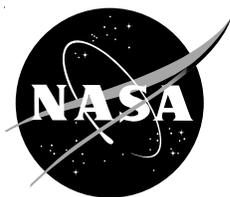NASA/TM-1999-206578

Simulator Evaluation of Simplified Propulsion-Only Emergency Flight Control Systems on Transport Aircraft

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June 1999

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ABSTRACT

With the advent of digital engine control systems, considering the use of engine thrust for emergency flight control has become feasible. Many incidents have occurred in which engine thrust supplemented or replaced normal aircraft flight controls. In most of these cases, a crash resulted, and more than 1100 lives have been lost. The NASA Dryden Flight Research Center has developed a propulsion-controlled aircraft (PCA) system in which computer-controlled engine thrust provides emergency flight control capability. Using this PCA system, an F-15 and an MD-11 airplane have been landed without using any flight controls. In simulations, C-17, B-757, and B-747 PCA systems have also been evaluated successfully. These tests used full-authority digital electronic control systems on the engines. Developing simpler PCA systems that can operate without full-authority engine control, thus allowing PCA technology to be installed on less capable airplanes or at lower cost, is also a desire. Studies have examined simplified "PCA Ultralite" concepts in which thrust control is provided using an autothrottle system supplemented by manual differential throttle control. Some of these concepts have worked well. The PCA Ultralite study results are presented for simulation tests of MD-11, B-757, C-17, and B-747-400 aircraft.

NOMENCLATURE

ACFS   advanced concepts flight simulator

AGL   above ground level (radar altitude)

CGZ   vertical center of gravity, vertical distance from fuselage centerline, in.

EPR   engine pressure ratio

FADEC   full-authority digital engine control

FDS   flight deck simulator

FPA   flightpath angle, deg

ILS   instrument landing system

PCA   propulsion-controlled aircraft

PLA   power lever angle, deg

S   Laplace operator

TOC   thrust-only control (manual throttle manipulation)

V/S   vertical speed

INTRODUCTION

In the past 25 years, a minimum of 10 aircraft, including B-747, L-1011, DC-10, B-52, and C-5A aircraft, have experienced major flight control system failures that caused the aircrew to resort to using engine thrust for emergency flight control. In most cases, these desperate attempts resulted in a crash; the B-747, DC-10, and C-5A crashes claimed more than 1100 lives (ref. 1).

With the advent of digital engine control systems, considering the use of engine thrust for emergency flight control became feasible. To investigate this possibility, NASA, the U. S. Department of Defense, industry, and university researchers have been conducting flight, ground simulator, and analytical studies. One objective is to determine the degree of control available with manual manipulation of engine throttles for various classes of airplanes. Tests in simulation have included B-720, B-747, B-727, MD-11, MD-90, C-402, C-17, F-18, and F-15 airplanes. Tests in flight have included B-747, B-777, MD-11, T-39, Lear 24, F-18, F-15, T-38, and PA-30 airplanes.

The pilots have used differential throttle control to generate sideslip, which through the dihedral effect results in roll. Symmetric throttle inputs were also used to control flightpath. These tests have shown sufficient control capability for all tested airplanes to maintain gross control; both flightpath and track angle can be controlled to within 2° to 4°. These studies have also shown that, for all airplanes tested, making a safe runway landing is exceedingly difficult using manual thrust-only control (TOC) (ref. 2). This difficulty is caused by slow engine response, weak control moments, and difficulty in controlling the oscillatory phugoid and dutch roll modes. This sluggish response can result in airplane-pilot coupling oscillations as the ground is approached and pilot gains increase.

To provide safe landing capability, NASA Dryden Flight Research Center (Edwards, California) engineers and pilots have conceived and developed a system called propulsion-controlled aircraft (PCA) that uses only augmented engine thrust for flight control. A PCA system uses pilot flightpath inputs, airplane sensor feedback parameters, and control law computations to generate appropriate engine thrust commands to provide emergency flight control. The concept was first evaluated on a piloted simulation of the B-720 aircraft (ref. 3). This augmented system was evaluated in simulation and flight tests on the F-15 airplane (ref. 1) and the MD-11 transport (ref. 4), including actual landings using PCA control. The PCA technology was also successfully evaluated using a simulation of a conceptual megatransport (ref. 5).

Another major PCA simulation study has been conducted at the NASA Ames Research Center (Moffett Field, California) using the advanced concepts flight simulator (ACFS) (ref. 6), an airplane that closely resembles a B-757 twin-jet airplane. More recently, a PCA system was designed and tested on the B-747-400 simulator at NASA Ames. PCA approaches and landings have been flown by more than 40 government, industry, and airline pilots (ref. 7). A PCA system for the C-17 military transport has also been designed and tested in simulators. The system worked adequately for all flap positions (ref. 8).

In the above tests, the assumption was made that each engine could be individually controlled over its entire thrust range with a full-authority digital control system. On older aircraft not equipped with digital engine controls and data buses, a simpler system called "PCA Ultralite" can be used. In this system, longitudinal control can be obtained by collectively driving all throttles using the autothrottle servomotor rather than relying on digital thrust commands. Lateral control is provided by manual throttle manipulation. Recently, the PCA Ultralite system was tested on B-720, MD-11, C-17, and B-747-400 simulators and the B-757 ACFS. Some preliminary results from the B-747-400 and MD-11 simulations have been published (ref. 9). Results showed a probability of a survivable landing, but considerable practice was needed and some pilots encountered a strong airplane-pilot coupling oscillation tendency. To aid the pilot in the manual lateral control task, cockpit display cues have also been investigated. The flight director has been used for lateral cueing on the NASA Dryden B-720 simulator and the ACFS at NASA Ames.

This paper provides a brief review of the principles of throttles-only flight control and the baseline PCA system. The PCA Ultralite concept is explained, and PCA Ultralite results without flight director

cueing are presented for high-fidelity simulation tests of MD-11, C-17, B-757, and B-747-400 aircraft. The PCA Ultralite results with flight director cueing are presented for the ACFS.

PRINCIPLES OF THROTTLES-ONLY FLIGHT CONTROL

The principles of throttles-only flight control are presented in the following subsections. These principles are separated into two categories: lateral-directional control and longitudinal control.

Lateral-Directional Control

Differential thrust generates sideslip, which, through the dihedral effect, results in the airplane rolling to a desired bank angle. Subsequently, this rolling results in a turn and change in aircraft heading. Figure 1 shows an open-loop throttle step response for the MD-11 airplane at a speed of 220 kn. The 10° throttle split results in approximately 20,000 lbf of differential thrust and a roll rate averaging 1.5 deg/sec. Note that the engine pressure ratio (EPR) lags the throttle by approximately 1 sec, and the roll rate lags the yaw rate. A lightly damped dutch-roll mode is excited by this throttle step. Full differential thrust for the MD-11 airplane at a speed of 150 kn yields a peak roll rate of approximately 8 deg/sec.

Longitudinal Control

Pitch control caused by throttle changes is more complex than lateral-directional control. Several effects occur. These effects include flightpath angle (*FPA*) changes caused by speed stability, pitching moment resulting from thrust-line offset, *FPA* changes caused by the vertical component of thrust, and the long-period longitudinal phugoid oscillation. These effects can be observed in flight data from a thrust step increase of the wing engines on the MD-11 airplane (fig. 2, ref. 4) as explained in the sections that follow. The thrust increase of approximately 0.1 EPR is approximately 10,000 lbf for each engine.

Pitching Moment Caused by Thrust-Line Offset

If the engine-thrust line does not pass through the vertical center of gravity (*CGZ*), a pitching moment introduced by thrust change occurs. For many transport aircraft, the thrust line is below the *CGZ*; increasing thrust results in a desirable noseup pitching moment. Having the thrust line below the *CGZ* is the desirable geometry for throttles-only control because a thrust change immediately starts the nose in the same direction needed for the long-term *FPA* change. The effect is more a function of change in thrust than of change in speed and occurs near the time of the thrust increase. Figure 2 shows an increase in angle of attack of approximately 0.25° immediately after the thrust increase, thus increasing lift and resulting in a climb. The increase in angle of attack has the long-term effect of reducing the trim speed of the airplane.

Flightpath Angle Change Caused by Speed Stability

Most airplanes exhibit positive speed stability. Over a short period of time (approximately 10 sec), a thrust increase will cause a speed increase, which will cause a lift increase. With the lift being greater than the weight, the *FPA* will increase, causing the airplane to climb. Figure 2 also shows this effect,
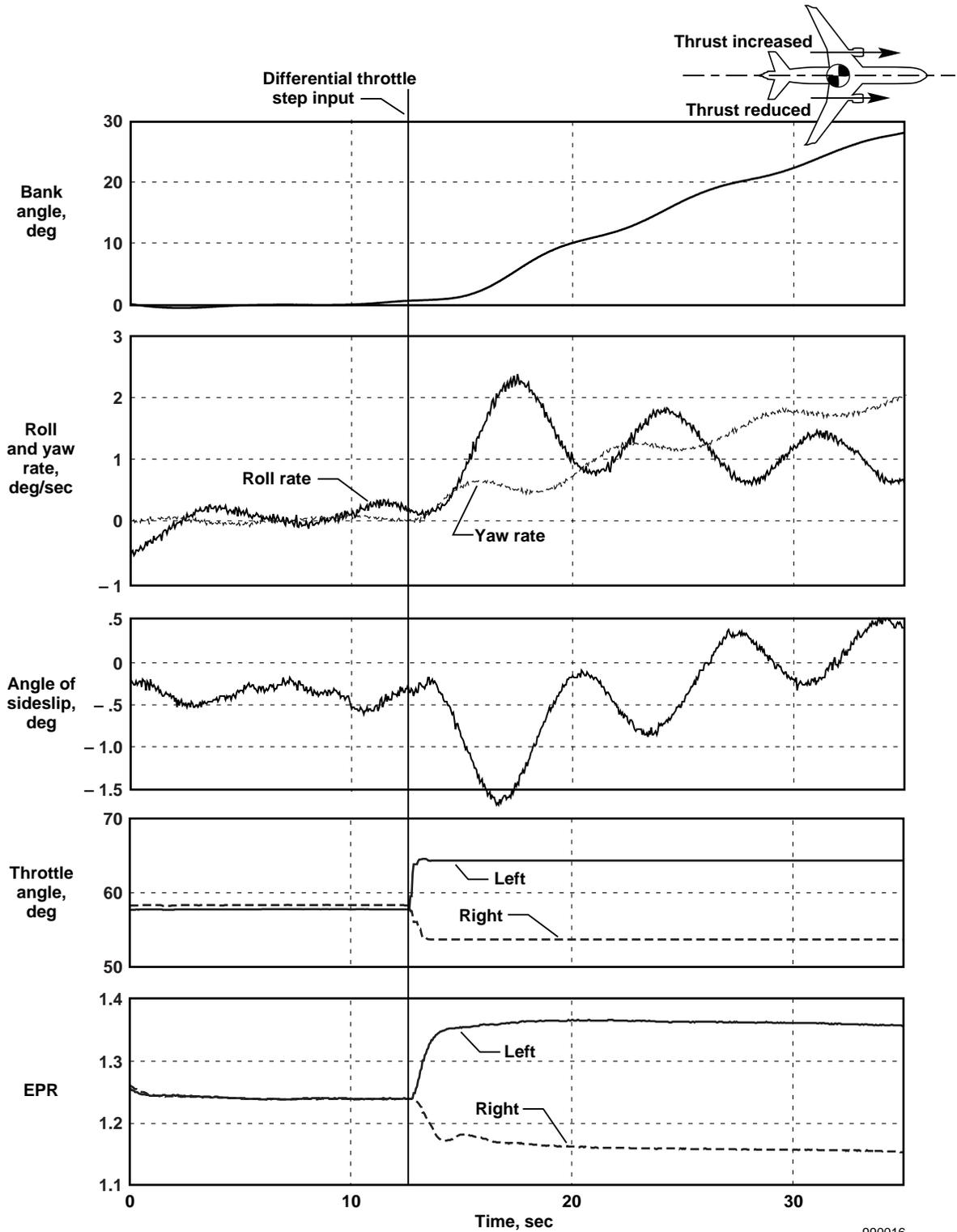
Figure 1. MD-11 lateral response to open-loop differential throttle step; conditions include an airspeed of 220 kn, an altitude of 15,000 ft, flaps up, gear down, center engine idle, and no control surface movement.
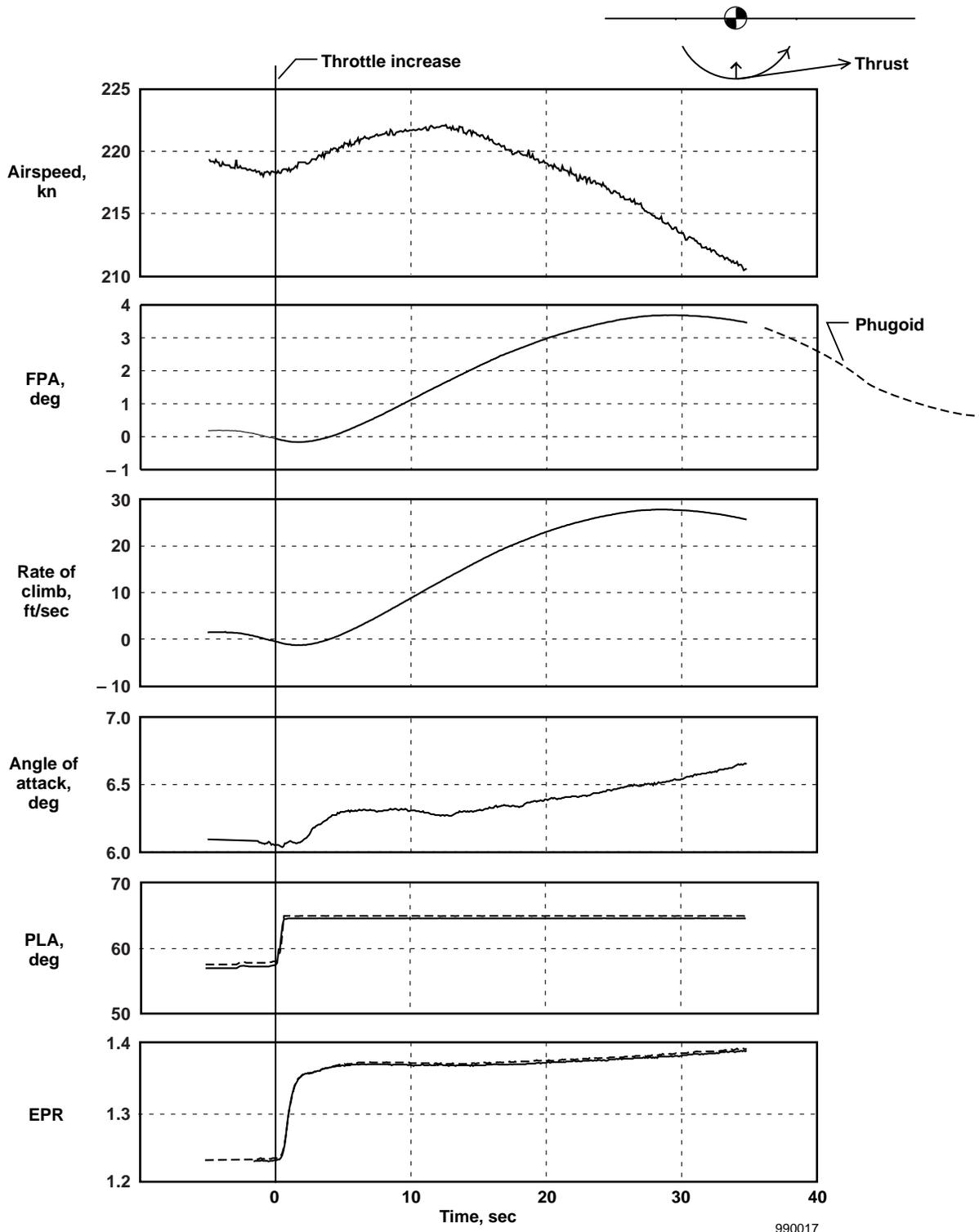
Figure 2. Longitudinal response to open-loop step throttle increase from MD-11 flight data; conditions include center engine idle, gear down, flaps up, an altitude of 15,000 ft, and no control surface movement.

where the speed increase adds to the climb. Unless disturbed, this effect will be oscillatory, as indicated by the dashed line in figure 2 and discussed in the Phugoid subsection.

Flightpath Angle Change Caused by the Vertical Component of Thrust

If the thrust line is inclined to the flightpath, as is usually the case, an increase in thrust will increase the vertical component of thrust, which will cause a vertical acceleration and a resulting increase in *FPA*. For a given aircraft configuration, this effect will increase as angle of attack increases. This effect is usually small but does contribute to the climb rate shown in figure 2. The 20,000-lbf increase in thrust provides an approximately 2000-lbf added component of thrust in the vertical direction.

Phugoid

The phugoid is the longitudinal long-period oscillatory mode of an airplane. Phugoid is a motion in which kinetic and potential energy (speed and altitude) are traded, and may be excited by a pitch, thrust, or velocity change. Such oscillations have a period of approximately 1 min. Phugoid may or may not naturally damp. Properly sized and timed throttle inputs can be used to damp unwanted phugoid oscillations; these techniques are discussed in reference 2. Figure 2 shows the phugoid mode is excited by the thrust increase, with *FPA* and rate of climb decreasing after 30 sec.

Relative Position of Inlet to Exhaust Nozzle

The relative positions of the inlet and the exhaust nozzle of each engine can be an important effect for throttles-only flight control. The ram drag vector acts through the centroid of the inlet area, along the flightpath, and thus rotates with respect to the airplane geometric reference system as angle of attack and angle of sideslip change. The gross thrust vector usually acts along the engine nozzle centerline, and thus maintains its relationship to the airplane geometric reference system. Reference 1 discusses this effect. For fighter airplanes with highly integrated propulsion systems, these effects may be quite significant; whereas for transport airplanes with podded engines, these inlet-nozzle effects are small.

