DOCKET NO. **SA - 510**

EXHIBIT NO. **13X - D**

NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C.

KINEMATIC STUDY UPDATE

NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, D.C.

October 31, 1995

Kinematic Study Update

A. ACCIDENT **DCA-94-MA-076**

Location	:	Aliquippa, Pennsylvania
Date	:	September 8, 1994
Time	:	1904 Eastern Daylight Time
Aircraft	:	Boeing 737-300, N513AU

B. GROUP IDENTIFICATION

Not Applicable

C. SUMMARY

On September 8, 1994 at 1904 Eastern Daylight Time, USAir Flight 427, a Boeing 737-3B7, N513AU, crashed while maneuvering to land at Pittsburgh International Airport, Pittsburgh, Pennsylvania. The airplane was being operated on an instrument flight rules (IFR) flight plan under the provisions of Title 14, code of Federal Regulation (CFR), Part 121, on a regularly scheduled flight from Chicago O'Hare International Airport, Chicago, Illinois, to Pittsburgh. The airplane was destroyed by impact forces and fire near Aliquippa, Pennsylvania. All 132 persons on board the airplane were fatally injured.

D. DETAILS OF INVESTIGATION

The attached letter (of June 20, 1995) and accompanying graphs detail an update of the kinematic study of the USAir 427 FDR data. The data was originally presented at the Aircraft Performance Group meeting of May 8, 1995, in Seattle, Washington. An additional presentation was made at the May 9 all-party meeting in SeaTac, Washington.

[redacted]
Tom Jacky
Aerospace Engineer

Attachment - Kinematic Study Update

ATTACHMENT

Kinematic Study Update

Boeing Commercial Airplane Group
P.O. Box 3707
Seattle, WA 98124-2207

June 20, 1995
B-U01B-15291-ASI

Mr. Thomas Jacky, RE-60
National Transportation Safety Board
490 L'Enfant Plaza SW
Washington D.C. 20594

Subject: Kinematic Analysis Update USAir 737-300 N513AU Accident Near Pittsburgh - September 8, 1994

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References: a) Planning meeting, Seattle, May 9, 1995
b) Boeing letter, B-U01B-15081-ASI, January 10, 1995

Dear Mr. Jacky:

In the reference (a) meeting, Boeing presented an updated version of the kinematic analysis discussed in reference (b). The analysis presented was requested to be written-up and submitted for review by the NTSB. The following is in response to that request.

Summary:

In reference (b) document it was reported that using the kinematic equations of motion, data from the USAir 427 flight data recorder (FDR) were analyzed, providing estimates of sideslip angle, angle-of-attack and other parameters not directly measured or recorded. These data were then further analyzed to provide estimates of the total airplane aerodynamic coefficients and equivalent control deflections for rudder and wheel. As stated in that report, external factors such as FDR errors, winds aloft, wake turbulence, and structural damage are not known and can not be separated from the analysis. The estimated coefficients and calculated equivalent control deflections include all of these external factors, plus the effects of any actual airplane control deflections, deficiencies in the simulator aerodynamic model, etc.

This report summarizes our current understanding of the basic airplane motion, the estimated effects of a probable wake encounter on the airplane motion, and the estimated airplane control deflections.

Results of this study, and details of the analysis are presented and discussed below.

Discussion

As discussed in reference (b) the analysis of FDR data often requires the estimation of parameters which were not recorded. As previously reported, the two methods for doing this were both rather time consuming and required a great deal of engineering expertise.

The current analysis methodology is a hybrid of the two methods. This results in the elimination of much of the iterative effort involved in the use of either of the previous methods alone.

The procedure involves two distinct steps: Data from the kinematic processor are used, together with a special back-drive technique to achieve a high quality match of the motion data using the airplane simulation (See Figure 1). The results of the simulation back-drive provide an improved estimate of the sideslip angle (assuming calm air) which may then be used as the starting point for the next iteration beginning again with the kinematic analysis. Convergence on a final solution is rapid (only two or three iterations are required), starting with an assumed value of zero for sideslip angle.

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The simulation back-drive technique mentioned above computes incremental aerodynamic coefficients to produce a match of the calculated linear and angular accelerations of the aircraft. This, in turn, results in an excellent match of airspeed and altitude as shown in comparisons of the FDR, kinematic analysis, and simulation back-drive data in Figure 2.

Figures 3 and 4 show the basic FDR data and a comparison of the kinematically derived data presented in the reference, vs the current estimates. The current data show the expected Dutch Roll activity in sideslip at 139 seconds, as well as generally larger peak sideslip values throughout the final 25 seconds of flight. Also, the current prediction of stall warning (stick shaker) shows intermittent activity in the final 3 seconds of flight , consistent with the cockpit voice recorder, as will be noted in forthcoming corrections to the CVR transcript. This is consistent with the expected airplane response to elevator blow-down at this point in the accident sequence.

As noted in reference (b), except for column, the actual control deflections from USAir 427 are unknown. To aid in the understanding of the flight scenario, the estimated yawing and rolling moment coefficients have been converted to equivalent rudder and wheel deflections, using the flight characteristics of the 737-300. Figure 5 shows these data, along with relevant roll and yaw motion variables and CVR events. These data represent the total combined effects of actual control deflections, plus the unknown effects of the wake, FDR errors, possible structural damage, deficiencies in the simulator aerodynamic model, etc.

Based on the analysis results to date, it is believed that there are no significant, uncorrectable errors in the basic FDR data, and that the kinematic analysis of the data provides a reasonably accurate, detailed representation of the actual airplane motion. It is also believed that the simulator aero model adequately represents the airplane characteristics prior to and during the primary area of interest in the accident sequence (130 to 145 seconds). And finally, there does not appear to be any significant evidence from this analysis to support a hypothesis that the airplane experienced structural damage before impact.

Note: Determination of transport delays in the IRU data is still an issue, leaving open the possibility of small timing shifts in the data.

It has also been shown, given a healthy airplane and calm air, that the methodology used in this analysis is capable of producing good quality engineering estimates of rudder and wheel deflections. (Note: This is addressed in greater detail in Appendix A.)

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Based on these findings it may be stated that the predicted airplane control deflections should be reasonably accurate outside the region of influence of the 727 wake, and prior to entering stall at 145 seconds. (Note: Accurate post-stall prediction of wheel deflection is not possible; it is simply assumed that the pilot maintained full right wheel from that point on.)

Given the desire to understand the control deflections throughout the accident sequence, and the possible roles played by the pilot and/or airplane in producing those deflections, it is necessary to understand what influence, if any, the 727 wake had on the aircraft.

There is considerable evidence to suggest that the aircraft did encounter a 727 wake at a distance of about 4 1/4 miles (69 seconds) behind DAL 1083:

- Tower radar data indicate probable intersection of the ground tracks of the two aircraft at the right point in space and time (Figure 6). Also, the vertical separation of the aircraft (based on transponder data recorded by the tower for both aircraft) is reasonably consistent with the distance the wake would be expected to drop in 69 seconds. (Note: The dashed line representing the path of USAir 427 is kinematically derived data, overlaid on the radar data to achieve best fit. The solid line representing DAL 1083 is a simple curve fit through the radar data.)

- Abnormalities in the airplane response during auto-pilot rollout onto a selected heading change to 100 degrees suggest the presence of an external influence tending to yaw and roll the aircraft to the right of its intended path. This is consistent with the expected initial effects of the left vortex core as the aircraft is passing about 150 feet underneath, moving from left to right. The anomalous behavior of the aircraft may be seen in Figure 7 which compares the rollout starting at 129 seconds with the rollouts of the two preceding turns. (Note: The data for Turns 5 and 6 were biased in time and heading angle to simulate turns to 100, starting at the same point in time as Turn 7.)

  These data suggest that the influence of the wake on the roll axis may begin earlier than previously believed, causing the aircraft to begin rolling out of the turn slightly before the initiation of the auto-pilot rollout sequence. Further evaluation of this scenario will be required to determine the probable response of the auto-pilot to this type of disturbance.

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- Abnormalities in the lift and pitching moment coefficients (Figure 8) required to match the predicted airplane flight path are also consistent with a wake encounter. The coefficients show a loss of lift and a tendency to pitch up, as well as the effects of a sudden increase in turbulence. These symptoms are all consistent with the effects of a wake acting on an aircraft located generally between the two vortex cores; a region of strong downwash.

Given the probability that the aircraft did in fact encounter the 727 wake, as outlined above, it becomes necessary to estimate the roll and yawing moment effects of the wake during that encounter.

There are many unknowns involved in such an encounter: wake strength, exact location of the vortex cores relative the the aircraft, diameter of the vortex cores, random turbulence in the wake, etc., all of which combine to produce a non-uniform flow field acting on the aircraft, with resulting aerodynamic forces and moments which are not simple to predict.

The effects of these unknowns were modeled and evaluated as follows:

- A Rankine Vortex model was used to represent the wake. The wake circulation was varied from 1400 to 2100 ft**2/sec, vortex core diameter was varied from 4 to 16 feet and the "bank angle" of the wake was varied from -10 to +10 degrees. A wake span of 80 feet was assumed. The final values arrived at in this analysis are as follows:

    - Circulation = 2100 ft**2/sec
    - Diameter = 16 ft
    - Bank Angle = 10 deg
    - Span = 80 ft (distance between vortex core centerlines)

    Note: These values were assumed constant throughout the entire wake encounter.

- A distributed lift model was developed, based on simple strip integration theory, to represent the effects of the wake on the wing and tail. The model produces lift, pitch, roll and yaw effects. The effects of the wake on the body are not represented.

Probably the most difficult aspect of the wake to predict is its position in space, relative to the airplane, at each point throughout the encounter. Any maneuvering (primarily in roll and pitch) of the generating aircraft has the potential of introducing significant distortion in the shape of the wake. A roll to the left, for example, will cause the wake to move to the right as it descends. Also, wind will cause unpredictable distortion and destabilization of the wake. And finally, there are mutual interactions which occur when an aircraft encounters a wake: i.e. each one influences the other. (Note: This latter effect was not modelled.)

