# NASA Dryden Flight Research Center

## "Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane"

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# Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane

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## Abstract

Flight tests of the PCA system on the NASA F-15 airplane evolved as a result of a long series of simulation and flight tests. Initially, the simulation results were very optimistic. Early flight tests showed that manual throttles-only control was much more difficult than the simulation, and a flight investigation was flown to acquire data to resolve this discrepancy.

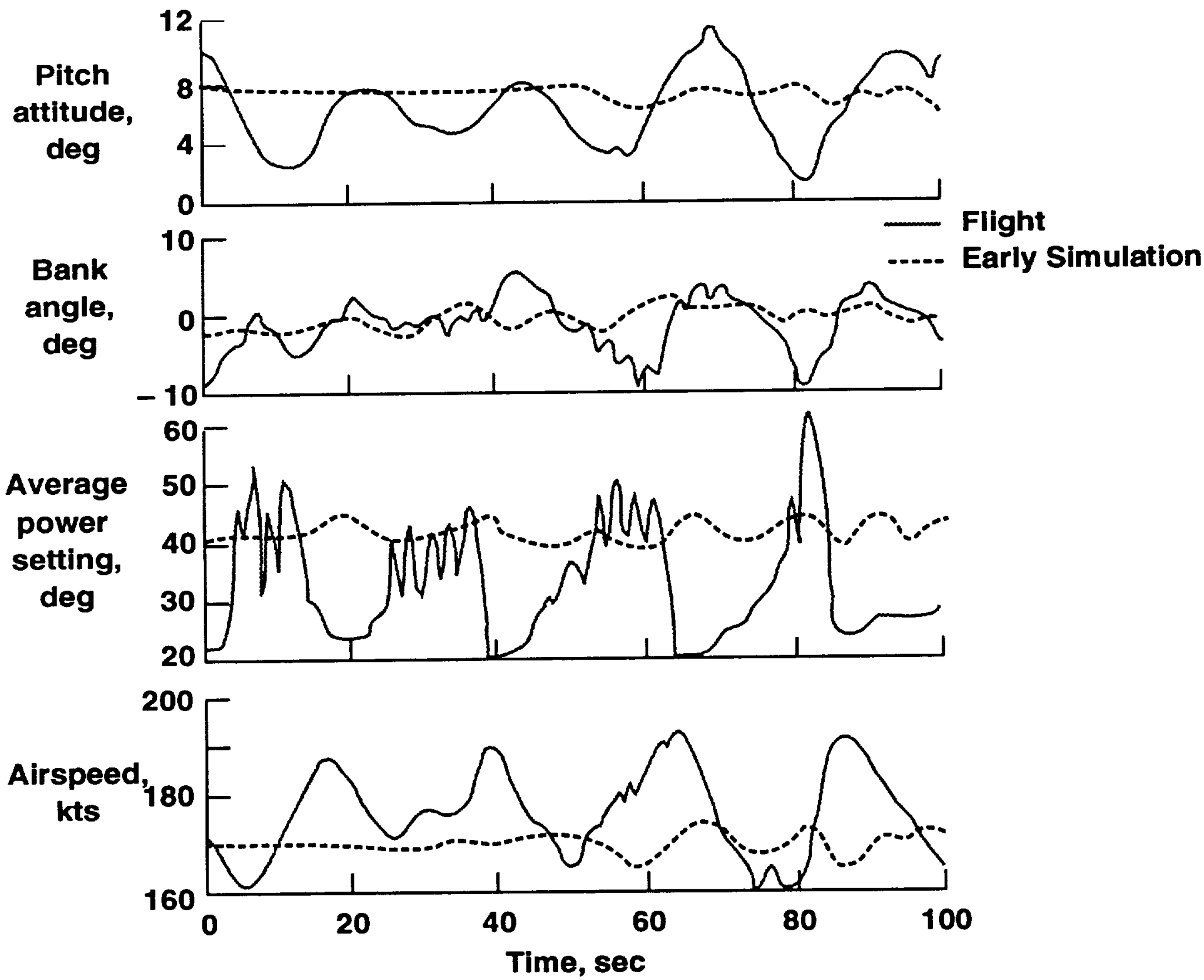
The PCA system designed and developed by MDA, and described in the previous paper, evolved as these discrepancies were found and resolved, requiring redesign of the PCA software and modification of the flight test plan. Small throttle step inputs were flown to provide data for analysis, simulation update, and control logic modification.

The PCA flight tests quickly revealed less than desired performance, but the extensive flexibility built into the flight PCA software allowed rapid evaluation of alternate gains, filters, and control logic, and within 2 weeks, the PCA system was functioning well. The initial objective of achieving adequate control for up-and-away flying and approaches was satisifed, and the option to continue to actual landings was achieved.

After the PCA landings were accomplished, other PCA features were added, and additional maneuvers beyond those originally planned were flown. The PCA system was used to recover from extreme upset conditions, descend, and make approaches to landing. A heading mode was added, and a single engine plus rudder PCA mode was also added and flown. The PCA flight envelope was expanded far beyond that originally design for. Guest pilots from the USAF, USN, NASA, and the contractor also flew the PCA system and were favorably impressed.

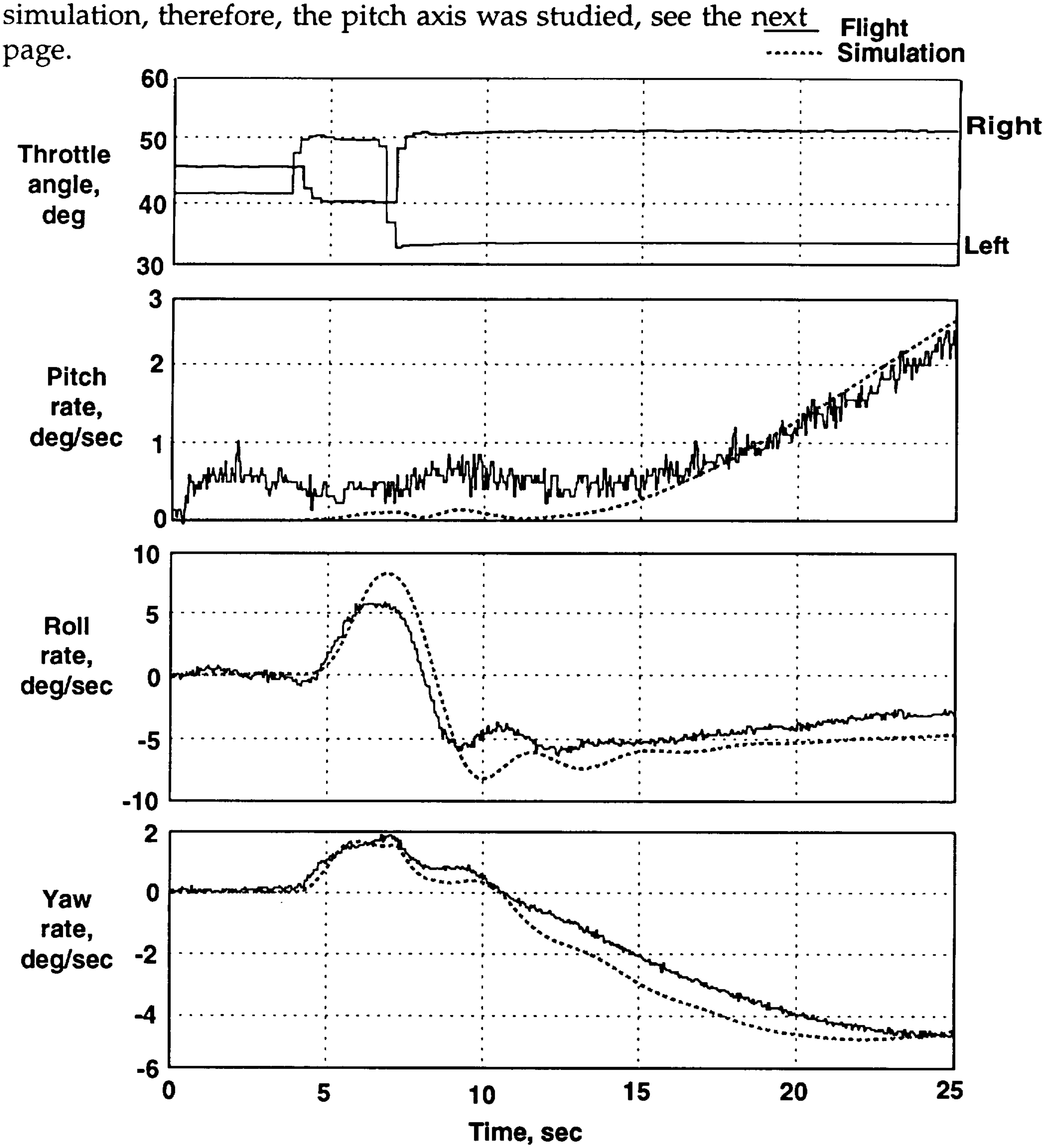
## Comparison of Early Simulation and Flight Approach

The early F-15 throttles-only simulation at Dryden showed that manual throttles-only approaches were difficult initially, but after some practice, pilots became proficient enough to make successful landings every time. First attempts at manual approaches in the NASA F-15 airplane were made, and were surprisingly unsuccessful, even after much practice. Shown below is a comparison of a flight and simulation approach at the same conditions; the much poorer performance in the airplane is clearly evident. The video shows a typical example. The basic airplane stability in the "CAS-off Pitch and roll ratios emergency" mode and "inlets emergency" mode was lower than in the simulation. The pilot had great difficulty in stabilizing on the desired flightpath, and had the throttles on the idle stop part of the time. The airplane would not stay wings-level for more than a few seconds. The pilot rated the chances of a safe throttles-only landing in the airplane at zero. The reasons for the simulation-to-flight discrepancies had to be resolved prior to designing the PCA logic.



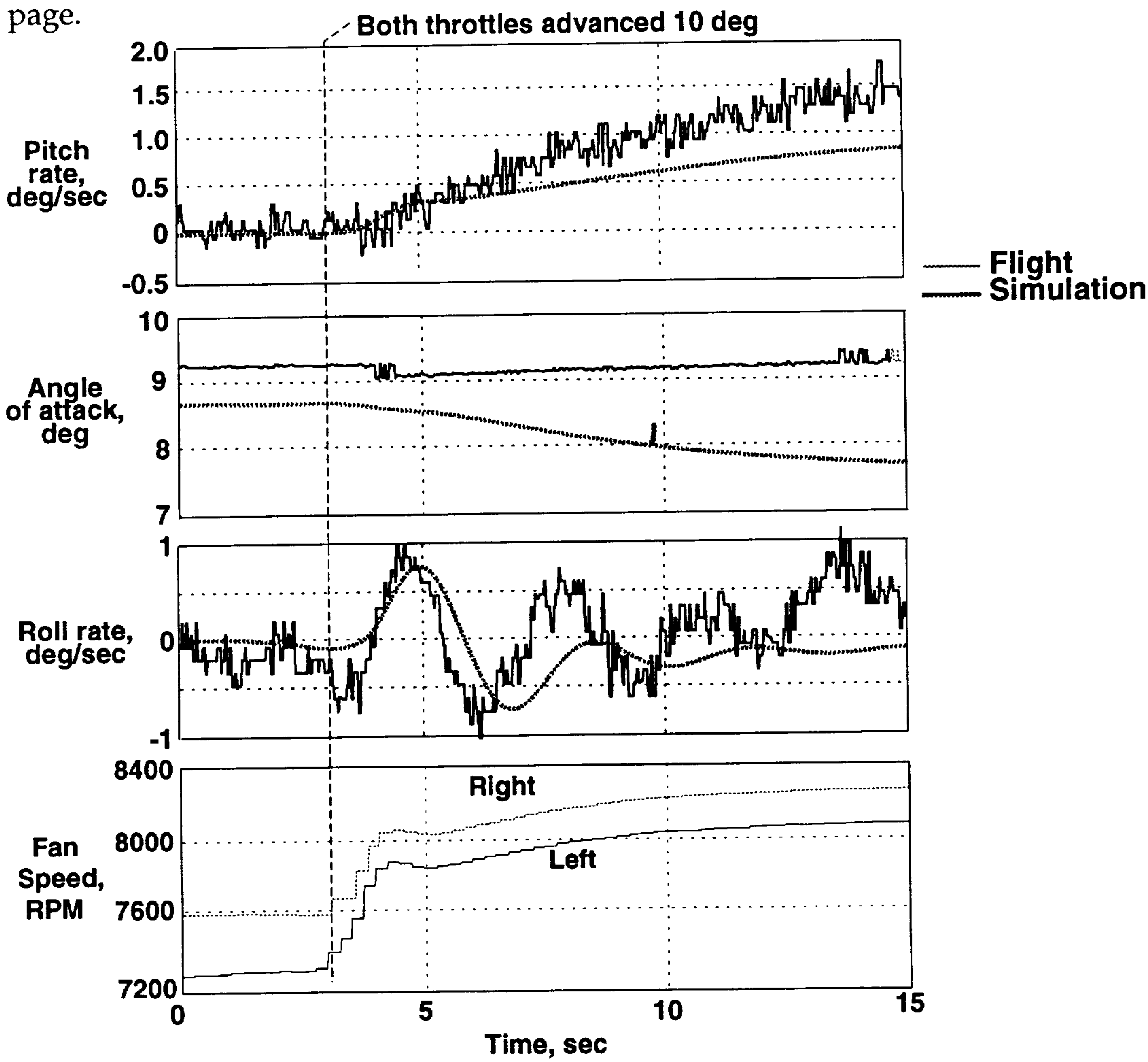
## Differential Throttle Step Tests

Small step inputs in throttle settings were made to obtain data to compare to the simulation. A typical differential throttle roll test case is shown below. The pilot initially split the throttles approximately 2 inches and held that for 3 seconds, then split the throttles 2 inches in the opposite direction. The flight-to-simulation yaw rate match is very good. The resulting roll rate oscillations were comparable in frequency and damping in both the flight and the simulator response, although the roll rates are higher in the simulation than in the flight data. This good agreement does not explain the discrepancy between flight and simulation, therefore, the pitch axis was studied, see the next page.