Thrust Vectoring and Powered Lift

If the thrust of the engines is deflected by a vectoring device or wing flaps, large effects on the airplane can occur. These effects can be pitching, rolling, or yawing moments and changes in lift and drag. The effects are very specific to the aircraft configuration. The C-17 transport is the only powered lift airplane studied at NASA Dryden; the blown flap effects are discussed later.

Trim Speed Control

When the normal flight control surfaces of an airplane are locked at a given position, the trim airspeed of most airplanes is only slightly affected by engine thrust. In general, the speed will need to be reduced to an acceptable landing speed, which requires developing noseup pitching moments. Methods for developing moments include moving the center of gravity aft, lowering flaps, increasing the thrust of low-mounted engines, decreasing the thrust of high-mounted engines, or burning off or dumping fuel. Extending the landing gear often decreases trim speed because it requires an increase in engine thrust to compensate for the added drag, which increases angle of attack and reduces trim airspeed.

Speed Effects on Propulsive Control Power

The propulsive forces (differential thrust for lateral control and collective thrust for flightpath control) tend to be relatively independent of speed. Conversely, the aerodynamic restoring forces that resist the propulsive forces are proportional to the dynamic pressure, which is a function of speed squared. This relationship results in the propulsive control power being approximately inversely proportional to the square of the speed, as discussed in reference 1. This result is fortuitous in that the propulsive forces are relatively greater at landing speeds than at higher cruise or climb speeds, where control precision is not so critical.

Control Surface Float With Hydraulics Turned Off

With the hydraulic system failed, a control surface will float to the zero hinge-moment condition. For the rudders and elevators of many aircraft, this position is essentially the trail position, and ailerons usually float trailing edge up. Rudder float would have a negligible effect on trim speed but would somewhat reduce directional stability, possibly increasing the yaw caused by differential thrust, which could be a favorable effect. Elevators are usually trimmed to near zero force; hence, elevator float would have a small effect. The stabilizer is usually moved with a jackscrew actuator, which, in the case of hydraulic failure, remains fixed because of friction.

Modeling of surface positions with control system failures is usually based on analysis rather than test data, and may be subject to substantial errors. Some simulations do not include a floating surface capability.

FLIGHT CONTROL USING ONLY ENGINE THRUST

If normal aircraft flight control surfaces fail for some reason, engine thrust can be used to provide gross control of *FPA* and bank angle. The following subsections discuss manual throttle manipulation by the pilot, a closed-loop PCA system, and the PCA Ultralite system.

Manual Throttles-Only Control

With the flight control surfaces inactive, a flight crew can use the throttles for flight control. Differential throttle inputs cause yaw, which through the dihedral effect causes roll. With proper differential thrust control, bank angle can be modulated and used to control heading to within 2° to 4°. Collective thrust provides pitch control. Thrust increase will increase, and thrust decrease will decrease, the *FPA*. With proper collective throttle control, pitch can be controlled to within 2° to 4°. Unfortunately, manual throttle control is not adequate for achieving a safe landing. Difficulties arise from the small moments, the slow response, and the difficulty in damping the phugoid and dutch-roll oscillations.

Figure 3 shows a time history of an experienced B-747 test pilot trying the first landing using only manual throttle control. The phugoid oscillation was persistent and lateral control was poor. The simulation ended with an impact 1 mi short of the runway at a sink rate of more than 3000 ft/min. In other cases, too much thrust was added as the ground was approached, and the airplane ballooned into a position where landing was not possible and another approach would be required. This situation was typical of pilots without manual TOC experience. With more practice, approaches improved but safe

landings were still quite unlikely. Reference 1 discusses the principles of thrust-only flight control. Reference 2 discusses techniques for improved manual TOC.

Propulsion-Controlled Aircraft Baseline System and Prior Results

The full PCA baseline system, using computer-controlled thrust, has been shown to provide emergency flight control capability suitable for safe landings. In this PCA system, pilot commands are compared with the measured feedback parameters, and thrust commands are computed and sent to the engines. Simulations of PCA systems on the F-15, C-17, MD-11, B-720, B-747, and B-757 aircraft and a conceptual megatransport have all shown the ability to make safe landings. Flight tests of PCA systems have been conducted on the F-15 and MD-11 airplanes; safe landings were made without movement of the flight control surfaces.

Figure 4 shows a schematic diagram of a typical PCA system. Existing autopilot controllers in the cockpit, as is typical, are used for pilot inputs. The *FPA* thumbwheel is used to make pitch inputs, and the heading/track knob is turned to command a turn to a specified angle.

Control laws reside in the existing flight control computer. In the lateral axis, pilot track command is compared with the measured track. Feedback parameters such as yaw rate provide dutch-roll damping, and differential throttle commands are computed (fig. 5(a)). In the pitch axis, pilot *FP*A thumbwheel commands are compared with the measured *FPA*. Pitch rate and velocity feedback are provided for phugoid damping, and collective thrust commands are computed (fig. 5(b)). The track and flightpath commands are combined and thrust commands are issued over the existing data bus to the full-authority digital engine control (FADEC) system. Only software changes are required to implement the MD-11 PCA system. More details of the MD-11 PCA system have previously been published (ref. 4).

The B-747 and B-757 PCA systems were developed and installed on high-fidelity simulators at NASA Ames, and the C-17 PCA system was installed on the C-17 hardware simulator at The Boeing Company in Long Beach, California.[*] The systems are similar in concept to the MD-11 PCA system and also use existing cockpit autopilot controls for pilot commands.

The C-17 airplane uses externally blown flaps to reduce approach speeds. Unlike the other airplanes tested, collective thrust directly affects lift, and differential thrust directly affects roll and yaw.

In all of the PCA systems, track is typically controlled to within 1.0° of command, and *FPA* is typically controlled to within ±0.5° of command. Control was adequate for safe landings without using any of the normal flight controls; landings were made on the MD-11 airplane and on the B-757, C-17, and B-747 simulators.

The PCA control response on all airplanes tested was sluggish, and some pilot experience was required for consistent safe landings. To reduce the need for pilot training, an instrument landing system–coupled (ILS-coupled) capability for approach and landing was provided for the MD-11, B-747, C-17, and B-757 airplanes. This capability provided a thrust-only automatic landing capability that greatly reduced pilot workload and improved landing performance. The ILS-coupled PCA landings were made on the MD-11 airplane and C-17, B-757, and B-747-400 simulations by pilots with little or no PCA experience.

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[*]Formerly McDonnell Douglas Aerospace, which merged with The Boeing Company during these tests.
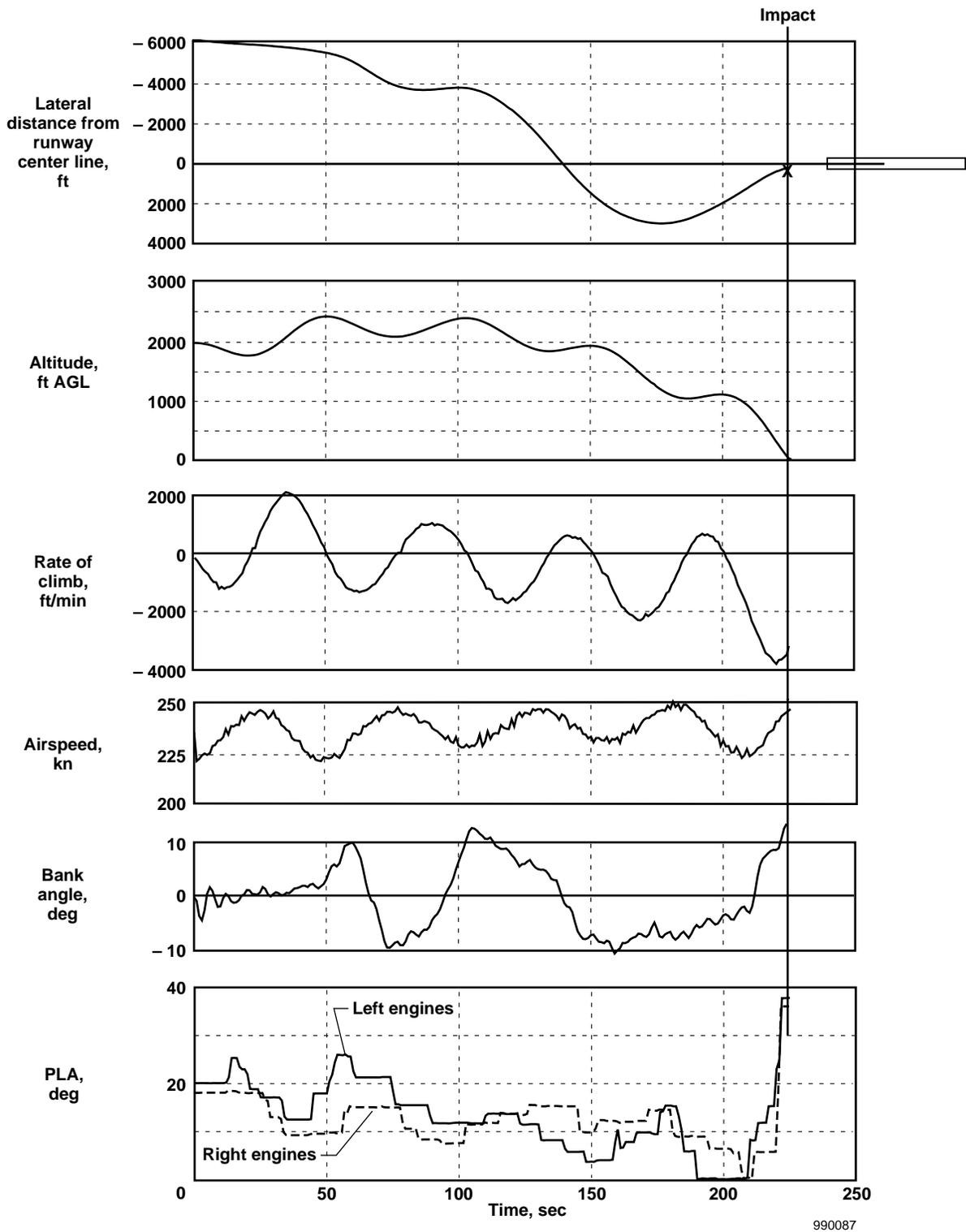
Figure 3. B-747-400 simulator manual throttles-only control approach with all flight controls failed; conditions include an experienced B-747 test pilot, gear down, and flaps up.

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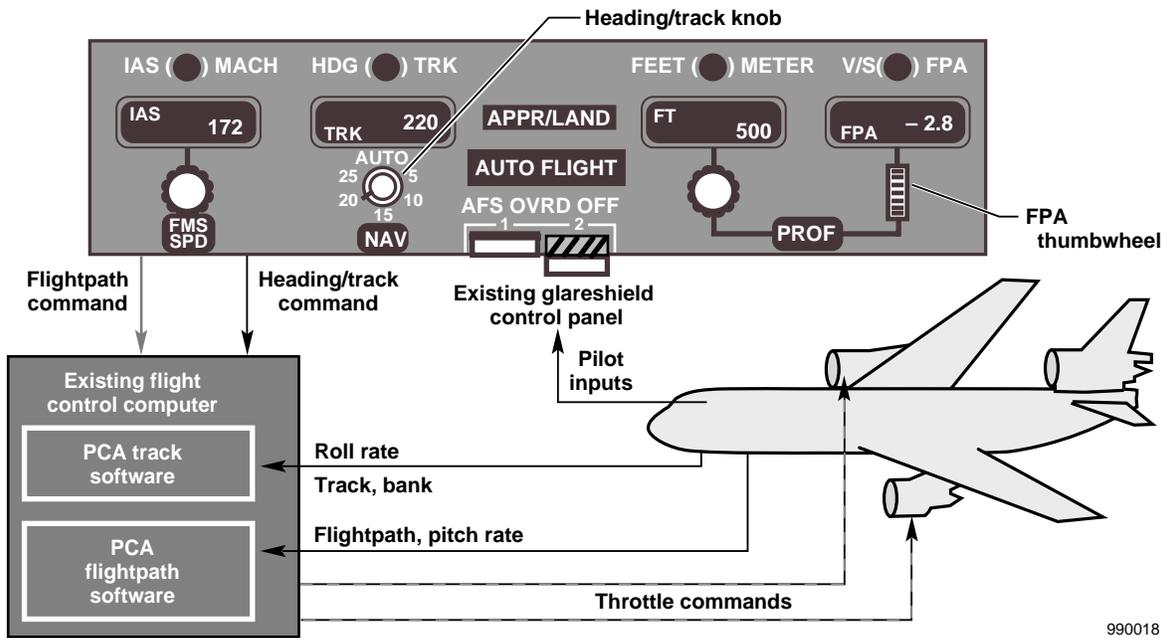
Figure 4. MD-11 PCA system concept diagram.
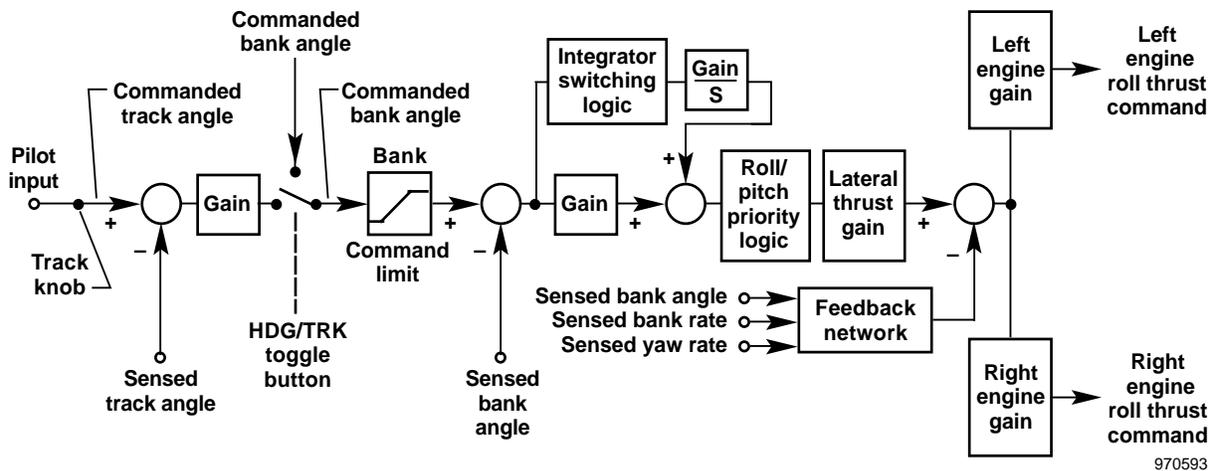
(a) PCA lateral control system (track and bank angle modes).

Figure 5. MD-11 PCA system (simplified block diagram).

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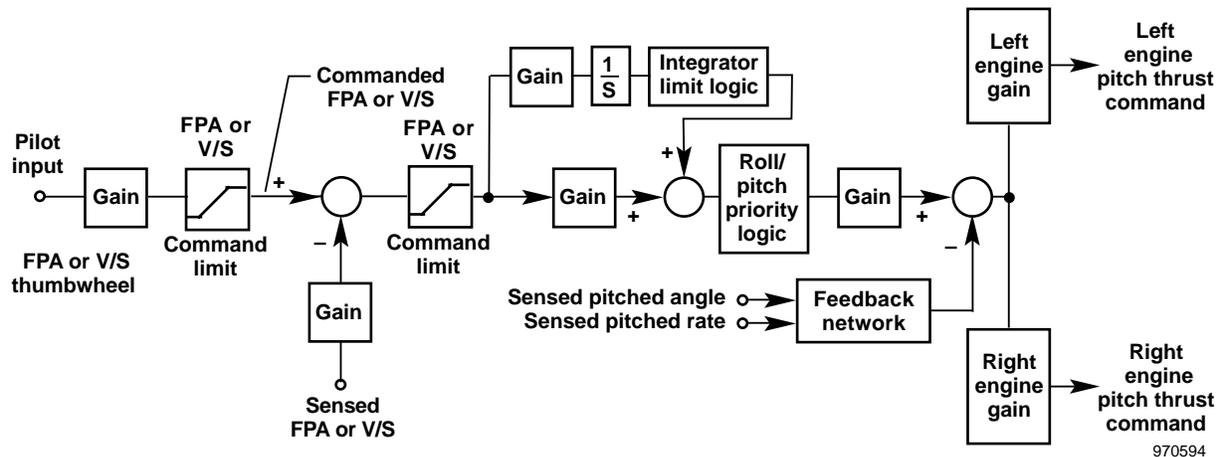
(b) PCA longitudinal control system (center engine modes not shown).

Figure 5. Concluded.

"PCA Ultralite" Control System

The PCA baseline system uses full-authority engine control implemented through digital commands sent to the digital engine controllers. In a typical transport airplane, this system would require the presence of a FADEC system and software changes to the FADEC to accept full-authority commands from the PCA software. For easier implementation, having a system that could function without FADEC would be desirable.

Approaches that allow emergency flight control using normally available systems such as autothrottles have been studied at NASA Dryden and NASA Ames. One such simplified PCA system, called PCA Ultralite (fig. 6), could provide somewhat reduced but possibly still adequate emergency control capability, depending on the characteristics of the airplane and the availability of approach and landing guidance.

"PCA Ultralite" Longitudinal Control

The PCA Ultralite system has control laws for longitudinal control similar to the baseline system, except that the longitudinal commands use the existing autothrottle system to symmetrically drive the throttles instead of being issued over a digital data bus to the FADECs. In the case where the pilot has made a differential thrust input, throttle stagger is maintained by the autothrottle system as long as the idle or maximum thrust stops are not encountered. As with the PCA baseline system, *FPA* is commanded by a pilot using the *FPA* thumbwheel or by coupling to an ILS glide slope or other landing aid.

