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REAL-TIME PILOT GUIDANCE SYSTEM FOR IMPROVED
FLIGHT-TEST MANEUVERS

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Abstract

The Dryden Flight Research Facility has devel-
oped a pilot trajectory guidance system that is
intended to increase the accuracy of flight-test
data and decrease the time required to achieve and
maintain desired test conditions, or both. The
system usually presented to the pilot computed dif-
ferences between reference or desired and actual
flight state conditions. The pilot then used a
cockpit display as an aid to acquire and hold
desired test conditions. This paper discusses
various flight-test maneuvers and the quality of
data obtained using the guidance system. Some com-
parisons are made between the quality of maneuvers
obtained with and without the system. Limited
details of the guidance system and algorithms used
are included. In general, the guidance system
improved the quality of the maneuvers and trajec-
tories flown, as well as allowing trajectories to be
flown that would not have been possible without the
system. This system has moved from the developmen-
tal stage to full operational use in various Dryden
research and test aircraft.

Nomenclature

a   = model scale factor

A_N = normal acceleration

b   = coordinates of specific pole and
         zero in s-plane transfer function

FTF = flight-test fixture

HDOT = vertical velocity, ft/sec

H_p = pressure altitude, ft

M   = Mach number

s   = s-plane complex variable

α   = angle of attack, deg

Δ   = incremental change

Introduction

The flight-test community is continually seek-
ing to improve the quality of flight-test data and
to decrease the time required to obtain it. Ulti-
mately this results in higher quality data and lower
fuel usage. Normally the pilot achieves and main-
tains flight-test conditions utilizing either stan-
dard or flight-test quality conventional cockpit
instrumentation. However, conventional instruments
require that the pilot mentally compute the error
between actual flight conditions and desired condi-
tions and then estimate the control inputs required

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to reduce the error. It is more efficient to use a
computer to calculate the error based on measured
aircraft parameters, and to fly the aircraft based
on the error from pilot "fly to" guidance (cockpit
displays) or autopilot commands.

NASA Ames Research Center's Dryden Flight
Research Facility has developed a system that
allows command signals to be telemetered (uplinked)
real-time from a ground-based computer to either
cockpit displays or to an autopilot.[1,2] This
system allows not only unique flight trajectories
to be flown routinely but more conventional stabi-
lized point data to be more efficiently obtained.

An earlier description of the development of
this flight system is available in Ref. 1. Addi-
tionally, Ref. 1 discusses the use of the trajec-
tory guidance system during maneuvers, such as
constant-altitude turns and space shuttle-simulated
launch trajectories. More recently Dryden has been
using a NASA-owned, Lockheed-built F-104G aircraft,
described in Ref. 3, for continued development of
the technique of using a telemetry (uplink) system
for real-time displays/guidance. Recent work has
investigated the use of uplink guidance for five
additional flight-test maneuvers and trajectories,
in addition to the two discussed in Ref. 1. A brief
summary of the pilot display guidance system can be
found in Ref. 4, in which piloting technique and
comments are emphasized. This paper emphasizes the
technical aspects of the study and discusses the
quality of data obtained and the data acquisition
time. Some data are compared for maneuvers flown
with and without the aid of the guidance system.
Limited details of the guidance system and algorithms
used are included, along with general pilot comments
regarding use of the system.

Test Aircraft

A NASA-owned, Lockheed-built F-104G aircraft
(Fig. 1) was used as the test-bed aircraft for this
study. The aircraft data system was composed of a
40-channel pulse-code modulation system. Data
could be telemetered to a ground-based station or
recorded on board. Reference data, such as Mach
number, pressure altitude, and angle of attack, were
obtained from an aircraft noseboom system. An
uncompensated pitot-static probe, installed in the
nose boom, was used for reference air-data measure-
ments. In-flight airspeed calibration data were
used to correct indicated values of Mach number,
static pressure, and altitude to free-stream condi-
tions. No corrections were applied to angle of
attack. A detailed description of the aircraft and
instrumentation system is given in Ref. 3.

Two cockpit configurations were used for this
study. One was the basic aircraft cockpit, which
incorporated a special angle-of-attack indicator
(Fig. 2). The other, shown in Fig. 3, incorporated
a modified 3-in attitude/direction indicator (ADI).

System Design

Concept

The objective of the system is to provide the pilot with guidance to increase the accuracy or decrease the time with which maneuvers are flown and to allow more complex trajectories to be flown. The uplink guidance system usually presents the pilot with computed differences between the reference, or desired, and the actual flight state conditions. Typical variables which comprise actual flight state conditions are Mach number, angle of attack and pressure altitude. For this study, the data required to calculate these variables were telemetered from the aircraft to a ground-based computer, where the signals were converted to engineering units, and appropriate corrections made. For example, total and static pressure obtained from the test aircraft's noseboom were telemetered from the aircraft and used to determine indicated Mach number, which is corrected with calibrations to obtain free-stream Mach number. The engineering unit variables were then compared with the reference conditions. From the ground-based computer, the information was telemetered to the aircraft in the form of errors, or guidance, presented on a cockpit display. Figure 4 presents the system used.

Algorithms

Aircraft state values that had been converted to engineering units and had appropriate corrections applied (in the ground-based computer) were used as input to the specific algorithms for the guidance system. This system is shown in Fig. 5. Some of the aircraft state values were processed to either enhance or filter the time rate of change of the state value with a "digital lead-lag equation" before comparison with comparison with reference conditions. The general s-plane form of the lead-lag equation is

$$G(s) = \frac{s+a}{s+b}$$

The method used to transform this s-plane description into a time-domain function is contained in Appendix B, Ref. 5. A detailed discussion of trajectory guidance control analysis can be found in Ref. 6.

Cockpit Display

A single cockpit display was used to avoid monitoring multiple cockpit instruments simultaneously. The display used was a modified 3-in attitude/direction indicator (ADI). The instrument was mounted above the instrument panel in a position similar to that of a head-up display, although it could have just as well been mounted in the instrument panel. The normal horizontal needle, vertical needle, and vertical pointer functions were used to display the computed differences between the aircraft state measurements and the desired, or reference, conditions, as shown in Fig. 6. The vertical pointer was used to provide the pilot with throttle commands, the horizontal needle was used to provide pitch commands, and the vertical needle was used to provide roll commands.

Description of Flight-Test Trajectories and Pilot Techniques

The specific flight maneuvers or trajectories that were flown, as well as general pilot technique, will be briefly described. Detailed descriptions of pilot techniques for these maneuvers can be found in Ref. 4. Limited details of the display format are included for each maneuver, and details are summarized in Table 1.

Level Turns

For the level turn, the aircraft was stabilized at constant altitude, Mach number, and angle of attack. This maneuver required the pilot to control angle of attack with pitch, Mach number with thrust variation, and altitude with roll attitude. The cockpit display provided angle-of-attack guidance on the horizontal needle, Mach number error on the vertical pointer, and altitude guidance on the vertical needle. The display was mechanized for a left turn only.

Constant-Thrust Turns

For the constant-thrust turn, constant thrust was stabilized in addition to constant Mach number and angle of attack. The turn must be either descending (the deficit thrust condition) or climbing (the excess thrust condition). This maneuver required the pilot to control the angle of attack with pitch and the Mach number by varying bank angle. The display was mechanized with angle-of-attack guidance on the horizontal needle and Mach-number guidance on the vertical needle. This resulted in Mach number being controlled by changing vertical velocity through bank angle.

Dynamic-Pressure Trajectories

Two types of dynamic-pressure trajectories were flown, using the trajectory guidance. In the first, dynamic pressure was held constant and Mach number was varied. In the second, both dynamic pressure and Mach number were varied according to a predetermined schedule.

Initially, one of two techniques was used to fly the profiles. In the first, a 2° to 5° pitch-attitude climb was established, and the trajectory was controlled by utilizing the throttle to hold Mach-number error at zero. In the second, an excess thrust condition was set with the throttle, and the trajectory was controlled on the basis of pitch-attitude variations as commanded by horizontal needle guidance. However, the final technique used was a combination of the two above. The pilot set an initial pitch attitude of 3° to 5° nose-up and then varied throttle (primarily) and pitch attitude (secondarily) to keep the horizontal needle centered. At approximately Mach 0.95, full afterburner was selected with pitch-attitude corrections being used only to center the horizontal needle for the remainder of the run. The display was mechanized with Mach number error on the vertical pointe and dynamic pressure guidance on the horizontal needle.

Constant-Radar-Altitude Accelerations and Decelerations

For the constant-altitude acceleration-deceleration (accel-decel) maneuvers, radar altitude was held constant while Mach number was varied from 0.7 to 1.4 and then back to approximately 0.7.

This maneuver required the pilot to perform a level accel-decel by varying pitch attitude according

to commands from the horizontal needle. The display is mechanized with altitude guidance on the horizontal needle.

Reynolds-Number Profiles

In the Reynolds-number trajectory flown, the Reynolds number was held constant against varying Mach number. The piloting technique was to establish an excess-thrust climb and to control Reynolds number by changing pitch attitude based on horizontal needle guidance (in a manner analogous to that described for the dynamic-pressure trajectory). The display was mechanized with Reynolds-number guidance on the horizontal needle.

Zero-g Profiles

This trajectory was a parabolic flightpath; it started from level flight, which was followed by a pull-up of the aircraft to a predetermined pitch attitude and then a "push-over" to establish a short zero-g trajectory. Load factor during the zero-g trajectory was held constant while other parameters were allowed to vary. The piloting technique required the pitch-attitude to be varied during the push-over according to horizontal needle guidance to hold zero-g. The display was mechanized so that load-factor guidance was displayed on the horizontal bar.

Constant-Mach-Number/Altitude Conditions

For these points, both altitude and Mach number or airspeed were held constant. This required the pilot to stabilize the aircraft in level flight at a given altitude and Mach number according to the vertical pointer and horizontal needle. The display was mechanized with Mach-number error on the vertical pointer and altitude guidance on the horizontal needle.

Approach and Procedures

The developmental approach of the uplink system consisted first of ground-based simulator testing which allowed variation of algorithms for the pointer and needles of the uplink cockpit display. This provided the pilot with preliminary optimization of the guidance commands and error signals. The ground simulator was also used to allow the pilot to practice the maneuvers to be flown both with and without uplink. A detailed explanation of similar studies can be found in Ref. 1.