For the purpose of this analysis, it was decided that the aforementioned radar data in Figure 6, the initial positive roll and yaw associated with Figure 7, and the lift and pitching moment data in Figure 8 would serve as the primary guide in the development of the wake encounter scenario.

> Note: It was decided that considerations of roll and yaw characteristics would not be used to aid in the design of the wake scenario in regions of the data where the wheel and rudder deflections are seriously in question. (As will be shown later in Figure 17, the region of uncertainty in control inputs begins shortly after 134 seconds.)

This effort was carried out and the estimated roll and yaw influences of the resulting wake, were then subtracted out of the airplane motion to arrive at a new estimate of the wheel and rudder deflections throughout the encounter.

The results of this analysis are shown in Figures 9 through 13.

Figure 9 shows the geometric details of the wake encounter scenario worked out in accordance with aforementioned guidelines. It should be noted that the distortion in the wake (top view), in the region of 138 to 140 seconds, is qualitatively justified, based on the fact that the 727 turned about 6 degrees to the left at that point in space, pushing the wake to the right of its flight path, as previously discussed.

Figure 10 shows a frame by frame view (once per second), looking from the back, as the aircraft moves through the wake from underneath the left core at 133 seconds, out over the top of the right core at 137 seconds, then back to the left over the top of the left core at about 140 seconds. Spoilers are illustrated on the wings to indicate the probable pilot wheel input at each point in time. Rudder deflection is also indicated.

Figure 11 shows a preliminary comparison of the lift and pitching moment anomalies experienced by the aircraft during the wake encounter, vs the predictions from the analytical wake model for the scenario just described. Figure 12 shows the residual lift error when the theoretical wake induced lift is subtracted out. That which remains may be characterized simply as low level noise.

Figure 13 shows the yaw and roll effects associated with the derived wake, together with the lift coefficient discussed above. These data indicate a general trend of yaw to the right (opposing the derived rudder) and roll to the left through the central portion of the encounter.

Figure 14 shows the rudder and wheel position data which result from subtracting out the predicted yaw and roll effects of the wake. As in Figure 5, these data are shown together with the relevant roll and yaw motion variables and CVR events.

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Note: These data represent our current best estimate of the rudder and wheel deflections, but are subject to change with the addition of wake effects on the forebody. Also the entire wake effects model may be further refined as wake flight test data become available.

Figure 15 shows the estimated rudder position data from Figure 14, along with the predicted yaw damper activity (assuming a normal, functioning yaw damper). It also shows an approximate, derived rudder pedal position, calculated by subtracting the yaw damper command from the rudder, then dividing by an approximate rudder-to-pedal gearing ratio. The yaw damper command used in this analysis is derived from the simulator match of the flight data (primarily yaw rate, which is derived directly from the FDR data), and assumes normal yaw damper operation. Note that the simulated yaw damper commands right rudder from 135.5 to 138.5 seconds, which is opposite to the rudder input which is required to match the airplane motion.

These data were used to back-drive the physical controls in the Boeing Multi-Purpose cab in a simulation of the accident sequence, including visuals, sound and enhanced motion for the benefit of NTSB approved participants in this phase of the investigation.

Figure 16 is a composite plot of the FDR column position and engine speed (N1), along with the estimated control wheel and rudder pedal (corrected for estimated wake effects). CVR cockpit sounds and pilot comments are annotated across the top of the plot.

The first grid in Figure 17 shows a comparison of a simulated autopilot wheel response during a normal heading change rollout and during a match of the initial USAir 427 roll upset. The autopilot responds to the upset by commanding 26 degrees of wheel to the right. The second grid shows the estimated USAir 427 wheel position data with an initial deflection to the left of about 25 to 30 degrees, occurring over about 0.6 seconds. The estimated wheel deflection departs significantly from the predicted autopilot response at about 134.3 seconds.

Figure 17 also shows the actual FDR column position compared to the predicted normal autopilot pitch response. These data show reasonably good agreement until about 134.6 seconds, at which point they begin to diverge significantly.

Taken together, these data suggest possible pilot intervention as early as 134.3 seconds in the accident sequence, increasing to a high probability of intervention by 134.6 seconds.

If you have any questions, please contact me.

Very truly yours,

FLIGHT TEST

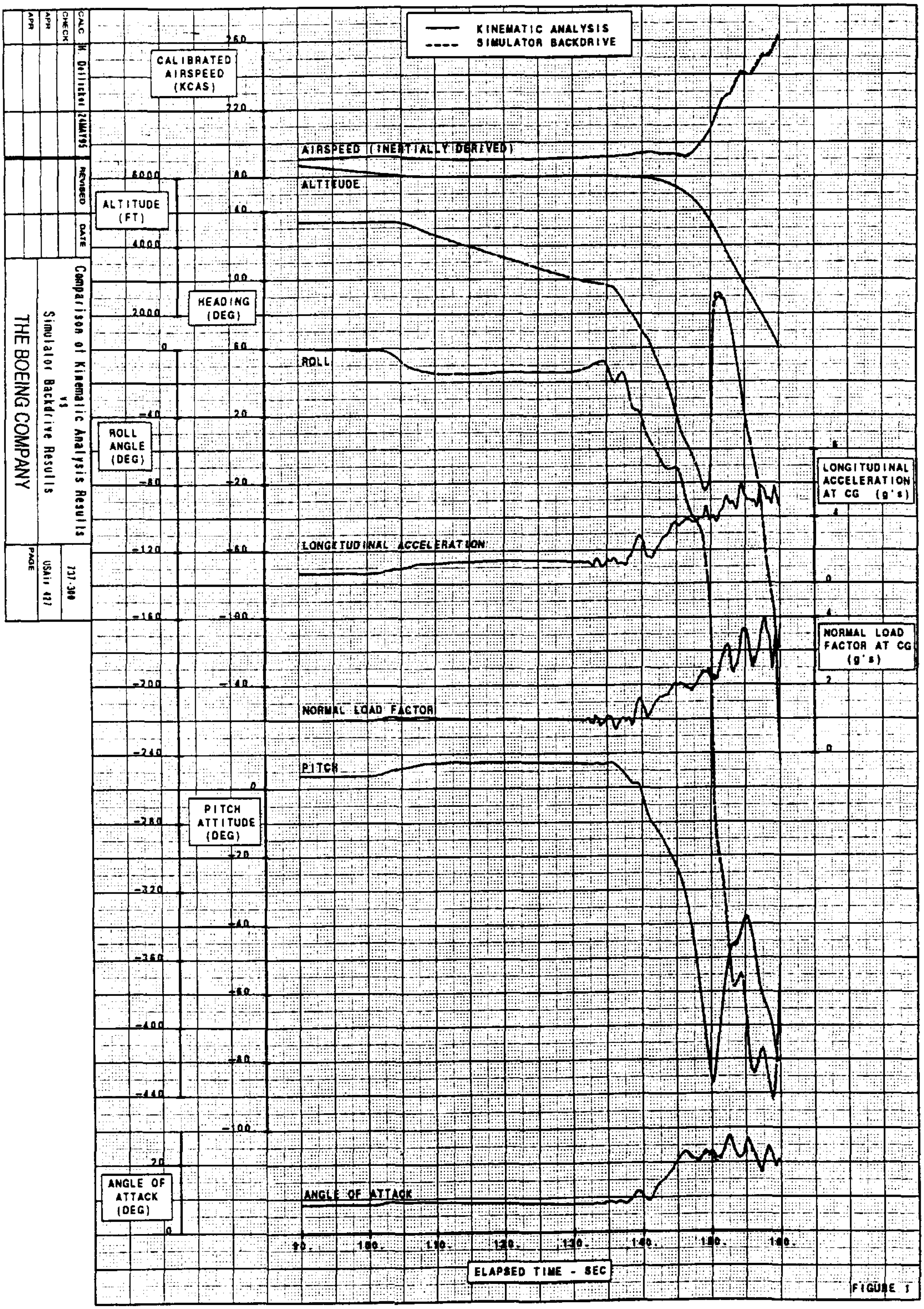
[redacted]

for

John W. Purvis
Director, Air Safety Investigation
Org. B-U01B, Mail Stop 14-HM
Telex 32-9430, STA DIR PURVIS
[redacted]

Enclosures: Figures 1 through 17, Appendix A and figure A-1

cc: Mr. Thomas Haueter, NTSB, AS-10



KINEMATIC ANALYSIS
SIMULATOR BACKDRIVE
CALIBRATED AIRSPEED (KCAS)
ALTITUDE (FT)
HEADING (DEG)
ROLL ANGLE (DEG)
PITCH ATTITUDE (DEG)
ANGLE OF ATTACK (DEG)
LONGITUDINAL ACCELERATION AT CG (g's)
NORMAL LOAD FACTOR AT CG (g's)
AIRSPEED (INERTIALLY DERIVED)
ALTITUDE
ROLL
LONGITUDINAL ACCELERATION
NORMAL LOAD FACTOR
PITCH
ANGLE OF ATTACK
ELAPSED TIME - SEC
FIGURE 1
Comparison of Kinematic Analysis Results vs Simulator Backdrive Results
THE BOEING COMPANY
737-300
USAir 427
CALC M. Dellicker 24MAY95