"PCA Ultralite" Lateral Control

Lateral control in PCA Ultralite is provided by manual throttle manipulation. Although full lateral and pitch manual control is not practical, if the pitch control problem is solved, providing lateral control adequate for lineup and landing may be possible for the crew. This concept was tested on the MD-11,

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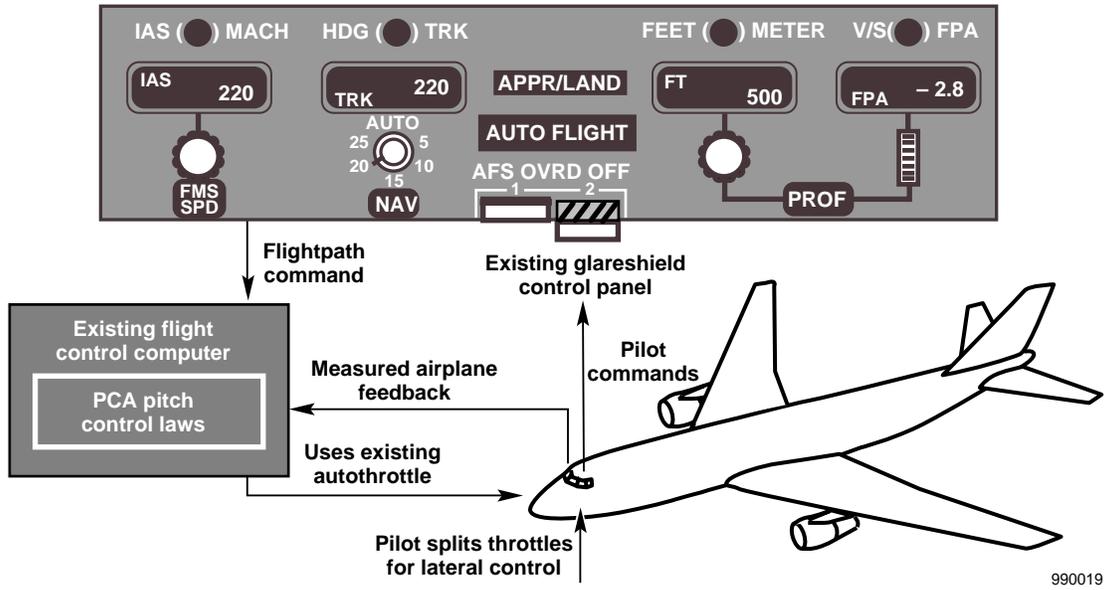
Figure 6. Schematic view of the PCA Ultralite concept.

C-17, and B-747-400 simulations. One issue was expected to be the difficulty in making differential throttle inputs to throttles that were constantly being moved by the pitch control logic. Another issue was whether the pilot would be able to adequately control the runway lineup and keep the dutch roll adequately damped. To assist the pilot in lateral control, cockpit display cues were also investigated.

AIRPLANE AND SIMULATOR DESCRIPTION AND PROPULSION-CONTROLLED AIRCRAFT RESULTS

The following subsections describe the MD-11, B-747, C-17, and B-757 aircraft and their respective simulators used in the testing of the PCA Ultralite system. Results from PCA Ultralite simulator tests are also discussed for each airplane. Table 1 shows a list of evaluation pilots.

Table 1. Evaluation pilots for PCA Ultralite tests.

Pilot	Title	Experience
A	PCA Project Pilot	Extensive transport and TOC
B	NASA Research Pilot	Extensive fighter
C	NASA Research Pilot	Extensive transport
D	NASA Chief Engineer	Private pilot, extensive TOC
E	FAA Test Pilot	Extensive business jet

MD-11 Transport Airplane

The MD-11 airplane (McDonnell Douglas Aerospace, Long Beach, California) is a large, long-range, wide-body transport. The airplane is powered by three 60,000-lbf thrust-class engines, two on underwing pylons and one mounted in the base of the vertical tail (fig. 7). The wing engines are 26 ft, 10 in. out from the centerline. Maximum takeoff gross weight is 630,000 lb. Three independent hydraulic systems power conventional ailerons, rudders, elevators, flaps, and the horizontal stabilizer. The MD-11 braking system is provided with hydraulic accumulators so that limited braking is available even with all hydraulics failed.

The MD-11 flight deck simulator (FDS) is a high-fidelity, fixed-base simulation of the MD-11 airplane that contains much actual flight hardware. The simulator incorporates six-degree-of-freedom equations of motion, complete aerodynamic and propulsion models, analytical models of the MD-11 systems, and a projected video out-the-window display system. The MD-11 airplane simulated and flown was powered by PW4460 engines (Pratt & Whitney, East Hartford, Connecticut) with 60,000 lbf thrust each. These engines were controlled by dual-channel FADEC systems that accepted trim commands from the flight management system computer. Thrust as a function of EPR for the PW4460 engine is a nonlinear function, with approximately 97,000 lbf/EPR at low thrust and approximately 57,000 lbf/EPR near maximum thrust, as shown in reference 4. The FDS had limited control surface float models for hydraulics-off operation, but the models did not agree well with flight data. A ground effect model was validated with flight data for a 28° flap setting, but was not validated for lower flaps settings.
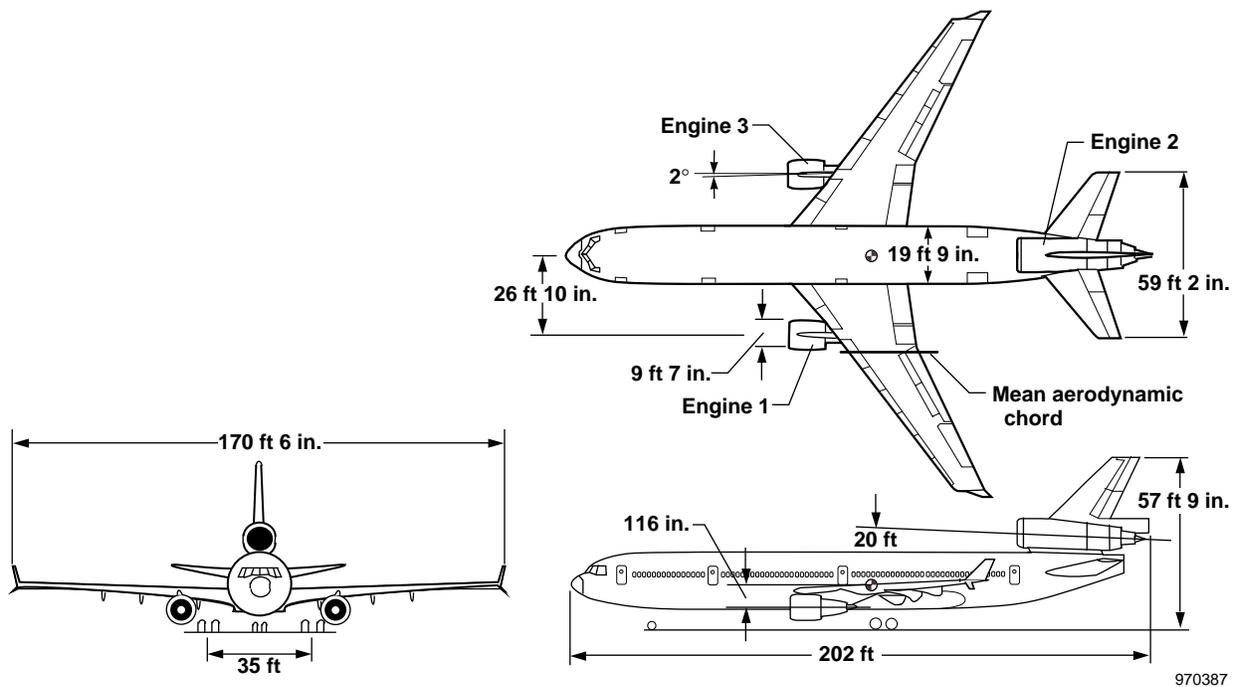
Figure 7. Three-view drawing of the MD-11 airplane.

MD-11 Full Propulsion-Controlled Aircraft System Flight Test Results

The full MD-11 PCA system that was flight-tested used the FADEC engine controllers and provided good pitch and lateral control. Figure 8 shows a time history of an MD-11 PCA landing. Pilot A used the autopilot control knobs to command the PCA system for the landing at Edwards Air Force Base (California). The center engine was not actively controlled and was set near idle thrust. Weather at the time was characterized by light winds and light turbulence with occasional thermal upsets. The pilot made small track changes to maintain runway lineup and set the flightpath command at –1.9° for the initial part of the approach. Airspeed was 175 kn. At 200 ft above ground level (AGL), the pilot shallowed the flightpath to –1° and at 100 ft to –0.5°. The airplane touched down smoothly on the runway center line at a 4 ft/sec sink rate 3000 ft from the threshold with no flight control inputs from either pilot.

Note the upset from a thermal updraft that caused the airplane bank angle to increase to 8° at 100 ft AGL; the PCA track mode corrected this upset without any pilot input. The airplane was stopped using reverse thrust and light braking but no flight control inputs. The pilot rated the pitch control as excellent and the lateral control as adequate on this landing. Note the engine thrust changes during the approach. The majority of the thrust changes are differential to maintain the pilot's commanded ground track, although two large, collective thrust pulses occurred as the flightpath was shallowed near the ground. After landing, differential braking and thrust reversing was used, but no flight control or nosewheel steering was used.

Three other landings of the MD-11 airplane and 40 low approaches were flown with PCA control during the flight program. A demonstration evaluation of the MD-11 PCA system was made by 16 pilots, including pilots A and C. Each pilot flew TOC, engaged PCA and flew with the autopilot knobs, and then made a low approach to 100 ft AGL, either using the autopilot knobs or coupling to the ILS (ref. 4).

MD-11 "PCA Ultralite" System

In September 1997, a brief PCA Ultralite simulation test was performed. A total of 32 approaches was flown by two pilots. Most of the tests were flown by pilot D, a low-time general aviation pilot with extensive TOC and PCA experience, mostly in simulators. For this initial PCA Ultralite concept evaluation, the MD-11 FDS full PCA simulation was slightly modified. The output of the pitch logic of the PCA control laws was fed to a simulation of the autothrottle servomotor system. Because of hardware and implementation constraints in the FDS, actually driving the autothrottle servosystem was not practical, so the autothrottle output provided a throttle position that was converted into a thrust input to the equations of motion without moving the throttles. Figure 9 shows the PCA Ultralite longitudinal control system for the MD-11 simulation.

The PCA lateral control law output was not used; differential thrust was a function of throttle position only. Because the autothrottle system was not moving the throttles, no constraint existed to keep the pilot from making inadvertent collective throttle inputs in addition to the differential throttle inputs. An ILS display was available, but no ILS-coupled capability existed in this FDS implementation of the PCA Ultralite system, so the copilot typically made pitch control inputs with the FPA thumbwheel while the pilot used differential throttle control for runway lineup. The effect for the pilot was therefore similar to a glide slope–coupled approach.

The hydraulic systems were left on during these tests, but the dampers were turned off and the flight controls were not used. The PCA Ultralite system was first evaluated in up-and-away flight and was
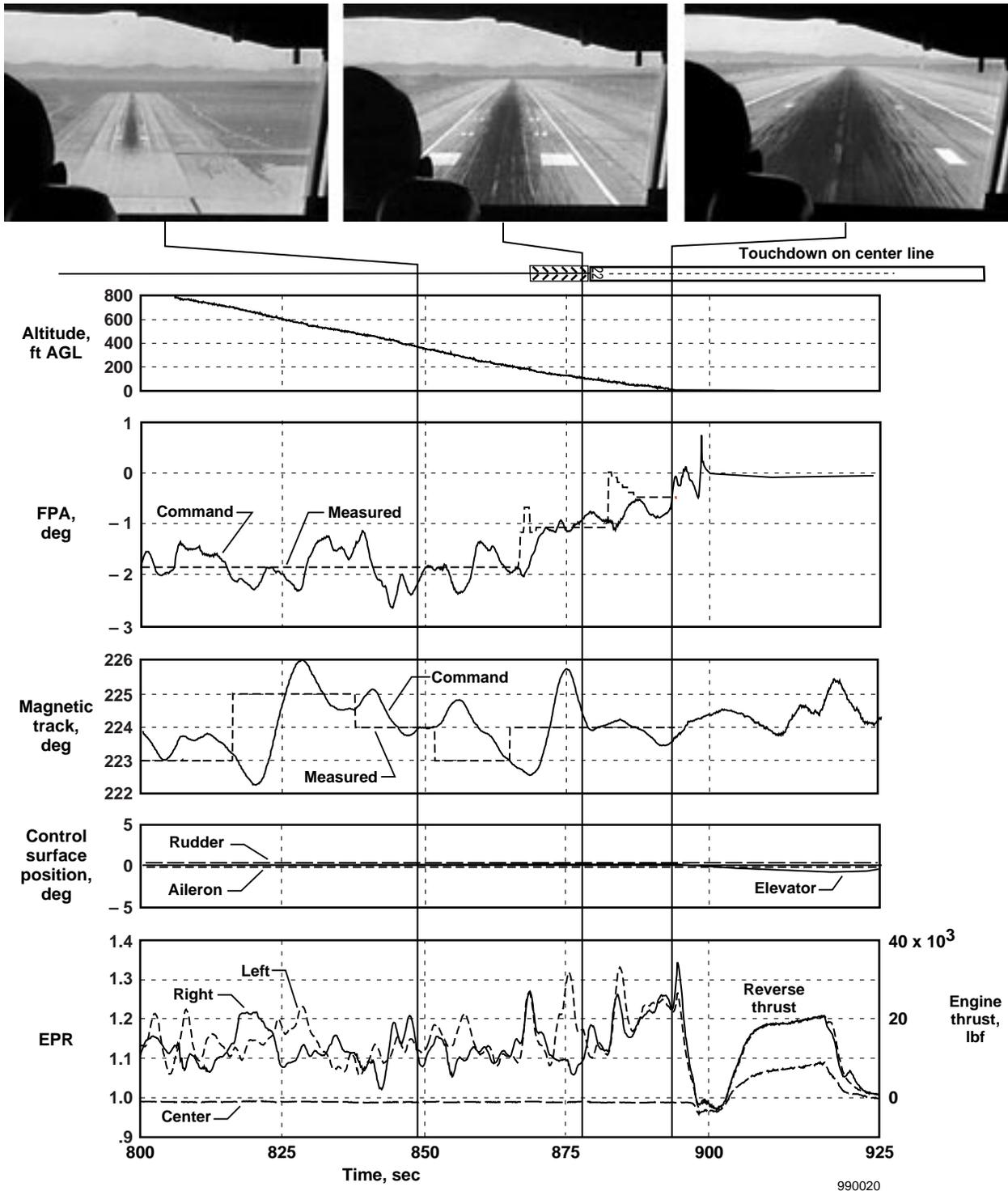
Figure 8. MD-11 PCA landing from flight test data; flown by pilot A under conditions including light turbulence, flaps 28°, an airspeed of 175 kn, and center engine idle.
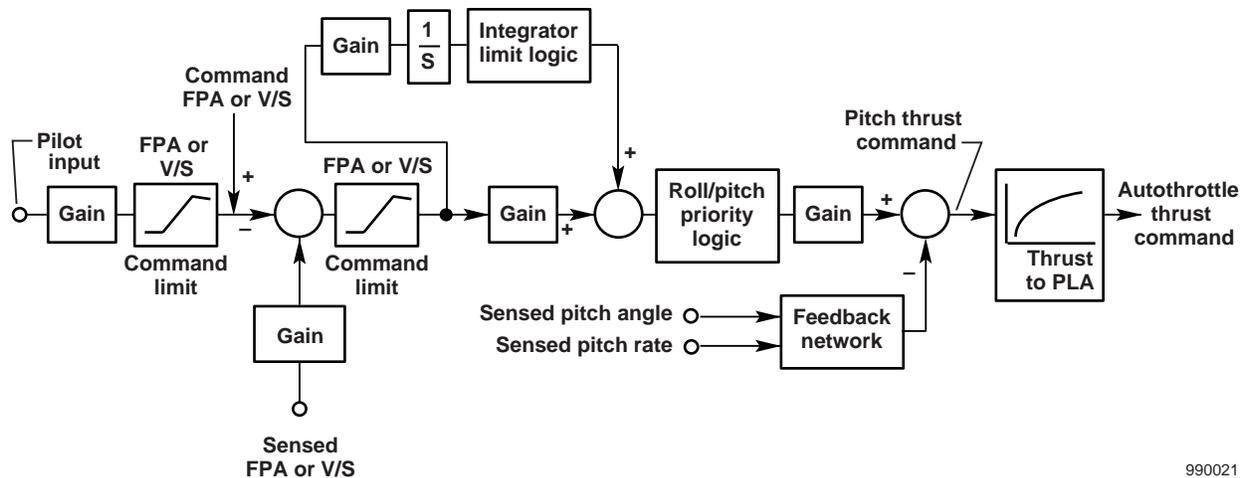
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Figure 9. MD-11 FDS PCA Ultralite pitch control (simplified block diagram).

found to be satisfactory. Pitch control was very good, similar to the full PCA system. For nonprecision lateral tasks, the manual differential throttle control was adequate.

Simulation landing approaches were flown to runway 24R at Los Angeles International Airport (California). Initial approaches were flown from a long, 20-mi straight-in approach. The initial lineup was not found to be an issue; problems occurred in the latter part of the approaches. For the results shown, approaches were initiated 9 mi out at an altitude of 2300 ft AGL, an airspeed of 180 kn, approximately 0.25 mi left of the localizer, somewhat below the glide slope, and a heading of 280°. Thus, an approximate 30° right turn needed to be made and a descent needed to be started. This relatively close-in initiation was used to allow many approaches to be flown and to concentrate attention on the difficult part of the approach. In an actual emergency approach, a longer straight-in approach would be recommended.