Following the ground-based work, flights were flown to verify the optimization of the lead-lag gains (when applicable), which were then fixed for data-gathering flights. For some flights, comparisons were made for data points flown both with and without use of the uplink. For flight tests with the uplink, the display was the primary instrument used to achieve and maintain the desired flight conditions. For flight tests without uplink guidance, an angle-of-attack gauge (calibrated in degrees), as well as standard cockpit instruments, were used to achieve and maintain the desired flight conditions. For unique trajectories, such as constant-Reynolds-number profiles, the uplink was used without comparison with conventionally acquired data (none could be obtained).

Two types of maneuvers were flown for the flight-test data obtained without uplink guidance for level turn and constant-altitude/Mach-number conditions. In one case, the Mach-number and pressure-altitude values the pilot was asked to fly were corrected for position and instrument errors, and in the other case they were not. These are referred to as corrected values and uncorrected values, respectively.

Results and Discussion

This section will compare maneuver or trajectory data obtained with and without trajectory guidance. For maneuvers that could not easily be flown without trajectory uplink guidance, for example, the Reynolds-number profile, uplink data are presented for documentation purposes only. Lead-lag equation value development is discussed when applicable.

The data presented in this paper were obtained on a time-available basis and in some cases are limited; however, the data were acceptable for purposes of determining the system's value.

Level Turns

The initial use of the trajectory guidance system for level turns,[1] utilized bank angle (ϕ), pitch angle (θ), and roll rate (p) as separate inputs for the algorithm used with the vertical needle (bank command). This mechanization of the display proved successful; however, the aircraft used during that study had an inertial or stable platform, which was used for accurate determination of aircraft attitudes (ϕ and θ). Additionally, that algorithm required knowledge of reference bank angle and pitch angle from simulator studies before it could be used in flight.

There was no inertial platform available for the aircraft used in this study; as a result, accurate aircraft attitudes (ϕ and θ) could not be determined. Therefore, it was desirable to develop a new bank-command algorithm, one that required neither aircraft attitudes nor simulator studies before flight. This was attempted by displaying pressure-altitude error on the vertical needle, which had pressure altitude processed with a digital lead-lag equation (described in the algorithm section).

The initial development effort for the new bank-command algorithm was to determine suitable lead-lag equation constants for processing pressure altitude. The Mach number and angle-of-attack algorithms were not changed from those described in Ref. 1. Therefore, for simplicity those parameters are not discussed in the lead-lag gain development.

Figure 7 presents pressure altitude error (actual minus reference) versus test point (time) for with-trajectory-guidance, flight obtained level turn maneuvers for various lead-lag equation values. In Figs. 7(a) and 7(b) for lead = 0.5/lag = 5.0 and lead = 0.2/lag = 5.0, the pilot work load was quite high and there was a tendency to diverge from the reference altitude. In Figs. 7(c) and 7(d) for lead = 0.2/lag = 2.5 and lead = 0.3/lag = 2.5, the gains were acceptable. In Fig. 7(e) for a

lead = 0.3/lag = 2.0, the trend was to maintain a constant-amplitude deviation about the reference altitude. Fig. 7(f) shows the data for what were considered to be the optimum lead-lag equation values of lead = 0.2 and lag = 2.0.

Figure 8 presents a typical level turn obtained with trajectory guidance and shows how Mach number, angle of attack, and altitude were maintained, while using the pressure altitude lead-lag values associated with the turn of Fig. 7(f). The reference conditions for this maneuver were a pressure altitude of 25,000 ft, Mach number of 0.8, and an angle of attack of 8°. The maneuver was started above the reference altitude and intercepted it at approximately 30 sec into the maneuver. The best data were obtained between 50 and 60 sec after the maneuver was begun; there was a 0.002 error in Mach number, a 0.3° error in angle of attack, and a 20-ft error in altitude. The particular conditions chosen for the maneuver required the use of afterburner in the F-104 to maintain altitude. However, the pilot elected to use military power, which caused a small thrust deficit and a subsequent "bleed-off" of Mach number beginning at a time after maneuver start of about 60 sec. This error in Mach number is not related to the algorithms used, but to the aircraft performance for the particular flight conditions selected for the maneuver.

One of the main objectives of this study was to improve the accuracy with which or the time in which a typical flight request can be accomplished with and without trajectory guidance. To evaluate the system, some maneuvers were flown with and without trajectory guidance. Figures 9 and 10 present such comparisons for the flight requests of Table 2.

As mentioned earlier, the without-trajectory-guidance level turns were flown using standard cockpit instruments and an angle-of-attack gauge (Fig 2). It is well known that cockpit instruments, such as Mach indicators and altimeters, have errors associated with them, most notably the transonic-speed-region position error. In the case without uplink guidance, two types of maneuvers were flown. In the first type, the Mach number and altitude values the pilots were asked to fly were corrected for instrument and position errors. For the other type, no corrections were applied. The flight request for each type is presented in Table 2.

The corrected values (diamond symbol, Fig. 9) took more time to accomplish than the uncorrected values (square symbol). This is attributed to the increased pilot workload required to resolve the corrected values on the cockpit indicators. For example, corrected values corresponded to M = 0.77 and H_p = 19,650 (Table 2(b)); the uncorrected values corresponded to the more easily resolved numbers of M = 0.80 and H_p = 20,000 (Table 2(a)). The data with-trajectory-guidance (circular symbol) took longer than either type of the without-trajectory-guidance data. The reason for the increased time for the data with-trajectory-guidance is not fully understood; however, the pilot experienced difficulty in determining the magnitude to which he was off the desired condition and, consequently, spent extra time attempting to completely null the display needles and pointer.

With regard to accuracy, Fig. 10 presents Mach-number error, pressure altitude, and angle-of-attack

errors (actual minus reference) versus time for data obtained with and without uplink guidance. The data presented are typical of one Mach number condition or test point series of Table 2. The request was to fly trim angle of attack (condition A), then trim plus 2° (condition B), and finally trim plus 4° (condition C) for each test point. No pressure altitude error data were obtained for the with-trajectory-guidance, condition A data. The particular flight conditions (M, α, H_p) chosen for the condition-C data required the use of afterburner to maintain conditions. However, the pilot elected to use military power, which resulted in a bleed-off of Mach number. This occurred for data obtain both with and without trajectory guidance.

Figure 10(a) compares the with-trajectory-guidance data (circular symbols) and without-trajectory-guidance uncorrected values (square symbols). The without-trajectory-guidance uncorrected value resulted in errors as great as Mach number 0.02 and 400 ft in pressure altitude in the data; these errors are attributed to a combination of instrument and position error. The angle of attack for condition B was approximately 0.5° less than the requested 2° increment above trim, and for condition C it was almost 1° less than the requested 4° increment above trim. These angle-of-attack errors were caused by indicator errors, which were not accounted for during these test point series.

Figure 10(b) compares the with-trajectory-guidance data (circular symbols) to without-trajectory-guidance corrected values (square symbols). The without-trajectory-guidance data result in very acceptable errors, with the exception of Mach-number error. For all three conditions, the actual Mach number was more than 0.02 below the desired or reference condition. This was apparently caused by incorrect application of instrument or position error, or both, to the Mach number values the pilot was asked to fly. A small error occurred in the without-trajectory-guidance angle-of-attack data of condition C, which was approximately 0.5° less than the 4° increment requested.

In both cases (Figs. 10(a) and 10(b)), the with-trajectory-guidance data resulted in more accurately obtained flight-data results. Also, in both cases, depending on the accuracy required, the data without-trajectory-guidance would probably have been repeated to obtain more accurate data. In Fig. 10(a) this was caused by lack of application of instrument or position-position errors. In Fig. 10(b) this was apparently caused by incorrectly applying the position or instrument error to the Mach number values the pilot was asked to fly. Although the data obtained with uplink took longer to acquire, the uplink would have, in this case, prevented repeating all or a portion of the flight, which ultimately results in more quickly obtained data.

Constant-Thrust Turn

Figure 11 presents data from a thrust-limited turn with trajectory guidance. No comparison data were obtained without trajectory guidance. The requested maneuver was to maintain an angle of attack of 8° and a Mach number of 0.8 in a deficit-thrust situation while passing through 25,000 ft. The maneuver was started at an altitude of about 29,000 ft so that steady-state conditions would be achieved when passing through 25,000 ft. At

25,000 ft (time = 45 sec), the angle of attack was about 7.75° and the Mach number was 0.790. The Mach number trace had a constant-amplitude oscillation, which is shifted below the target Mach number of 0.8. This apparently resulted from improperly chosen lead-lag values on Mach number.

Dynamic-Pressure Trajectories

Figure 12 presents typical constant-dynamic-pressure trajectories obtained with trajectory guidance. No comparison data were obtained without guidance. For the data presented, the trajectory was started at a Mach number of about 0.8 and continued to a Mach number of 1.1, although the beginning and end Mach numbers were somewhat arbitrary. For the 300-lb/ft^2 trajectory (Fig. 12(a)), the maximum error was 7 lb/ft^2 (2 percent) and for the 600-lb/ft^2 profile (Fig. 12(b)) the maximum error was 12 lb/ft^2 (2 percent). As can be seen from the figure, the trajectory was maintained very accurately.

Another application of the trajectory guidance system was to duplicate the dynamic-pressure versus Mach-number trajectory of the space shuttle during a launch, although the trajectory as flown in the F-104 takes about 10 times longer than actual launch. Figure 13 presents a comparison of shuttle launch-trajectory data obtained with and without guidance. The solid line represents the desired or reference condition. The symbols denote the flight-obtained data.

Figure 13(a) presents data obtained without the use of trajectory guidance. The flight request for these data consisted of predetermined target Mach number and pressure-altitude conditions. The maximum error in dynamic pressure was 15 lb/ft^2 (2 percent).

Figure 13(b) presents data obtained with the use of uplink guidance. In this case, data were obtained for both a "design" dynamic pressure and for a "1.4 design" dynamic-pressure shuttle launch profile. Again the solid line represents the desired or reference condition, which was pre-programmed in the ground-based computer. For the design launch profile, the maximum error was 5 lb/ft^2 (0.6 percent); for the 1.4 design profile, the maximum error was 15 lb/ft^2 (1.5 percent).