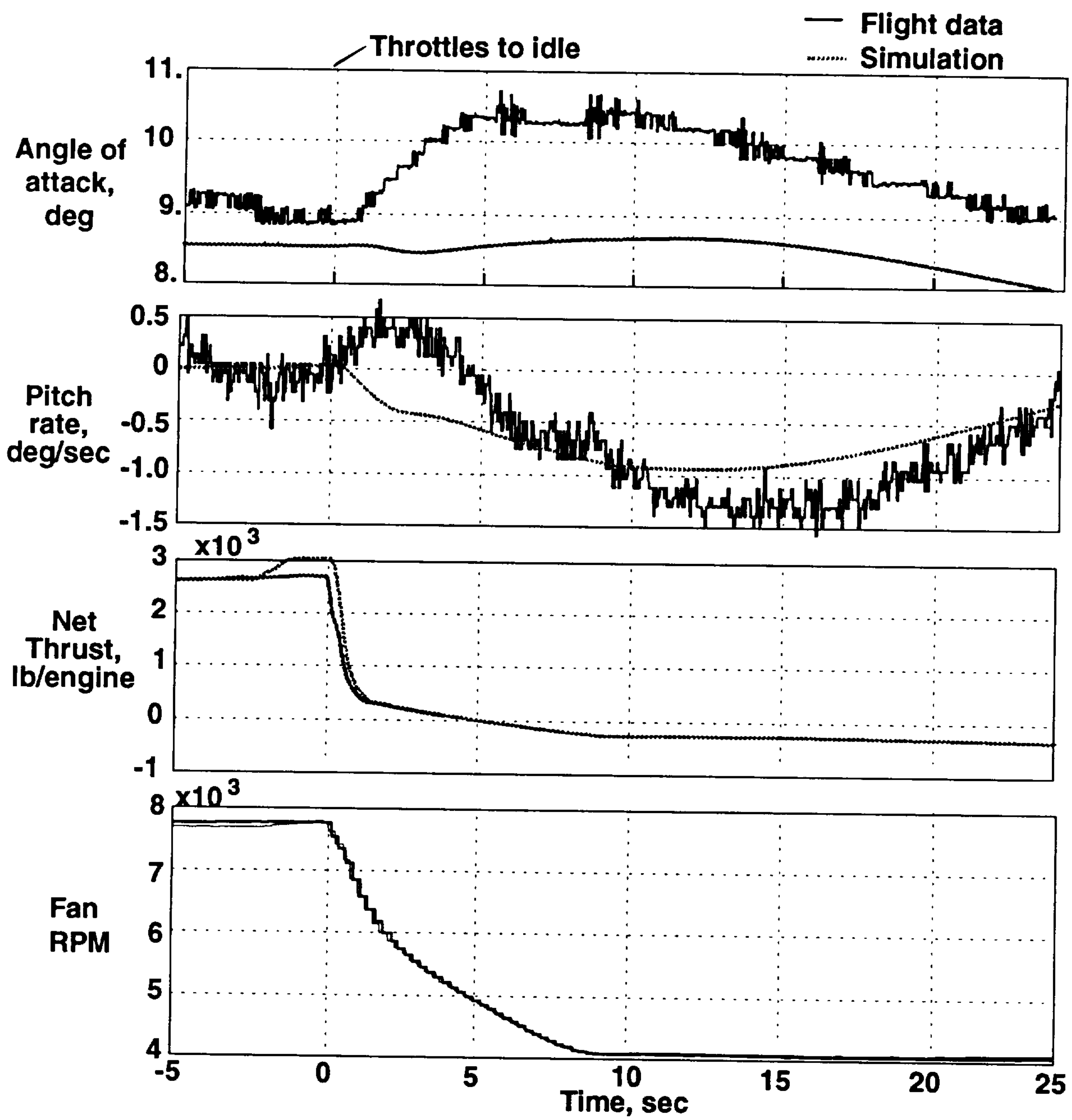
## Small Step Throttle Increase

Results of tests in which the throttles were both increased about 10 deg from the level flight setting, shown below, showed the expected pitch up, although less than the simulation predicted. The measured angle of attack varied only slightly, and did not display the reduction seen in the simulation. The small roll oscillation in the simulation matched closely that seen in flight. The flight fan speed data show that the right throttle was increased slightly more than the left. (The presence of a roll response from what was supposed to be a small pitch input is indicative of a problem that contributes to difficulty in flying manual throttles-only control, that is, inability of the pilot to make perfectly equal throttle inputs, or, if he does, that the engine thrust changes are not equal) Next, small throttle decreases were tested, as shown on the next page.



### Step Throttle Reduction

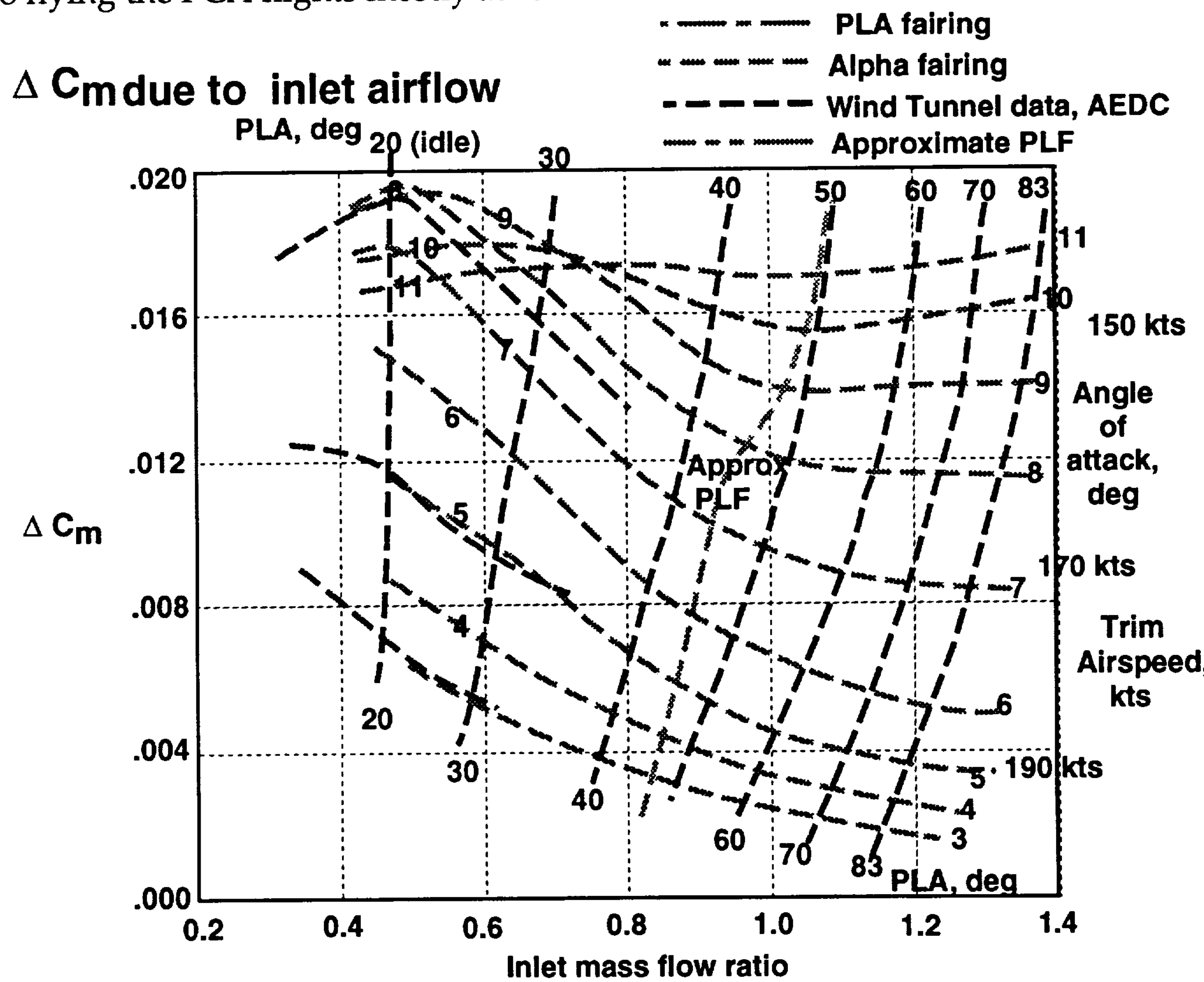
Differential throttle steps and throttle increase steps shown on the 2 previous pages agreed fairly well with simulation. Shown below is a typical step PLA reduction. The pitch rate comparisons of flight and simulation data are shown where both throttles were reduced from PLF to idle. While the long term response of the flight data was the expected pitch-down, there was a significant initial pitch-up. There was also a significant increase in angle of attack. Data at other flight conditions also showed the same initial pitch-up and angle of attack increase. These results called attention to what appears to be a serious discrepancy between the simulation and flight. Although thrust falls off rapidly (due to the nozzle opening), fan RPM decays slowly, taking almost 9 sec to stabilize, due to the slow respose of the "non-production" engine control logic. Fan rpm, which is proportional to engine (and inlet) airflow, and angle of attack show a direct inverse relationship. Because of this trend, inlet wind tunnel test data reports were examined.



## Inlet Airflow Effect on Pitching Moment

Wind tunnel data from an AEDC test showed a significant airflow effect on pitching moment, shown below. Unfortunately, it was a Mach number of 0.6, rather than the desired 0.25. Using data from the throttle step tests shown in the previous pages, along with other data, some of which was not available until the last PCA flights, the curves shown below were developed. Also plotted are the power lever angle (PLA) values, and the angle of attack values for level flight conditions over a range of speeds. Typical power for level flight (PLF) is also shown, varying between 45 and 50 deg for the flaps-down configuration.

These data show that at the low inlet mass flow ratios and low angles of attack, there is an adverse negative slope (decreasing throttle pitches the nose up). This causes the observed pitchup with the throttle step to idle, and the difficulty in manual throttles-only control that the pilots found in the airplane. The next page shows the throttle step with this inlet effect in the simulation. The data below also show that at higher angles of attack above 10 deg, and at higher mass flow ratios above 1, (which occur at lower speeds) that the inlet effect becomes less adverse, and possibly even favorable (positive slope). Decreasing speed at a fixed PLA also increases capture area ratio. Both of these effects would result from lower speed, thus the improved control at 150 kts, where the slope of $\Delta Cm/\alpha$ is near zero. This led to flying the PCA flights mostly at 150 kts.

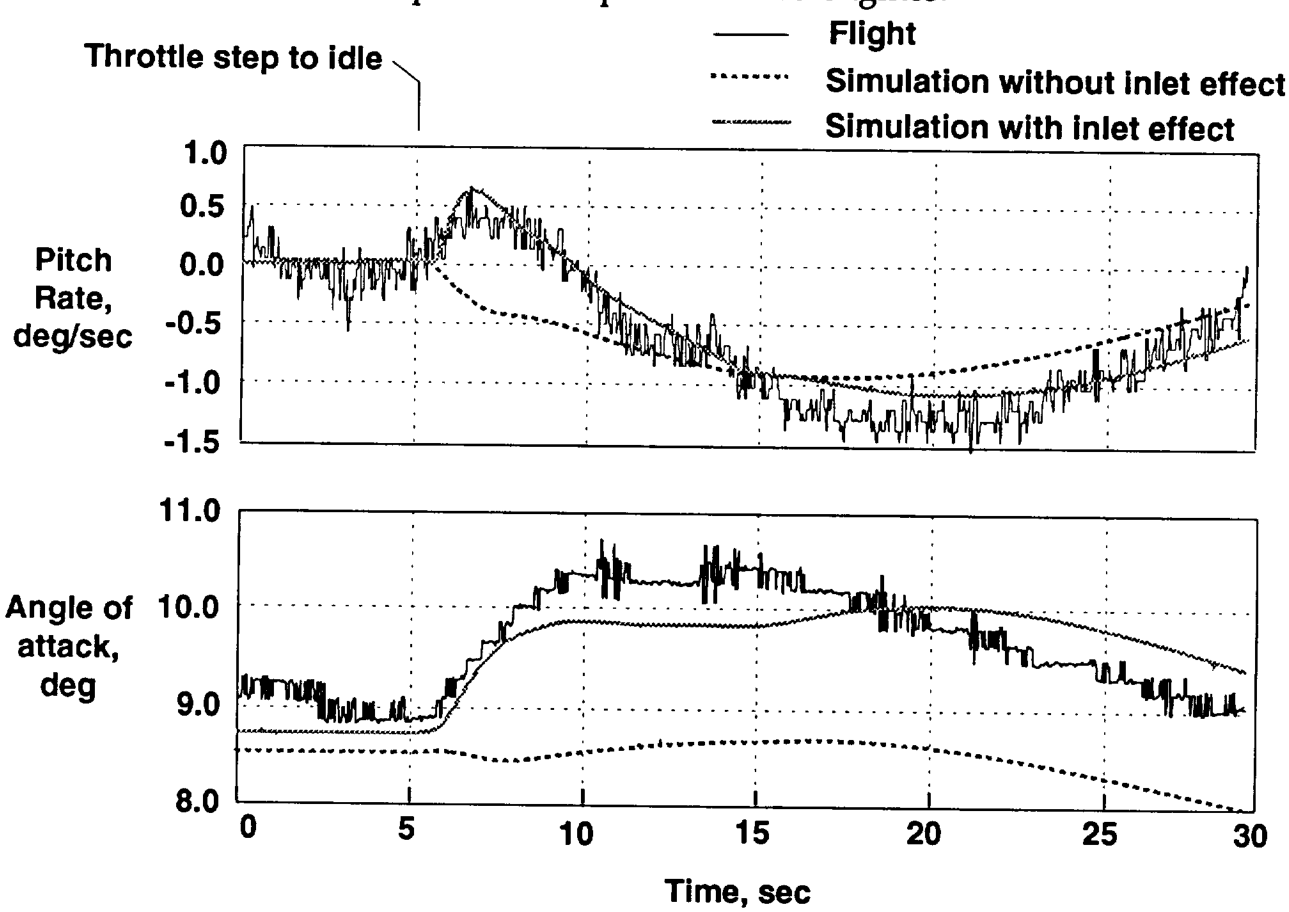


## Flight and Simulation Match with Inlet Airflow Effect Modeled

With the inlet airflow effect from the previous page included, the agreement between the simulator and flight results was substantially improved. The results of this inlet airflow effect are shown below, the same flight data shown two pages earlier. The initial changes in pitch rate and angle-of-attack are now properly modeled. With this match in-hand, the Dryden and MDA simulations were modified to incorporate the inlet effect, and the control laws were redesigned to add velocity feedback in the flightpath control logic.

The simulation with this effect added, showed many of the characteristics of the flight data; poor phugoid damping, a pitch PIO (pilot induced oscillation) tendency, sluggish response to pitch inputs, and an initial response in the opposite direction to that desired. The simulation match to the flight data was markedly improved.

The inlet airflow effect was very small, and would often be neglected in an airplane simulation. However, when the only moments being used for control are the small moments from the propulsion system, normally neglected effects may become significant. This is particularly true for airplanes with highly integrated propulsion systems such as fighters where inlet /airframe interactions are strong. It would likely be less true for subsonic airplanes with pod-mounted engines.



## F-15 Throttles-Only Control Simulation Upgrades

The inclusion of the inlet airflow effect was only one of many simulation upgrades required for the PCA flight evaluation. The list below summarizes the major changes to the NASA Dryden simulation in the order in which they were made. At the beginning of the throttles-only studies, the Dryden F-15 simulation consisted of a 6 degree of freedom fixed base piloted simulation, with a high-fidelity aerodynamic data base, and lower fidelity flight control system and engine models. The aero database assumed the inlets were operating on their nominal schedules.

Some of the additions were minor and had only a small effect, while others were major, and required continued iteration as additional data became available. Some of the inlet effects upgrades were not finalized until after the flight program was completed and the envelope expansion flight data became available.

The most significant additions included the improved engine dynamics model, the PCA logic, and the inlet airflow effects model. The availability of a highly flexible simulation was critical in the development of the PCA concept for the F-15.