In each run, the simulation was operated with the center engine at idle in order to provide a favorable pitching moment with engine thrust. Pitch control was attained through the autothrottle with the copilot dialing in the selected *FPA*. Lateral control was achieved either by the pilot symmetrically splitting both wing engine throttles or by controlling a single throttle. Gross weight was approximately 398,000 lb. Flaps ranged from 0° to 35°, and rudder offsets were input from 0° to 6° for some approaches. Although "go-arounds" were possible (and easy to accomplish), the pilot's task was to complete the landing; go-arounds were not allowed until a landing attempt had been made.

The pitch control attained through the simulated autothrottle was very good, but lateral control using manual throttle manipulation was sluggish and quite difficult. A strong tendency existed to oscillate back and forth across the localizer on approach, even after some practice. In spite of these difficulties, most of the landings were on or nearly on the runway, and many would likely have been survivable. Go-arounds were possible at altitudes as low as 100 ft AGL for approaches that were not well–lined up. Rudder offsets to a maximum of 4° could be accommodated with flaps down, and to a maximum of 3° with flaps up.

Figure 10 shows a typical time history of a PCA Ultralite approach and landing. This approach, flown in smooth air with 15° flaps, was the first PCA Ultralite approach by pilot D. The copilot, who initially
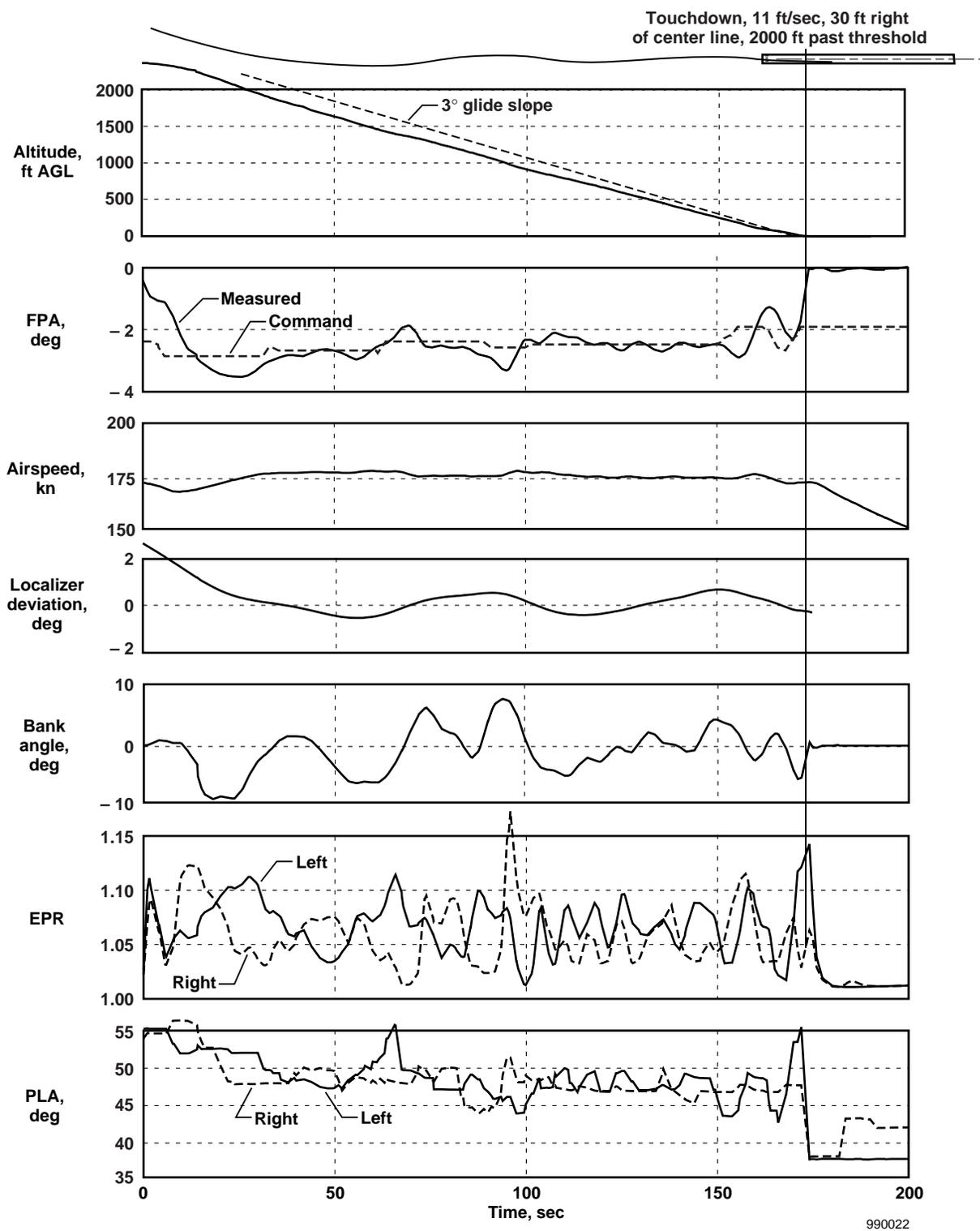
Figure 10. MD-11 FDS PCA Ultralite approach and landing (first PCA Ultralite landing of pilot D); conditions include 15° flaps, no flight control movement, center engine idle, and smooth air.

selected a –2.8° flightpath, was instructed to fly approximately one dot (approximately 0.35°) below the 3° ILS glide slope. Throughout the approach, small flightpath command changes were made. The autothrottle system generally maintained flightpath within 0.5° of command. For lateral control, pilot D used manual differential control of both throttles. Small differential thrust inputs of approximately ±0.05 EPR were needed. The pilot was able to stay relatively close to the localizer, not deviating more than 1°, but oscillated back and forth across the localizer because of the difficulty in anticipating aircraft response. Localizer oscillation was a recurring problem in most tests and is reflected in bank angle. Bank angle was quite often more than 5°, nearing 10° at certain points. Even when the aircraft was near the runway, bank angle drifted to slightly more than 5°, which is dangerously close to the 7° landing limit. At approximately 160 sec, the flightpath was shallowed for landing. Touchdown occurred 30 ft right of the runway center line at a high sink rate of 11 ft/sec and a high bank angle of approximately 5°. The approach was lined up well with the runway, but was not very stabilized. This landing would have been safe but was not far from being a crash.

Figure 11 shows a time history of the seventh PCA Ultralite approach and landing by pilot D. This landing was probably the best made in the MD-11 FDS test series. This approach was flown in smooth air with 28° flaps. The copilot initially selected a –3° flightpath, and the autothrottle system provided good pitch control, generally within 0.5° of command. The pilot primarily used the left throttle for lateral control. When on the localizer, good lateral control was achieved, the localizer deviation was small, and bank angles were less than 3°. Only small thrust inputs of approximately ±0.05 EPR were used. Beginning at 100 sec, the flightpath was shallowed for landing. Touchdown occurred 1000 ft past the threshold at a sink rate of 8 ft/sec and slightly left of the runway center line. The approach was well-stabilized, and only small thrust changes were needed to stay on the localizer.

Figure 12 shows an unsuccessful PCA Ultralite landing by pilot D. The approach was flown in smooth air with 28° flaps. A –3° flightpath angle was initially selected by the copilot. For lateral control, the pilot used only the left throttle, setting the right throttle at midrange. Large thrust changes of approximately ±0.1 EPR occurred for both engines. The pilot was able to stay close to the localizer until 100 sec, approximately 2.7 mi from the runway. At approximately 75 sec, the pilot became distracted and made a long differential throttle input lasting approximately 15 sec. This throttle change resulted in a deviation to the left of the localizer. The pilot made large throttle inputs in an effort to line back up on the localizer, but sluggish response hampered these efforts and large, oscillating bank angles resulted. The large and frequent bank angle changes coupled into the pitch axis and caused the sink rate to also oscillate. Touchdown occurred approximately 300 ft off of the left runway edge at a high sink rate of 17 ft/sec and an 8° bank angle. This landing possibly would have been a crash with a wingtip strike and a sink rate high enough to seriously damage the landing gear. The FDS indicated a bounce, so a go-around was attempted by increasing the *FPA* thumbwheel command to 2° and was successful. The deviation that occurred because of the distraction at 100 sec shows the very high pilot workload and the need for 100-percent concentration on the lineup task. After the deviation had occurred, correcting the runway lineup in time for a successful landing was not possible for the pilot.

If an airplane is somehow damaged, it may not be laterally trimmed. Such an "out-of-trim" situation was simulated by inputting a fixed rudder offset. For example, in the Sioux City accident discussed in reference 1, damage to the center engine nacelle induced a yaw equivalent to approximately 2° of rudder deflection. The PCA Ultralite approaches were flown with rudder offsets to a maximum of 6°.

Figure 13 shows a typical 3° rudder offset approach and landing flown by pilot D. The approach was in smooth air with 28° of flaps. The rudder offset was initiated at approximately 5 sec. Approximately 8°

Figure 11. MD-11 FDS PCA Ultralite approach and landing flown by pilot D under conditions including an 180-kn approach speed, 28° flaps, smooth air, center engine idle, and no flight control movement.

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Figure 12. MD-11 FDS PCA Ultralite approach and go-around flown by pilot D under conditions including 28° flaps, a 180-kn approach speed, smooth air, center engine idle, and no flight control movement.
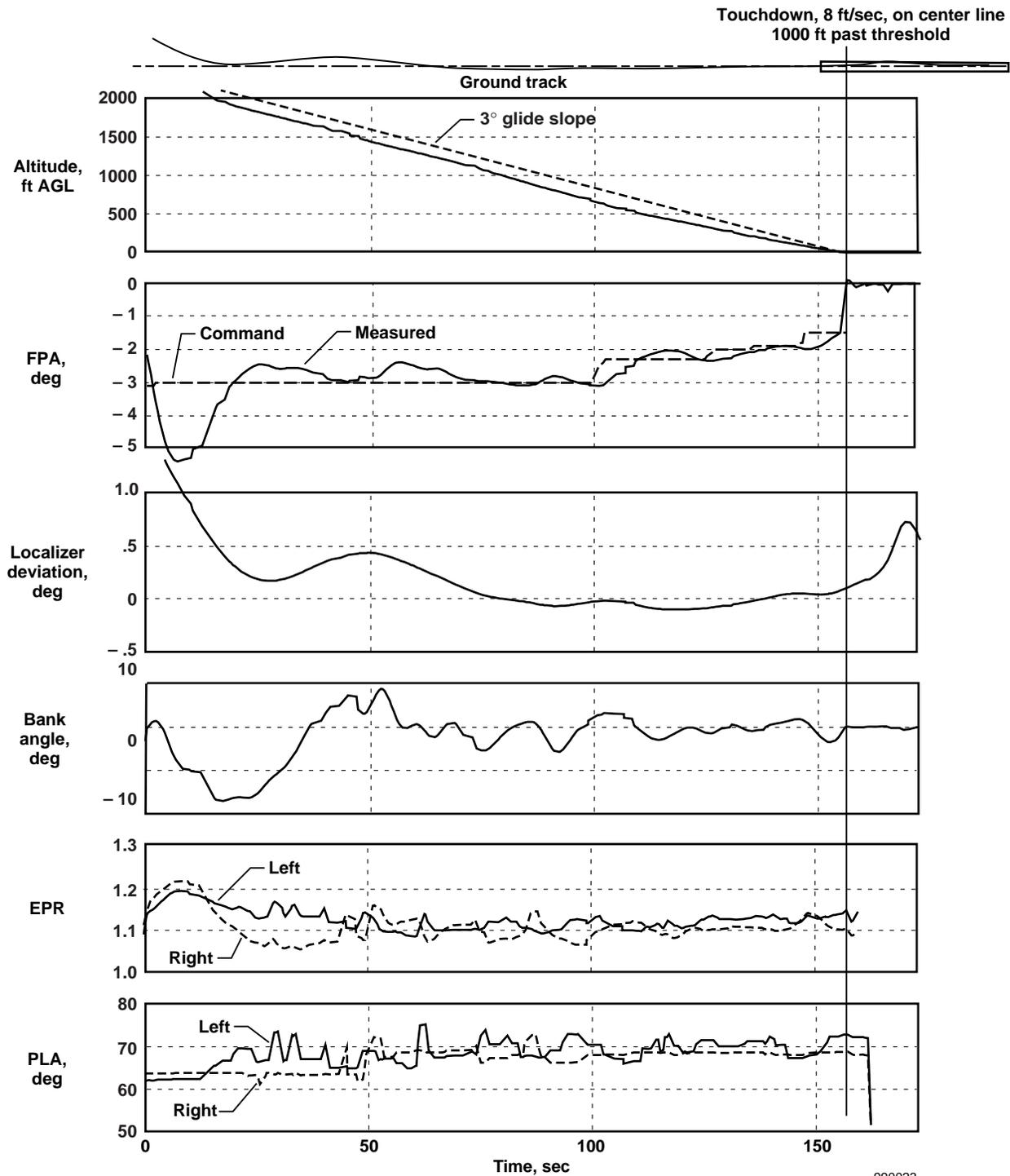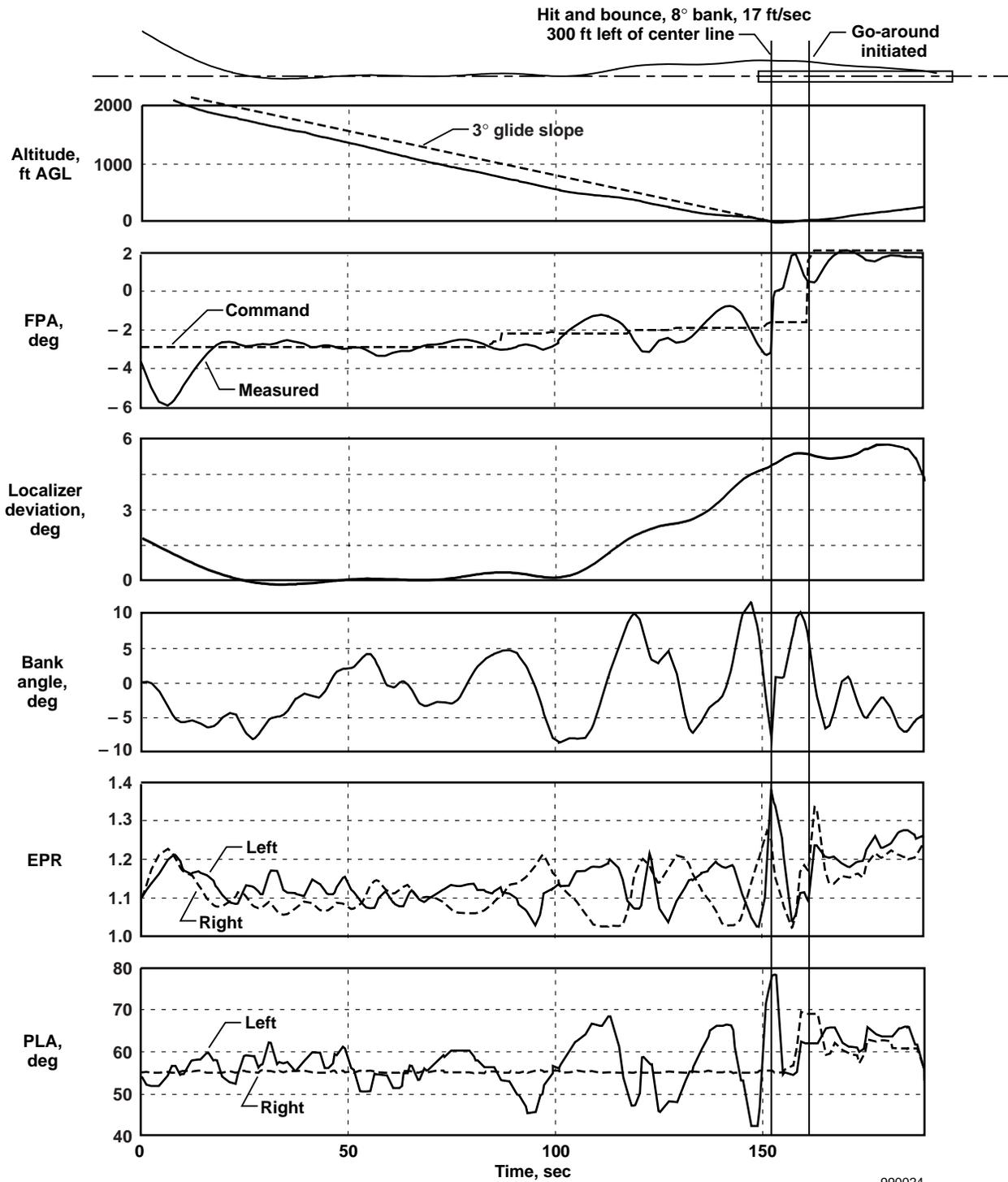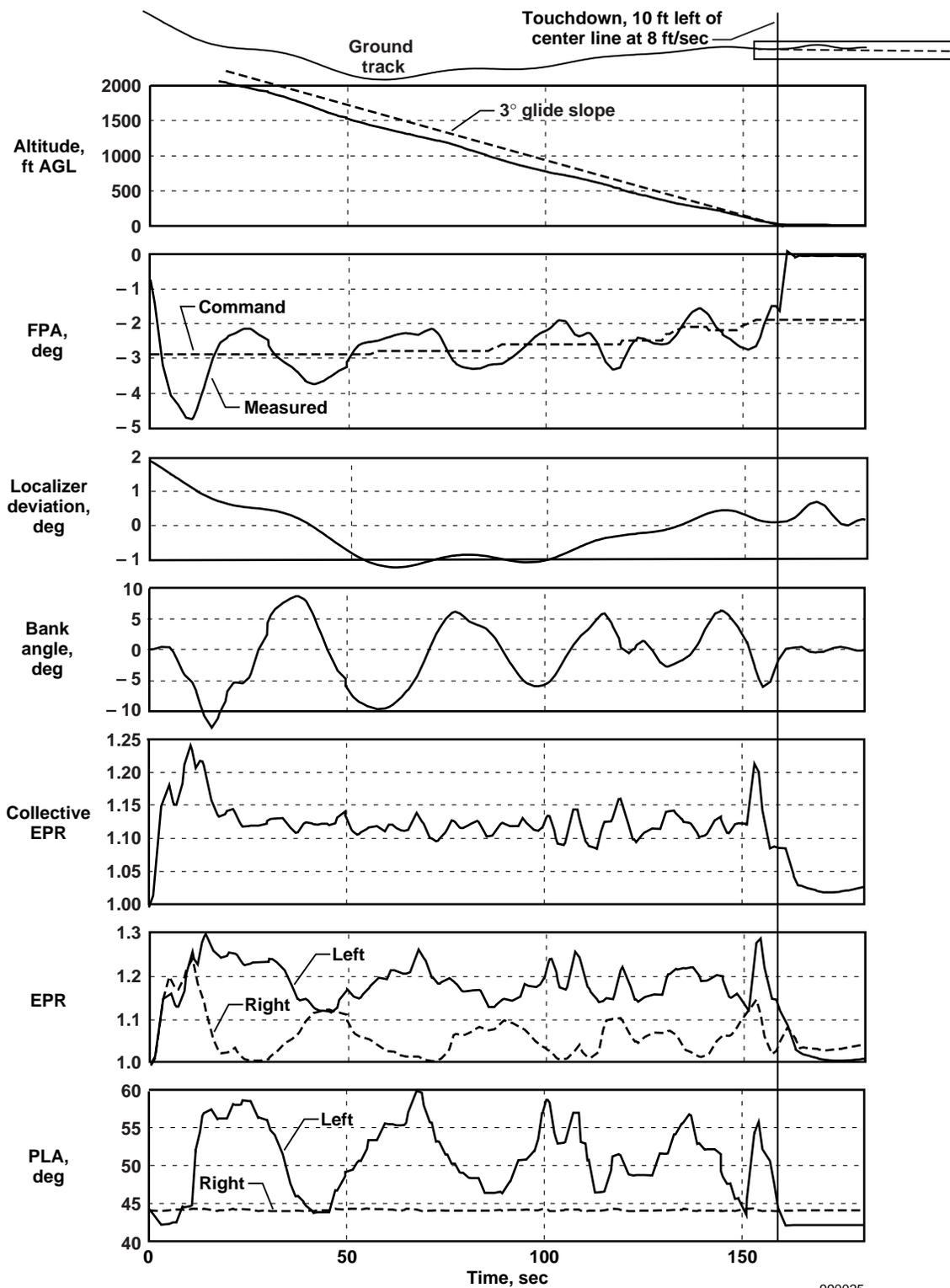
Figure 13. MD-11 FDS PCA Ultralite approach and landing flown by pilot D under conditions including a 3° rudder offset, a 180-kn approach speed, flaps 28°, smooth air, center engine idle, and no flight control movement.