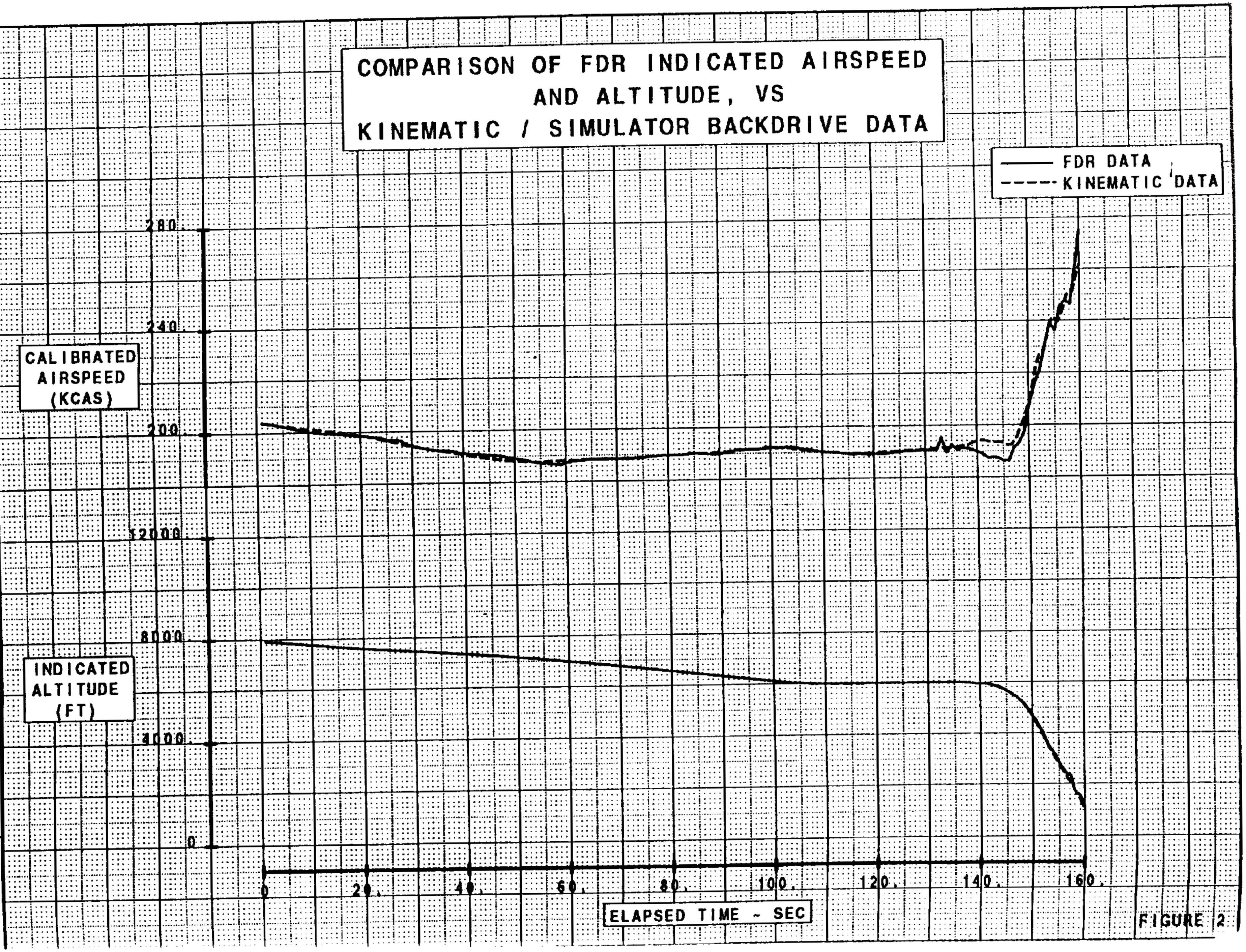


FIGURE 2

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Comparison of FDR Indicated Airspeed and Altitude, vs Kinematic / Simulator Backdrive Data

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USAir 427 Airplane Motion Data
Comparison of May '95 Status
to Jan '95 Status

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USAir 427
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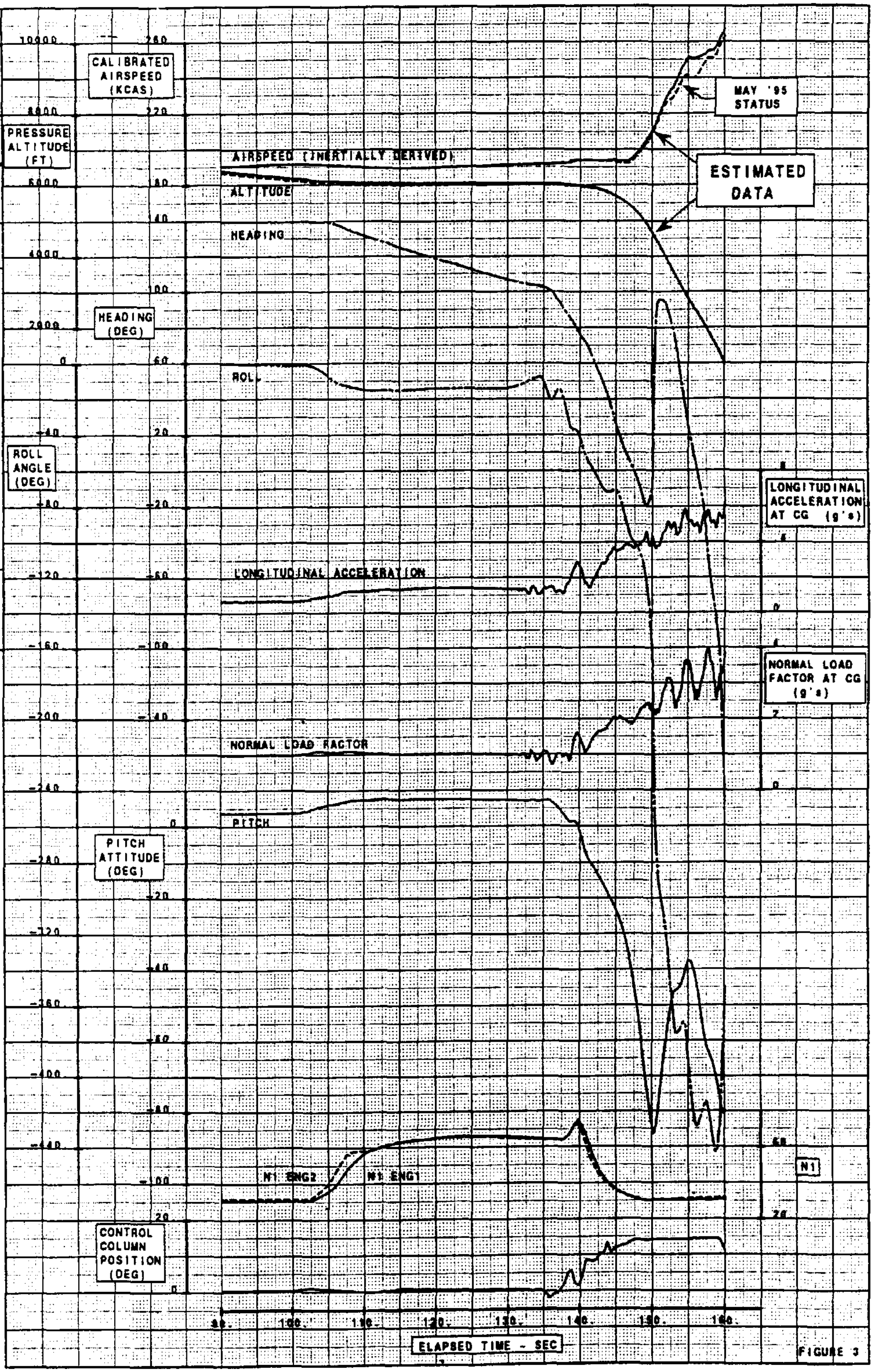
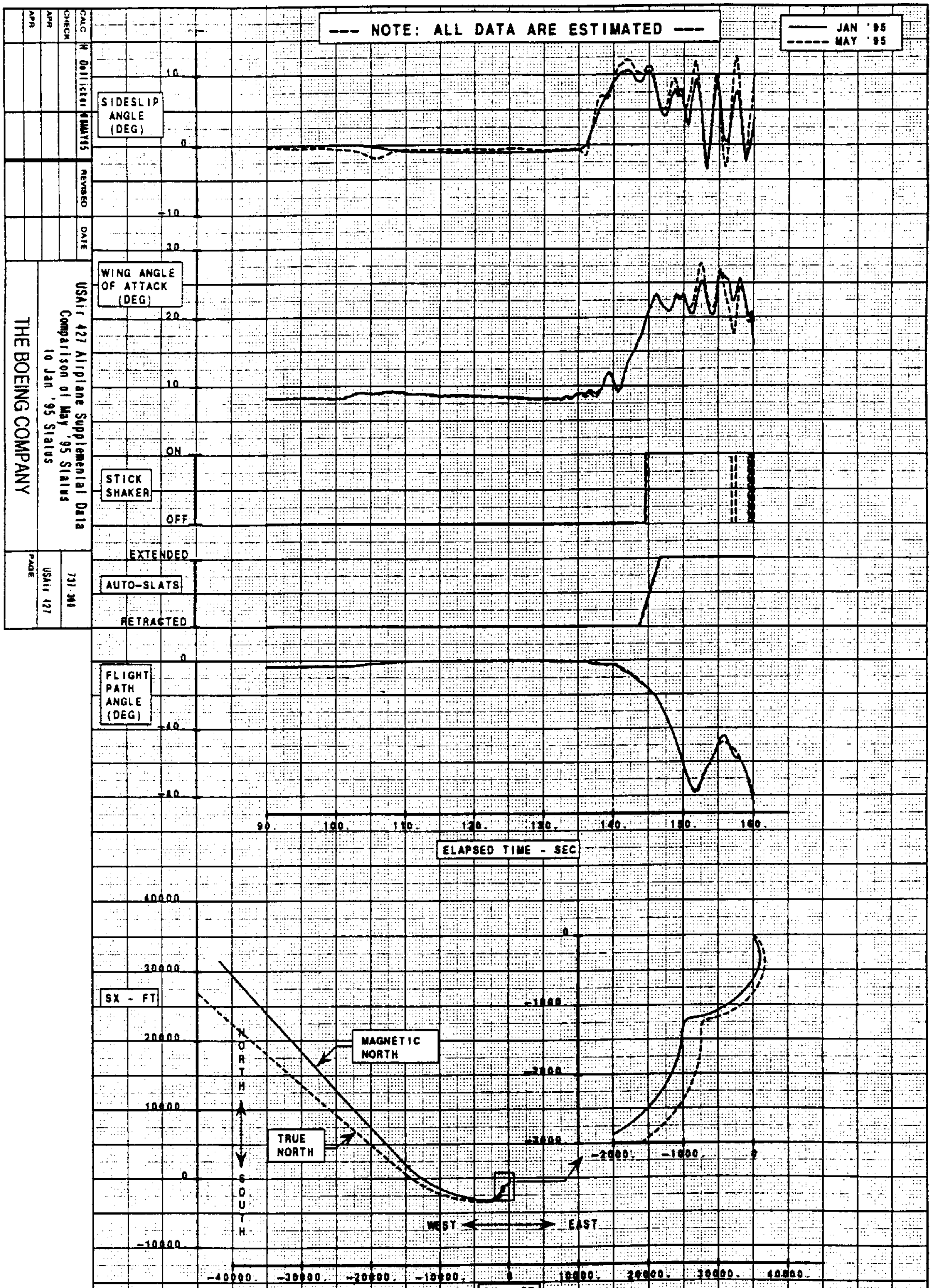