Although the data without trajectory guidance are surprisingly accurate, the pilot workload was significantly higher. Additionally, it is our opinion that there would have been no initial attempt to fly a shuttle launch trajectory if the guidance system had not been available.

Constant-Radar-Altitude Acceleration-Deceleration

Another application of the trajectory guidance system is in displaying geometric altitude information obtained from ground-based radar.

Figure 14(a) presents altitude and vertical velocity (HDOT) versus time for a level accel-decel maneuver. For this maneuver, the uplink was not used and the pilot flew the maneuver aided only by standard cockpit instruments. Cockpit instruments that require static pressure for input, such as altimeters and Mach indicators are known to have significant errors in the transonic speed region. As can

be seen in Fig. 14(a), there is more than a 1,000-ft deviation in altitude during the maneuver. The large deviation in altitude is attributed to the change in the position error with Mach number and has associated with it significant vertical velocity. For example, from a time of approximately 75 sec to 110 sec, the vertical velocity (HDOT) averaged more than 15 ft/sec and at one time exceeded 40 ft/sec. For extended periods of time, these large vertical velocities provide unsatisfactory data for the users.

Figure 14(b) presents a similar maneuver using the trajectory guidance. As can be seen, both the altitude error and magnitude of the vertical velocity (HDOT) have been significantly reduced. The maximum altitude deviation during the maneuver was +100 and -90 ft, while changing the Mach number from 0.9 to 1.4 and back to 0.9.

It is apparent from a comparison of Figs. 14(a) and 14(b) that the trajectory guidance system allows a higher-quality level accel-decel maneuver to be flown than using cockpit instruments alone. However, it was felt that for comparison purposes a maneuver should be performed without uplink, but aided by a ground controller who had radar altitude information. Figure 14(c) shows data obtained from such a maneuver. As can be seen, the maneuver was flown nearly as accurately as the with-trajectory-guidance flight (Fig. 14(b)), although the vertical velocity (HDOT) was somewhat greater, reaching a maximum of 30 ft/sec. This ground-controlled maneuver required constant radio communication and the pilot felt that the overall workload was significantly higher.

The most notable point in the data with-trajectory-guidance from the user standpoint is that the time periods when the vertical velocity does exist are short in duration and allow for easier reduction of the data.

Reynolds-Number Trajectory

One of the unique trajectories flown using the trajectory guidance is the Reynolds-number profile. This trajectory requires the pilot to hold Reynolds number constant while varying Mach number. No conventional cockpit instruments are available to display Reynolds number, nor can Mach number/altitude points be easily predicted before a flight, a result of deviations in the actual atmosphere from that of a "standard day." Consequently, data without-trajectory-guidance are not available for comparison.

Figure 15 presents Reynolds number versus Mach number for unit Reynolds numbers of 2 x 10^6 and 5 x 10^6 per ft, which represent the practical lower and upper unit Reynolds number of the F-104. As can be seen from Fig. 15, the trajectories were maintained within ±0.1 x 10^6 per ft.

Zero-g Profiles

A very limited attempt was made to use the trajectory guidance during a parabolic zero-g maneuver. The F-104 aircraft is capable of maintaining a zero-g maneuver for almost a minute; however, the maneuver presented in this report was only intended to demonstrate the feasibility of the trajectory guidance system for a zero-g maneuver.

Figure 16 presents the maneuver that holds zero-g for approximately 10 sec. Nominally, the maneuver was held within 0 to +0.05 g of zero and the trajectory guidance system was found to perform quite satisfactorily.

Constant-Altitude/Mach-Number Conditions

Similar to the level turn, a particular flight request (Table 3) was flown with and without trajectory guidance. Again, two types of corrections were applied for maneuvers obtained without trajectory guidance. In one case, the Mach number and altitude values that the pilot was asked to fly were corrected for instrument and position errors; in the other case, no corrections were applied.

Figure 17 presents time required to accomplish the flight request of Table 3 with and without trajectory guidance. The data with trajectory guidance were obtained in nearly 3 min less (25 percent faster) than those obtained without trajectory guidance; the difference is considered significant.

Figure 18 presents Mach number and pressure altitude error (actual minus reference) versus test point (time) for the maneuvers presented in Fig. 17. In Fig. 18(a), the data were obtained without trajectory guidance, but the pilot was asked to fly corrected values. This resulted in a maximum Mach number error of -0.03, which diminished to zero with time. The altitude error was a nominal 200 ft with a maximum error of 400 ft. The data shown in Fig. 18(b) were obtained without trajectory guidance and are uncorrected indicated values. In this case, the nominal Mach number error was 0.015, with a maximum error of 0.025. The nominal altitude error was 200 ft, with a maximum error of 600 ft. Figure 18(c) presents data obtained with trajectory guidance and clearly presents the most accurately obtained data. The nominal Mach number error is 0, with one deviation to 0.01. The nominal altitude error is 0 and the maximum error is approximately 75 ft.

Figures 17 and 18 show that for constant-altitude and Mach-number points the data can be obtained more accurately and up to 25 percent faster with the use of uplink guidance.

Conclusion

In conclusion, it is thought that the limited study of the trajectory-guidance system discussed in this report has shown that systems of this kind hold great promise for improving the quality of flight testing. This system has advanced from the developmental stage to full operational use in various Dryden research and test aircraft.

This guidance system not only reduces pilot workload but it usually shortens the time required to obtain data, resulting in fuel savings and lower costs for the user. In all cases, the trajectory guidance system provided more accurate data, usually more quickly obtained data; and in some cases it made it possible to fly profiles that could not have been accomplished any other way.

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Table 1 Guidance display format

Maneuver	Horizontal needle	Vertical needle	Vertical pointer

Level turn	Angle-of-attack guidance
	Range: $\pm4°$
	Excess α causes down
	  needle deflection
		Altitude guidance
		Range: ±500 ft
		Excess altitude results
		  in left needle deflec-
		  tion. Altitude proc-
		  essed with lead-lag
		  equation
			Mach error
			Range: ±0.05
			Excess Mach number
			  results in an up
			  pointer deflection

Constant-thrust
  turn
	Angle-of-attack guidance
	Range: $\pm4°$
	Excess α causes down
	  needle deflection
		Mach number guidance
		Range: ±0.04
		Excess Mach number causes
		  right needle deflection	

Dynamic-pressure
  trajectories
	Dynamic pressure or Mach number
	  guidance
	Range: ±20 lb/ft^2 or ±0.10 Mach
	Excess dynamic pressure or Mach
	  results in up needle deflection
	Dynamic pressure processed with
	  leadlag equation
			Mach number error
			Range: ±0.05
			Excess Mach results
			  in up pointer
			  deflection

Radar acceleration-
  deceleration
	Radar altitude guidance
	Range: ±500 ft
	Excess altitude results in down
	  deflection of needle
	Radar altitude processed with lead-
	  lag equation		

Reynolds number
  trajectory
	Reynolds number guidance
	Range: ±0.05/ft
	Excess Reynolds number results in a
	  down needle deflection
	Reynolds number is processed with a
	  lead-lag equation		

Zero-g profile	Normal acceleration guidance Range: ±0.05 g Greater than zero g results in a down needle deflection		

Constant-
  altitude
Mach number
  points
	Altitude guidance
	Range: ±500 ft
	Excess altitude results in a down
	  needle deflection
	Altitude is processed with lead-
	  lag equation
			Mach number error
			Range: ±0.05
			Excess Mach results
			  in an up pointer
			  deflection

Note: All guidance signals are "fly to" and all error signals are "fly from" signals.

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Table 2 Flight request for level-turn maneuvers

(a) No trajectory guidance, uncorrected indicated values

Test point	Indicated Mach number	Pressure altitude, ft	Angle of attack
1A	0.7	15,000	Trim
1B	0.7	15,000	Trim +2°
1C	0.7	15,000	Trim +4°
2A	0.8	20,000	Trim
2B	0.8	20,000	Trim +2°
2C	0.8	20,000	Trim +4°
3A	0.9	25,000	Trim
3B	0.9	25,000	Trim +2°
3C	0.9	25,000	Trim +4°

(b) No trajectory guidance, corrected indicated values

Test point	Indicated Mach number	Pressure altitude, ft	Angle of attack
1A	0.68	14,740	Trim
1B	0.68	14,740	Trim +2°
1C	0.68	14,740	Trim +4°
2A	0.77	19,650	Trim
2B	0.77	19,650	Trim +2°
2C	0.77	19,650	Trim +4°
3A	0.86	24,500	Trim
3B	0.86	24,500	Trim +2°
3C	0.86	24,500	Trim +4°

Table 3 Flight request for constant Mach number and altitude test points

(a) No trajectory guidance, uncorrected indicated values

Test point	Indicated Mach number	Pressure altitude, ft
1	0.90	22,300
2	0.85	19,600
3	0.80	16,700
4	0.75	15,900
5	0.70	10,000
6	0.65	5,000
7	0.60	5,000