**Initial F-15 Six degree of freedom non-linear simulation with nominal inlet schedules, engine modeled from net thrust tables with first order lags.**

- **Lock control surfaces at any given position**
- **Incorporate augmented control laws from NASA B-720**
- **Incorporate variable inlet effects on lift, drag**
- **Separate gross thrust and ram drag terms**
- **Add thumbwheels for control inputs**
- **Incorporate horizontal CG effects**
- **Incorporate vertical CG effects as a function of fuel quantity**
- **Model CAS-off stick fixed pitch and roll ratios emergency control system**
- **Add ground effect model**
- **Add landing gear model**
- **Improve engine dynamics (Ed Wells model)**
- **Add gyroscopic moments**
- **Add non-linear inlet airflow effects**
- **Add flight path command box to HUD**
- **Add McAir control laws and trimming**
- **Incorporate trim-while-fly**
- **Incorporate velocity feedback, variable inertias**
- **Incorporate 3 trim options**
- **Incorporate "help" path to control law**
- **Incorporate improved CG, inertias, weight for F-15 835**
- **Incorporate revised ground effect model**
- **Incorporate heading mode**
- **Incorporate added bank angle control logic features**
- **Incorporate updated inlet effects models**

### PCA Flight Evaluation

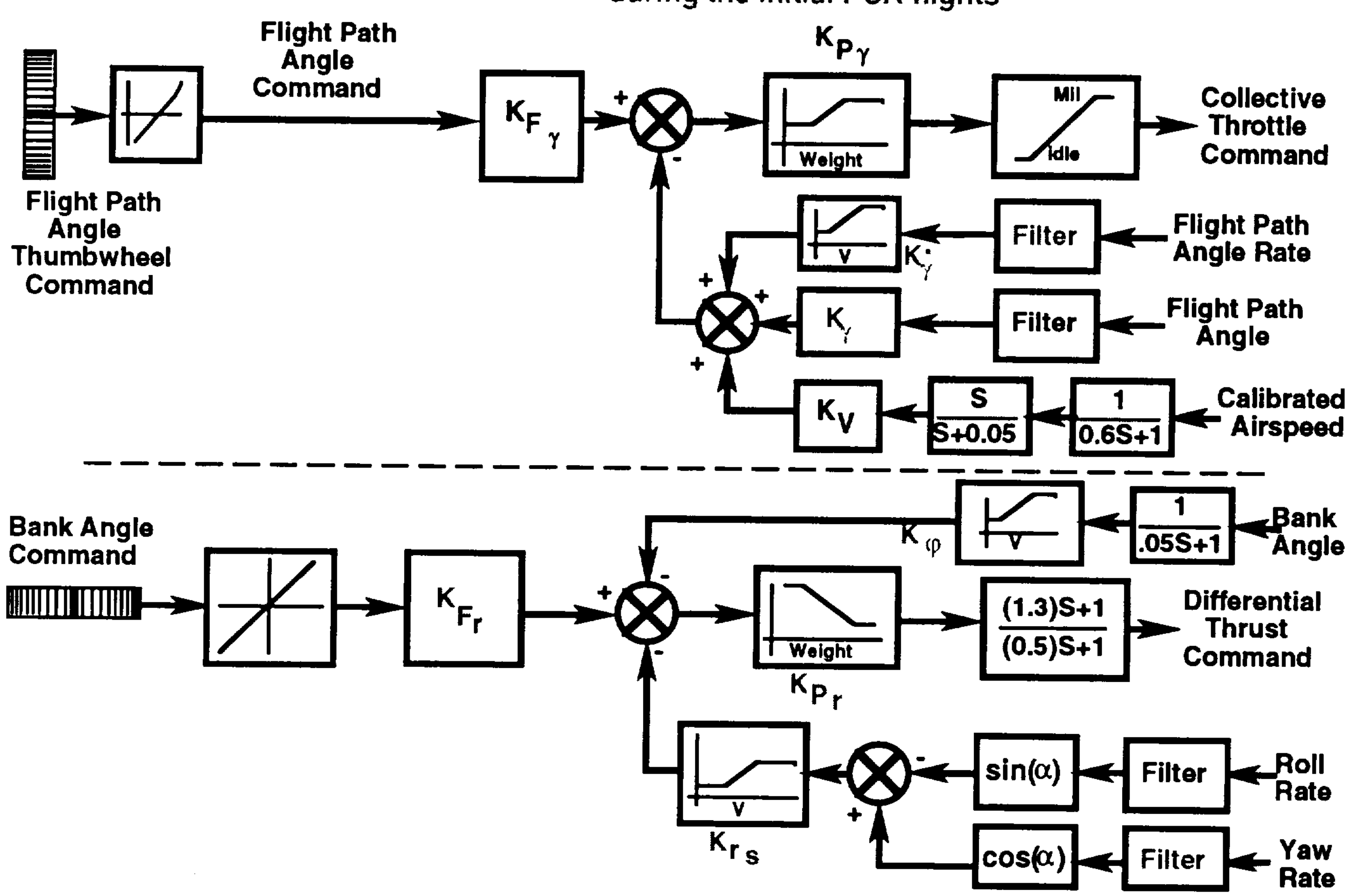
With a reasonably good match between simulation and flight data, the PCA control laws were finalized as shown below and the software and hardware-in-the-loop tests were performed, as outlined in the preious paper. Following the ground tests, the first PCA flight was flown in Jan 1993. The first flight was mostly devoted to showing that the many safety features worked as planned, and that the PCA system could always be disengaged. All worked as expected.

Toward the end of the first flight, the PCA system was engaged, allowed to trim, and was briefly evaluated at an altitude of 10,000 ft and 150 kts. Initial performance was less than desired, particularly in the lateral axis. With the extensive flexibility of the flight software, the real-time monitoring capability, and the pilot's ability to make changes through the NCI panel, it was possible to quickly make changes and evaluate the results. The parameters shown shaded below were changed.

PCA pitch performance was reasonably good, only small gain change was made. In the lateral axis, the previously unused bank angle feedback was increased, while the yaw rate feedback was filtered and reduced. The thumbwheel gains were also adjusted. A typical evaluation consisted of making a change, evaluating performance in level flight with small step inputs. Then, a closed loop tracking task was tried, typically tracking a road from an altitude of about 3000 above ground level(AGL). If the results were promising, a simulated or actual approach was then flown. If not, further adjustment were made. After 5 flights, the pilots and engineers were happy with the PCA performance, and approaches to lower altitudes were flown, with the pilot taking over with the stick at progressively lower altitudes, first 200 ft, then 100 ft, then 50 ft, and finally as low as 10 ft AGL. PCA go-arounds were also made from altitudes of 200 ft and 100 ft AGL.

## PCA Logic Block Diagram

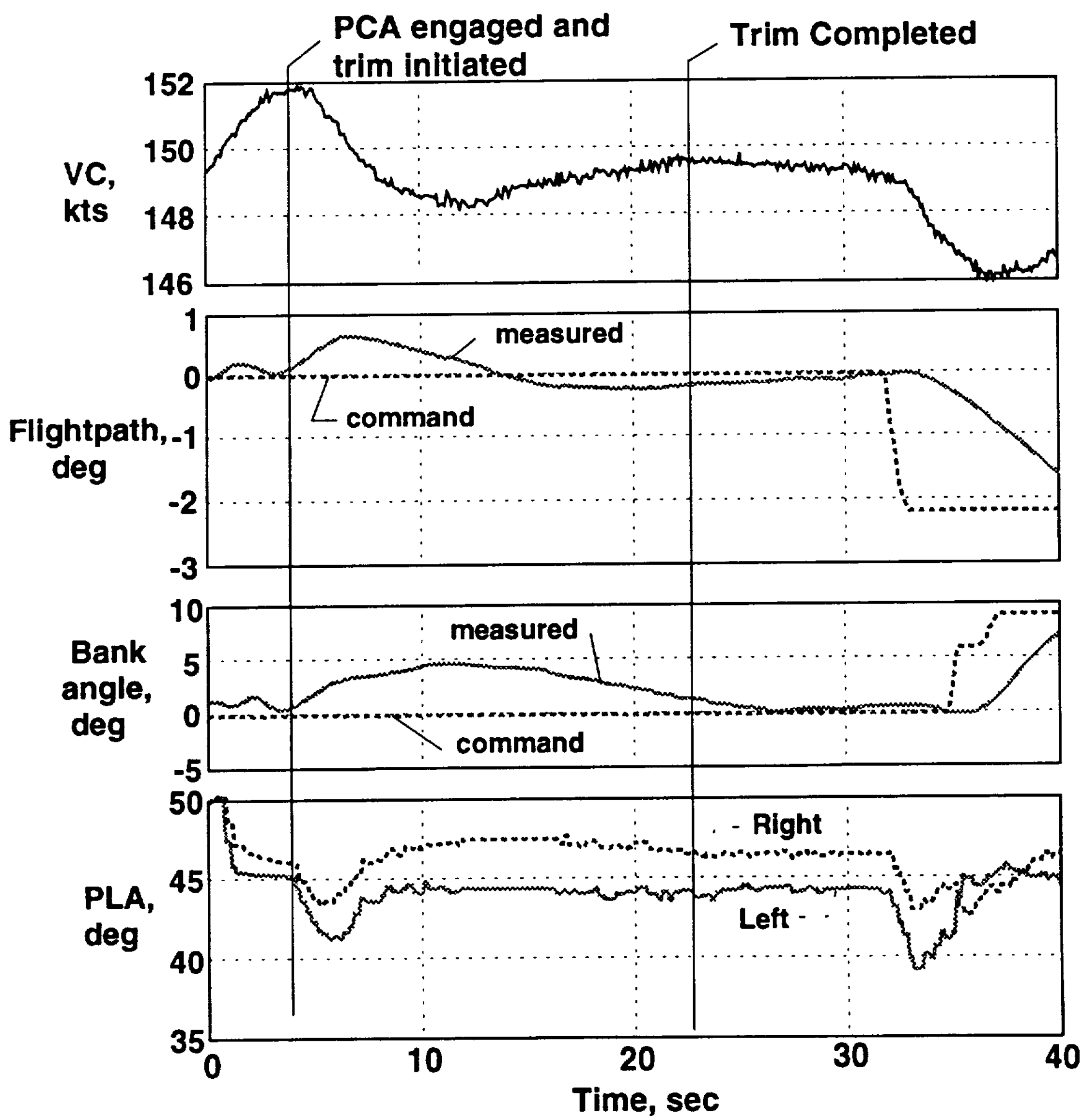
Shade indicate parameters changed during the initial PCA flights



### PCA Trim Tests

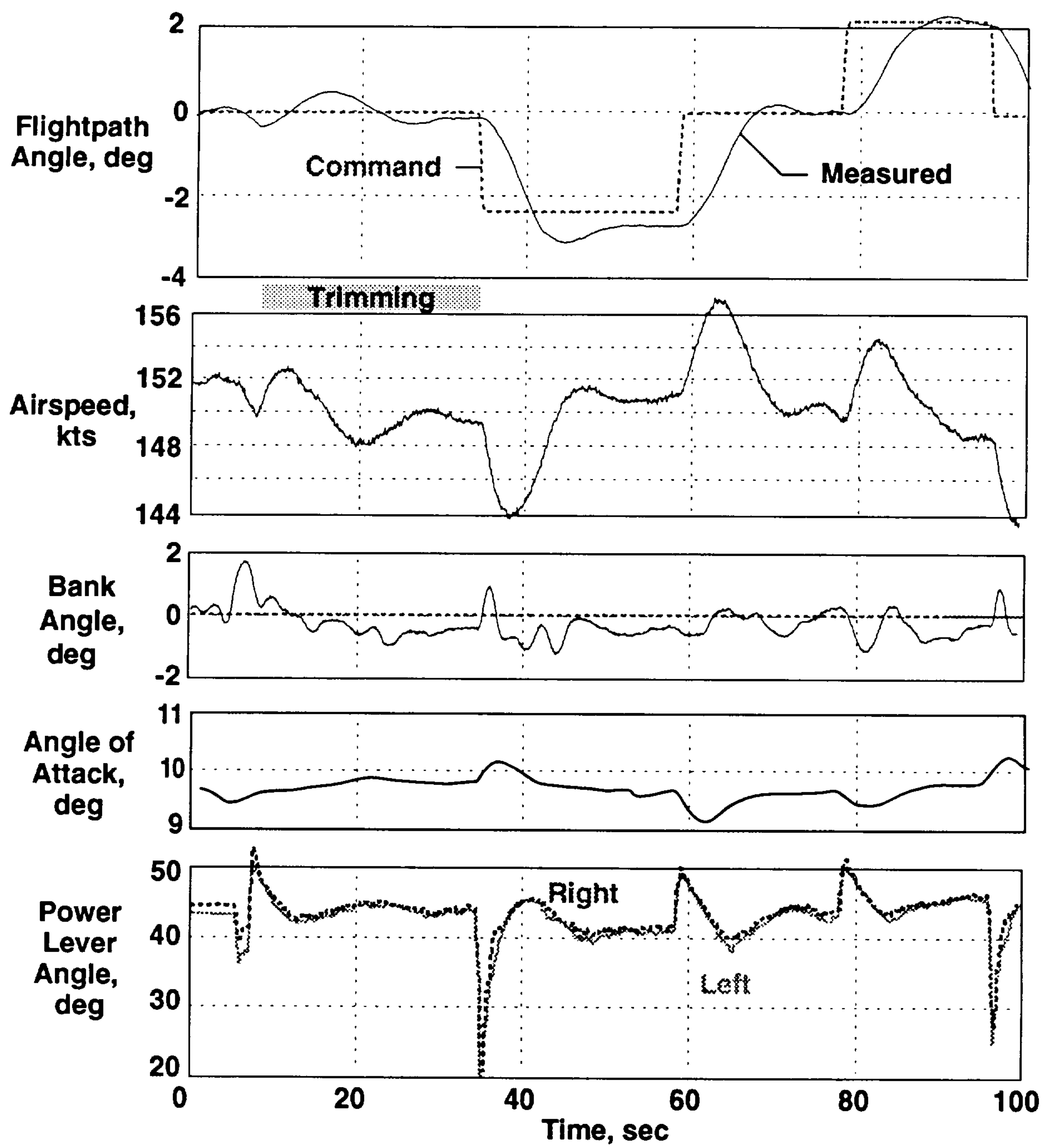
When PCA was first engaged, with pitch and roll thumbwheels in the detent position, the trimming function, described in the previous paper, slowly adjusted the thrust of the engines to achieve level flight. A PCA trimming operation is shown below, with about 20 sec required to satisfy the trim requirements. The trim performed well, much as it did in the simulation, although 30 seconds or more was normally required for trimming to be completed.

If the air was turbulent, the trim criteria might never be satisfied; if this occurred, the pilot would select trim off to improve the flightpath stability. After long periods of PCA operation (several minutes), biases would sometimes develop which would require the pilot to select other than the detent position on the thumbwheels to achieve level flight. When this occurred, the pilot would select trim on and then trim auto to trim out the biases. There were a few instances when the trim requirements were met immediately after PCA engagement, even though an adequate trim had not really been achieved. In these cases, when biases developed, the pilot would cycle trim to off and back to auto.