FIGURE 3


--- NOTE: ALL DATA ARE ESTIMATED ---
JAN '95
MAY '95
SIDESLIP ANGLE (DEG)
WING ANGLE OF ATTACK (DEG)
STICK SHAKER
ON
OFF
AUTO-SLATS
EXTENDED
RETRACTED
FLIGHT PATH ANGLE (DEG)
ELAPSED TIME - SEC
SX - FT
SY - FT
MAGNETIC NORTH
TRUE NORTH
NORTH
SOUTH
WEST
EAST
USAir 427 Airplane Supplemental Data
Comparison of May '95 Status
to Jan '95 Status
THE BOEING COMPANY
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USAir 427
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FIGURE 4

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USAir 427 Lateral/Directional Motion and Estimated Controls Data. (Wake Effects Have Not Been Removed)

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USAir 427

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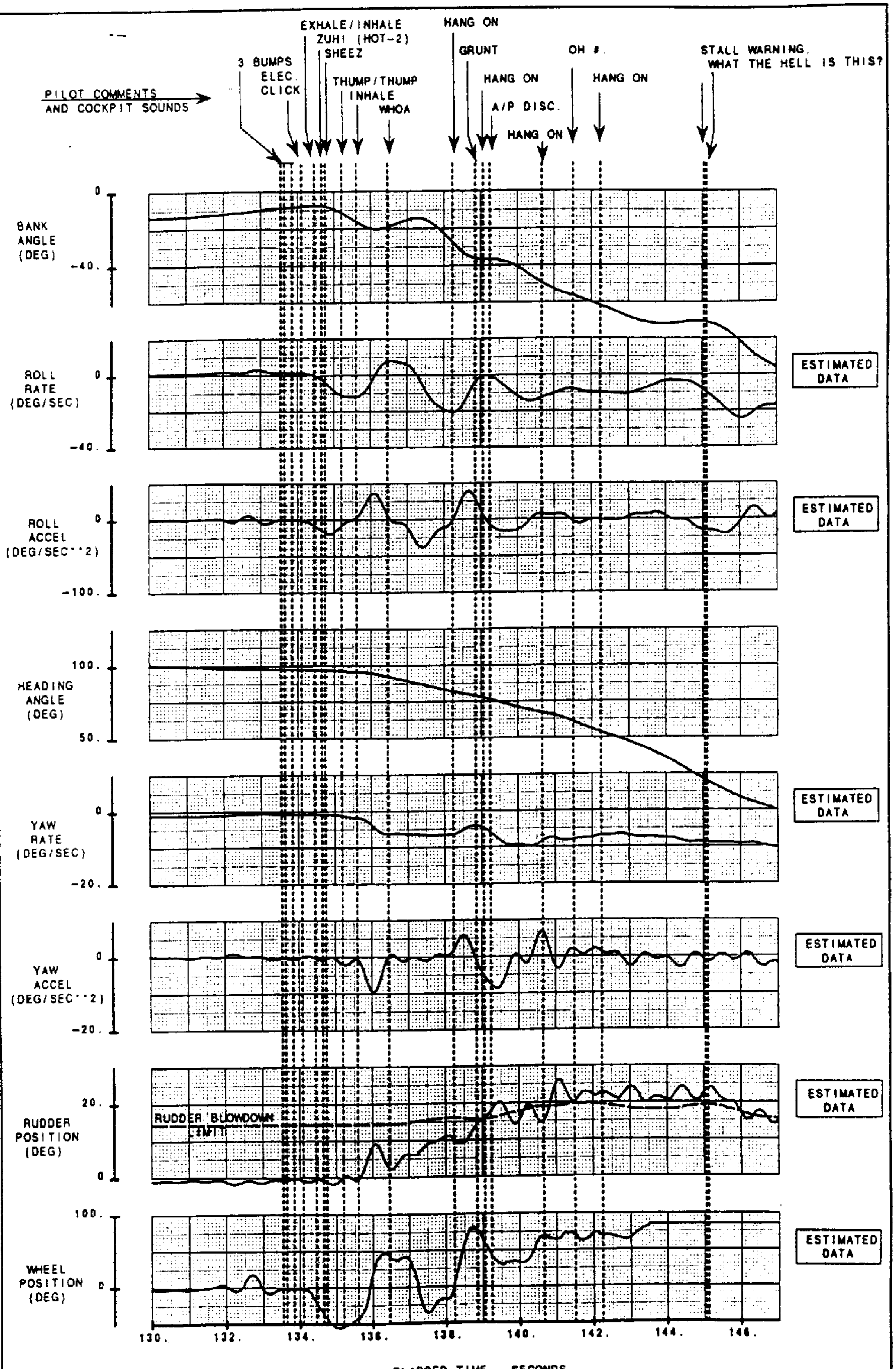

FIGURE 5

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Estimated Ground Track Data for USAir 427 and DAL 1083

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USAir 427

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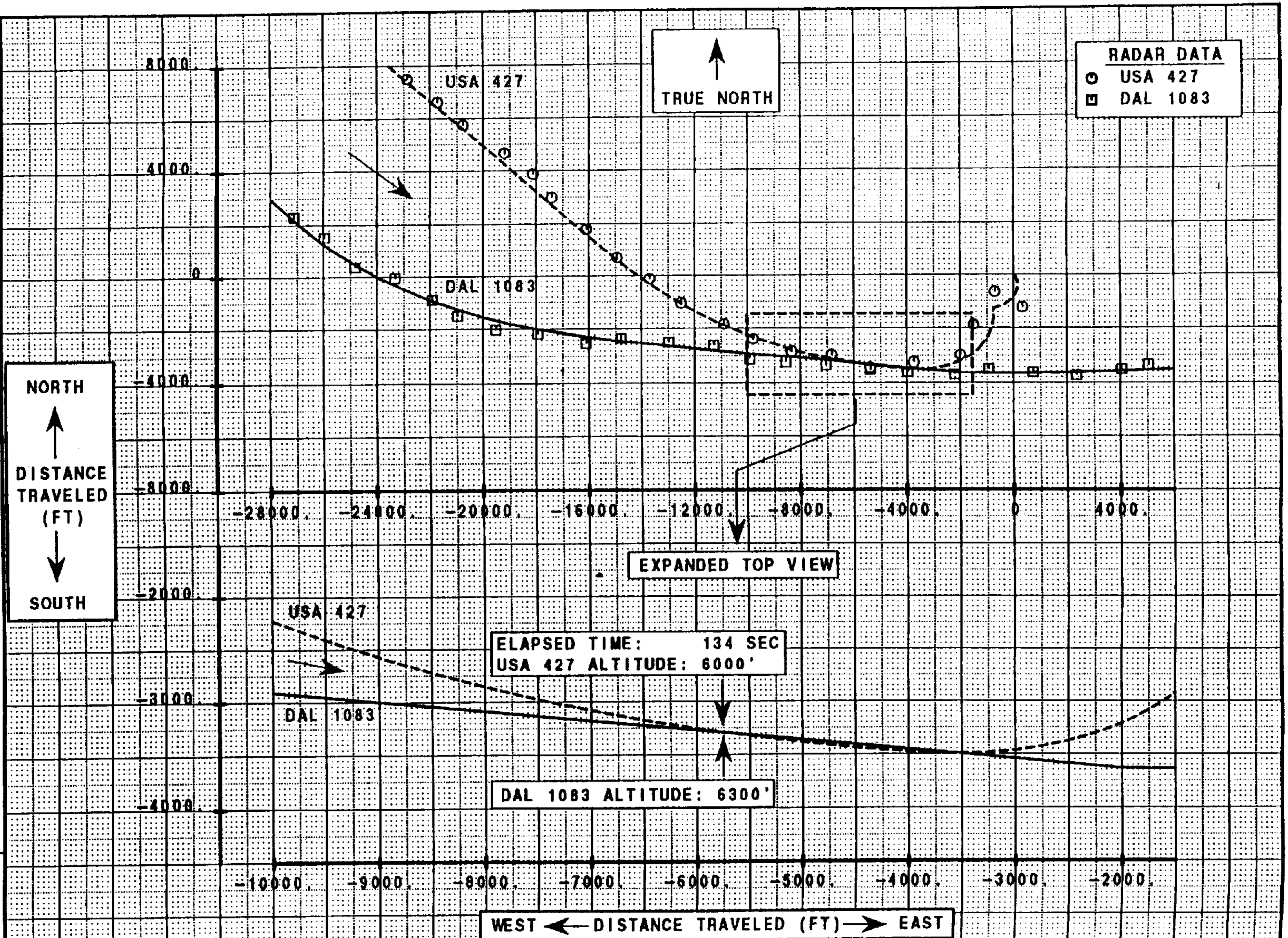