(b) No trajectory guidance, corrected indicated values

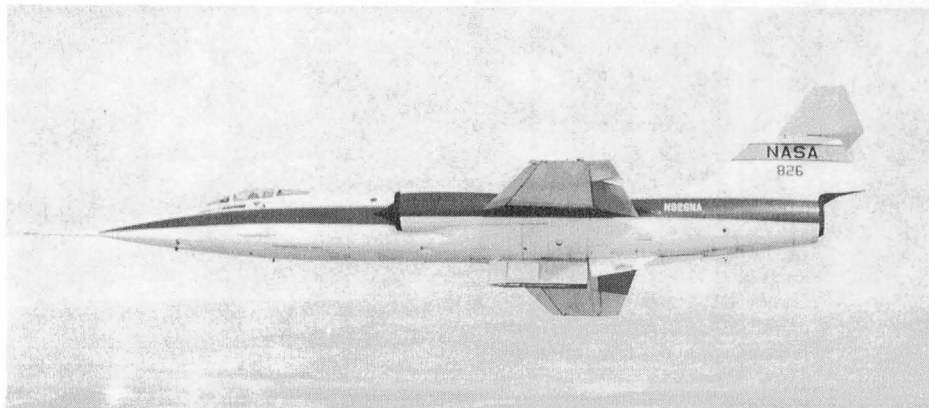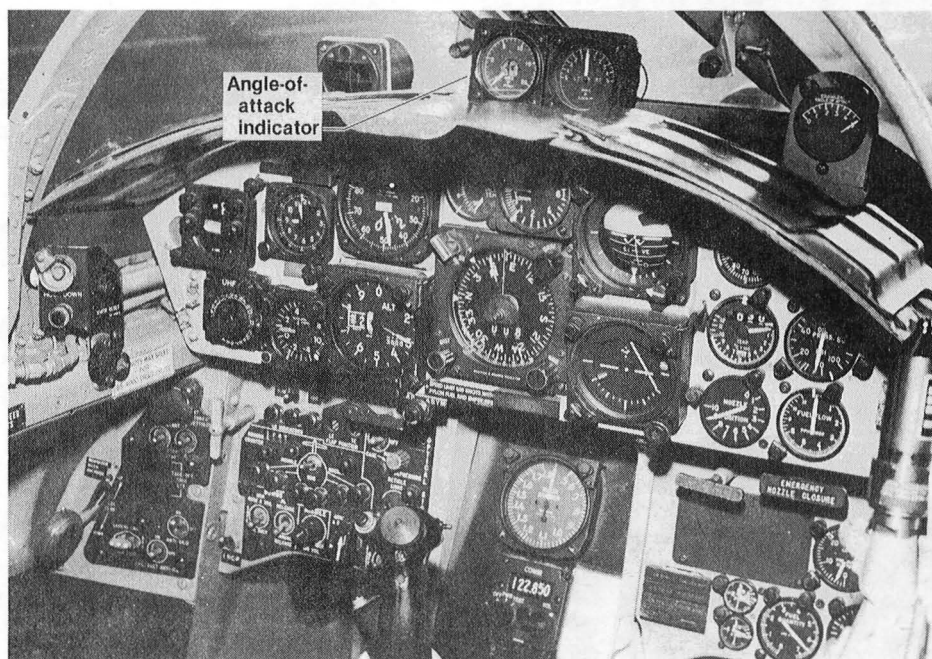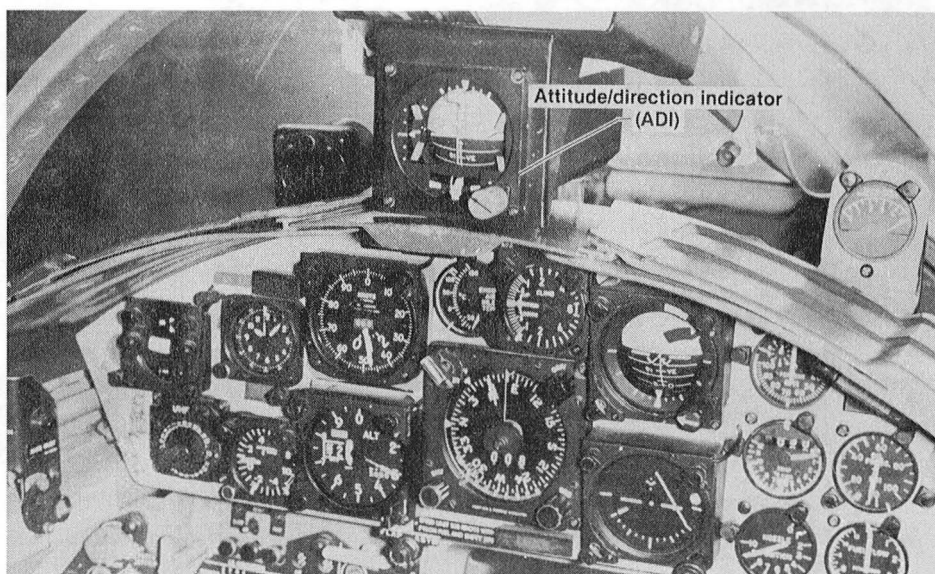| Test point	Indicated Mach number	Pressure altitude, ft
1	0.86	21,780
2	0.82	19,160
3	0.77	16,320
4	0.72	15,580
5	0.68	9,680
6	0.64	4,700
7	0.60	4,700

Fig. 1 F-104G test aircraft.

Fig. 2 Nontrajectory guidance system cockpit setup.

Fig. 3 Trajectory guidance system cockpit, showing standard 3-in attitude/direction indicator used as trajectory guidance display.
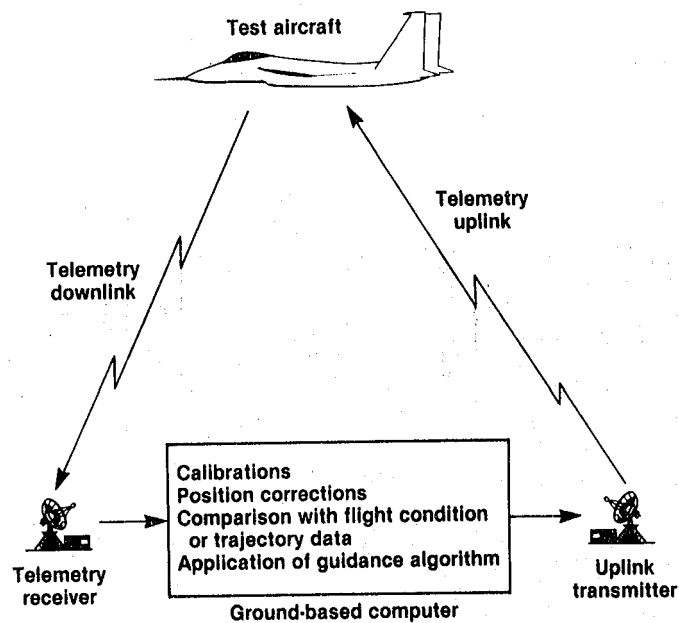
Test aircraft

Telemetry uplink

Telemetry downlink

Calibrations
Position corrections
Comparison with flight condition
  or trajectory data
Application of guidance algorithm

Telemetry receiver

Uplink transmitter

Ground-based computer

Fig. 4   Flight test trajectory guidance system used.

Aircraft
state
values

Error
signals

Display
signals

Guidance
algorithm

Test condition
or
trajectory data
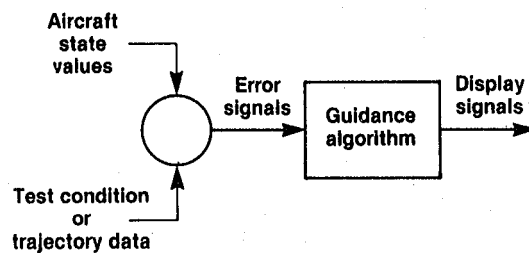
Fig. 5   Flight test trajectory guidance system elements.

