal probability.

Following a test flight, oscillograph and film records were flown on a shuttle airplane to the flight-test data processing facility at Burbank, Calif. These records were developed in the plant, with the exception of the downward-looking camera color film, which was sent out for processing. The data were read on existing "swing" and "graveyard" shifts to provide "quick-look" results for systems test and analysis engineers to review early the next day. Data were read on semiautomatic equipment coupled to card punches; all computations were accomplished on an IBM 7090 computer. Upon return of the developed color film, correction terms from the downward-looking camera and oscillograph were calculated and the quick-look data were modified to final data. The CEP was calculated on a constantly updated basis; early results were of course not significant because of the small data sample size.

The two-dimensional, normal distribution case is frequently used in design and analysis of navigation systems. In practice, the standard deviation of the error in one coordinate usually approaches or is essentially equal to the value of the standard deviation in the second coordinate. When sufficient data were accumulated, tests were made to determine if the assumption of a Rayleigh distribution was valid in analysis of F-104 inertial navigator flight data.

Statistical tests of four necessary conditions were validated in order to support the Rayleigh error distribution assumption. These were that 1) the errors in each channel (X and Y) are normally distributed, 2) the X and Y errors are statistically independent, 3) the mean X and Y errors are zero, and 4) the standard deviations of the X and Y errors are equal.

The first condition was validated directly from the data in the initial stages of processing. The second condition required determination of the error correlation coefficient ρ_{XY}. A measure of the statistical dependence of the two errors, ρ_{XY} varies from zero, indicating independence, to unity, indicating total dependence. Data analysis showed the estimate of $\rho_{XY} = 0.044$; this validated the second test with a 95% probability that $\rho_{XY} < 0.026$ at a significance level of 0.01. The t test was used to establish the probability level of nonzero μ_X and μ_Y (mean errors in X and Y), the third condition. Results showed that there was a 95% probability that $|\mu_X| < 0.097$ and $|\mu_Y < 0.066$ naut-miles/hr at a 0.001 significance level, validating the third condition. Last, a modified F test was used to test for equivalence of X and Y standard deviations. It was determined that the ratio of the true X and Y standard deviations would fall between 0.6 and 1.0, with a 99.95% probability. Further calculation showed that in this range the maximum difference between CEP calculated with an elliptical error distribution and the CEP calculated using the Rayleigh distribution is 5.15%; the CEP calculated with the Rayleigh distribution is the larger or more conservative of the two. For a 2.0-naut-mile/hr CEP, this amounts to a 0.103-naut-mile difference, which is relatively insignificant.

From results of these generally accepted statistical tests, it appears valid to assume that the LN-3 errors are Rayleigh or circularly distributed. Consequently, the navigator-error standard deviation can be obtained from Fig. 16 by multiplying the CEP at any time by 0.8493.

The inertial navigator equipment requirement states that the system errors shall not exceed a CEP of 2 naut-miles/hr. This is shown as a straight line on Fig. 16. The test data shown in Fig. 16 met and bettered this specification. The LN-3 is not damped to suppress the Schuler oscillation; consequently, the test data show a portion of the Schuler cycle. The data in Fig. 16 represent performance of current production navigators.

Inertial navigator errors propagate from several sources, such as initial position error, initial velocity error, initial level and azimuth misalignments, accelerometer bias and scale factor error, and level and azimuth gyro drift. Depending on the particular error source, these may propagate sinusoidally at the Schuler frequency, as functions of time or time squared, or in combinations of these. Since the system error was not updated during flight, the fact that a part of the error closes back on itself during the return-to-base portion of a round-robin course, such as in Fig. 9, together with the sinusoidal effects of the Schuler oscillation reduce the terminal errors, as shown in Fig. 16.

During the $1\frac{1}{2}$ years of flight testing the inertial navigator in the F-104, several problem areas were revealed. Two typical problems and their solutions are discussed below.

Effects of Power Transfers

Ground tests were run to determine if the alignment stability of the inertial navigator was disturbed during airplane power transfers, i.e., switching from external power to ship's power and back, or switching between airplane power systems (fixed frequency to variable frequency system and vice versa). Accelerometer outputs, velocity terms, and platform azimuth angle were continuously monitored on an oscillograph. The recorded data indicated that the LN-3 system operated normally in both "Align" and "Navigate" modes during all of the power transfers. Slight transient disturbances were noted in the A_x (accelerometer) output during external to internal power transfer while in the "Nav" mode, however, and A_x and A_y transients were noted during power transfer while the system was in the "Align" mode. Distance errors caused by accelerometer transients of these levels could range from 0.5 to 1.0 naut miles in both X and Y axes. For this reason, it was recommended that the system be in the "Nav" mode during engine starting and the transfer to ship's power.

Although power-transfer tests showed generally satisfactory LN-3 performance during early testing on the first two flight-test airplanes, subsequent and more detailed testing showed that the inertial navigator could not withstand the power interruptions required by normal switching times; the control panel "Fault" light would come on, indicating a system malfunction. A modification was incorporated and subsequently verified which permitted the system to sustain power interruptions of up to 50 msec without fault.

Effects of Moisture

During the test program, unexplained distance output runoffs occurred with one of the inertial navigators in flight test. After rapid descent from altitude or after landing, the cockpit distance-to-go indicator (PHI) and the X, Y counters on the AO panel showed a changing reading, errors frequently building up from 10 to 100 miles. It was initially suspected that intermittent electrical connectors were the cause of the problem. However, a check showed that no connectors were loose, and vibrating these on the ground could not induce the runoff.