FIGURE 6

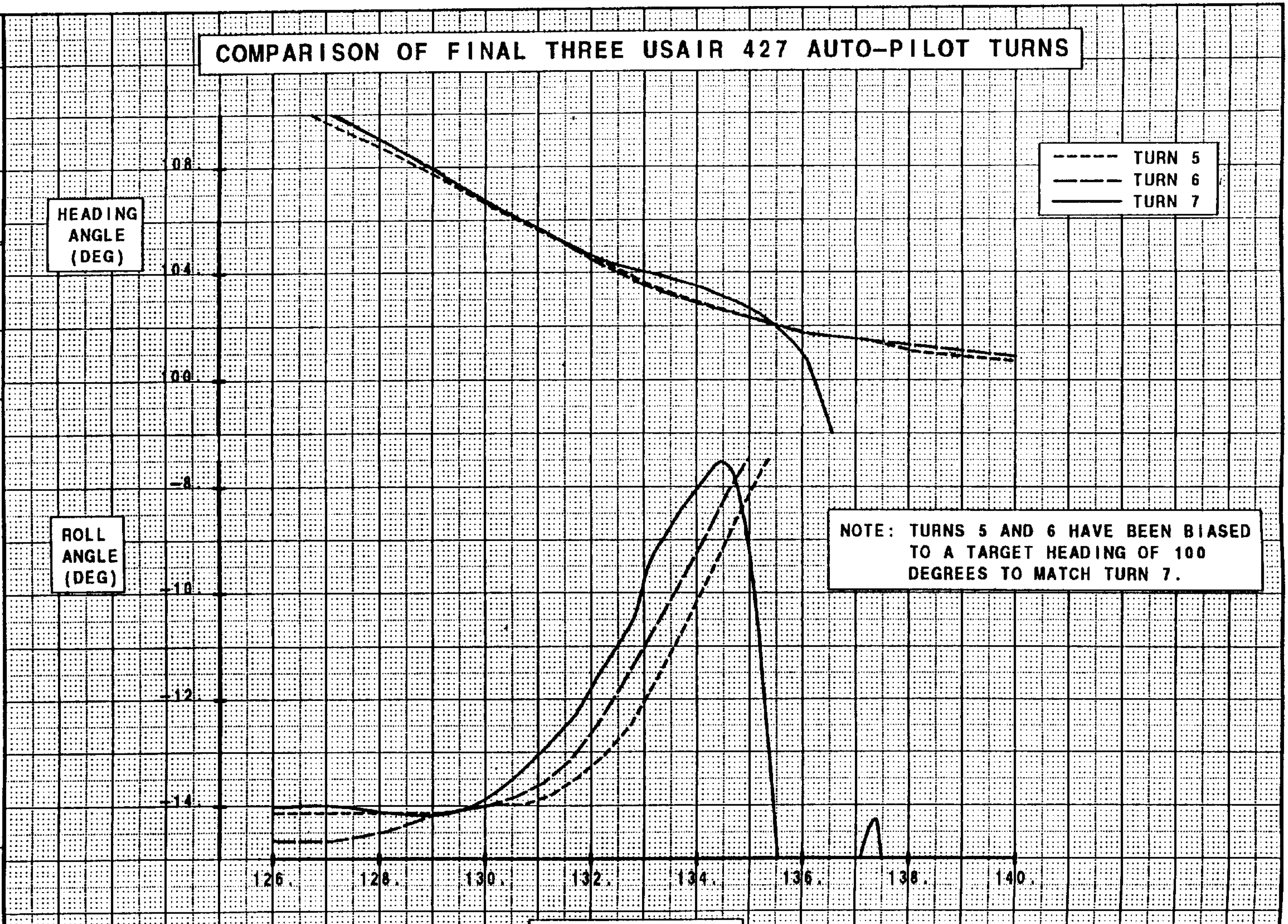

FIGURE 7

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Comparison of Final Three USAir 427 Auto-Pilot Turns

737-300

USAir 427

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ANOMALIES IN USAIR 427 LIFT AND PITCH COEFFICIENTS DURING WAKE ENCOUNTER

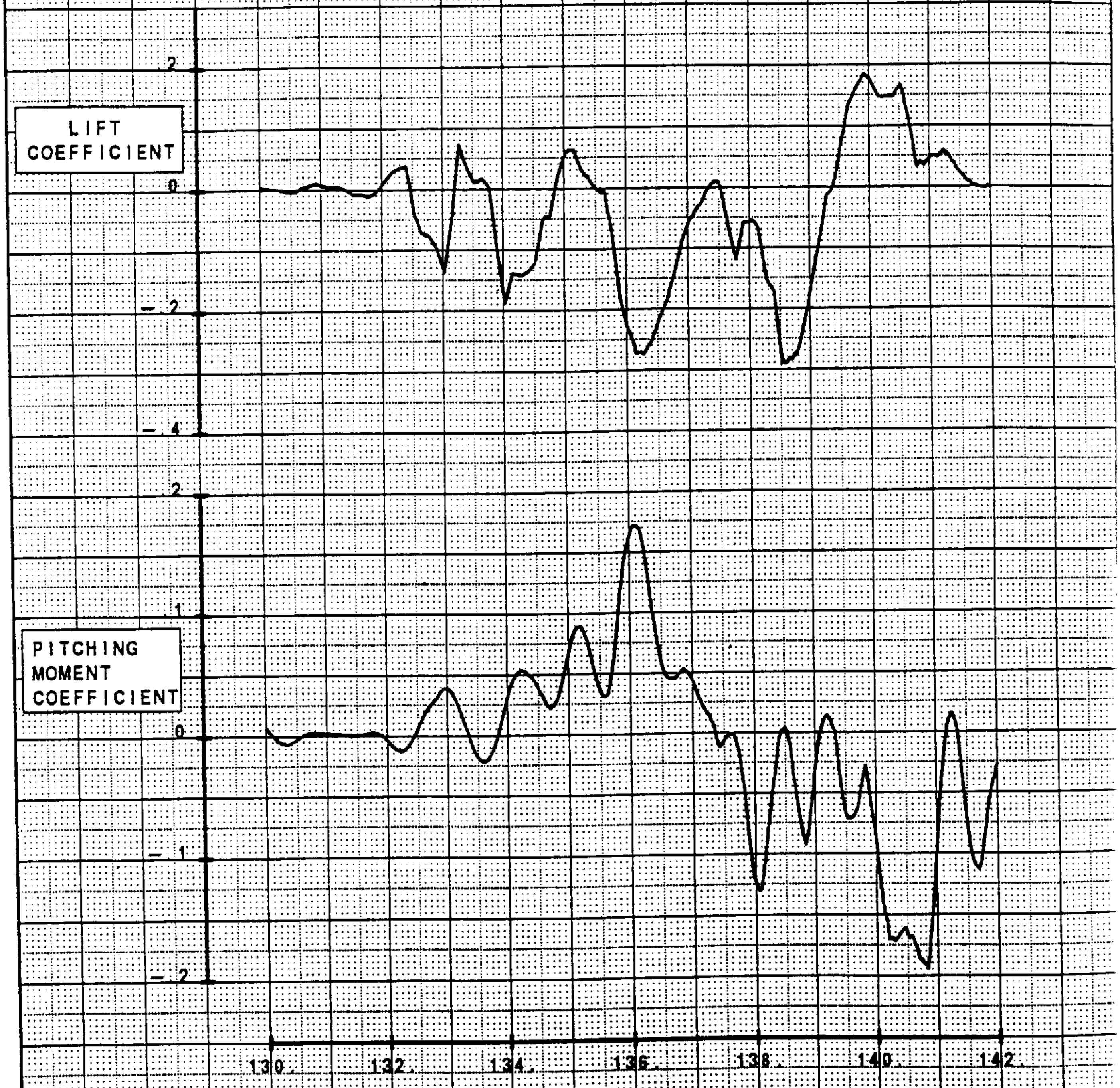

FIGURE 8

CALC	H. Dellicker	08MAY95	REVISED	DATE	Anomalies In USAir 427 Lift and Pitch Coefficients During Wake Encounter	737-300
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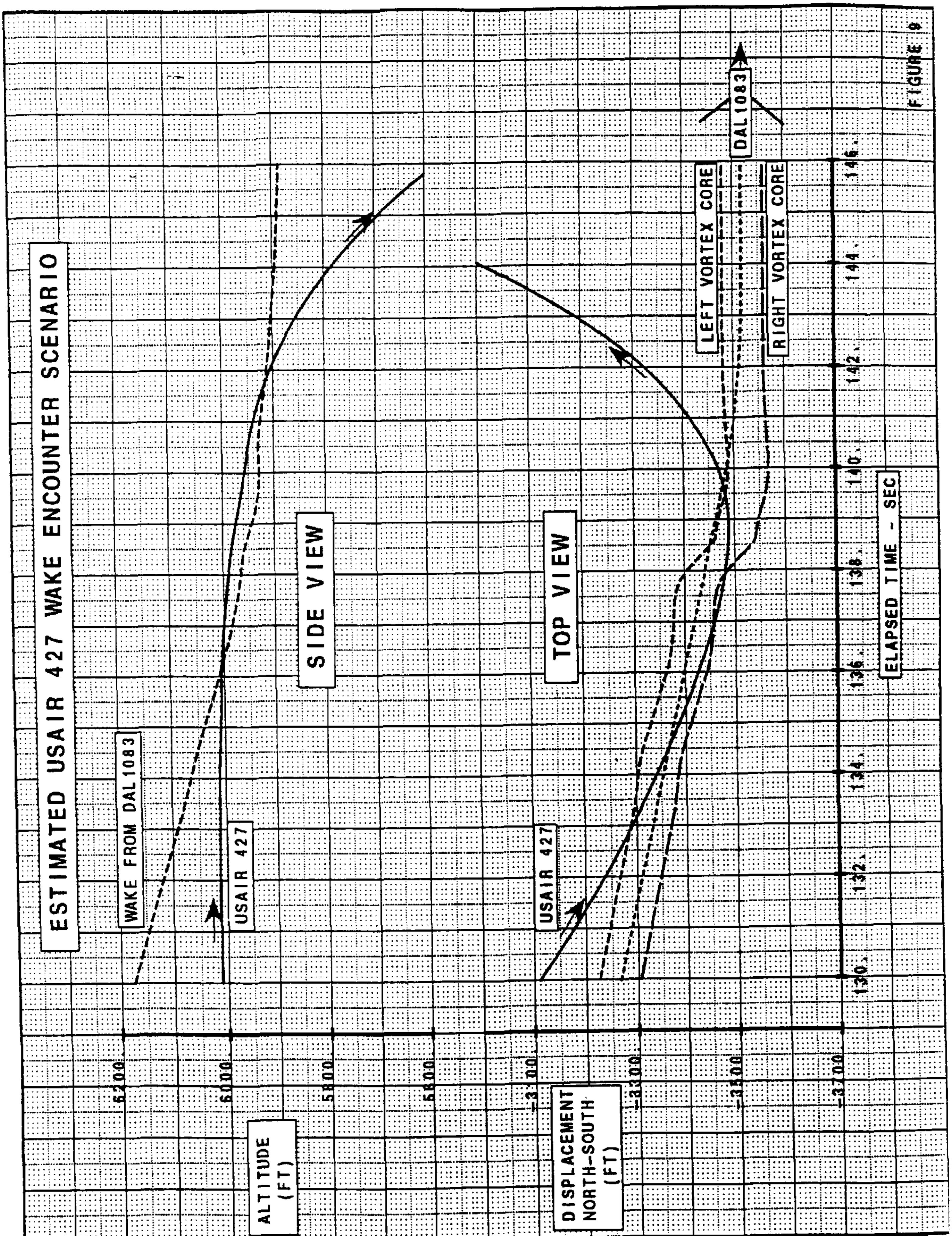