Vertical needle

Vertical pointer
side indicator

Roll axis scale

Throttle
position
scale

Horizontal needle
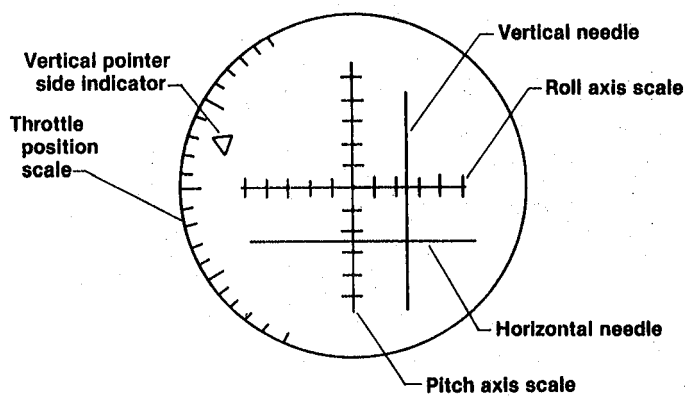
Pitch axis scale

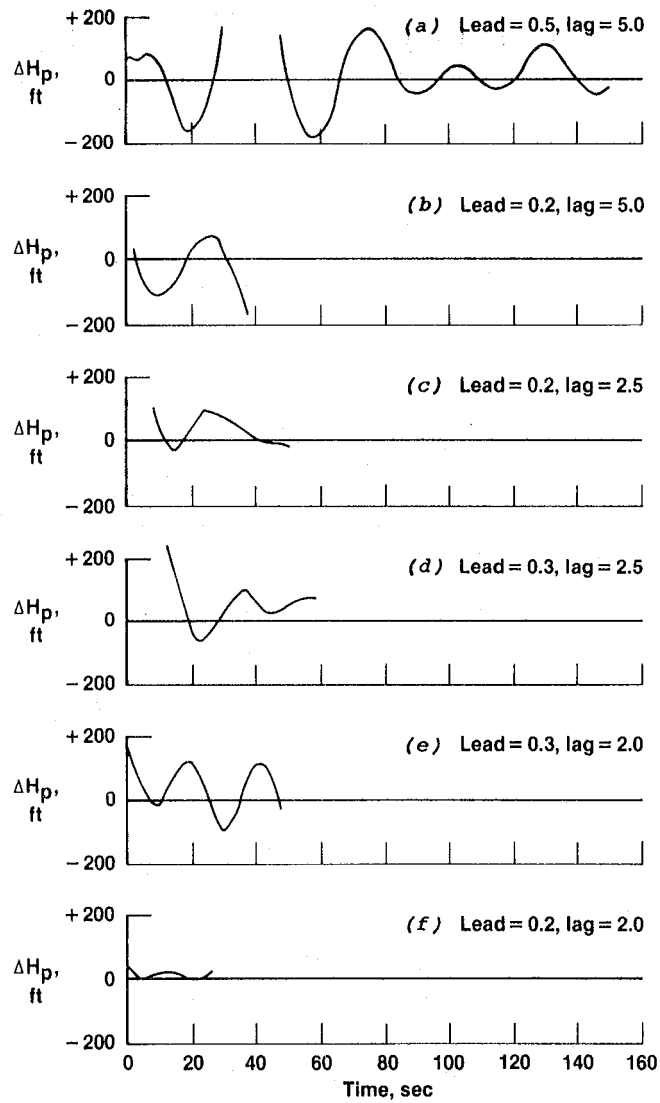*Fig. 6   Generic pilot display device.*

10

*Fig. 7   Altitude error as a function of time during
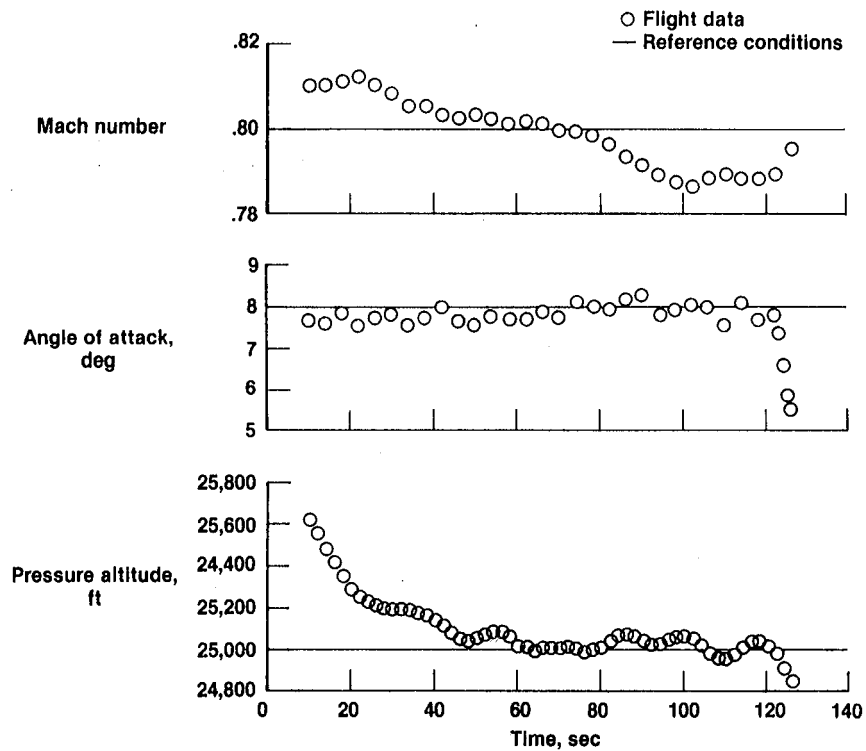level-turn maneuvers for several lead/lag values.*

Fig. 8 *Typical level-turn maneuver, using altitude error with lead-lag compensation.*
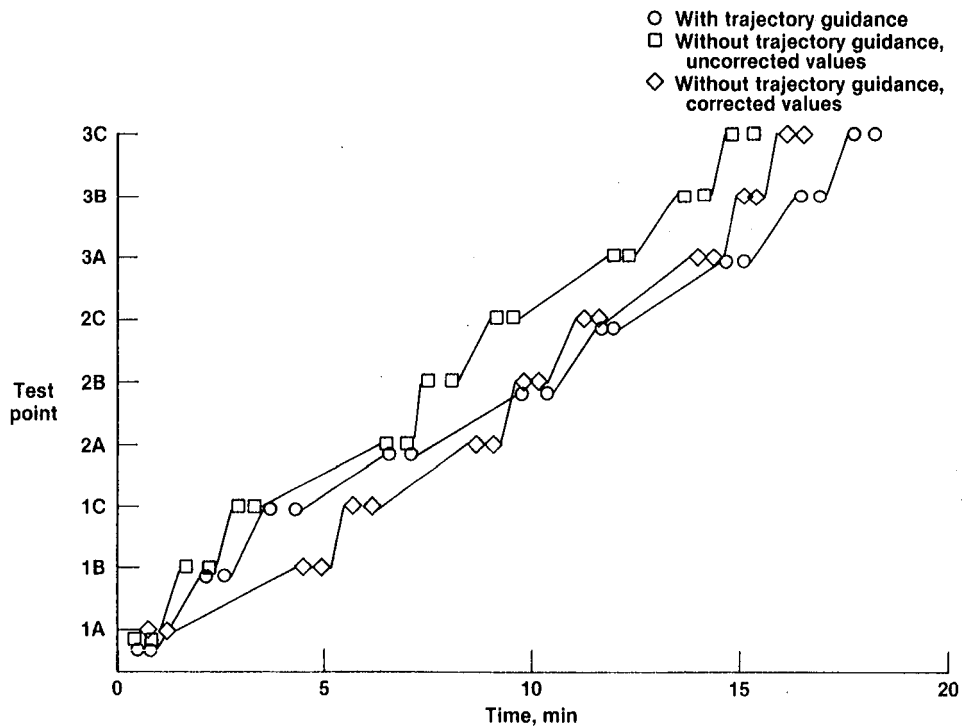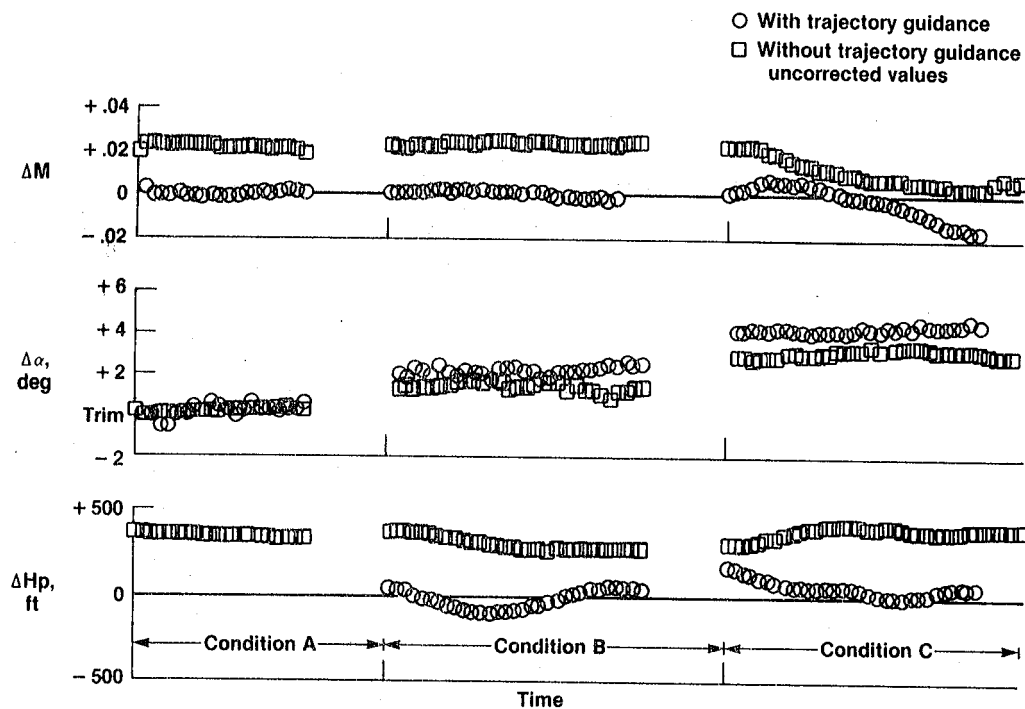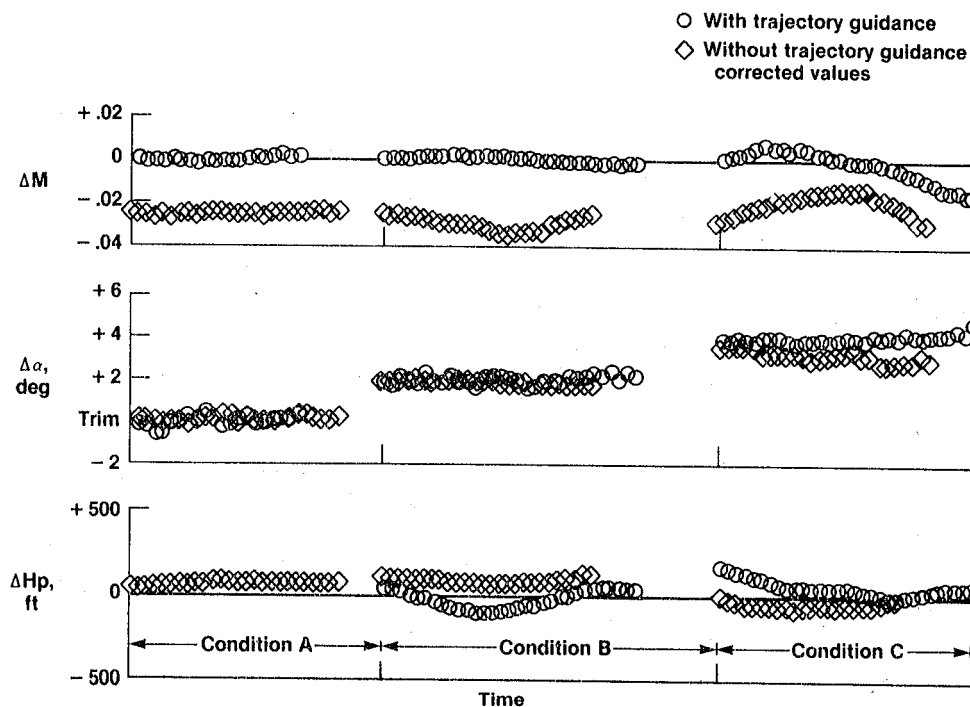

Fig. 9 *Time required to complete a specific flight card for level-turn maneuvers flown with and without trajectory guidance.*

○ With trajectory guidance
□ Without trajectory guidance uncorrected values

(a) Comparison of maneuver flown with guidance
and without guidance (uncorrected values).

○ With trajectory guidance
◇ Without trajectory guidance corrected values

(b) Comparison of manuever flown with guidance
and without guidance (corrected indicated values).