of power lever angle difference between the two throttles was needed to correct for the rudder offset. Because of this offset, grasping both throttles at the same time was difficult; therefore, one technique used was to move only the left throttle. With the use of only one throttle, large throttle changes had to be made to achieve a specific amount of differential thrust. The pilot, making larger-than-normal throttle changes with only one throttle, had trouble staying on the localizer. Large bank angles and a bank oscillation resulted, as in the previous examples, but the pilot was able to gradually reduce the size of the oscillations. The copilot initially selected a –2.9° *FPA*. With the rudder offset and larger differential throttle inputs, the PCA pitch control system had difficulty staying with the commanded *FPA* and tended to oscillate ±1° above and below the commanded angle. Touchdown was made 10 ft left of the runway center line at a sink rate of 8 ft/sec and a bank angle of 3°. Although the pilot had some trouble controlling the airplane on initial approach, the pilot was slowly—but not totally—able to correct for these problems and make an acceptable landing.

Large rudder offsets were input during approaches. For sufficiently large rudder deflections, the differential thrust requirements were found to exceed the differential thrust available for a given glide slope. The maximum rudder deflection that could be trimmed out with differential thrust for an approximate 2° glide slope was approximately 6° with flaps at 28° and approximately 4° with flaps at 0°. When on the runway, steering the MD-11 airplane with differential braking and stopping on the runway was possible.

Of the 32 approaches attempted in the MD-11 FDS, 4 were not able to land at all, and several others were probably crashes. Only five landings were judged to have been safe landings with no damage to the airplane. Thus, the MD-11 PCA Ultralite evaluation showed that some additional help was needed for consistent safe landings.

Based on a very limited amount of data, the use of a single throttle rather than both throttles for lateral control did not show a clear advantage. The difficulty of making differential throttle inputs to moving throttle levers was not addressed because the autothrottle system (as implemented in this test) did not move the throttle levers. In the actual MD-11 airplane, keeping the center engine at idle would have required a crew member to hold it on the idle stop.

C-17 Military Transport Airplane

The C-17 airplane (The Boeing Company, formerly McDonnell Douglas Aerospace, Long Beach, California) is a large, wide-body military transport (fig. 14). The aircraft features a "T" tail; a high-mounted supercritical wing; four engines mounted on underwing pylons; externally blown flaps; and a rough-field, high–sink rate landing gear. The airplane has digital fly-by-wire flight controls, powered by four independent hydraulic systems, and an advanced glass cockpit with a head-up display. A four-channel stability and control augmentation system is provided in all axes. The four F117 engines (Pratt & Whitney, East Hartford, Connecticut) have 40,000 lbf of thrust each and have digital controls. A typical midfuel weight with a medium payload is 450,000 lb.

C-17 Baseline Full Propulsion-Controlled Aircraft Test Results

The C-17 baseline PCA system was developed and implemented on the motion base simulator. Individual control of each engine was provided, and all flap configurations were tested. In the flaps-up tests, the C-17 airplane performed much like other aircraft such as the MD-11 airplane. With the flaps
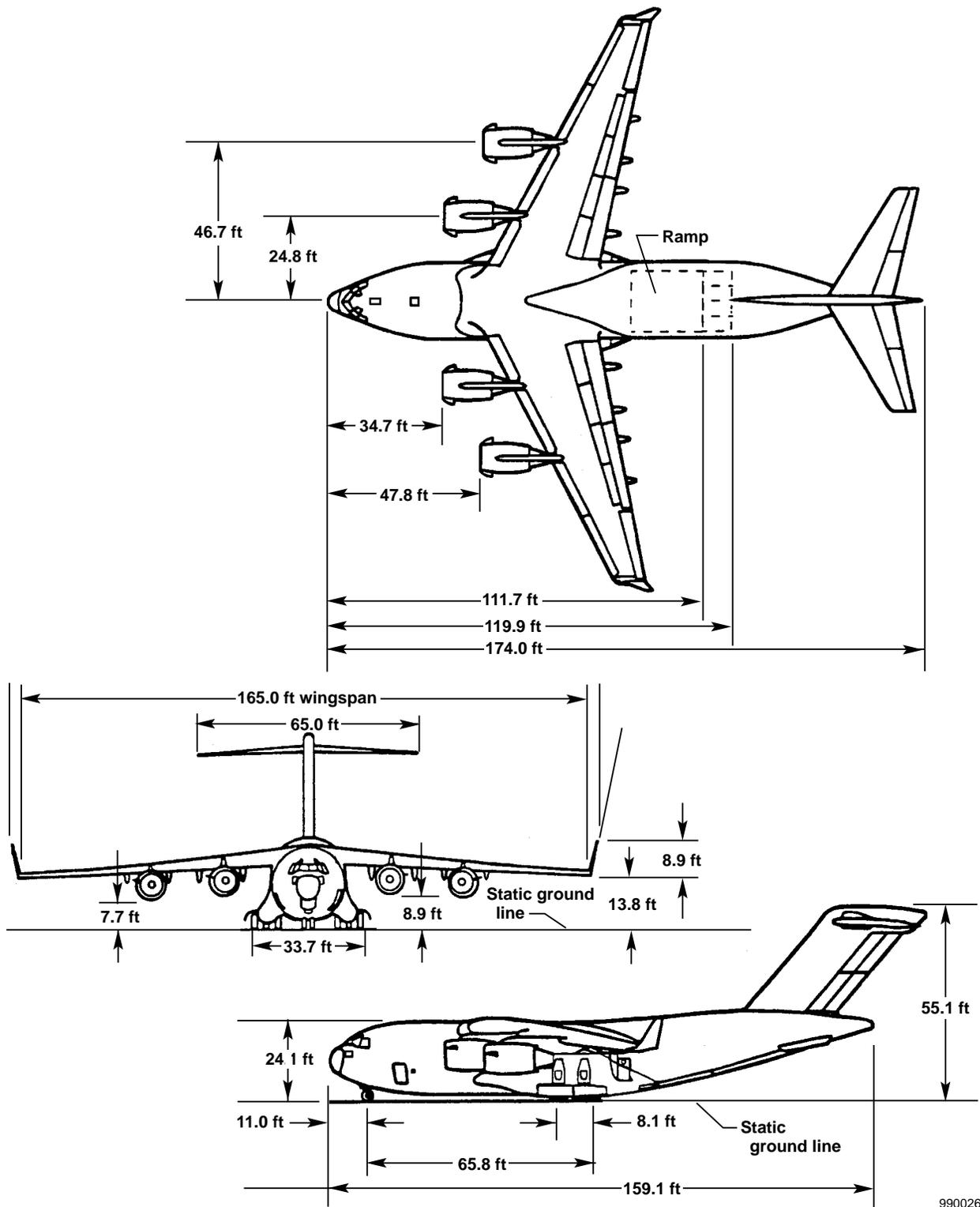
Figure 14. Three-view drawing of the C-17 military transport airplane.

extended into the engine exhaust, (flaps one-half, three-quarters, and full) the response was unconventional. Thrust caused direct lift and rolling moments in addition to the typical axial forces and yawing moments. Essentially separating roll and yaw response to thrust changes was possible over a limited range. Control laws were developed that took advantage of these unconventional effects with flaps extended. Results showed good control using the PCA system. The pilots could use the autopilot controllers or could couple to an ILS for landing. Ground effect produced high sink rates of 10 to 15 ft/sec at touchdown, but the C-17 airplane has a high–sink rate gear for rough field operation. This PCA system was evaluated by NASA, United States Air Force, and Boeing Company[†] pilots (ref. 8).

C-17 "PCA Ultralite" Test Results

The C-17 PCA Ultralite system was mechanized on the C-17 flight hardware simulator. The pitch control law output was used to drive the autothrottle servomotor and provided pitch control comparable to the full PCA system. Lateral control was provided by differential throttle movement by the pilot. No flight director cueing was provided.

Pilot D evaluated the PCA Ultralite system on the C-17 simulator. With the flaps up and the airspeed 200 kn or faster, the C-17 simulator response was much like that of other transport airplanes. Lateral control was sluggish and hard to anticipate, but dutch-roll damping was adequate and runway lineup, while difficult, was possible with some practice. The drag was sufficiently low enough that a 3° glide slope could not be flown without thrust levels being near idle, leaving very little differential thrust available for control. When the trim airspeed was reduced to 190 kn and a shallow approach was flown, a landing was possible, as shown in figure 15. The glide slope was initially 3° to 3.5° with attendant poor lateral control, and the C-17 airplane drifted well left of the runway center line. Thrust on the outboard engines was idle from approximately 15 to 40 sec, and inboard engine thrust (not shown and not recorded) was modulated to attempt to achieve runway lineup. At approximately 30 sec, the flightpath gradually was shallowed to 2.5°, and more thrust was available for lateral control. A left turn was made as the center line was approached, and the landing was on the left edge of the runway. Sink rate at touchdown was approximately 15 ft/sec.

With the blown flaps extended, which permitted flight at low airspeeds, lateral control became much more difficult. On the first approach, with flaps at one-half and at an airspeed of 120 kn, dutch-roll damping was so poor that control was almost impossible, and concern existed about keeping the simulated C-17 airplane in the air. After some practice, keeping the airplane headed in the general direction of the runway was at least possible, but precise control suitable for a landing could not be obtained. Other approaches were flown with flaps at three-quarters and at an airspeed of 110 kn, and with flaps at full and at an airspeed of 100 kn, with similar results. Eventually, a technique was developed in which only the inboard throttles were moved, and these were moved only very slightly. Control was also improved by increasing the trim airspeed. The only successful runway landing with flaps extended was made with flaps at one-half with the trim airspeed increased to 140 kn. As figure 16 shows, bank angles were kept quite small (less than approximately 3°), and a shallow flightpath of approximately 2° was flown. Touchdown sink rate was 10 ft/sec, and a bounce occurred. Pilot cueing for improved lateral control was not investigated on the C-17 simulator.

Overall, flight using the PCA Ultralite system on the C-17 airplane with the blown flaps extended was much more difficult than on the other three aircraft tested. Because of the airplane dynamics,

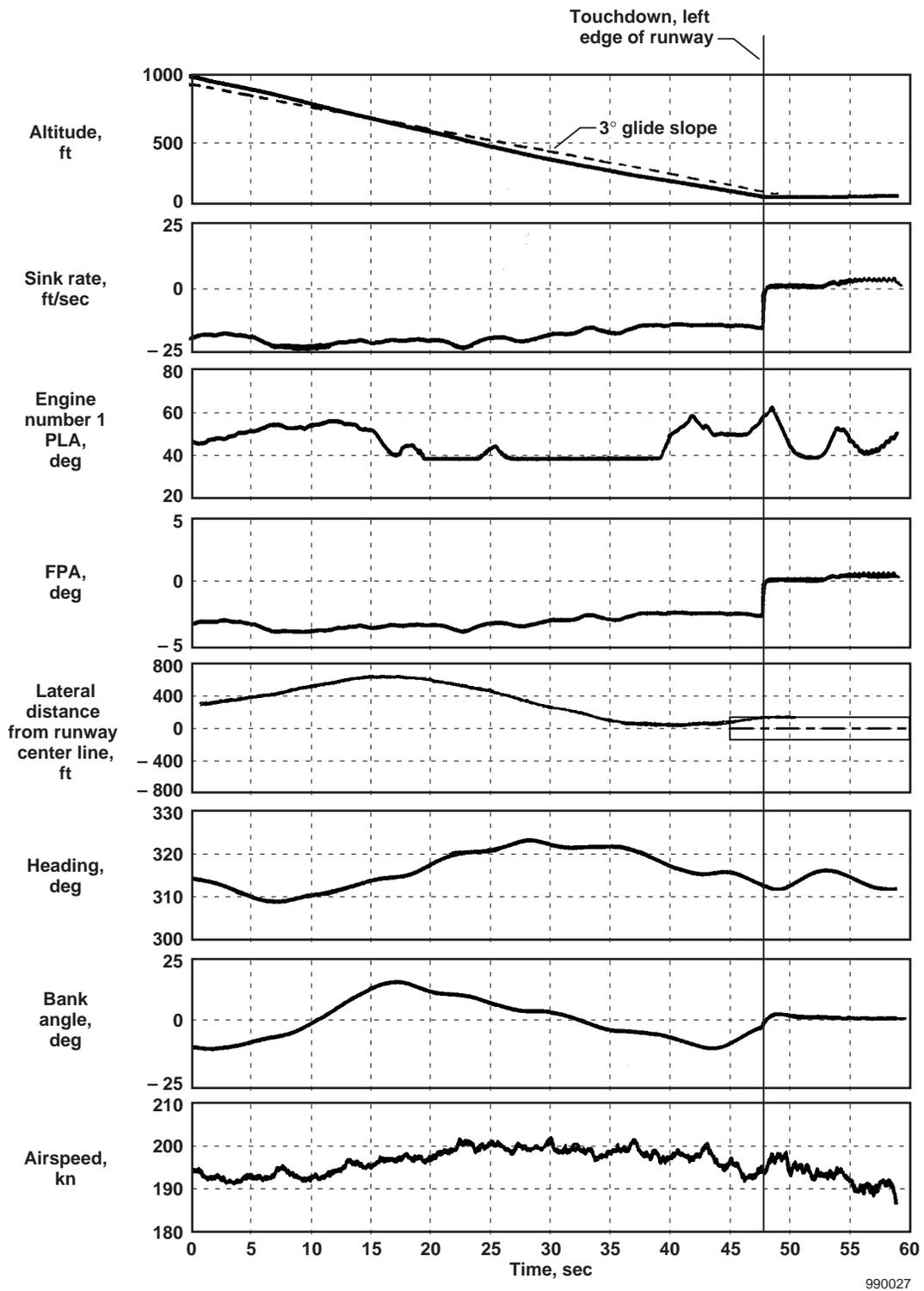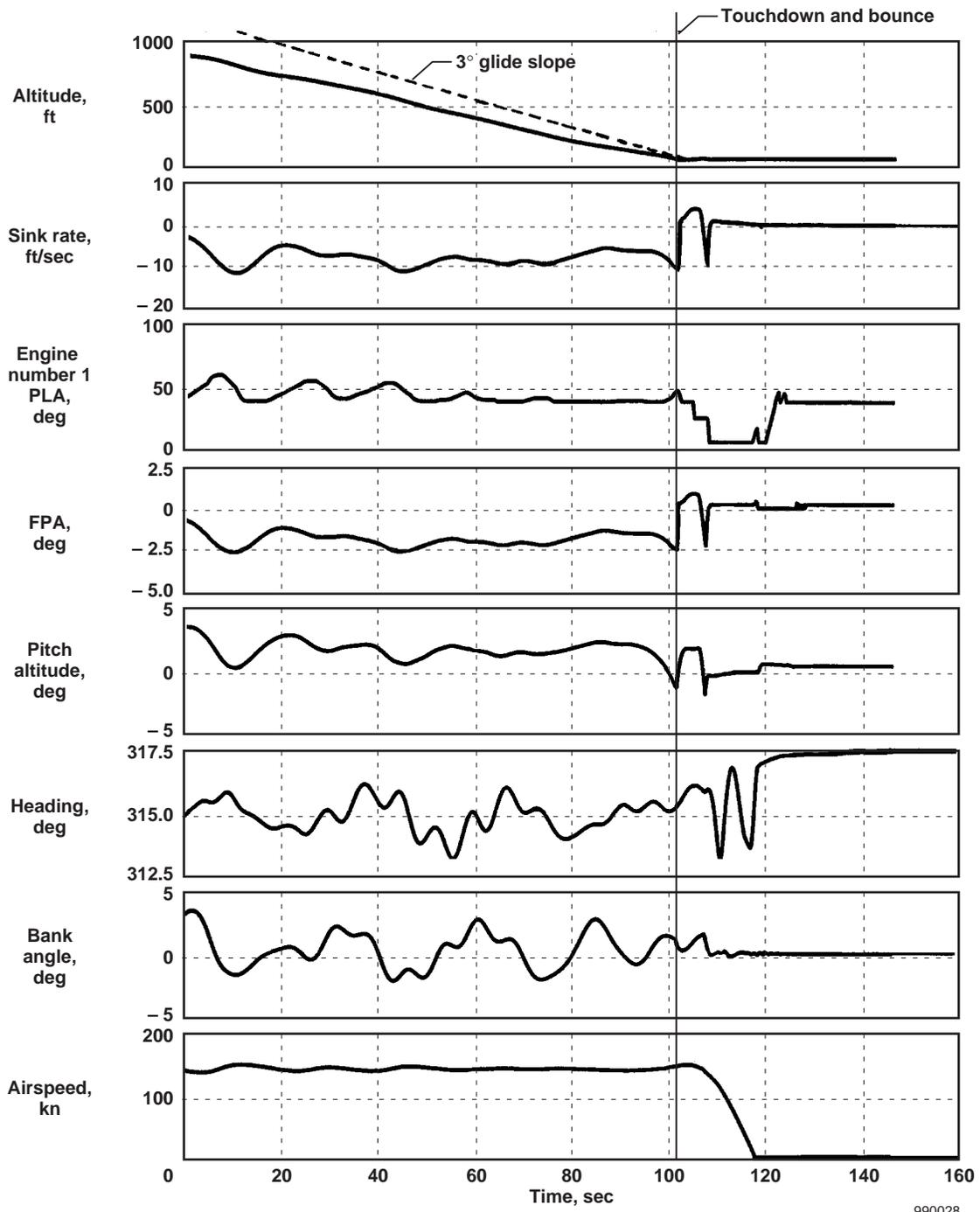[†]Formerly McDonnell Douglas Aerospace, which merged with The Boeing Company during these tests.