**PCA Flightpath Step Response**

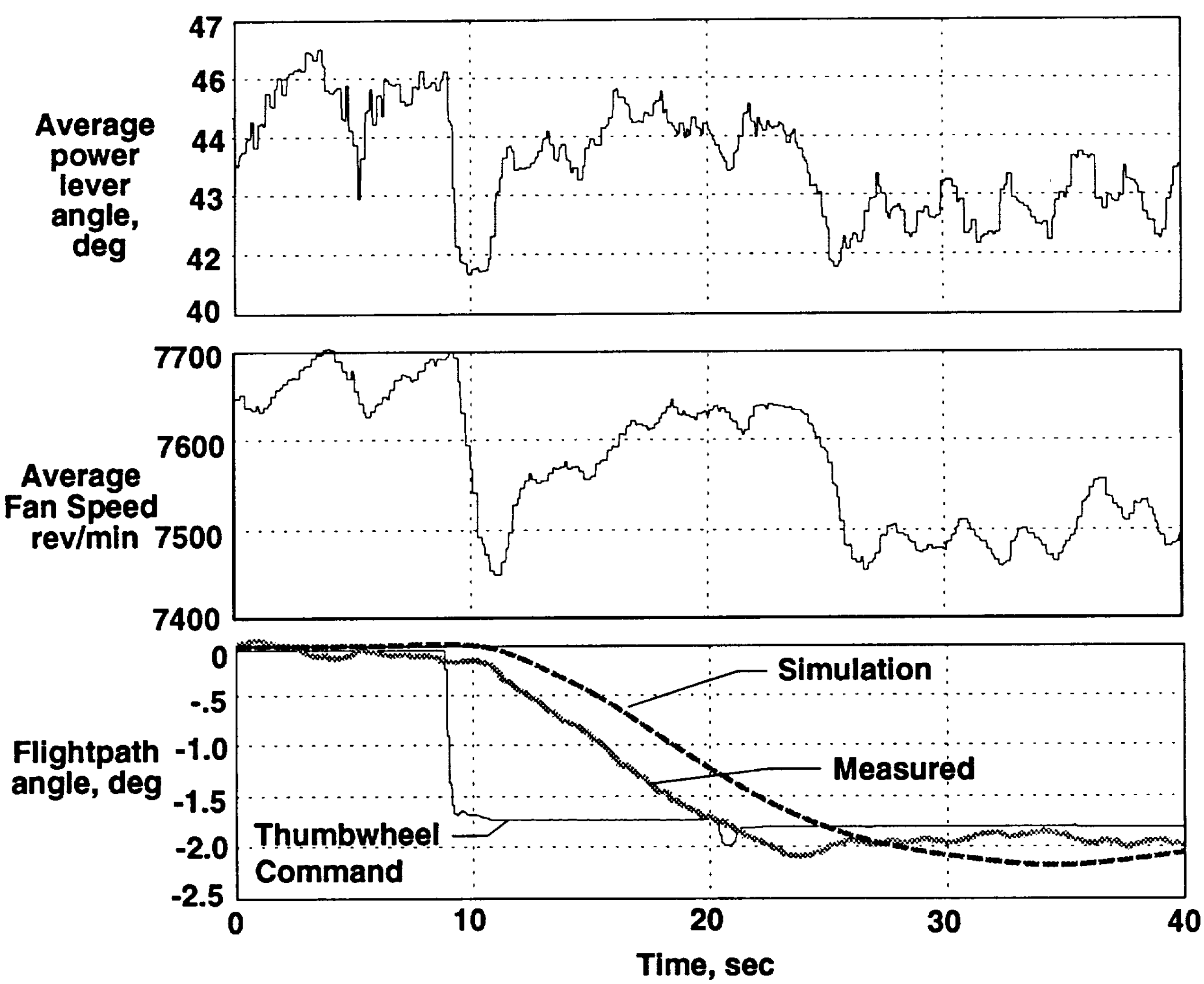
Shown below is a series of PCA flightpath angle step input responses. The pilot carefully matched the throttles before trimming the airplane, so that the engines were well-matched. The air was very smooth, as indicated by the minimal noise on the airspeed trace. After the trim cycle was completed, at 150 kts and 44 deg PLA, the pilot made a -2.4 deg step down. The PCA system reduced the throttles almost to idle, then back up and stabilized at about 42 deg; airspeed dropped 6 kts as the nose started down, then stabilized 1 kt above the initial speed in the descent. The response shows about 10 sec to reach the minimum flightpath with a slight overshoot. At the reduced PLA, the inlet effect resulted in a slight increase in angle-of-attack. The bank angle command remained zero, and only a 1 deg bank angle change occurred during the flightpath step. The step back to zero, the step to +2 deg flightpath, and the step back to zero all show similar trends. The throttle increases were similar in thrust, but less in PLA due to the non-linear thrust characteristics shown previously.



## PCA Step Response

Numerous step thumbwheel command inputs were made to both flightpath and bank angle axes at varying weights, airspeeds, and gain combinations. These step inputs were designed to allow detailed post-flight comparisons of actual flight performance with simulation predictions, and between differing flight control configurations tested. A response to a small negative flightpath angle command is shown below at 150 knots with the flaps down. The initial throttle decrease is followed by throttle modulation to achieve the desired flight path with minimum overshoot. The average fan speed, a good indicator of thrust, is also shown. Approximately 11 sec is required to achieve the 1.8 deg decrease in flight path angle. A comparison of the non-linear simulation at this condition shows a slightly slower response, but reasonably good agreement with the flight data.

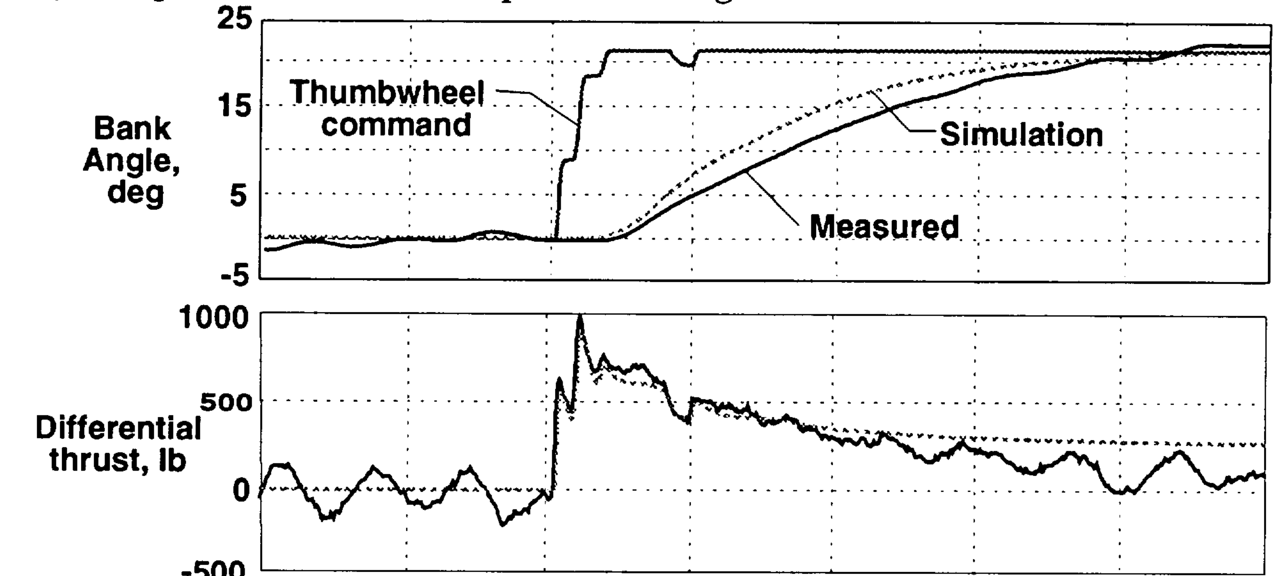
Pitch response at higher speeds was degraded due to the adverse inlet effect.



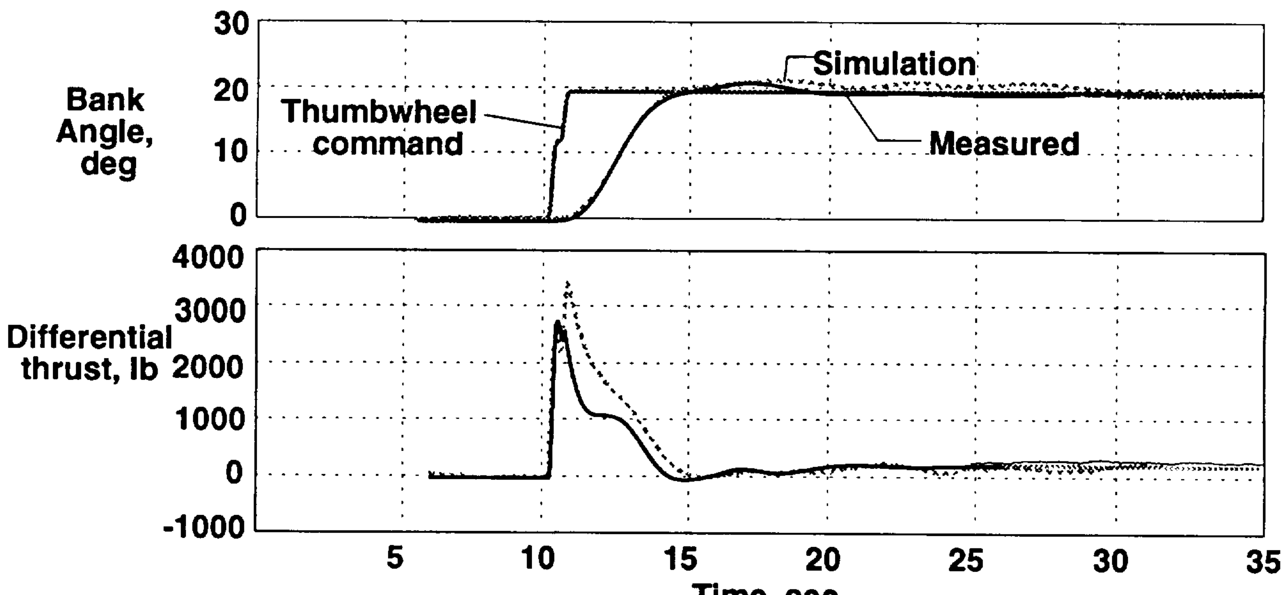
**Bank Angle Step Response**

Roll response to a full roll step command at 150 kts is shown below. Roll control was initially quite poor due to low roll rate, as shown, with 28 seconds required to achieve the commanded bank angle. Only a very small differential throttle command was generated by the control laws. This low roll rate was dictated by results from the MDA hardware-in-the-loop simulation, in which higher gains caused a limit cycle oscillation.

Extensive flight evaluations were conducted to improve roll performance. After several iterations over 5 flights, changes in gains, in yaw rate filtering, and addition of bank angle feedback greatly improved the roll response, as shown in the lower part of the figure, with the commanded bank angle being reached within 6 sec. A significant degree of differential thrust was commanded in this test. No evidence of the limit cycle oscillation was seen in the flight tests. Again, comparison to the non-linear simulation prediction for this condition is reasonably good. The flexibility of the flight software was absolutely critical in making the major improvement in roll response in 5 flights.