Fig. 10 Mach number, angle of attack, and pressure altitude error for
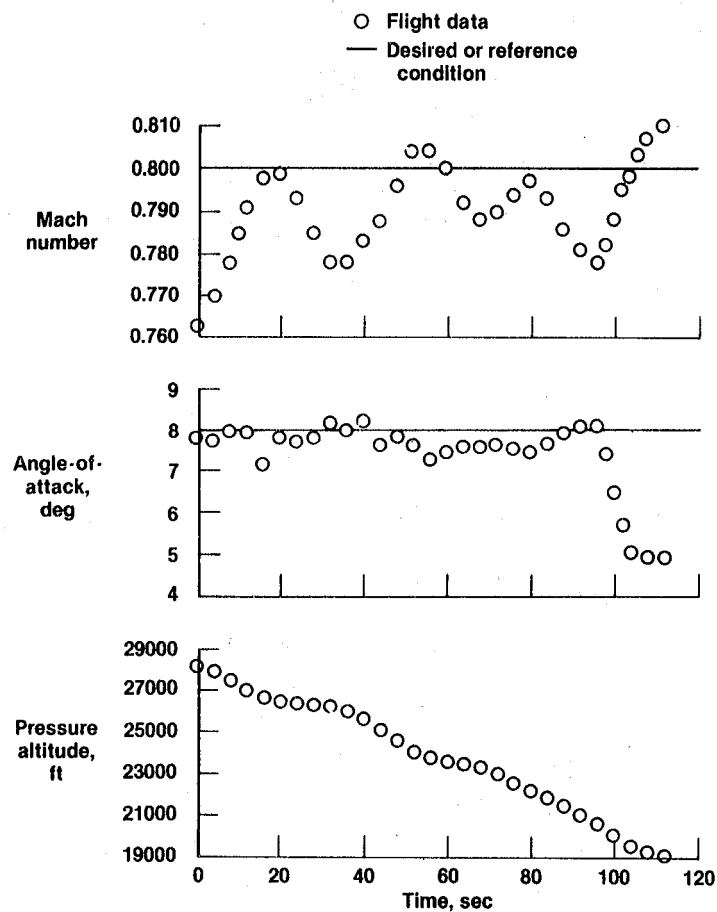typical level-turn maneuvers flown with and without trajectory guidance.

Fig. 11 Data from a thrust-limited turn
maneuver with trajectory guidance.
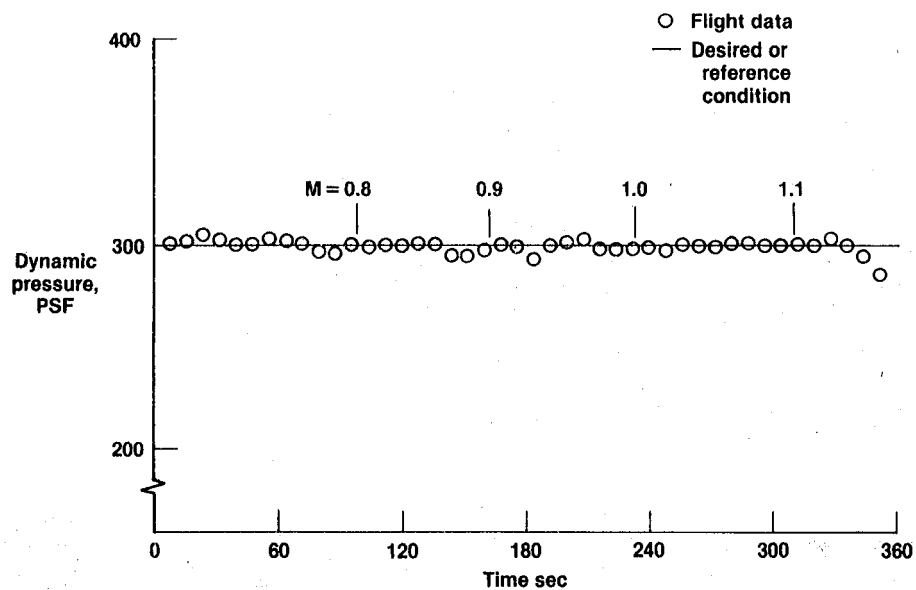
(a)   300 PSF.

Fig. 12 Constant dynamic pressure profile
obtained with trajectory guidance.

(b) 600 PSF.

Fig. 12 Concluded.

(a) Obtained without trajectory guidance.
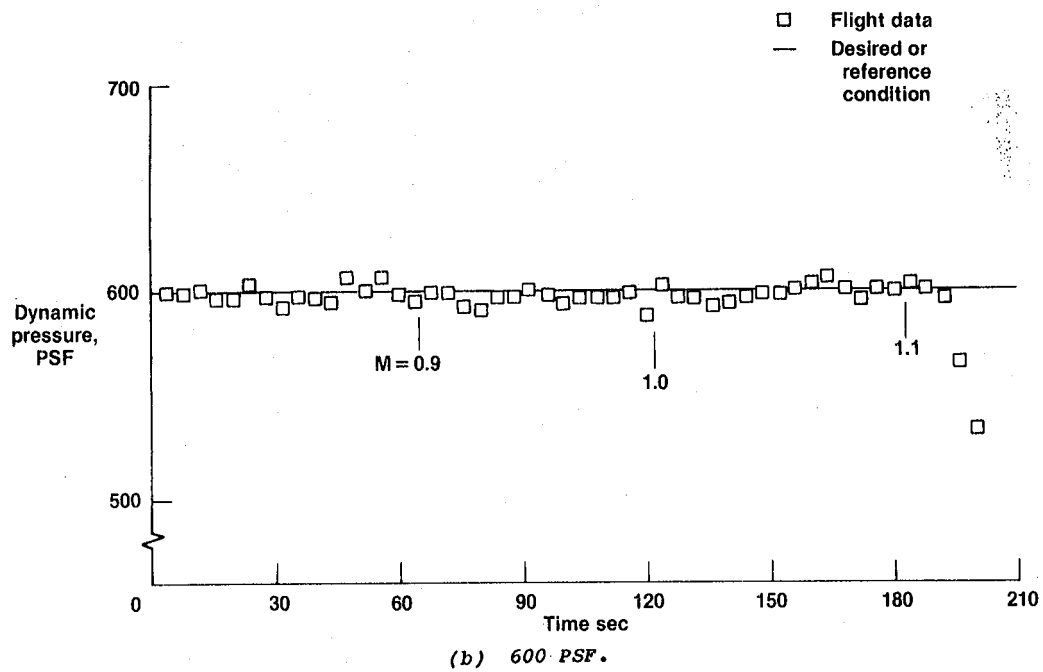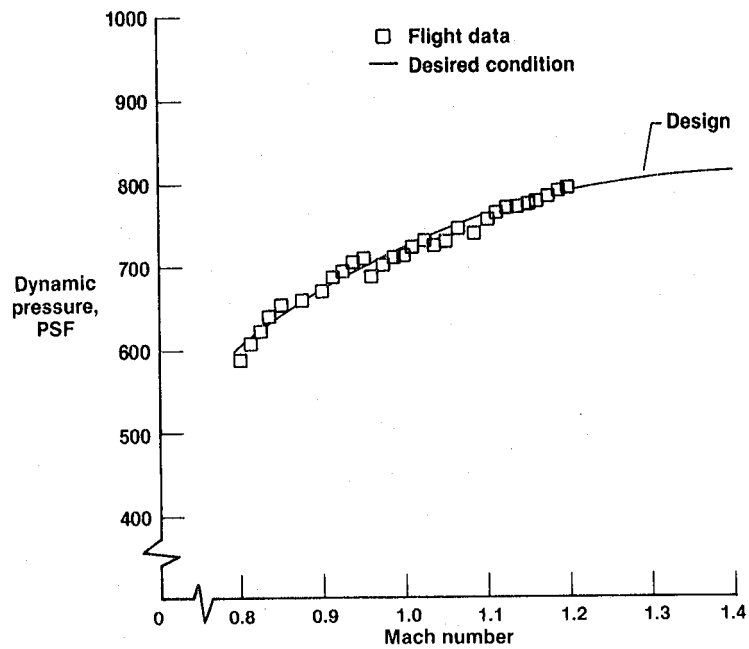
Fig. 13 Shuttle launch trajectory.

15
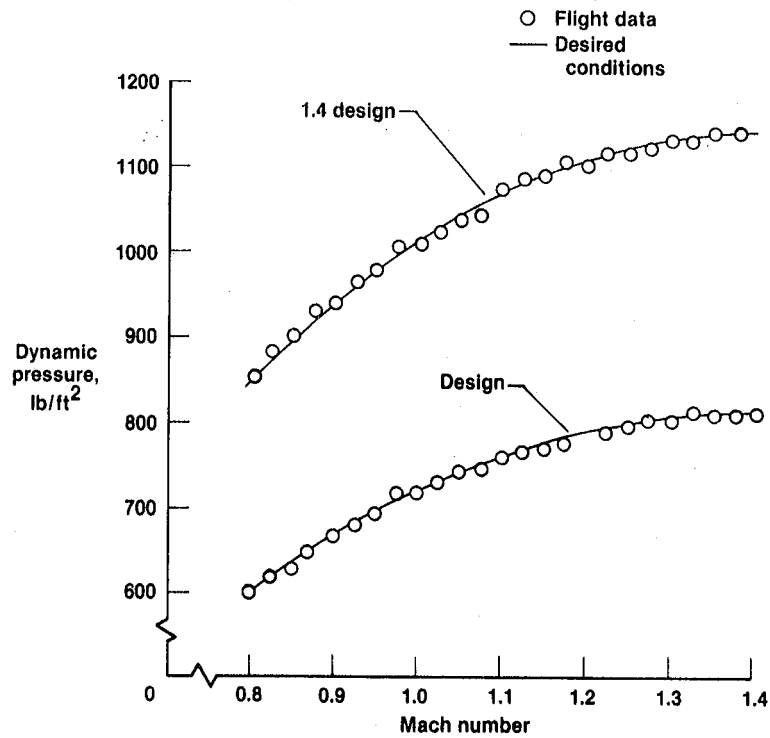
(b) Obtained with trajectory guidance.