Figure 15. C-17 simulation PCA Ultralite approach and landing flown by pilot D with flaps up.

Figure 16. C-17 simulation PCA Ultralite approach and landing flown by pilot D with one-half flaps.

including the low ratio of roll to yaw and the low dutch-roll damping, successful PCA Ultralite landings were very unlikely. Typical attempts to make a lateral correction involved making a small differential thrust input and seeing some yaw but little roll response. Then a larger differential thrust input would be made, often resulting in too much roll and resulting in a large-amplitude dutch-roll oscillation. Damping this oscillation was very difficult and often made it worse rather than better. Whether pilot cueing would improve lateral control sufficiently for safe landings is not clear.

B-747 Transport Airplane

The B-747 airplane (The Boeing Company, Seattle, Washington) is a large, swept-wing, wide-body transport with four engines mounted on underwing pylons (fig. 17). Maximum gross weight is 870,000 lb; maximum landing weight is 574,000 lb. Four independent hydraulic systems power conventional ailerons, rudders, elevators, spoilers, the horizontal stabilizer, and flaps; however, if all hydraulics are lost, no braking capability exists. A backup electrical actuation system exists for the flaps.
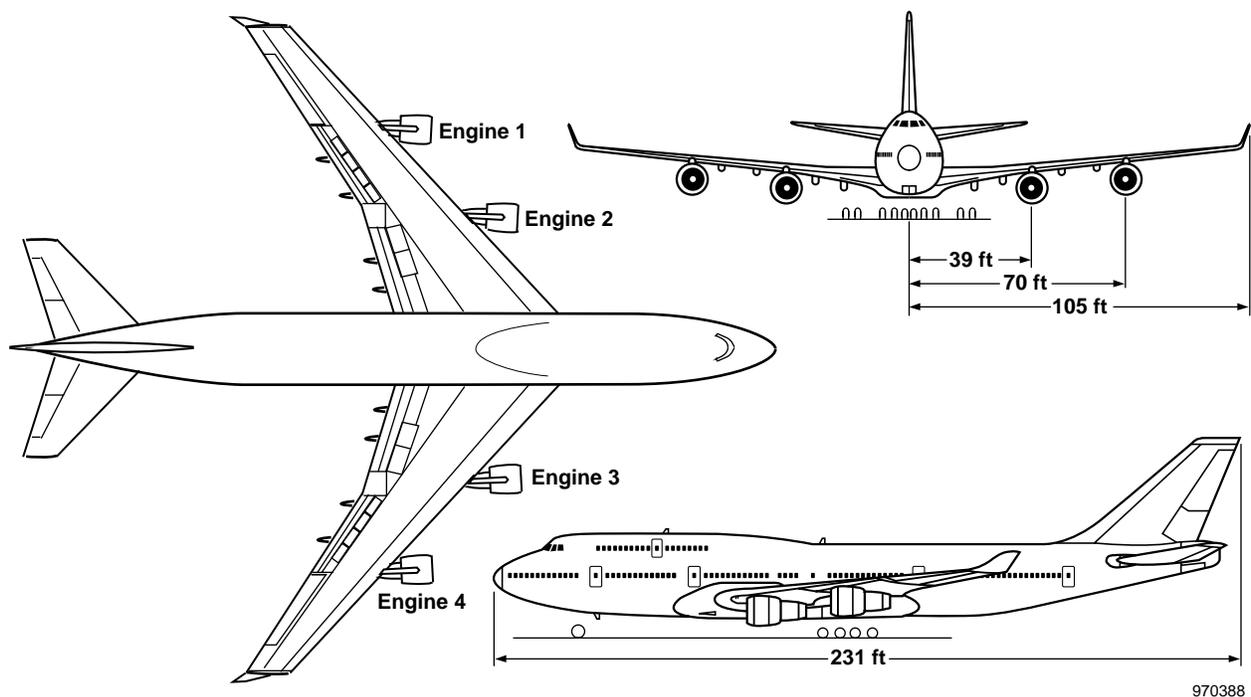
Figure 17. Three-view drawing of the B-747-400 transport airplane.

Tests have been performed on the NASA Ames B-747-400 simulator (fig. 18), a very-high-fidelity motion-base simulator that is certified by the Federal Aviation Administration to level "D." The B-747-400 simulator flown was powered by PW4056 engines (Pratt & Whitney) that have 56,000 lbf of thrust and FADEC systems. Thrust as a function of EPR for the PW4056 engine is a nonlinear function, with approximately 90,000 lbf/EPR at low thrust and approximately 45,000 lbf/EPR near maximum thrust. The B-747-400 simulator has very-high-fidelity models of control surface floating effects and ground effect, mostly based on wind-tunnel data.

Figure 18. B-747-400 simulator cockpit at NASA Ames.

B-747-400 Full Propulsion-Controlled Aircraft Results

Results of full PCA tests in the B-747-400 simulator have previously been published (ref. 7). In general, results were very good, nearly as good as the MD-11 flight test results. Pitch control was not quite as good as the MD-11 tests, but lateral control was quite good. Many of the tests were conducted at conditions that would result if a total hydraulic system failure were to occur at cruise conditions. With a cruise setting of the horizontal stabilizer, the resulting approach speeds were 235 kn, making for a difficult approach and flare because of the high speed. In addition, no braking was available with all hydraulics failed. Many pilots participated in evaluations of the PCA system on the B-747-400 simulator, including Boeing Company test pilots and engineers.

B-747-400 "PCA Ultralite" Results

The PCA Ultralite concept was also investigated on the B-747-400 simulator. The PCA pitch control laws were coupled to the autothrottle servomotor that moves the throttles in the cockpit. For lateral control, the pilot used differential throttle inputs without any cueing. In this B-747-400 PCA Ultralite evaluation, all approaches were flown at San Francisco International Airport (California) to runway 28R. Approaches were initiated at an airspeed of 235 kn, an altitude of 2,000 ft AGL, 13 mi out, 4,000 ft right of the localizer, and a heading of 280°. Therefore, an approximate 20° left turn needed to be made in order to intercept the localizer, and altitude needed to be held for approximately 1 min before a descent was started. Some tests were made with no wind and no turbulence, but most were performed with a 20 kn wind from 250° with light turbulence.

Pitch control was through the autothrottles either coupled to the ILS glide slope or the copilot selecting the *FPA* on the pitch thumbwheel. Lateral control was achieved by the pilot symmetrically splitting all throttles or by controlling one or more throttles. Gross weight was approximately 540,000 lb and flaps were set to 0°. Rudder offsets were attempted at 2° and 3°. Again, although go-arounds were possible, the pilot's task was to press on to landing until a landing near the runway was obviously not possible. Most of the simulation runs were flown by two experienced pilots, pilot A and pilot B. Pilot A is

a very-high-time pilot with many hours on transport-type aircraft and is very experienced with using the PCA system in flight and on simulators. Pilot B is a high-time test pilot with many hours on fighter-type aircraft but little time in transport-type aircraft and no previous PCA system experience.

Many of the B-747-400 approaches were similar to the MD-11 approaches. Pitch control was good, quite similar to the full PCA results. The lateral control task using manual throttle manipulation was quite difficult.

Figure 19 shows a time history of what was probably the best B-747-400 PCA Ultralite approach and landing for this evaluation. This approach was flown by pilot A in light turbulence and a 20-kn wind from 250°. No rudder offset was simulated, and the pitch control axis was coupled to the ILS glide slope. Flightpath control was good, usually within 0.5° of the ILS glide slope command. The pilot provided lateral control by making differential inputs to all four throttles. When established on the localizer, good lateral control was achieved, with a deviation generally less than 1° and bank angles of approximately 5°. Pilot A anticipated turns on the localizer very well, and very little overcontrolling occurred. Differential thrust inputs of approximately ±0.02 to ±0.05 EPR were generally used. Beginning at approximately 180 sec, the automatic flare command began and the aircraft began to pitch up. Approximately 5 sec later, the pilot pulled all throttles to idle and the aircraft entered ground effect. During this period of approximately 10 sec, the pilot did a good job of keeping the wings level and the heading straight by making only small throttle adjustments. Touchdown occurred at a sink rate of 4 ft/sec near the runway center line and approximately 3,000 ft from the threshold at a bank angle of 1°. This approach was well-stabilized with small bank angles and small amounts of differential thrust.

In the next simulator run (fig. 20), the same setup was used as in the previous run except pilot B was the pilot in command. This attempt was pilot B's first at flying the PCA Ultralite system, and the pilot had very little PCA or TOC experience. As is typical of someone with little PCA experience, pilot B tended to overcontrol the throttles throughout the approach. Pilot B started with an aggressive angle to intercept the localizer, but then lessened the angle when within 1000 ft of it. Often, large differential thrust inputs of as much as ±0.07 EPR were used to try to stay on the localizer. These relatively large differential thrust inputs resulted in large bank angles and caused the aircraft to oscillate across the localizer. Near the landing point, the aircraft was slightly off the right side of the runway. Subsequently, the pilot commanded a left bank angle to return to the runway. The bank angle reached 10°, then was reduced as the aircraft hit and bounced, touching down at a vertical speed of approximately 10 ft/sec and an 8° bank. The pilot then tried to line back up with the runway by rolling the aircraft 10° in the opposite direction. Immediately before the second touchdown, the pilot used differential throttles to try to achieve wings-level flight. The aircraft landed 11 sec later, 4500 ft down the runway, in a 2° bank with a vertical speed of approximately 3 ft/sec. This approach was not very well stabilized; many large differential thrust inputs were made trying to keep the aircraft on the center line. Near the runway, this overcontrol continued and came very close to dragging a wingtip on the first touchdown.

Figure 21 shows the same starting conditions used as in the previous two examples, except a 2° rudder offset was initiated and pilot B was in command. Most of the lateral control in this run came from the outboard engines. To compensate for the 2° rudder offset, approximately 0.06 EPR of differential thrust had to be maintained on the outboard engines.

Pilot B initially did well with a rudder offset, but when time came to turn onto the localizer, the pilot seemed to have trouble anticipating and finding the right amount of differential thrust to make the
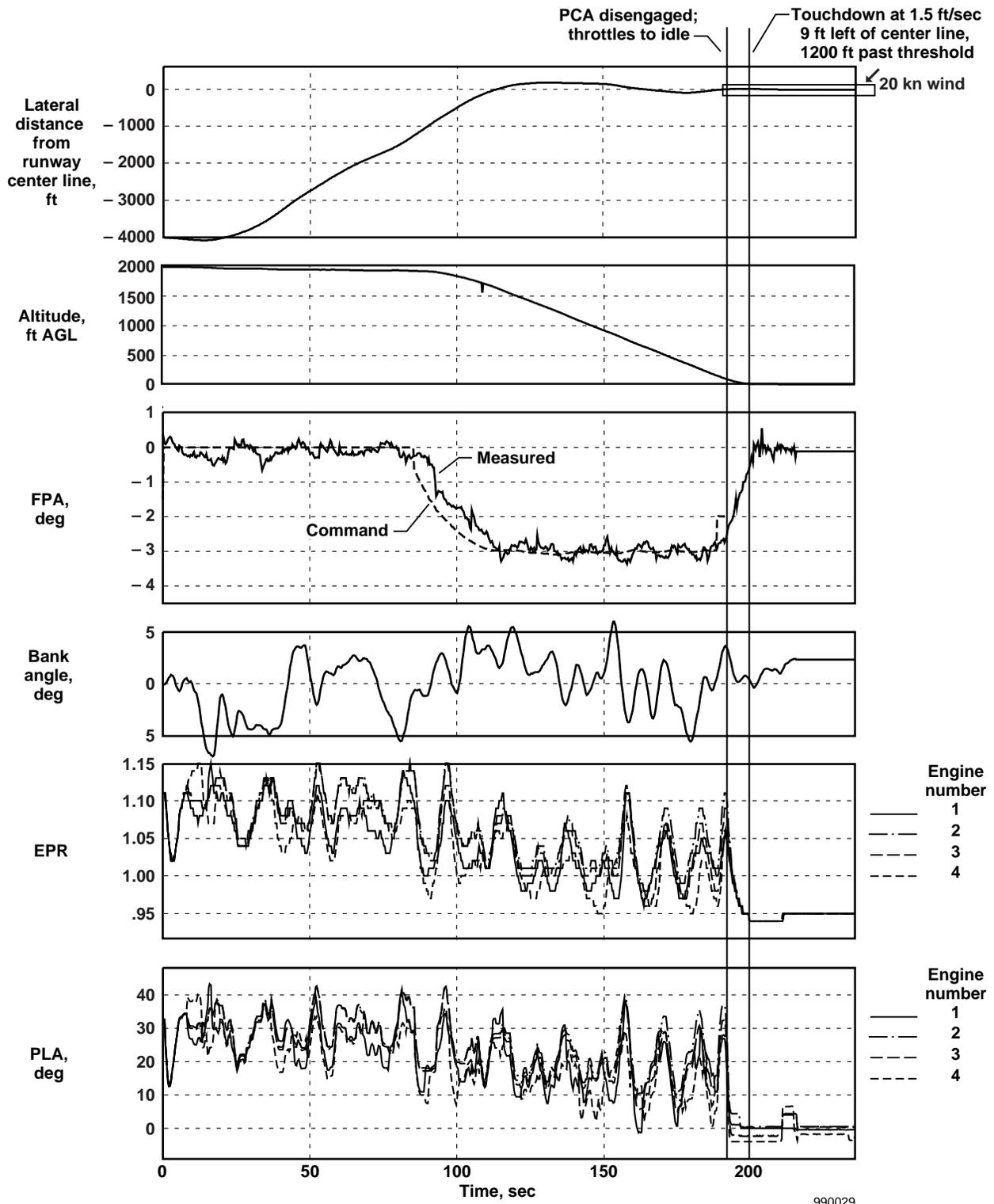
Figure 19. B-747-400 simulator PCA Ultralite approach and landing flown by pilot A under conditions including glide slope–coupled, a 240-kn approach speed, 0° flaps, and light turbulence.