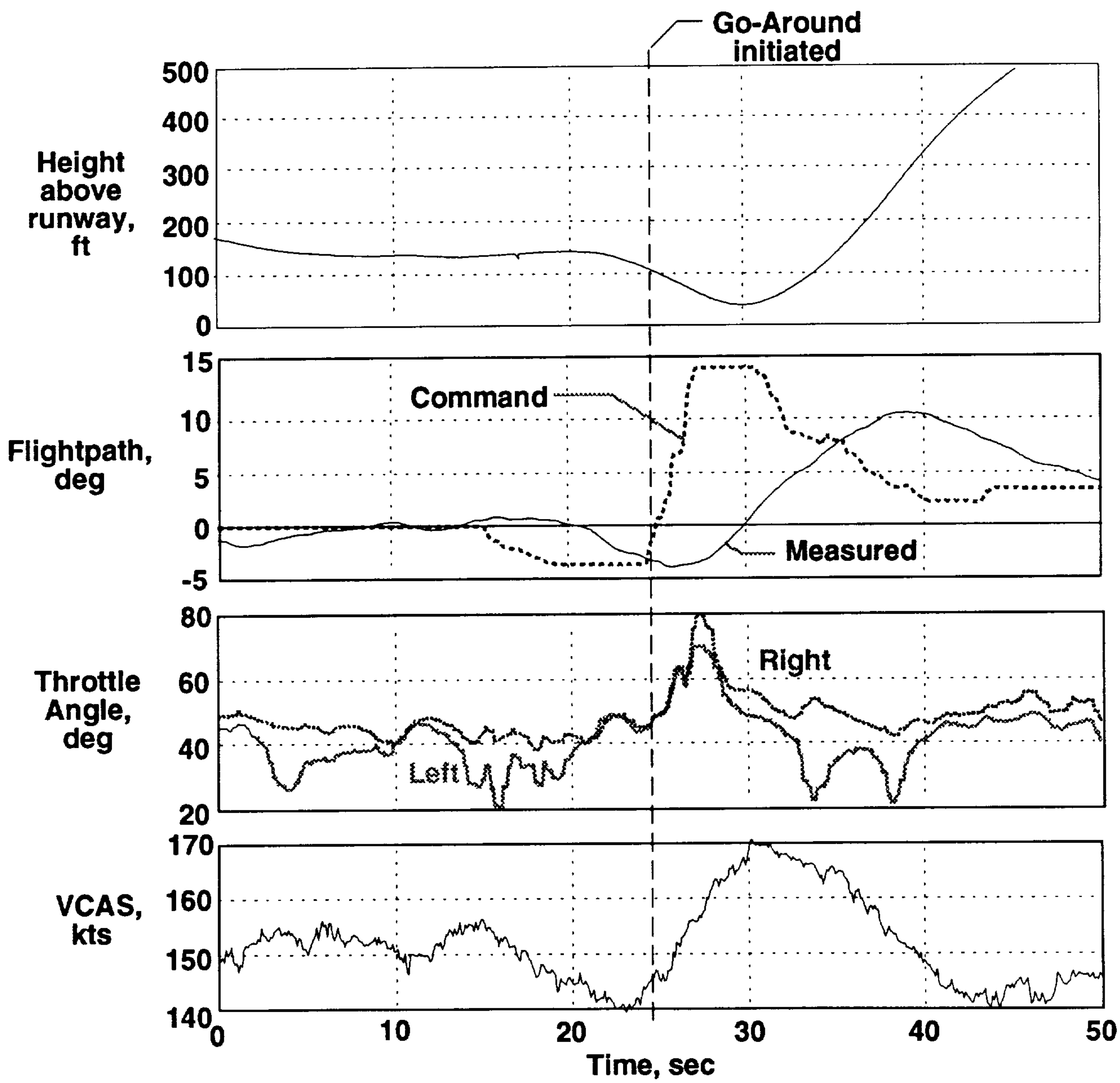

*Original bank angle control logic*




*Improved bank angle control logic*

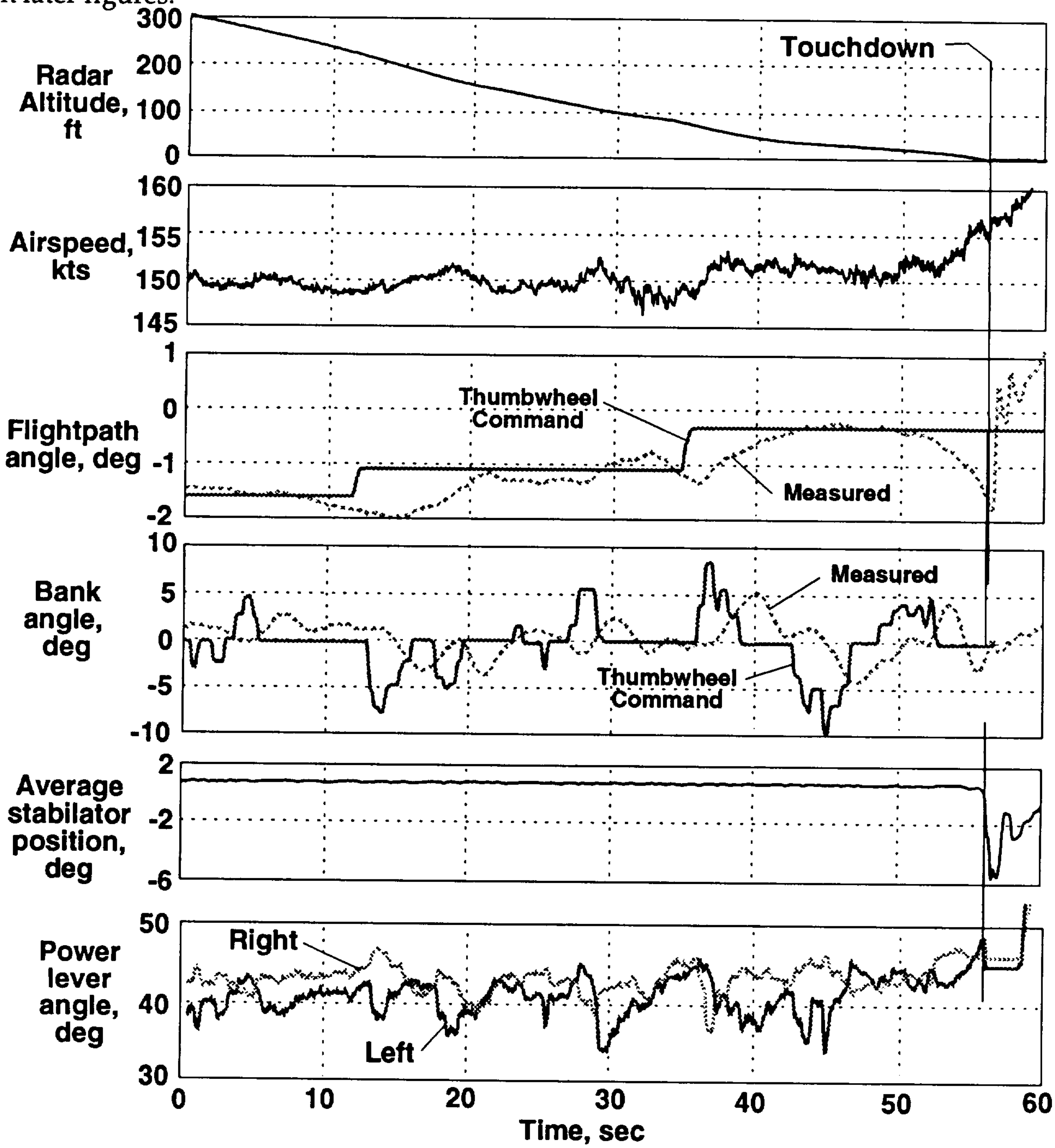
### PCA Approach and Go-Around

Once the PCA step response and up-and-away control were satisfactory, PCA approaches were made. Shown below is approach with a PCA go-around. In this case, the pilot had leveled off about 140 ft AGL, with a trim speed of 151 kts in light turbulence. At t = 15 sec, he reduced the flightpath command to -3 deg. Speed dropped to 140 kts, and at 110 ft AGL, he moved the flightpath command from -3 to +14 degrees to initiate the go-around. About 70 ft was lost, and it was 5 seconds from the go-around command until the flightpath became positive, as the speed increased to 170 kts. The PCA system command reached almost full throttle due to the large error between actual and commanded flightpath at t = 27 sec during the go-around. Throttle command then was reduced as flightpath angle rate (gammadot) became positive. This performance was considered good.



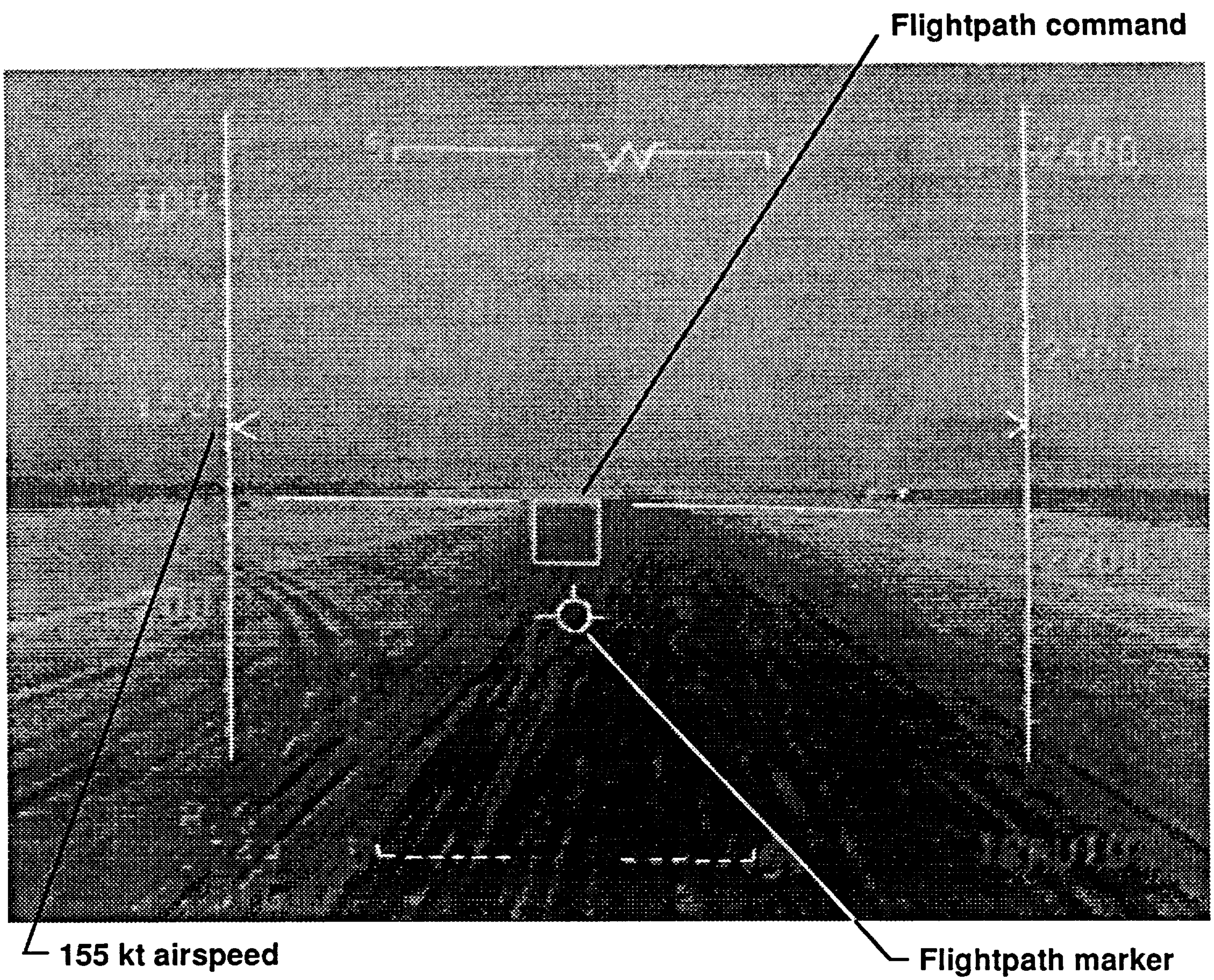
**PCA Approach and Landing:**

Following PCA low approaches, and PCA go-arounds, actual PCA landings were made. A time history of the last 56 sec of the first PCA landing is shown below. The conditions for this landing included an 8 kt headwind approximately down the runway, and only very light turbulence, except for a short period of light turbulence at t = 30 sec. Based on simulations with the revised ground effect model, the pilot reduced the flightpath command from -1.6 deg to -1.1 deg at an altitude of 200 ft AGL, and to -0.4 deg at 80 ft, resulting in a very shallow final approach. Pitch commands were few, and almost full time was spent making small bank angle commands to maintain runway alignment. At an altitude of 20 ft, 6 sec before touchdown the ground effect begins to affect the flightpath, primarily with a nose-down pitching moment. The PCA system increased throttle setting, and speed to try to counter the ground effect, but with no flight control input, the nose pitched down to -1.8 deg at touchdown, at which point the pilot made an aft stick input to cushion the impact on the main gear and to assure that the nosegear did not touch first. Bank angle control and lineup was good throughout the final approach. A small correction to the right was made just before touchdown. The HUD video at touchdown and the last 6 sec of this landing are shown in later figures.



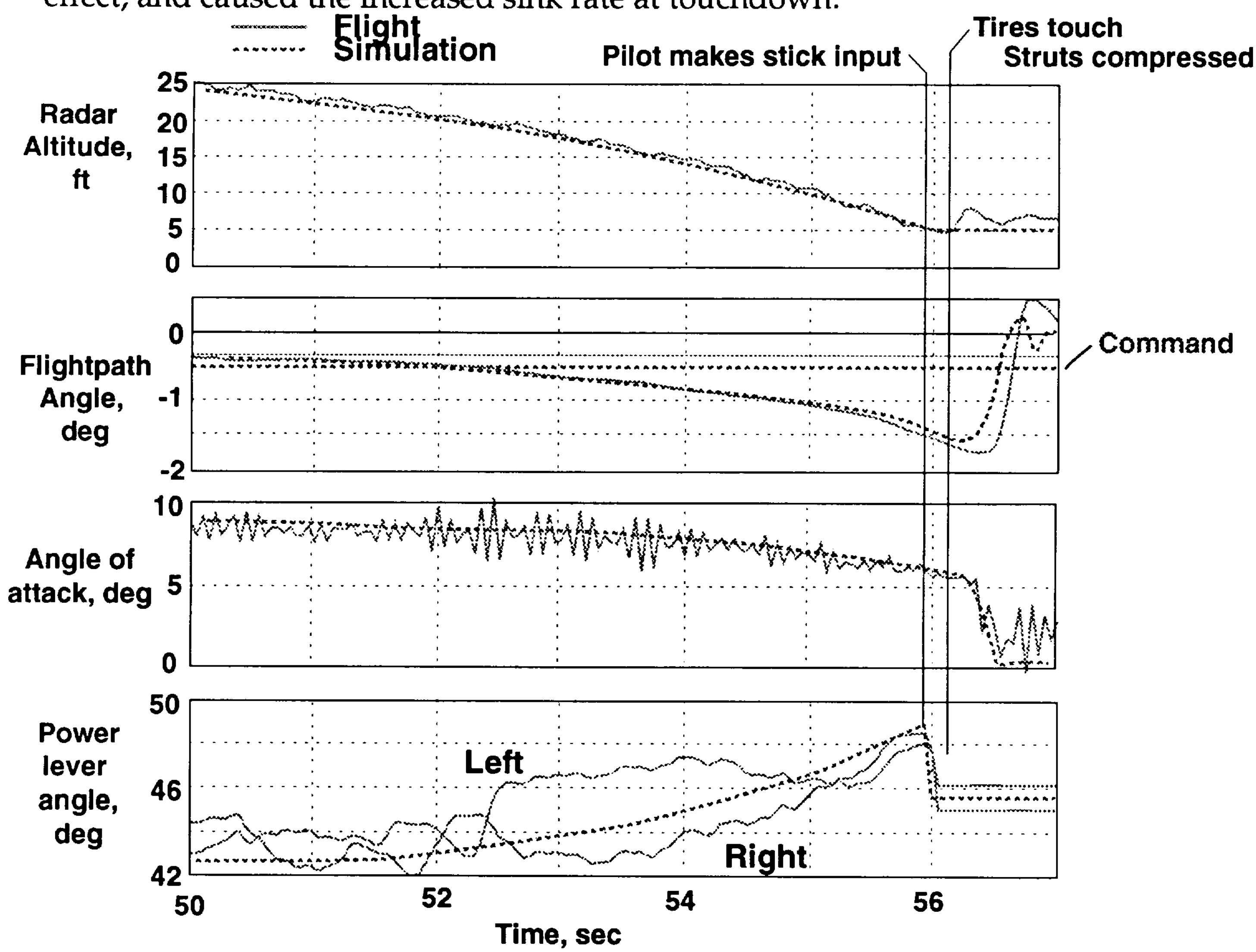
## F-15 HUD Video at first PCA landing

Shown below is the last HUD video frame prior to touchdown. It shows the flightpath command box at -0.4 deg, and the flightpath marker at -1.8 deg, well below the command due to the ground effect. The radar altimeter is off; it does not show an output below 10 ft. The bank angle at touchdown was -1 deg and the touchdown was approximately 6 ft of the left of the runway centerline. The pilot rated the pitch control as very good except for the ground effect, and roll control adequate for this first landing.