Fig. 13 Concluded.
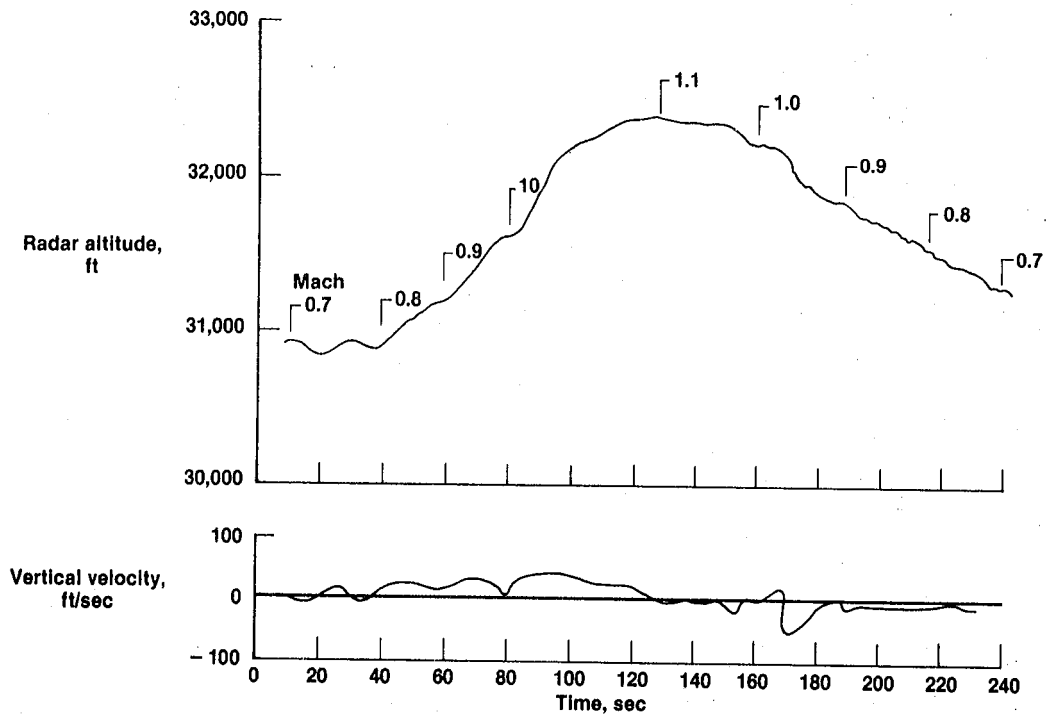
(a) No trajectory guidance.

Fig. 14 Level acceleration–deceleration maneuver.

16
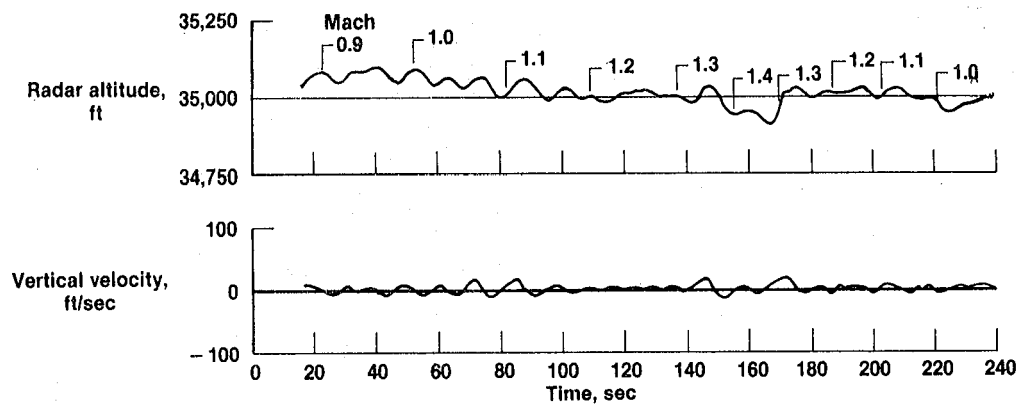
(b) With trajectory guidance.
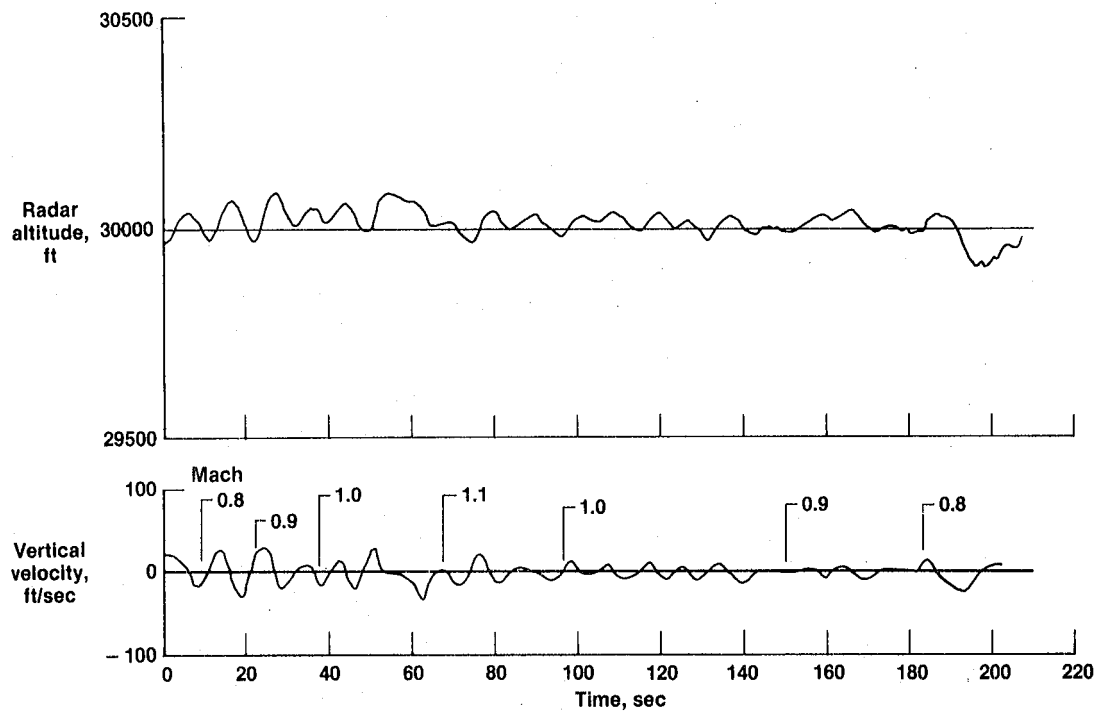
(c) No trajectory guidance with ground controller guidance.

Fig. 14 Concluded.

17
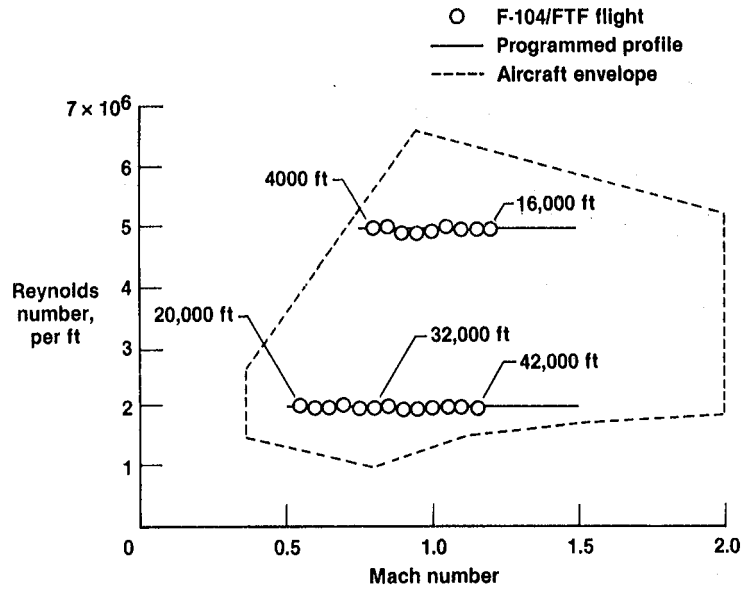
Fig. 15 Typical Reynolds number versus Mach
number trajectories flown with trajectory
guidance.
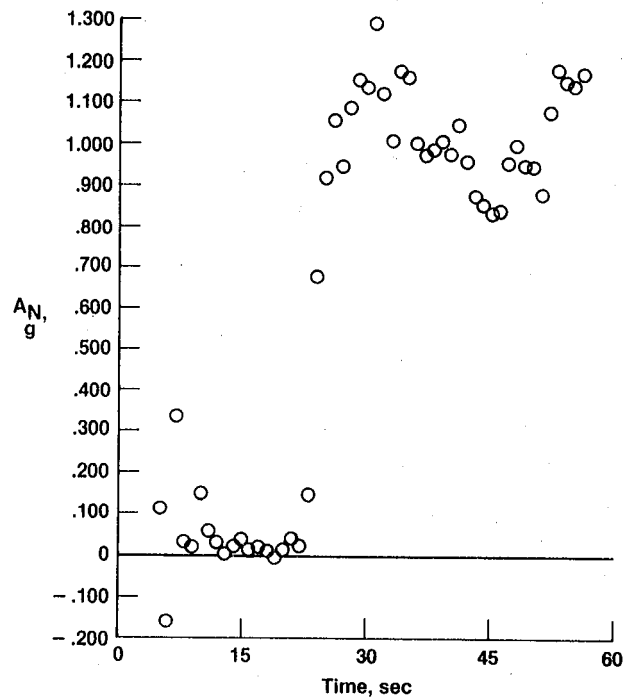
Fig. 16 Limited demonstration of zero-g
maneuver flown with trajectory guidance.
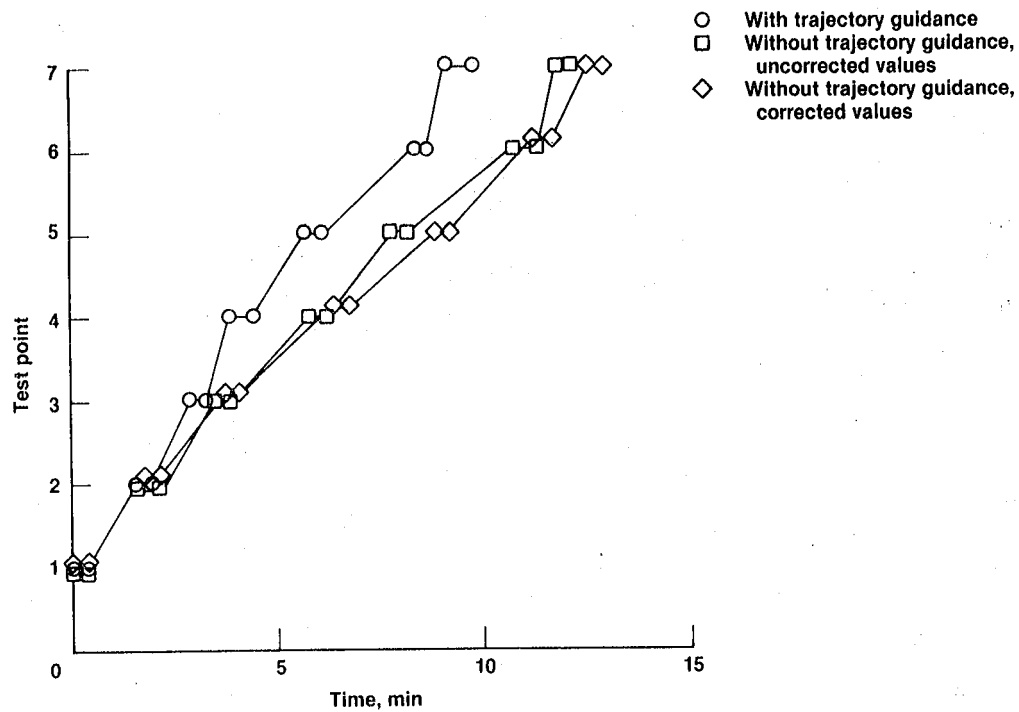
Fig. 17 Time required to complete a specific flight card for constant altitude/Mach number conditions, flown with and without trajectory guidance.
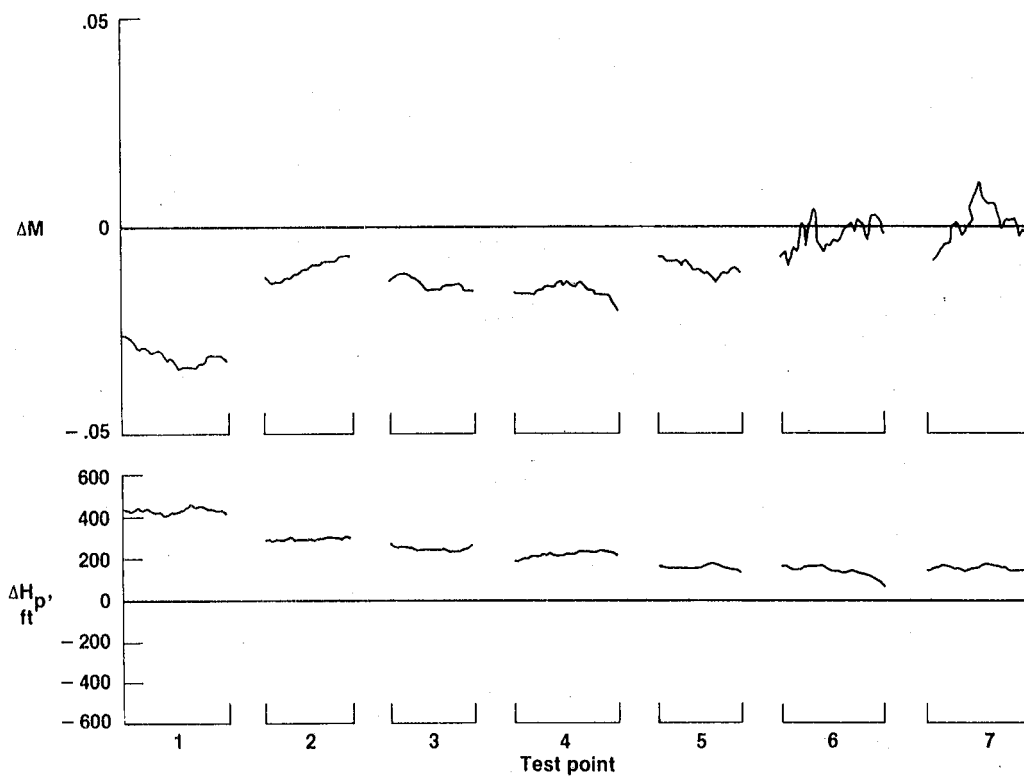
(a) Series of points flown without trajectory guidance and with corrected values.