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Figure 20. B-747-400 simulator PCA Ultralite approach flown by pilot B under conditions including a 2° rudder offset, glide slope–coupled, a 240-kn approach speed, 0° flaps, and light turbulence.
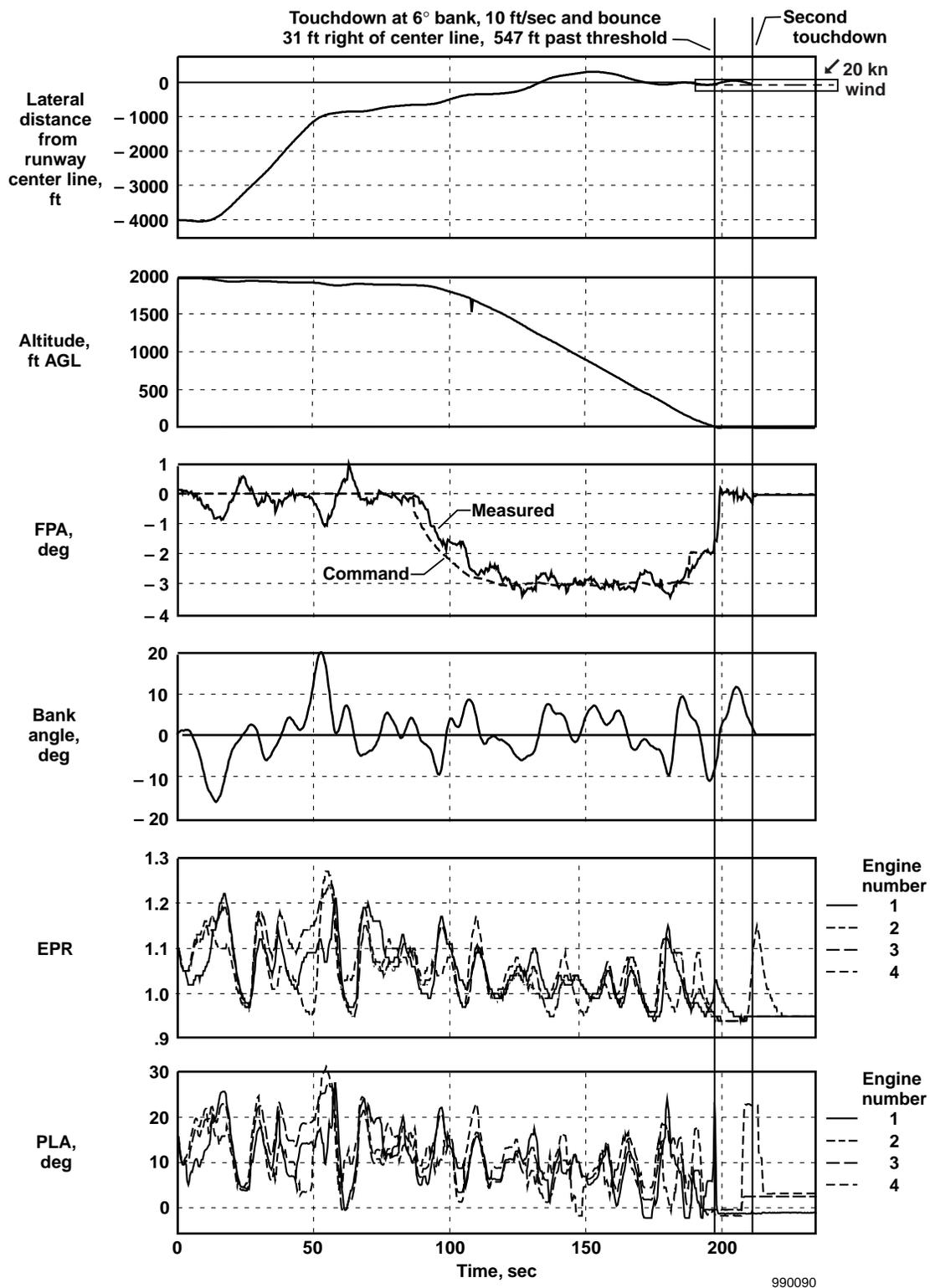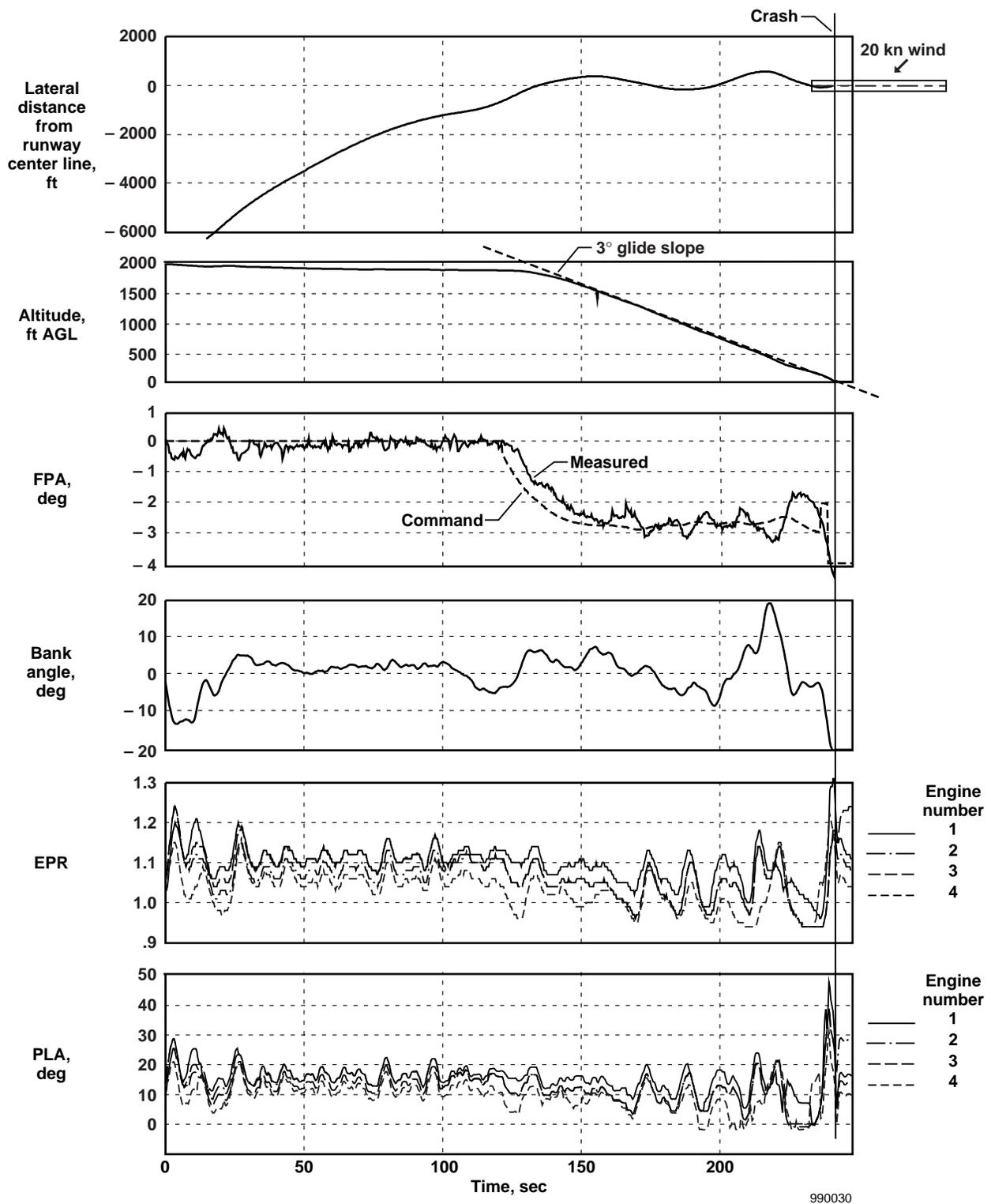
Figure 21. B-747-400 simulator PCA Ultralite approach flown by pilot B under conditions including a 2° rudder offset, glide slope–coupled, a 240-kn approach speed, 0° flaps, and light turbulence.

required turn. The turn onto the localizer came too late and an overshoot resulted. This overshoot may have been compounded by the simultaneous glide slope intercept that reduced overall thrust to the point where the right engines were very close to idle thrust. (Thrust response degrades as thrust approaches idle power.)

Upon turning onto the localizer, bank angles peaked at 7° and 9° before the runway was neared. On the descent, *FPA* began to oscillate around its commanded angle. At 195 sec, all of the throttles began to decrease in response to a flightpath error, but the number 3 and number 4 engines were near idle power and responded slowly while the number 1 and number 2 engines thrust dropped rapidly and exacerbated the roll to the left. This condition required a sharp bank of 20° back to the right, which further upset the pitch control. Because of the steep bank angle, *FPA* decreased and more collective thrust was added, bringing all of the throttles out of idle. At approximately the same time, the pilot quickly added more thrust on the left outboard engine to correct for the bank, and the aircraft leveled off. Now back into level flight with excess thrust, the *FPA* increased to –1.8° instead of the –2.7° needed. With the high *FPA*, collective thrust was again decreased and the number 2, number 3, and number 4 engines hit idle. Expecting to roll to the left again, the pilot added plenty of thrust to the left engines. This amount of thrust was too much. The aircraft rolled 20° to the right and the wingtip struck the ground. Throughout the approach, the pilot had trouble anticipating how much differential thrust was needed in order to make turns and hold headings. When near the runway, this trouble became very apparent and a crash resulted. The PCA Ultralite system on the B-747-400 simulation was comparable in difficulty to that of the MD-11 simulation. Difficulty in anticipating the lead required for lateral corrections was the major problem.

Advanced Concepts Flight Simulator

PCA has also been studied on the high-fidelity ACFS. The ACFS models an airplane that is approximately 90-percent equivalent to a B-757 transport airplane and has two 40,000-lbf thrust high-bypass turbofan engines mounted on underwing pylons.

Advanced Concepts Flight Simulator Full Propulsion-Controlled Aircraft Results

A full PCA system was developed and implemented on the ACFS in 1995 (ref. 6). Performance of the PCA system was very good, comparable to that seen in the MD-11 simulation and flight tests. The simulation was evaluated by airline, military, and industry pilots. An offline version of this simulator was also available.

Advanced Concepts Flight Simulator "PCA Ultralite" Results

In 1998, NASA Ames designed and developed a PCA Ultralite system for the ACFS. The autothrottle system was used to provide pitch control, and the pilot used manual differential throttle control for lateral control. Figure 22 shows the first PCA Ultralite approach of Pilot E on the ACFS. Pilot E is an experienced business-jet pilot but had no previous TOC or PCA experience. For this approach, the pitch axis was coupled to the ILS glide slope, and pitch control was good. The pilot flew a shallow intercept to the localizer and crossed the localizer prior to glide slope intercept. Pilot E did a good job of keeping throttle movements and bank angles small, but did overshoot the localizer twice. The pilot was on the extended center line one mile out, but drifted right. Over the threshold, the pilot was lined up to the immediate right of the right edge of the runway and made a large throttle input to correct
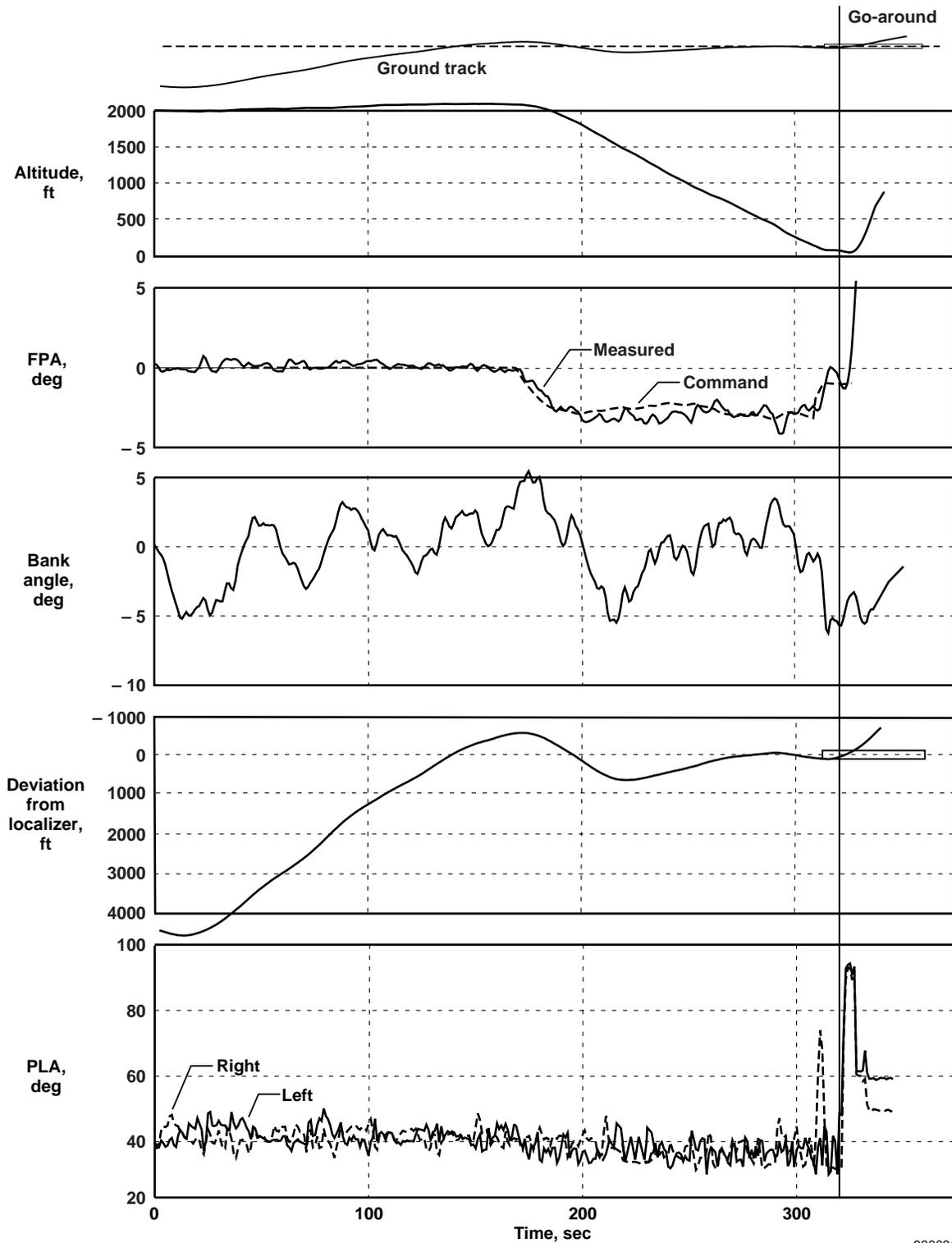
Figure 22. ACFS PCA Ultralite approach and go-around flown by pilot E under conditions including glide slope–coupled, a 180-kn approach speed, flaps up, light turbulence, crosswind, and no flight director guidance.

back. This extra thrust came just as the pitch control logic was adding thrust for the flare, and the combined thrust caused the airplane to float, drifting across the runway from right to left. Still airborne, off the left side of the runway and diverging further to the left, the pilot elected to go around and advanced both throttles, overriding the autothrottle servomotor. The airplane climbed out rapidly and the test was terminated. This unsuccessful approach was typical of an inexperienced pilot flying PCA Ultralite without any cockpit cueing for the first time.

Pilots more experienced with PCA and TOC were able to make successful PCA Ultralite landings on their first try. Of the four airplanes tested, the ACFS was the easiest to fly in the PCA Ultralite mode. Dutch-roll damping was quite good in the ACFS.

"PCA Ultralite" Cockpit Display

Given the MD-11, B-747-400, C-17, and ACFS results, the challenge facing the pilot in the use of a PCA Ultralite system is the precise differential control of the throttles needed to achieve and maintain runway alignment. Without cueing, the pilot tends to overshoot the extended center line, resulting in an oscillatory flightpath about the extended runway centerline. In many cases, this oscillatory flightpath results in less-than-acceptable landings. In order to resolve this problem, the use of cockpit cueing has been studied.

One method of cueing used two vertical tapes such as is used in engine displays: one to indicate current throttle position, and another to indicate where the throttle should be positioned. To successfully use this display scheme, two persons or one person and an ILS are required. The copilot or ILS handles longitudinal and lateral control in the same manner as in a full PCA system. The main differences from the full PCA system is that longitudinal commands are sent to the autothrottle and lateral commands are sent to the display. The pilot's only task then becomes to keep the throttle position indicator even with the throttle advisory indicator. Preliminary results using this display showed a reduction in bank angle and heading oscillations during an approach. However, a better method of cueing was devised, and the above approach was not continued.

A better method of cueing was to use the flight director present in many airplanes. The PCA control laws provide a differential throttle command, and the pilot moves the throttles to minimize the error as indicated on the vertical bar of the flight director. Initial development of this technique at NASA Dryden was promising, and pilots found it intuitive. The technique was also tried at NASA Ames on the ACFS. There, the dynamics of the lateral control laws and the flight director were refined until a promising system was developed. Figure 23 shows a simplified block diagram of the flight director part of the PCA Ultralite system. Filters and rate limits were selected to best match pilot response, engine response, and airplane dynamics. The value for lag filters was approximately 0.4 sec. The value for the rate limit was equal to 0.4 plus a function of the absolute error. The throttle position error flight director was found to be very useful. Another flight director implementation was tested in which the bank angle error was displayed rather than the throttle position error. Both were found to provide similar performance. The bank angle error flight director was intuitive for pilots. Therefore, the bank angle flight director was used for most of the later tests.
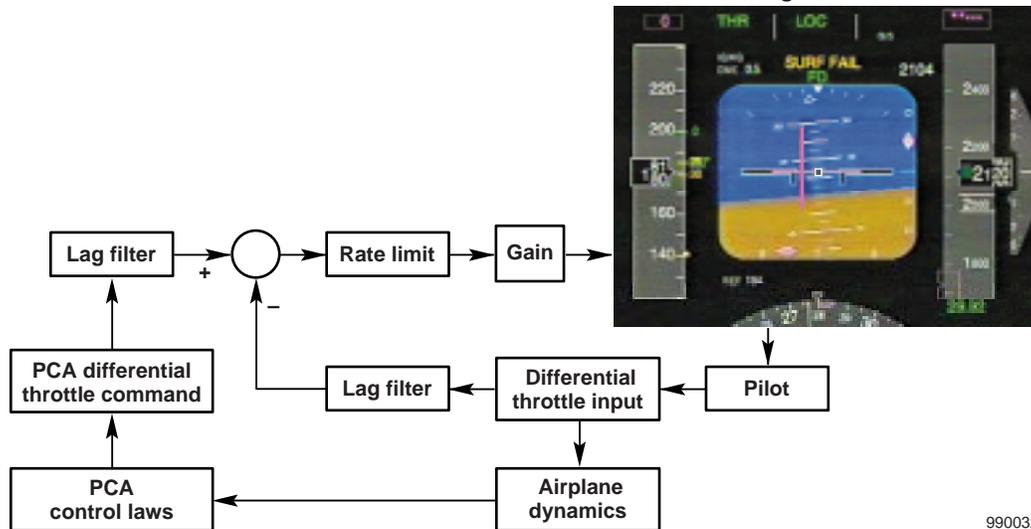
Figure 23. PCA Ultralite flight director lateral control mode (throttle mode).