The airplane was instrumented, and several flights were made with the accelerometer outputs, accelerometer biases, and Coriolis signals all grounded in an attempt to isolate the area in which the runoff trouble could be originating. It was determined that the distance runoffs were being caused by step changes from the velocity stages in the navigation computer. These step changes were verified as occurring in the latter part of the flight, particularly during letdown, approach, and landing.

Since computer over-temperature conditions were suspected, temperature-sensitive paint strips (templates) with a range of 150°–185°F were installed at selected points in the computer to establish whether the design operating temperature of 165°F was being exceeded. Runoffs occurred on two flights which were temperature monitored and in which the temperatures were not high enough to "mark" the templates. Accordingly, high operating temperatures were dismissed as a probable cause of LN-3 runoff.

Since low voltage to the LN-3 system could produce velocity stepoffs similar to those recorded in flight, airplane power-supply voltages were also instrumented and monitored during flight. Again results were negative; there were no transient or low voltages at the time the distance runoffs were initiated.

At this time the characteristics of the LN-3 runoff problem were summarized as follows:

1) Runoff occurred most often after a rapid decrease in altitude.

2) Runoff was initiated internally, as evidenced by one or both velocity servo shafts driving off from a balanced (zero-output) condition.

3) Flight data indicated the integrator components were working properly during runoff, but it appeared as if the d.c. input to the integrator amplifier were too large.

4) The inertial navigator platform, adapter, thermal effects, electrical connectors, and low voltage were apparently not the location of or cause of runaway distance outputs.

Next, tests were conducted in the Flight Test Laboratory in which moisture-laden air was induced into the computer under low-temperature conditions, representative of those existing internally at high altitude. After sufficient computer component cooling had occurred, the cooling air was then supplied at higher temperatures, representative of conditions encountered when the airplane had descended to low traffic pattern altitudes. Runoff similar to that encountered in flight was thus induced in the navigation system. Further evidence that moisture was the cause of runoff was noted when the number of such incidents increased on flight test and production airplanes when increased humidity conditions existed.

"Stick-on" humidity indicators were installed in the test airplanes in the navigator computer and at various other points in the electronics compartment. These indicated that high-humidity conditions had been encountered during flight; indeed, some of the indicators were still moist when the electronic compartment was opened for postflight inspection.

With moisture in the computer as a probable source of the distance runoffs, the airplane was flown to Eglin AFB, Fla., where over-all system operation could be determined under high-humidity conditions and concurrently to test various computer modifications which would reduce system susceptibility to conditions causing runoff. The airplane was thoroughly instrumented, including the installation of thermocouples for accurate monitoring of temperatures.

From the flights at Eglin the mechanism of moisture formation in the LN-3 was determined. It was found that electronics compartment cooling air was reduced below its dew-point temperature when passed over components which were chilled from "cold-soaking" at high altitude. As low altitudes were reached prior to landing, high-humidity air was introduced into the E compartment at relatively high temperatures, compared to the cold-soaked components.

It was found that moisture-proofing computer components (applying epoxy resin coatings, additional potting, etc.) reduced the severity of runoffs but could not eliminate them completely, so long as extreme cooling air temperature fluctuations were likely. To support this finding, a flight was made with an external cooling air blower mounted on the navigator computer package. During flight the passage into the computer from the normal cooling air supply was closed off; thus, only ambient compartment air would be forced through the computer by the blower. This test was based on data which showed that the E compartment air did not change temperature as rapidly as the supplied cooling air upon descent and was suitable for cooling requirements. This test was satisfactory, and runoff did not occur.

As a result of the tests made at Eglin, the airplane air-conditioning system was modified, and additional epoxy coating was applied to critical areas within the navigator computer, such that the distance runoff problem was eliminated.

Other inertial navigator improvements were made during the course of the flight-test program. These included:

1) Weight reduction: Redesign and repackaging saved 15 lb.

2) Improved shockmounts: These were redesigned to sustain 7.3 g without bottoming (previously bottomed-out at a steady 4 g's).

3) Warmup time reduction: More rapid oven warmup rate permitted gyros and accelerometers to reach their stabilized operating temperatures sooner, reducing system "get ready" time.

4) Wind buffet modification: Peak accelerations from wind buffeting and ground-crew activities were being rectified, and the unipolar signals were adversely affecting ground alignment times, until relays were added to the leveling circuitry to bypass limiting diodes used during alignment.

5) Reliability improvements: Redesign, revised manufacturing techniques, modifications, etc. of computer servo shaft assemblies, power supply, platform gyros, slip rings, transistor heat sinks, relays, and other components.

Although inertial navigator reliability data cannot be covered at length in this paper, reliability and maintainability evaluations were important factors in the test program. Maintenance records were meticulously kept and analyzed. Running-time meters provided accurate system-operating time data for determination of mean time between failures (MTBF) and ground running time during maintenance and preflight system checks. During final evaluation of the inertial navigator on the Super Starfighter, the system was operated trouble-free for 70.8 hr, including nine flights totalling 16 hr. There were no aborted missions because of navigator or other system malfunctions for the full 88.7 hr of system operation of the 11-flight program.

Since a major program objective was accuracy determination, the systems were run and tested extensively before and after each flight, evaluating gyro bias stability, Schuler cycle, and accelerometer and integrator signal quality. Consequently, the ratio of ground time to flight time was quite high.

Concluding Remarks

In this paper a review of Lockheed experience during flight testing of the F-104 inertial navigator has been presented. The inertial navigator, a complex avionic system, required extensive and intensive evaluation to verify system accuracy and reliability; consequently, the work had to be carefully planned and the tests skillfully executed. In addition, it was necessary to analyze the data meticulously and to provide prompt feedback of results to supplier, project groups, and test engineers. The final result was a system that was operationally satisfactory.