Fig. 18 Mach number and pressure altitude error for constant altitude/Mach maneuvers flown with and without trajectory guidance.
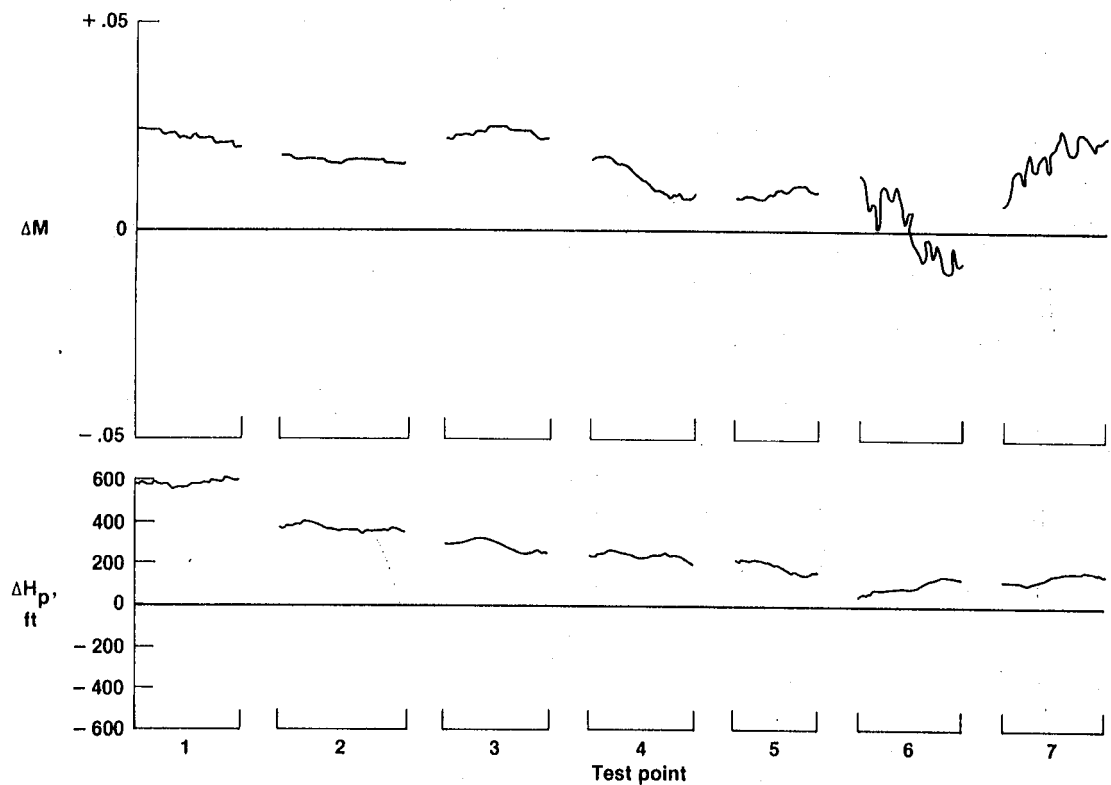
(b) Series of points flown without trajectory guidance and with uncorrected values.

(c) Series of points flown with trajectory guidance.

Fig. 18 Concluded.

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15. Supplementary Notes

This paper was presented at the AIAA 2nd Flight Test Conference, Las Vegas, Nevada, November 16-18, 1983.

16. Abstract

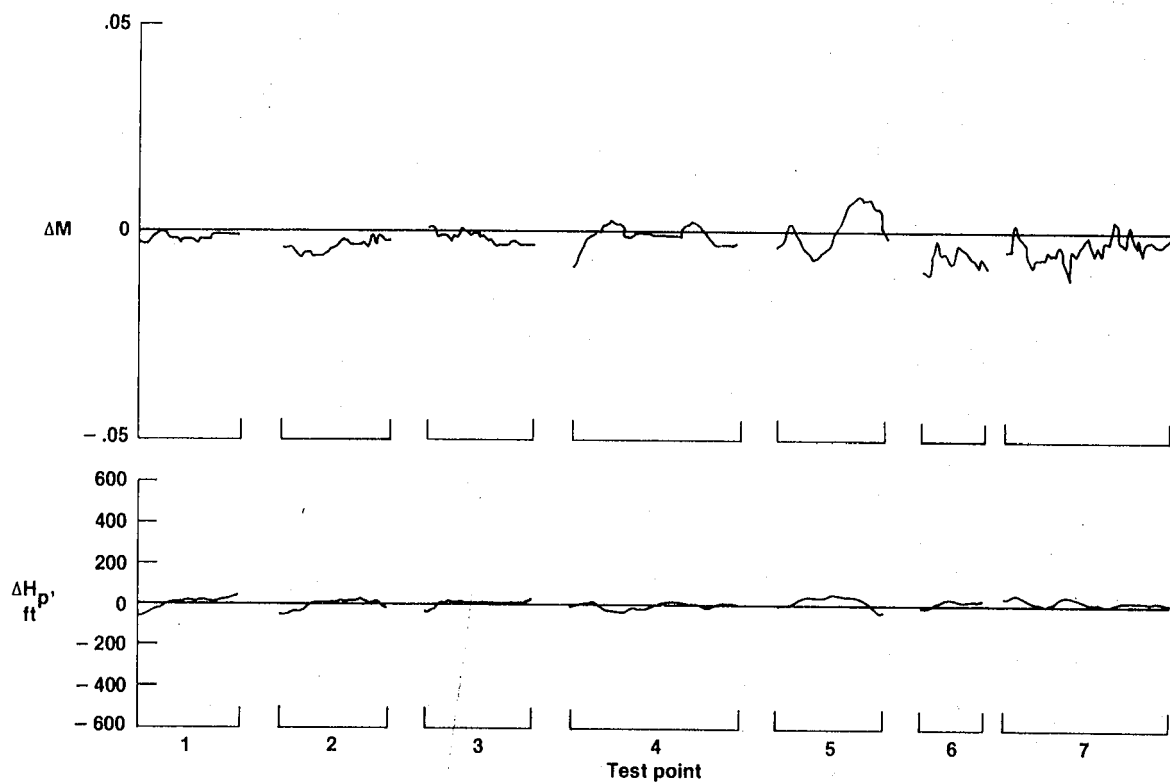The Dryden Flight Research Facility of the NASA Ames Research Center has developed a pilot trajectory guidance system that increases the accuracy of flight-test data and decreases the time required to achieve and maintain desired test conditions. The system usually presented to the pilot computed differences between reference or desired and actual flight state conditions. The pilot then used a cockpit display as an aid to acquire and hold desired test conditions. This paper discusses various flight-test maneuvers and the quality of data obtained using the guidance system. Some comparisons are made between the quality of maneuvers obtained with and without the system. Limited details of the guidance system and algorithms used are included. In general, the guidance system improved the quality of the maneuvers and trajectories flown, as well as allowing trajectories to be flown that would not have been possible without the system. This system has moved from the developmental stage to full operational use in various Dryden research and test aircraft.

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