Advanced Concepts Flight Simulator "PCA Ultralite" With Flight Director Results

Figure 24 shows an ACFS approach and landing with flight director guidance. Glide slope tracking was done automatically by the PCA Ultralite system using the autothrottle system. Lateral control was provided by pilot D cued by the flight director. Pilot D had extensive experience with PCA and TOC flights. Excellent performance was achieved, even with the crosswind and turbulence. All pilots found the display very intuitive and easy to use. Pilot A described the improvement with the addition of the flight director guidance as being very dramatic, "like the difference between night and day." Similar results were obtained in adverse weather with a 200 ft ceiling.

Figure 25 shows an ACFS PCA Ultralite landing using the PCA flight director. Pilot C had some previous PCA experience, having flown the MD-11 PCA flight demonstration, but this approach was the pilot's first using the flight director cueing. The pilot used the heading/track knob to set up a localizer intercept and used differential throttle to minimize the flight director error. The pilot's differential throttle input is overlaid over the flight director bar deviation. Figure 25 shows that the pilot quickly learned to use the flight director and lagged the command by 2 to 3 sec. When the ILS localizer capture occurred, the cueing provided a smooth capture. Glide slope capture followed shortly, and the autothrottle system maintained the commanded flightpath within less than 1°, reducing the average throttle setting from 42° to 36°. On the glide slope, only very small differential throttle corrections were needed in spite of the turbulence and crosswind. Localizer deviation was less than 0.2 of a dot. Touchdown occurred at a sink rate of 5 ft/sec on the center line. The pilot rated the PCA Ultralite system with the flight director as satisfactory without improvement.

Figure 26 shows an ACFS PCA Ultralite approach and landing under conditions including a 2° rudder offset, light turbulence, and crosswind. The rudder offset simulates a lateral asymmetry that might result from aircraft damage. The PCA flight director provided bank angle cueing to the pilot.

The rudder offset was introduced immediately after the simulation run began, and the flightpath was initially negative. The PCA pitch control logic initially increased both throttles to correct the flightpath,
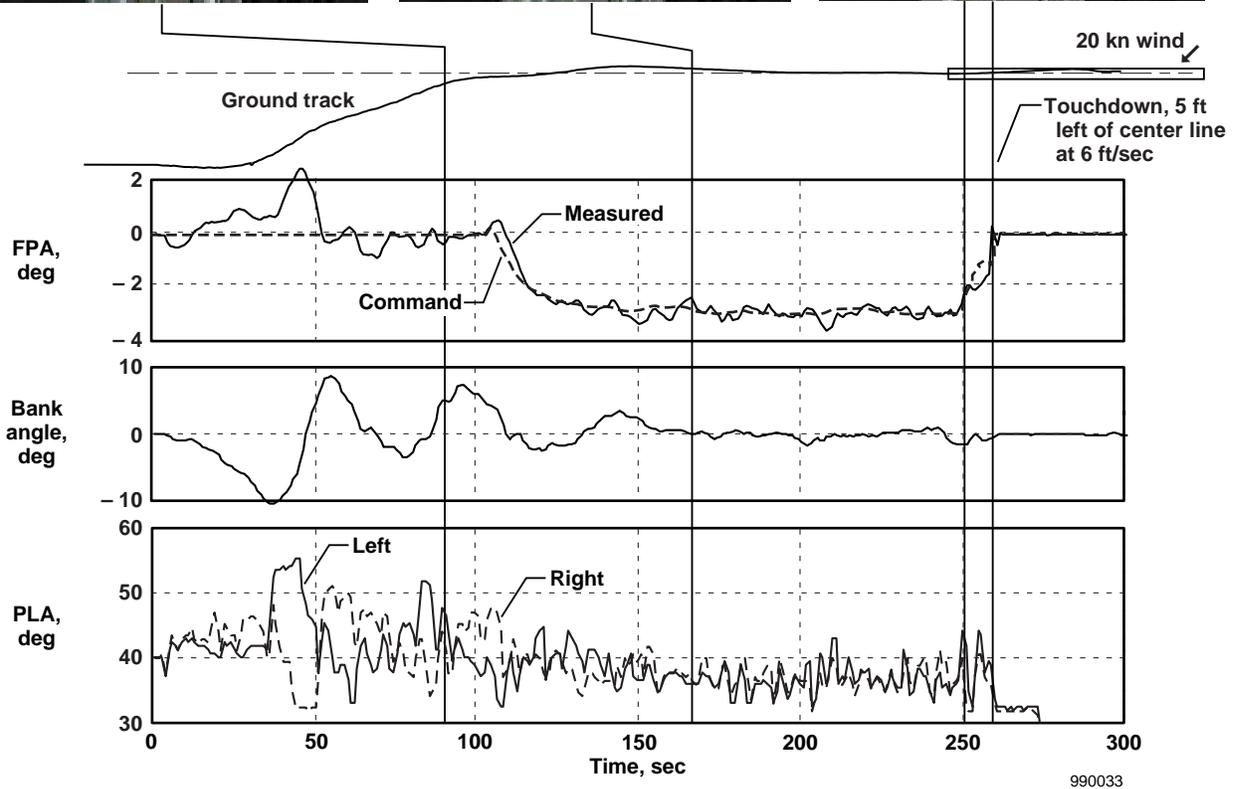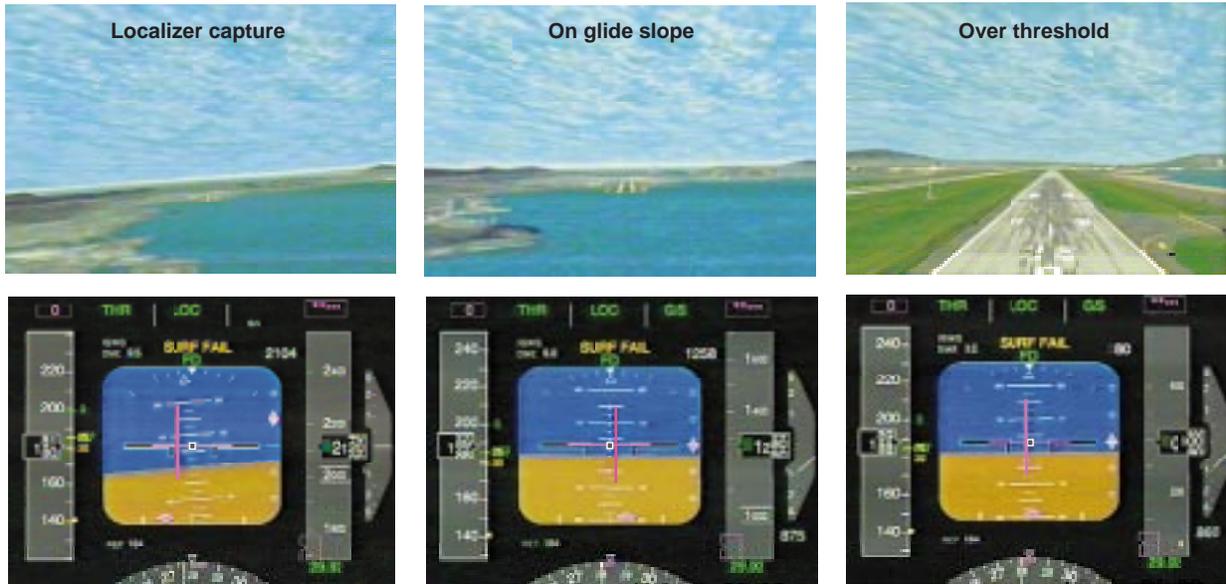
Figure 24. ACFS PCA Ultralite with flight director approach and landing flown by pilot D under conditions including light turbulence, a 185-kn approach speed, glide slope–coupled, and flaps up.
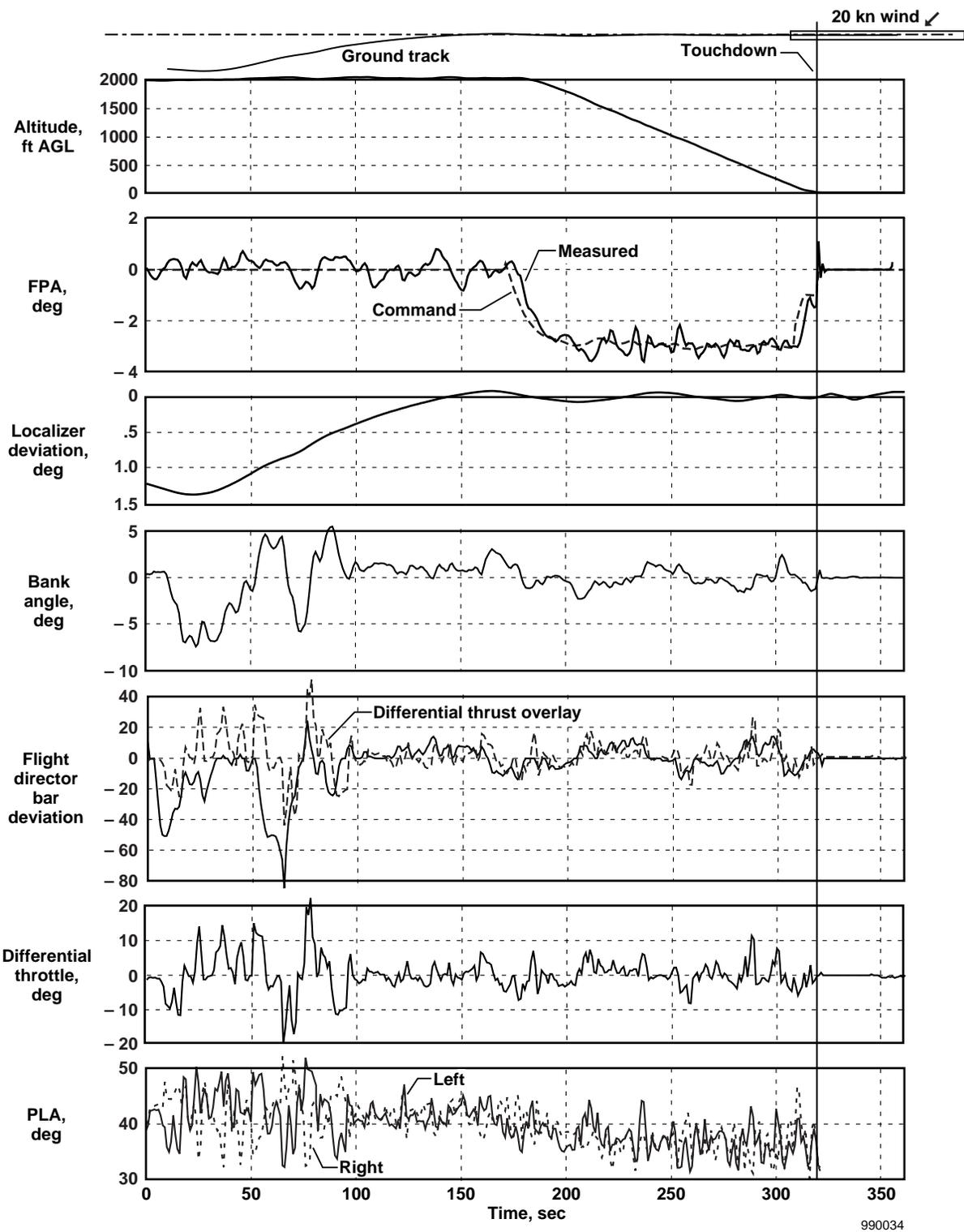
Figure 25. ACFS PCA Ultralite with flight director landing (first landing of experienced pilot) flown by pilot C under conditions including a 185-kn approach speed, glide slope–coupled, and flaps up.
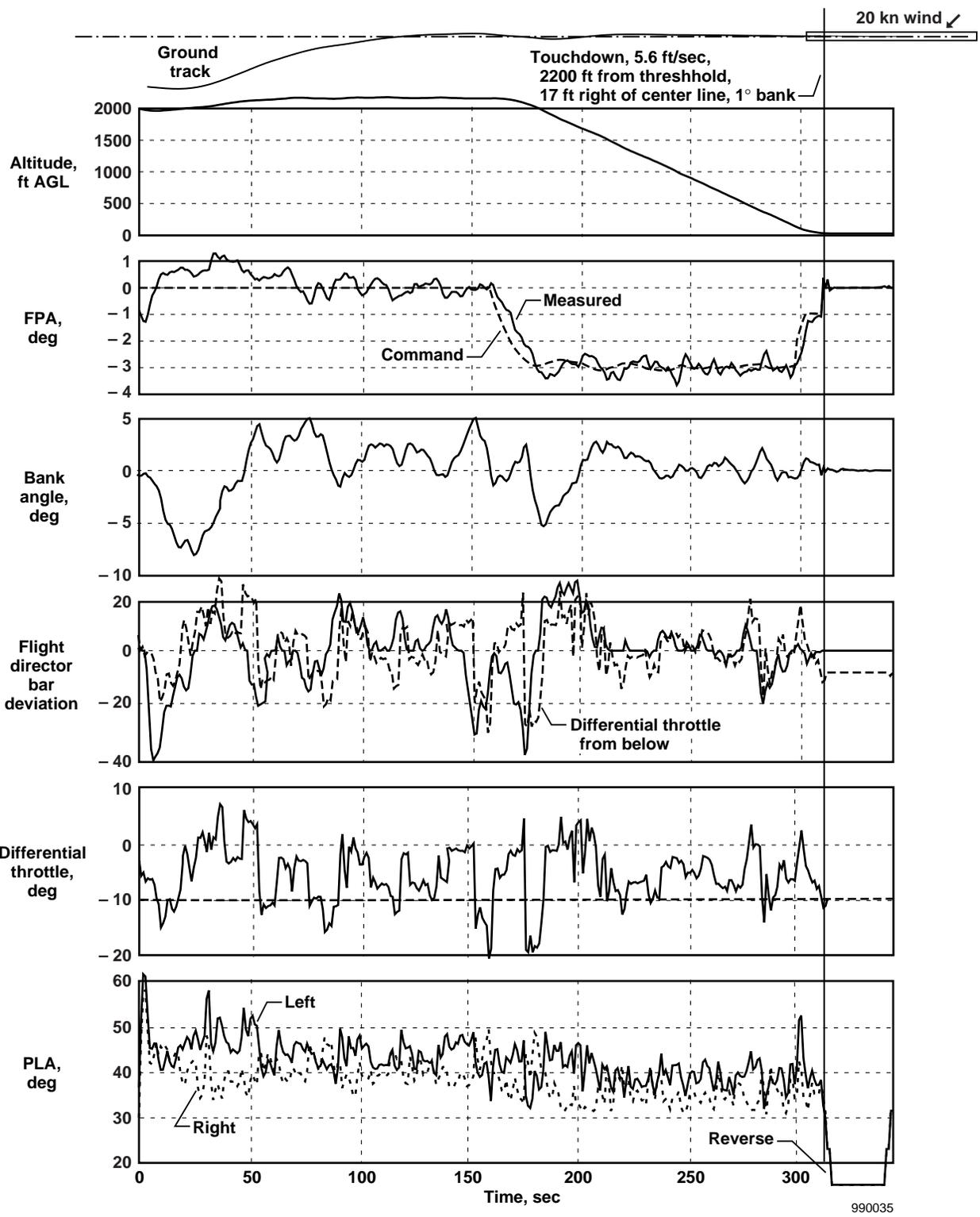
Figure 26. PCA Ultralite landing with flight director guidance flown by pilot C under conditions including a 2° rudder offset, a 185-kn approach speed, glide slope–coupled, and flaps up.

and the initial differential throttle command combined to cause a positive flightpath. When the ILS localizer was approached, the localizer was captured smoothly with one small overshoot. An average of approximately 4° of differential throttle was needed to compensate for the rudder offset. At 160 sec, a flight director cue was not followed for several seconds, resulting in a deviation to the right, but this condition was quickly corrected and no significant deviations occurred through landing. Flightpath control was held within less than 1° after the initial transient thrust inputs were completed. Bank angles during the final approach and flare were less than 2°. Touchdown was 1200 ft from the threshold on the runway center line at a sink rate of 4 ft/sec.

The addition of the flight director cueing has made PCA Ultralite a promising technology for the ACFS. Pilot ratings went from almost totally unacceptable to acceptable without improvement. A total of 16 landing attempts was made using PCA Ultralite by 8 different pilots, and all were successful landings. Whether this improvement will carry forward to other aircraft such as the B-747, C-17 and MD-11 airplanes remains to be seen.

CONCLUDING REMARKS

Simplified methods of emergency control for airplanes using only engine thrust have been studied in high-fidelity simulations. A method that uses autothrottles for pitch control and manual differential throttle control for lateral control has been evaluated in simulations of MD-11, C-17, B-747, and B-757 airplanes. Thrust-only pitch control is adequate with the existing autothrottle systems. Without lateral cueing and prior experience, major difficulty exists in achieving adequate lateral control for landing using manual differential throttle control. In the Advanced Concepts Flight Simulator, using flight director cueing to aid the pilot in differential throttle control provided a major improvement and provided adequate control for consistent safe landings by pilots without previous "PCA Ultralite" experience.

Dryden Flight Research Center
National Aeronautics and Space Administration
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13. ABSTRACT (Maximum 200 words)

With the advent of digital engine control systems, considering the use of engine thrust for emergency flight control has become feasible. Many incidents have occurred in which engine thrust supplemented or replaced normal aircraft flight controls. In most of these cases, a crash has resulted, and more than 1100 lives have been lost. The NASA Dryden Flight Research Center has developed a propulsion-controlled aircraft (PCA) system in which computer-controlled engine thrust provides emergency flight control capability. Using this PCA system, an F-15 and an MD-11 airplane have been landed without using any flight controls. In simulations, C-17, B-757, and B-747 PCA systems have also been evaluated successfully. These tests used full-authority digital electronic control systems on the engines. Developing simpler PCA systems that can operate without full-authority engine control, thus allowing PCA technology to be installed on less capable airplanes or at lower cost, is also a desire. Studies have examined simplified "PCA Ultralite" concepts in which thrust control is provided using an autothrottle system supplemented by manual differential throttle control. Some of these concepts have worked well. The PCA Ultralite study results are presented for simulation tests of MD-11, B-757, C-17, and B-747 aircraft.

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