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Estimated USAir 427 Wake Encounter

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USAir 427 Wake Encounter Scenario

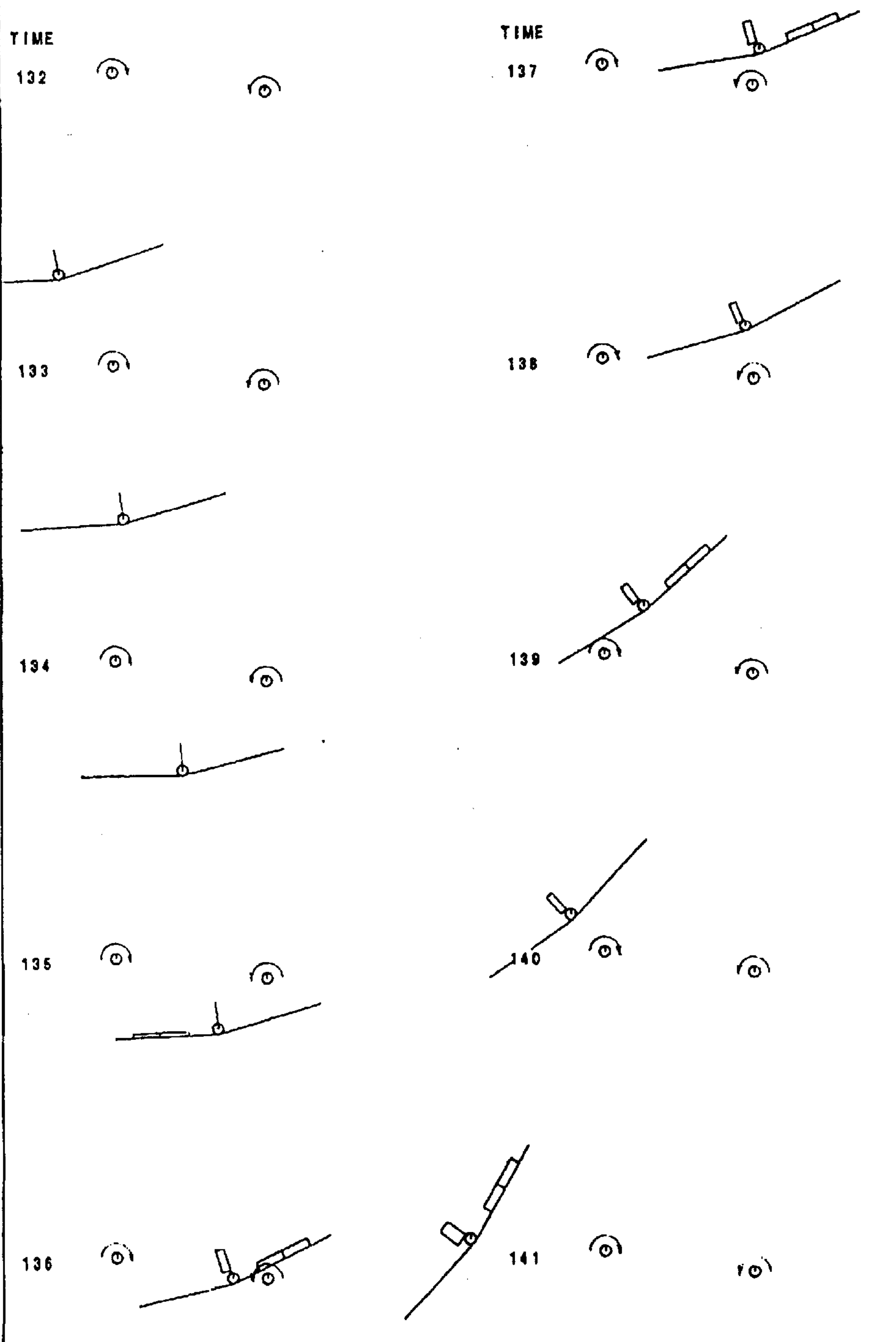

FIGURE 10

COMPARISON OF USAIR 427 LIFT AND PITCH ANOMALIES DURING WAKE ENCOUNTER VS ESTIMATED WAKE EFFECTS

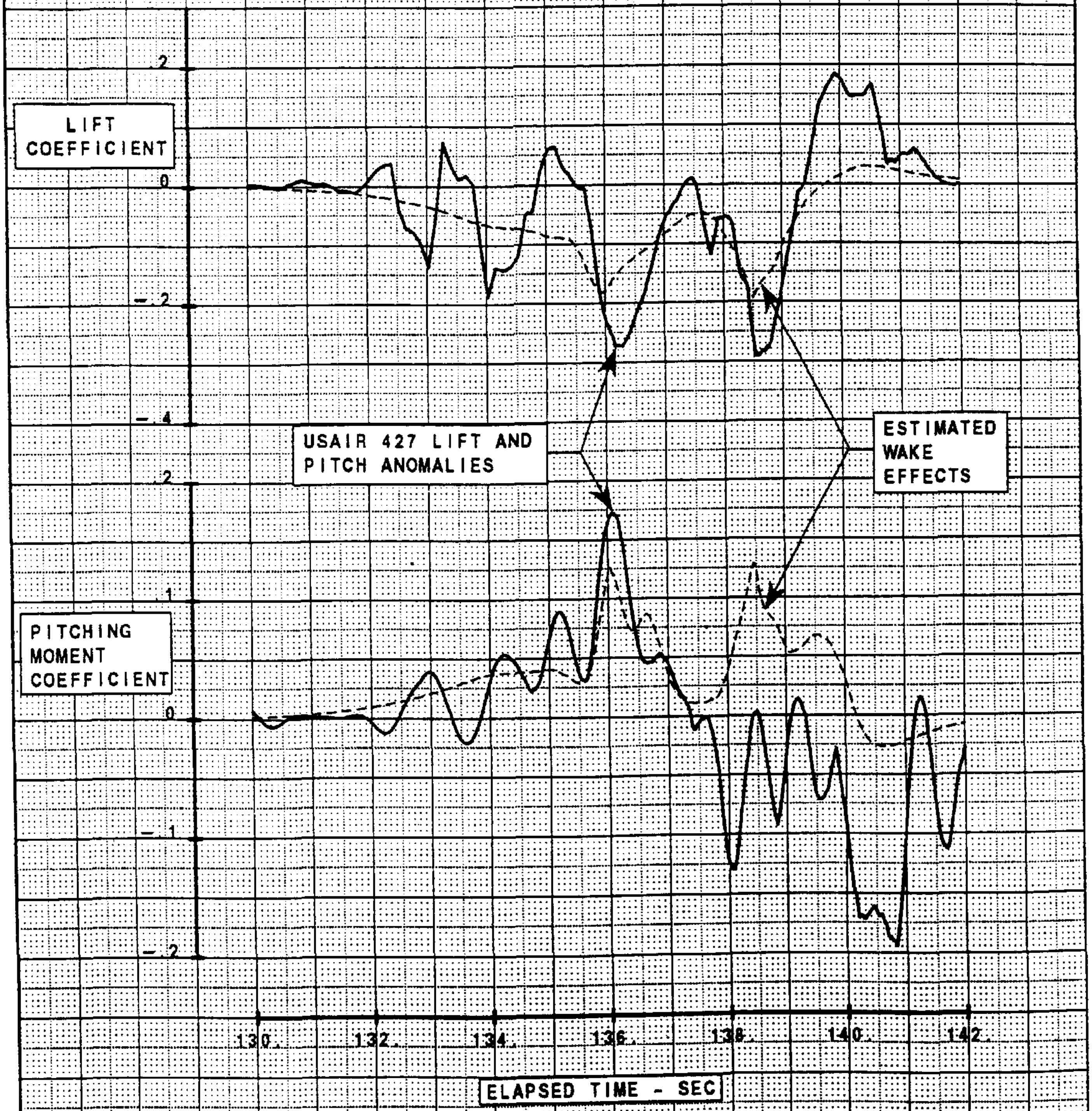

FIGURE 11

CALC	H. Dellicker	08MAY95	REVISED	DATE	Comparison of USAir 427 Lift and Pitch Anomalies During Wake Encounter Vs. Estimated Wake Effects	737-300
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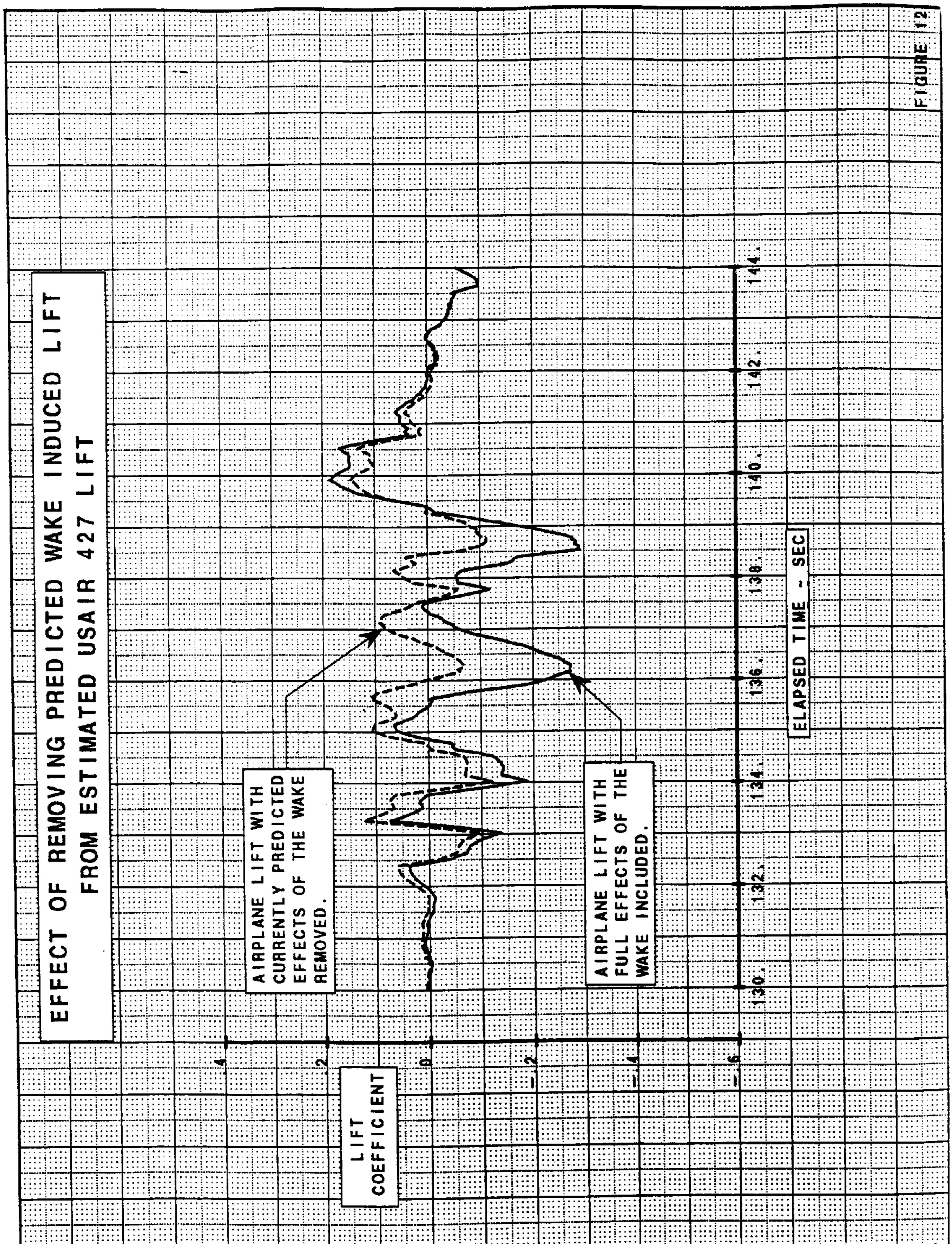