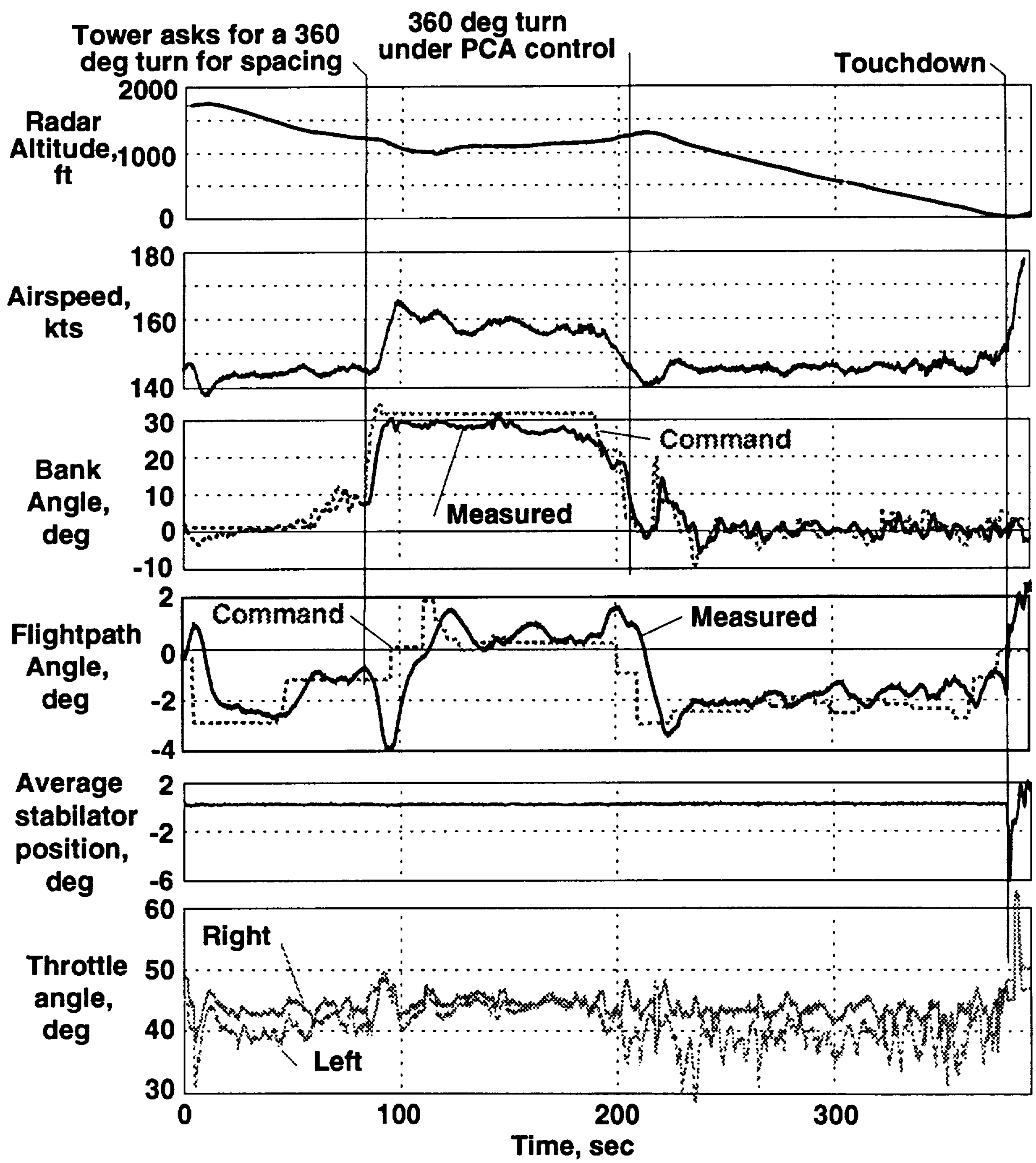
**Ground Effect on PCA Landings**

With the inlet effect modeled, and the ground effect model revised as discussed in paper 13, the observed large ground effect on landing could also be studied in the simulation. The data below from the first PCA landing, shown earlier, shows a comparison of the simulation to the flight data. Excellent agreement is seen. The ground effect, beginning about 20 ft AGL, caused the angle of attack to be reduced from 9 to about 7.5 deg. This angle of attack change caused the inlet effect to generate an additional nose-down pitching moment that reduced the angle of attack further to 6.5 deg. At this low angle of attack, the PCA action of increasing thrust to counter the pitchdown caused additional nose-down pitching moment that made the angle of attack at touchdown equal to 6 deg, (a 33% reduction in angle of attack) which more than compensated for the increased lift due to ground effect, and caused the increased sink rate at touchdown.



**Second PCA Approach and Landing**

Following the first PCA landing, another approach was made. In this case, shown below, the control tower requested a 360 deg turn for spacing 6 miles from the runway at 90 sec. The pilot made this turn under PCA control, selecting an immediate 32 deg bank. The nose dropped to -4 deg but was recovering when the pilot commanded a slight climb. At 200 sec, he rolled out and then continued the approach. Air was smooth until 200 ft AGL when very light turbulence began. On final approach, a steeper glideslope of -2.5 deg, then decreasing to -1 degree was flown until 20 ft when the command was raised to 0. In spite of this different technique, the ground effect caused a significant pitchdown, and touchdown was again at 8 ft/sec. Lineup was again good, with touchdown 6 ft from the centerline.

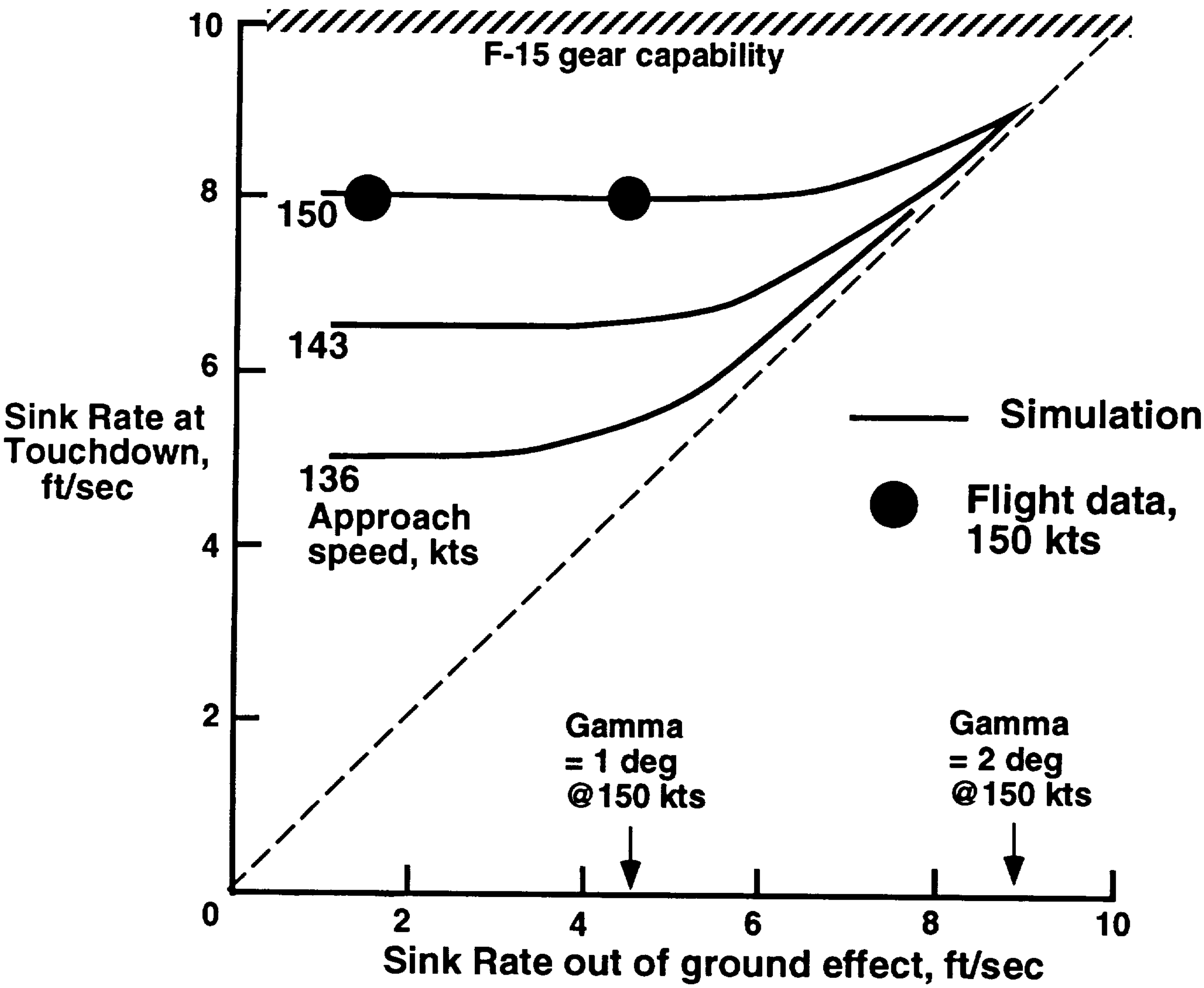


### Effect of approach flightpath on touchdown sink rate

With the excellent agreement between the updated simulation and the PCA flight data, the ground effects could be further studied. The Dryden simulation with the dynamic ground effect and the inlet effect modelled was used to evaluate the touchdown sink rate as a function of the approach flightpath angle. The simulation results are shown below for a range of approach flightpath angles (sink rates out of ground effect) ; the overall result at 150 kts. is that the touchdown sink rate is 8 ft/sec for a range of lower sink rates out of ground effect from 7 to 1 ft/sec. The 2 flight landings, one at a very low flightpath angle and the second at a 1 deg flightpath angle agree very well with the simulation.

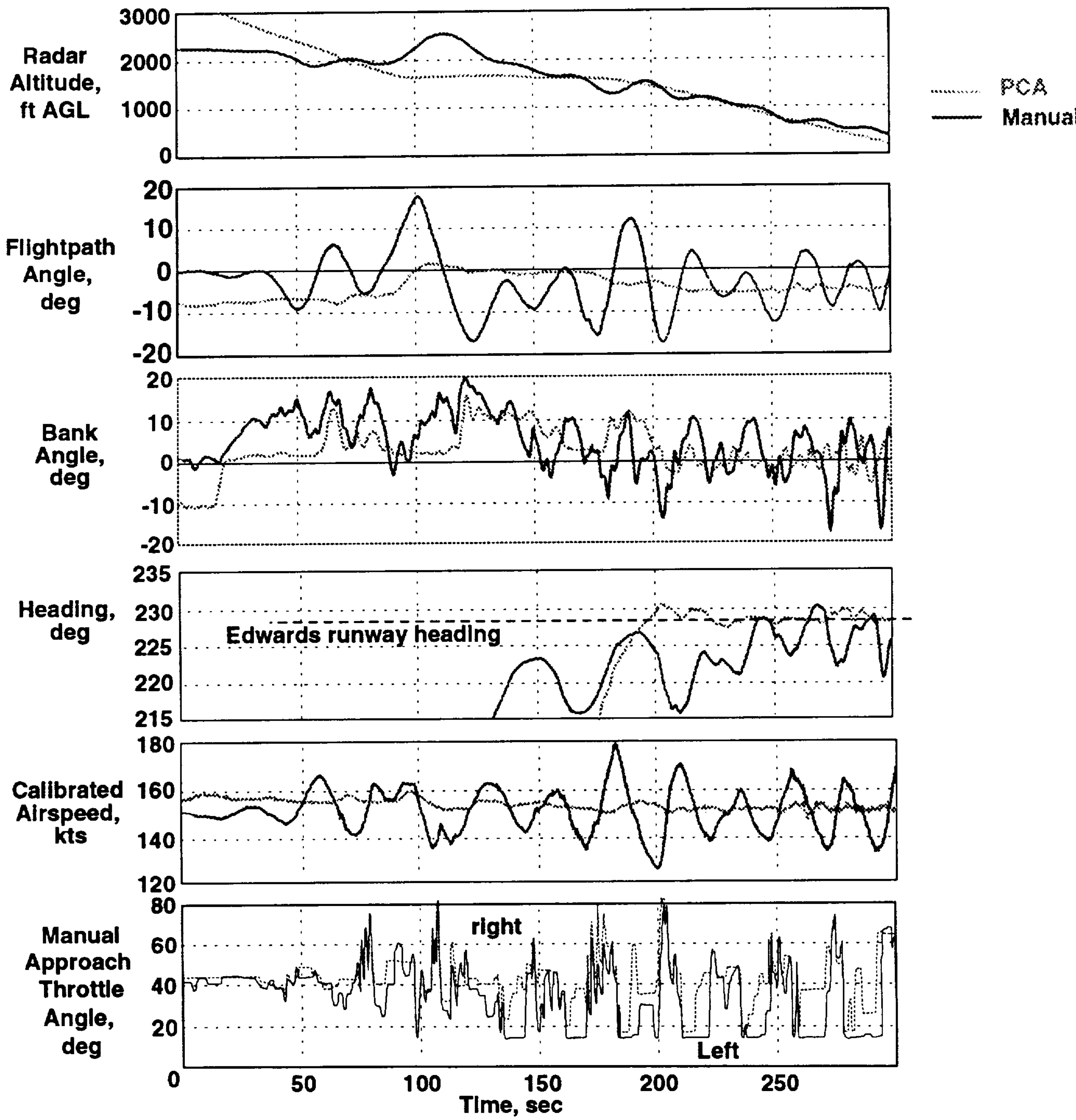
In the simulation, the effects of lower speeds were also evaluated. As expected, it was found that PCA landings could be made at lower touchdown sink rates if the speed was lowered. Lateral control deteriorated (due to lower natural dutch roll damping) at lower speeds, but remained acceptable in the simulation down to 136 kts, and pitch control continued to improve at lower speeds and the higher angles of attack.

Although ground effect will be a concern for any type of airplane using a PCA system, the added adverse ground effects due to the F-15 inlets should not in general, be a factor, particularly for transports with podded engines.



## Manual Throttles-only and PCA Approach Comparison

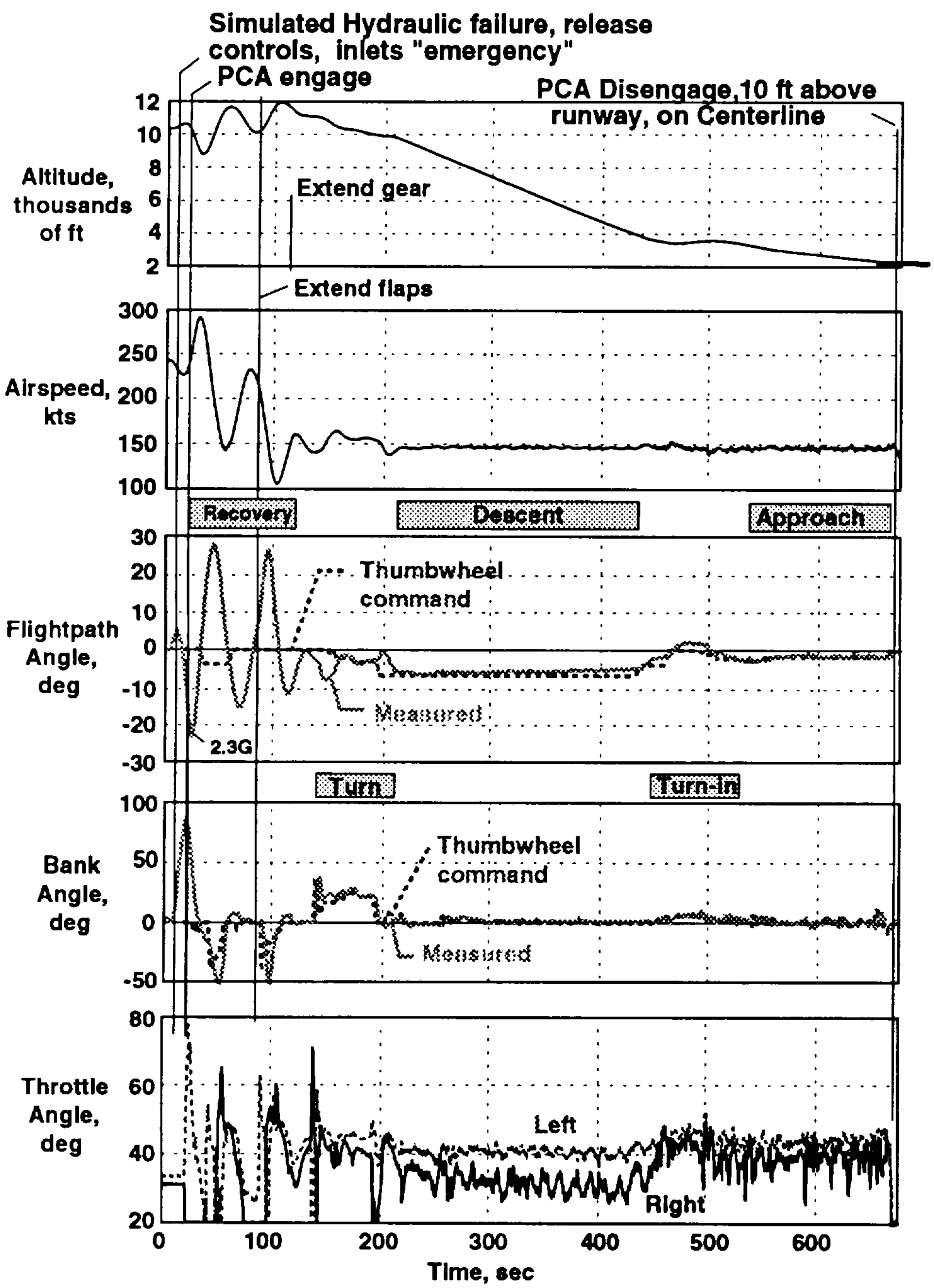
Manual throttles-only approaches were flown for comparison with the PCA approaches. A manual approach was flown by a guest pilot on the same flight in which he had flown the upset, PCA recovery and approach to 10 ft AGL. A 5 minute interval of the two approaches is shown below. The manual approach shows poor heading control and flightpath oscillations of at least ±5 deg at a time when PCA was controlling to ±0.5 deg. Large airspeed excursions are evident along with much throttle activity. The right throttle was on the idle stop for about half of the approach. The pilot concluded that he might be able to hit the runway, but it would have been a crash. All guest pilots tried manual throttles-only approaches, none were successful, and all agreed that a safe landing was very unlikely. The PCA project pilot, even after extensive practice, also concluded that a safe landing was most unlikely.