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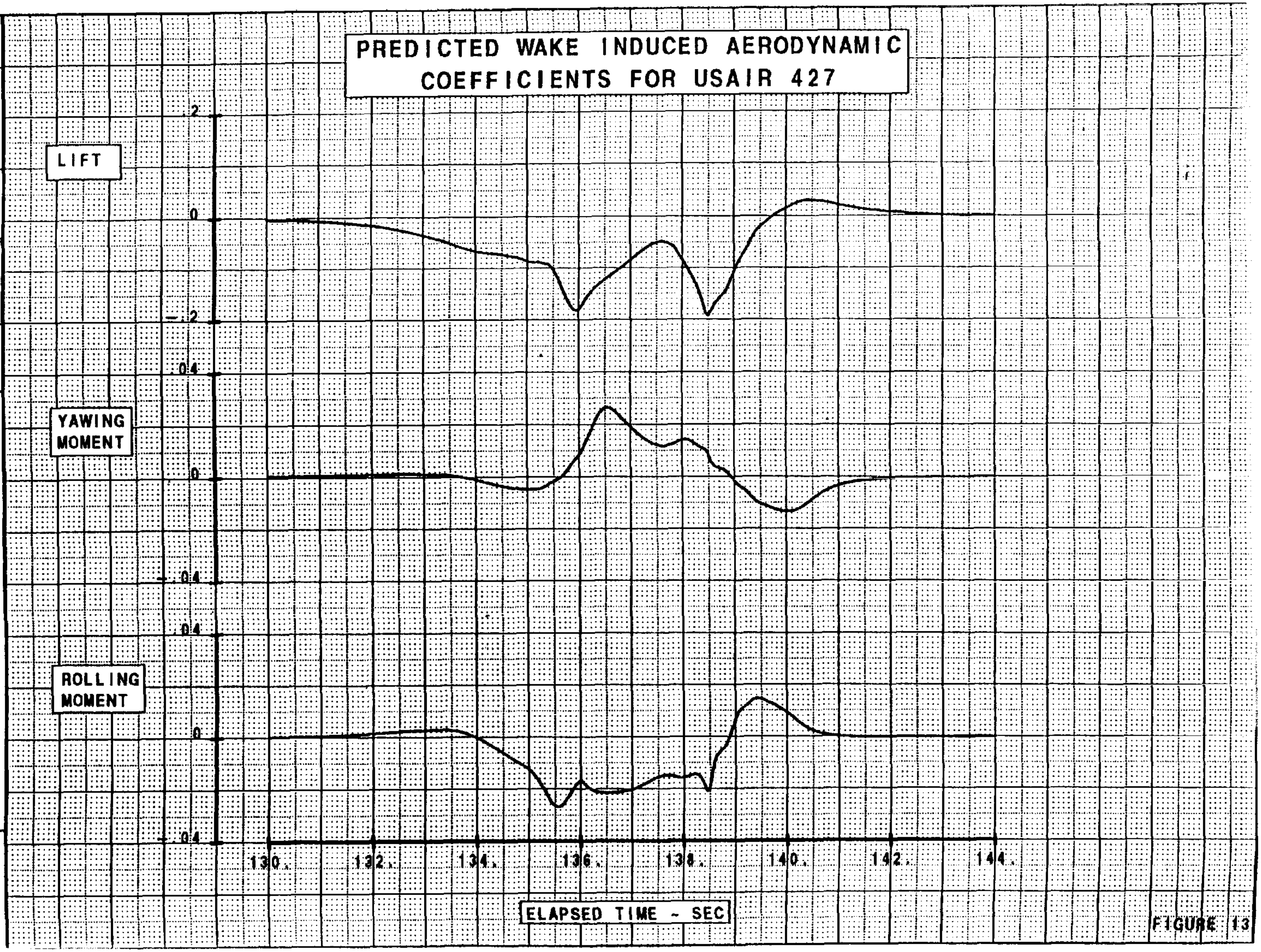

FIGURE 13

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Predicted Wake Induced Aerodynamic Coefficients for USAir 427

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USAir 427

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USAir 427 Lateral/Directional Motion and Estimated Controls Data, Based on Currently Estimated Wake Effects

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737-300 USAir 427

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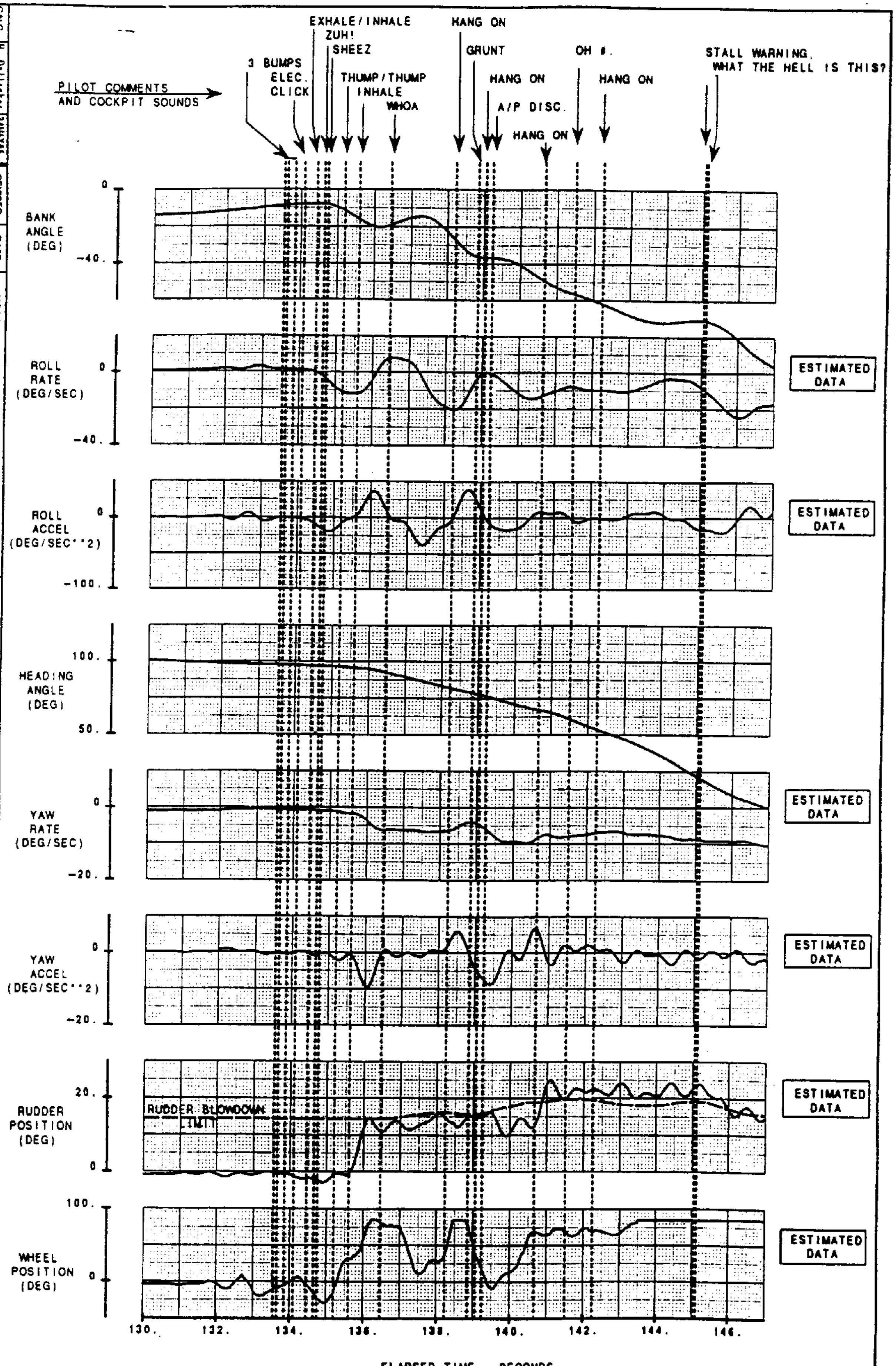