## Simulated Upset and PCA Recovery

A PCA guest pilot performed a test which simulated a loss of hydraulics upset followed by a PCA system engagement and recovery, shown below. In this test, the pilot trimmed the airplane at 250 kts at 10,000 ft, used the stick to roll to a 90 deg bank, released the controls, and moved the inlets to the "emergency" setting where they would go if hydraulics were lost. PCA was engaged, with trim auto at an 85 deg bank and -18 flightpath. The PCA system commanded full differential thrust, rolled the wings level, then reduced thrust to begin the phugoid damping. The pilot put in a bank command to convert some of the excess pitch energy into a turn to reduce the pitchup, airspeed decayed to 150 kts over the top. After one full pitch cycle, he lowered the flaps, which caused another pitchup and speed reduction, with speed falling to a minimum of 105 kts. The landing gear was extended, and the pitch oscillation was damped quickly. PCA trim was satisfied. Trim speed was 150 kts. He then turned back towards the Edwards runway and began a descent, with a -6 deg flightpath command. At 450 sec, he leveled and made a turn to start a long straight-in approach to runway 22. The approach was continued with minimal deviation until 10 ft over the runway and on centerline in perfect position to land, 11 minutes after the upset. At that point, he used the stick to disengage PCA and then flared slightly for touchdown.

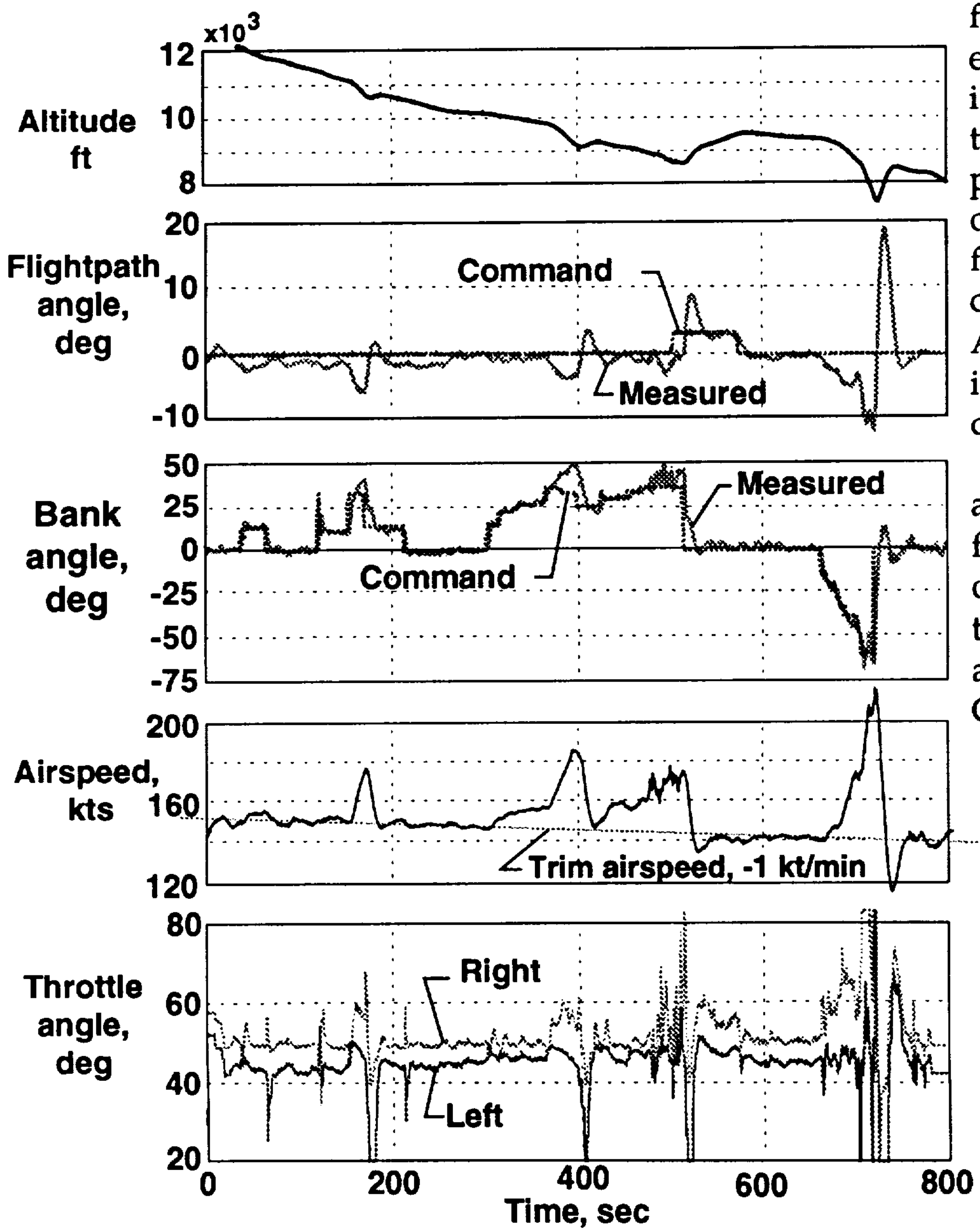
All PCA guest pilots flew this simulated upset as part of their PCA demonstration.



## PCA Maximum Bank Angle Test

Tests were performed to determine the maximum bank angle capability of the PCA system in the F-15. The software limits and thumbwheel scaling were modified to permit bank angle commands up to 60 deg. Results are shown below with flaps and gear down. Initial trim speed was 151 kts at an altitude at 12,000 ft. Commands to 15 deg were flown for reference, and were held accurately. A command of 35 deg resulted in an overshoot to 40 deg and a drop in pitch attitude to -5 deg. Speed increased to about 180 kts to sustain the bank and keep the nose from dropping more. The higher throttle setting makes the inlet effect more destabilizing. Repeating the test, bank commands to 25 deg were accurately held, and again the 35 deg command resulted in an overshoot to nearly 50 deg. After 400 sec, altitude was down to 9000 ft and a 35 deg command was held at approximately 40 deg in light-to-moderate turbulence (note dynamics on airspeed) Trim speed was down to 145 kts. At this point, the pilot, still with PCA control, rolled to wings level and commanded a climb to get above the turbulence. At 650 sec, a right turn was commanded, 40 deg was held, and then bank angle was increased to the full 60 deg command. Bank angle oscillated ±10 deg, and the flightpath fell to -10 deg, even though speed increased to 210 kts. On the rollout command, a pitch overshoot to +20 deg occurred as the energy from the higher speed was converted into pitch. After the flightpath stabilized, the trim speed was down to 140 kts.

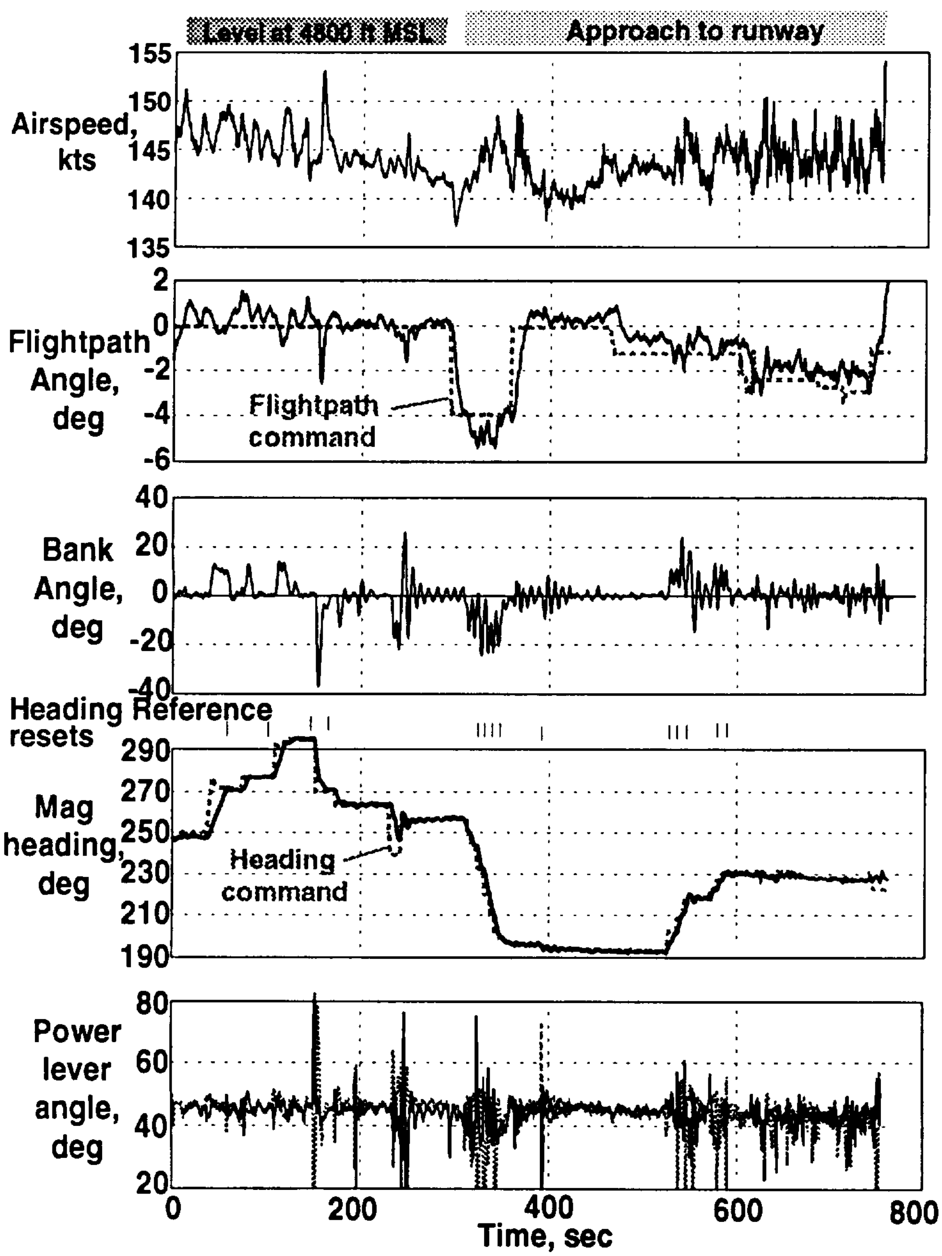
The speed reduction of about 1 kt/min in level flight was also observed at other times, and was due to the weight reduction and aft movement of the CG as fuel was burned.



**PCA Heading Mode**

A heading mode was developed for the F-15 PCA system. This mode was designed to maintain a commanded heading mode when the bank angle thumbwheel was in or near the detent, and to allow a heading to be selected with the bank angle thumbwheel. This mode was developed late in the PCA project, and did not get extensive simulation nor flight test. The heading mode control law is shown on the next page. Since there was no convenient input device, (such as a heading command knob) in the F-15 for making heading commands, the bank thumbwheel was used, but could only be reasonably scaled for about ±10 deg of heading change. When in the heading mode, the pilot would depress the PCA "engage" button on the throttle to establish a new heading reference (the heading at that time), and the thumbwheel would then be used for heading command. If more than a 10 deg heading change was needed, the engage button would be depressed again.

The gain for large heading commands was initially too high, resulting in a very large initial bank angle, and lightly damped bank angle oscillations. With the flexibility of the PCA software, a 60 percent reduction in gain was made and performance was much improved. Flight test of the heading mode is shown in the figure. The pilot first made heading changes in level flight, then turned toward the runway and made an approach. Despite the cumbersome mechanization, the heading mode worked acceptably well. Note that the gain was still somewhat too high, with some bank angle oscillations. Heading was held to within ±0.5 deg, and pitch control was good. Bank angle limiting would need to be incorporated in this mode.

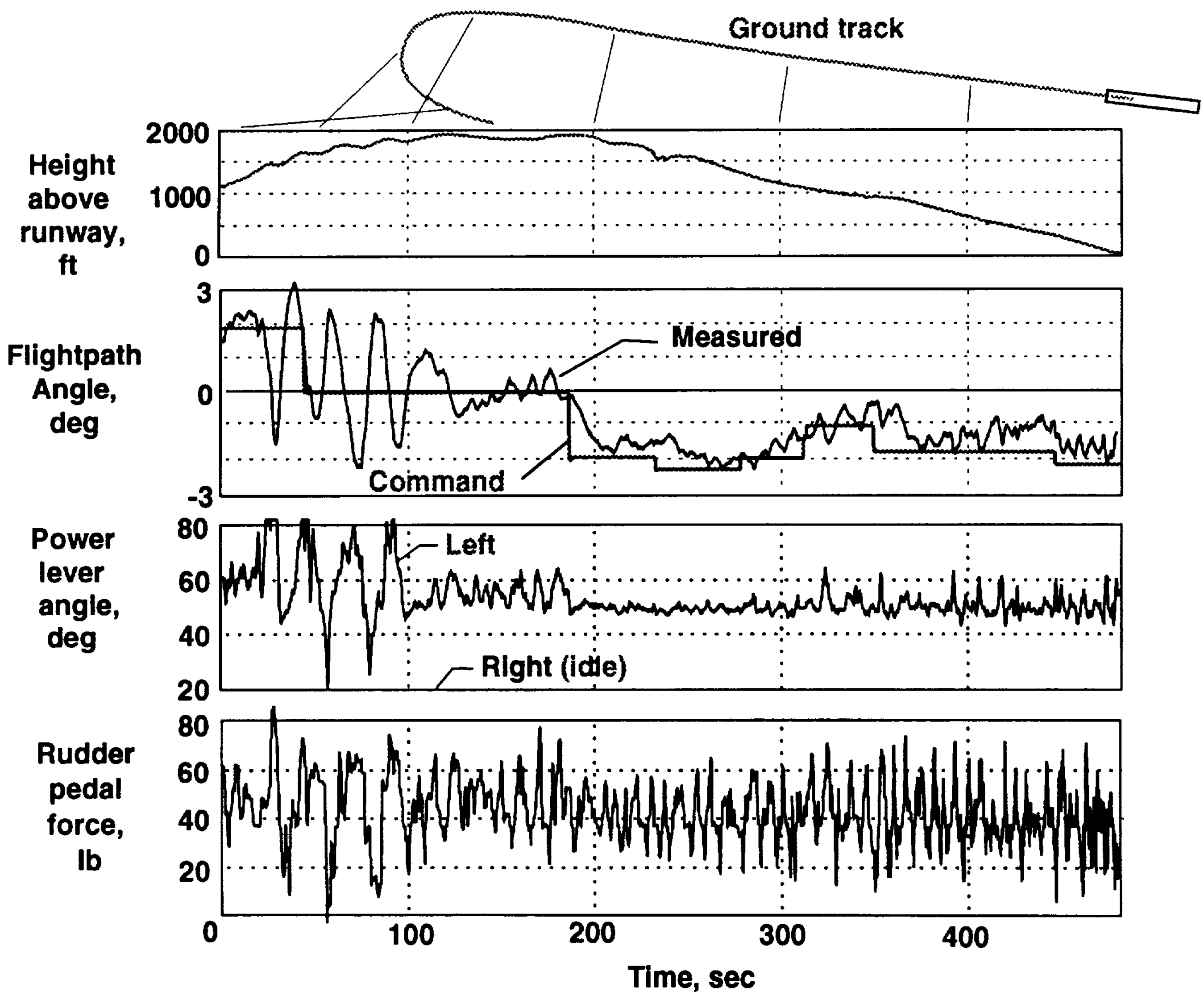


**Single engine Plus Rudder**

Analysis of flight control system failures has shown several cases in which pitch control was lost but roll control through rudder or ailerons was still possible. In this case, PCA could be used for flightpath control, and, in fact, one engine under PCA control could be sufficient to control pitch.

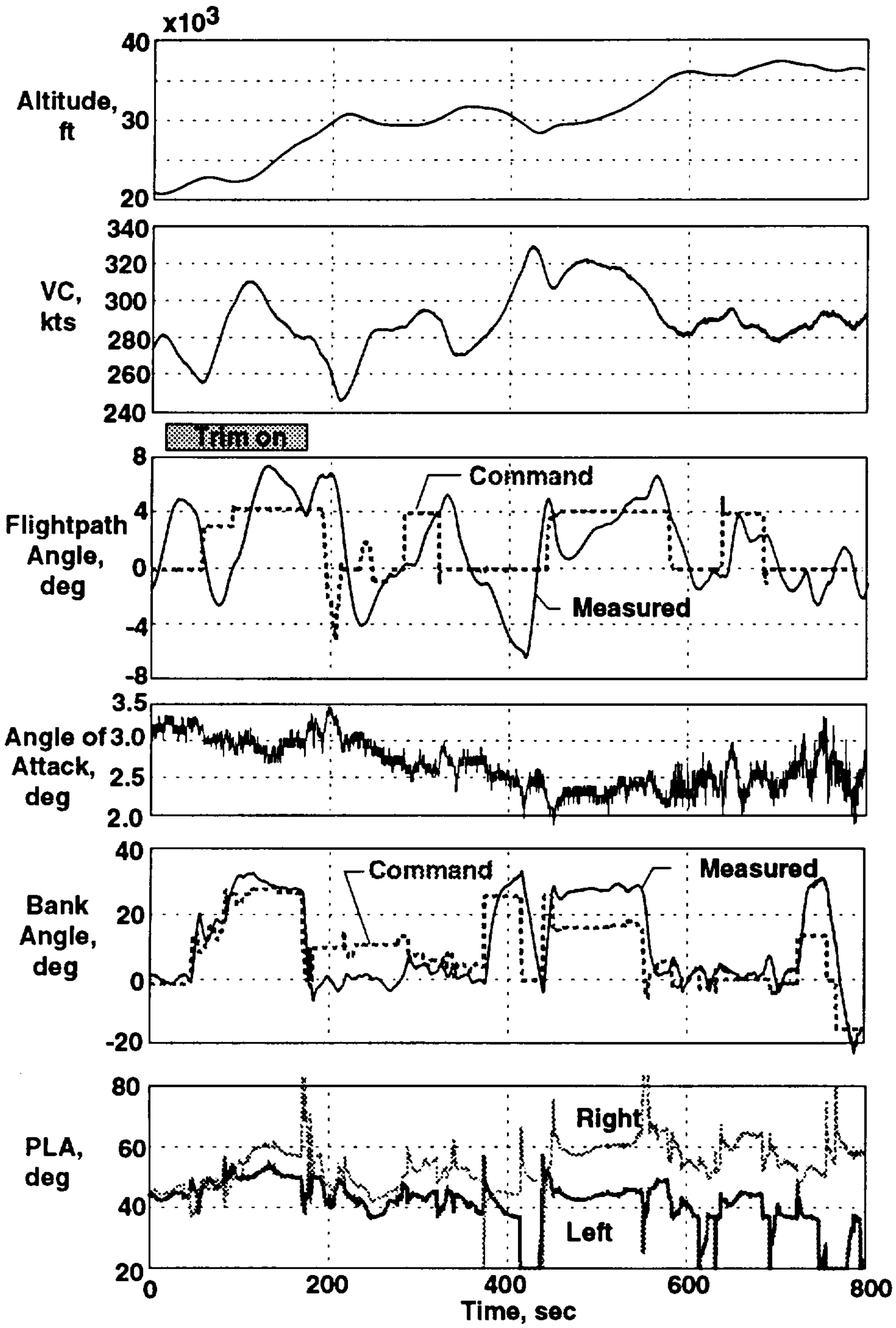
To investigate this mode, an option to fly a "single engine plus rudder" mode was provided. The pilot controlled bank angle and heading with rudder, while the PCA flightpath command controlled flightpath with one engine. The other engine throttle was moved to idle for the test. The only control law change needed was to eliminate the differential thrust command, and increase the gain on the flightpath angle command. Shown below is an approach flown in this mode at 170 kts with the flaps up. The pilot had to get used to this method for controlling bank angle, and found strong interactions between his rudder control and the yaw due to the engine serving as a pitch controller. During the turn, the PCA trim had not been completed, and phugoid damping was poor. Once the turn was completed, PCA trim was completed, and as experience was gained, control improved. The oscillations in pitch were reduced, and the rudder inputs became smaller. Over the latter part of the approach, flightpath was held within a degree of command, about half of that due to an apparent bias of 1/2 deg. Pitch control at 170 kts was improved because the one engine used was at higher than normal power, and the inlet effect was minimal at the higher mass flow ratio.

The pilot was uncomfortable with this mode due to lack of experience, and the fact that every pitch input caused a roll disturbance. In spite of these problems, he was able to maintain runway lineup down to 100 ft AGL, and thought he could make a safe landing on the lakebed where precise lineup would not be critical.



**PCA Flight Envelope Expansion**

The PCA system was designed for operation between 170 and 190 kts and altitudes up to 10,000 ft. After the PCA landings, when PCA operation was better than expected, it was decided to expand the PCA system operation outside of the design envelope to see how robust the control algorithm was. Shown below is a 280 kt climb with flaps up, gear up, inlets emergency, and velocity feedback active. After engaging and initiating PCA trim, the pilot started a turn. The PCA trim process took over 150 sec due to poor phugoid damping and pilot inputs. Once trim was completed, PCA performance was better. At 30,000 ft, pitch and roll steps were made. Note at 410 sec, when the right roll command was removed, that the left throttle went to idle, which contributed to allowing the nose to drop 5 deg. The climb was then continued. At 35,000 ft, another set of flightpath and roll steps were made. Flightpath was generally maintained within ±2 deg. Roll was better than pitch. Maximum altitude was 37,000 ft and maximum Mach was 0.88. The climb was discontinued at this point not because of PCA limitations, but because CAS off flight is not recommended in the transonic region.

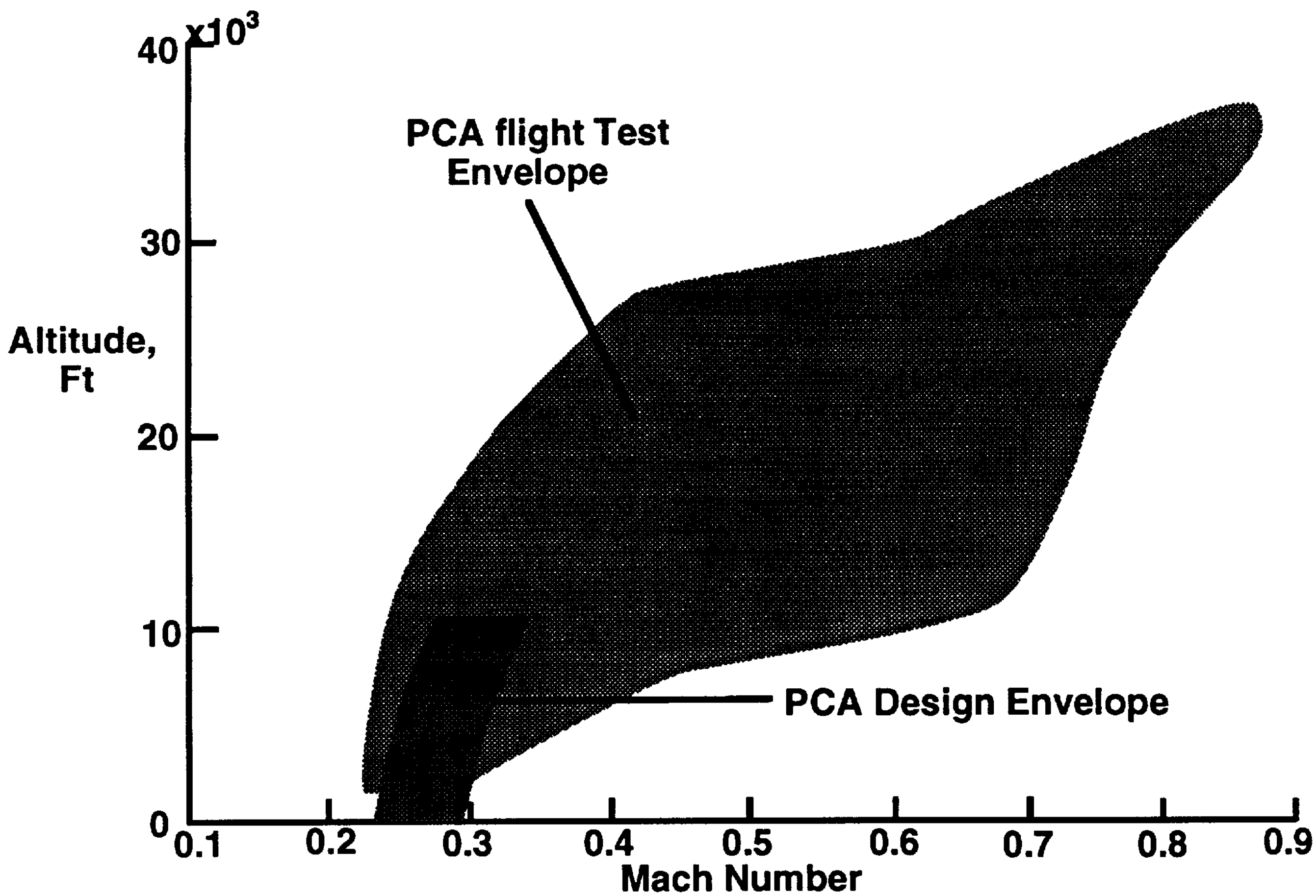



Note that the throttles, which were well matched at the beginning of the test, developed an increasing bias, with more right throttle required to hold wings level. This may be the result of wing fuel migration during the extended uncoordinated turn from 90 to 180 sec. Once the fuel had shifted to the right, increased right throttle would be required. Without a left turn to return the fuel the bias continued. Wing fuel quantity measurements also showed a bias consistent with fuel migration. Similar throttle splits had been seen at other flight conditions when extended periods of turning flight were flown.

## PCA Design and Flight Test Envelope

The PCA system for the F-15 was designed for an airspeed range from 170 to 190 kts at altitudes below 10,000 ft. Later, the PCA system was tested over a wider range to determine it's robustness. The tested PCA envelope is shown below. Data from the 250 kt upsets, which reached 320 kts during the recovery, and the PCA climb at 280 kts showed that performance continued to provide postive control over a much larger envelope than considered in the design. The engine model in particular used 10,000 ft data for all higher altitudes. The fact that the PCA system remained usable well beyond it's design envelope is encouraging for future applications.

### F-15 PCA Design and Test Envelope



**PCA Guest Pilots**

Several guest pilots were invited to fly the F-15 with the PCA system installed. The following is a list of all PCA pilots and their affiliations, along with a sample of comments.

| Pilot | Affiliation | Assignment |
|---|---|---|
| Gordon Fullerton | NASA | Dryden F-15 PCA Project Pilot |
| Jim Smolka | NASA | Dryden F-15 project pilot |
| Capt. Dave Cooley* | USAF | Experimental Test Pilot, 445th Test Squadron, Edwards AFB, CA |
| Steve Herlt* | MDA | Contractor Test Pilot, F-15 Combined Test Force, Edwards AFB CA |
| Ed Schneider* | NASA | Dryden F-18 project pilot |
| Tom McMurtry* | NASA | Dryden Chief, Flight Operations |
| Lt. Rick Gertz* | USAF | USAF Test Pilot School, Edwards AFB |
| Lt. Len Hamilton* | NAVY | F-14 test pilot, Naval Air Warfare Center, Patuxent River MD |

* indicate guest pilot

Excerpts from Lt. Len Hamilton, USN

The PCA system flown in the HIDEC F-15 was evaluated as highly effective as a backup recovery system should an aircraft lose total conventional flight controls. The system was simple and intuitive to use and would require only minimal training for pilots to learn to use effectively. Of course landing using PCA would require higher workloads than normal but this pilot believes landings could be done safely. The fact that the system provides a simple straight forward go-around capability allowing multiple approaches further supports the safe landing capability of the system. The dutch roll suppression characteristics of the system were extremely impressive to the pilot and would allow landings to be done even in non-ideal wind conditions. The PCA system exhibited great promise and if incorporated into future transport aircraft could further improve the safety of the passenger airlines.

Excerpts from Comments of Capt. Dave Cooley, USAF

General Handling Comments The aircraft responded adequately to all inputs commanded by the pilot. Pitch and roll response were both very sluggish yet always consistent and therefore predictable. The phugoid was surpressed by the system and was not noticeable except when making large changes in pitch. The dutch roll was very well controlled by the system. Generally, the system provided excellent flight path stability and good control of the aircraft without being overly sensitive to gusts.

Excerpts from comments of Steve Herlt, MDA

This Propulsion Controlled Aircraft demonstration, from the ground training and the demonstration profile to the actual PCA control law implementation, was very well done. More than simply a proof of concept demonstrator, today's flight exhibited capabilities that would enhance the survivability of aircraft. As long as aircraft have failure modes where you may lose the ability to fly the airplane with the control stick or yoke, I would like to have the backup capability demonstrated today by the Propulsion Controlled Aircraft.