FIGURE 14

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USAir 427 Estimated Rudder and Pedal Positions, Based on Currently Estimated Wake Effects

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USAir 427

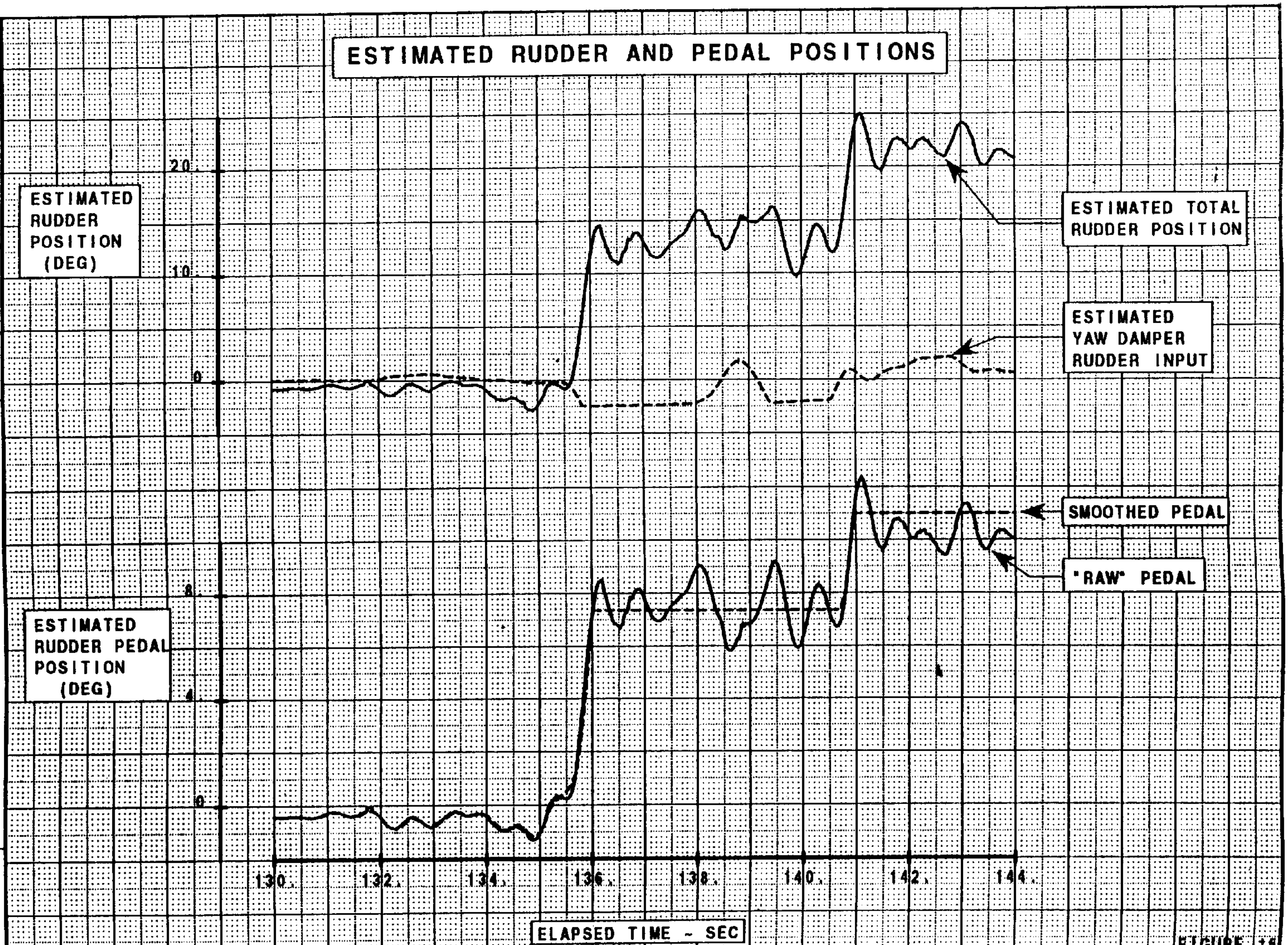

FIGURE 15

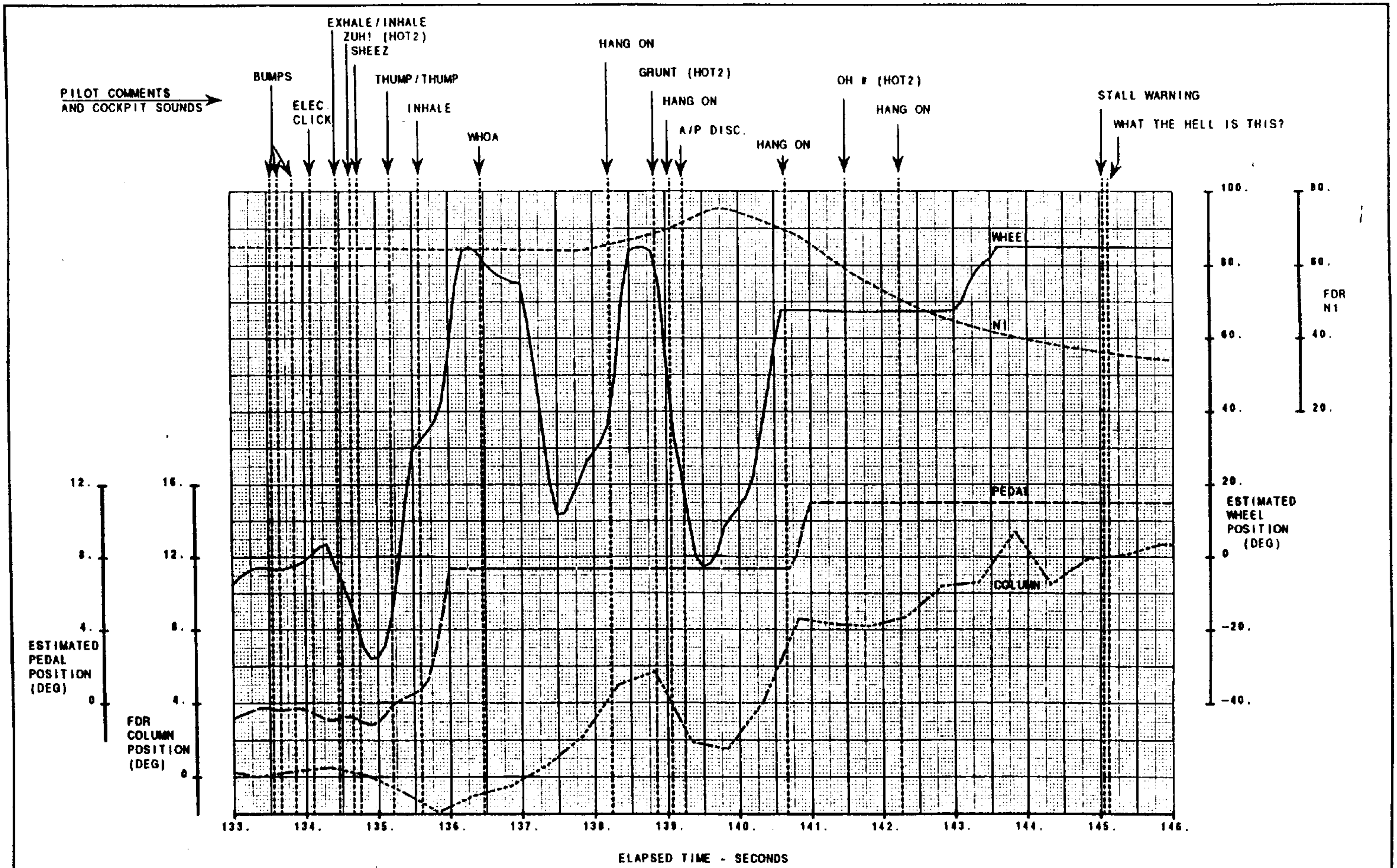

FIGURE 16

CALC	H. Dellicker	24MAY95	REVISED	DATE	USAir 427 FDR and Estimated Control Position Data, Based on Currently Estimated Wake Effects	737-300
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Appendix A: Validation of Methodology Used in Kinematic Analysis of USAir 427

Flight test data have been analyzed with the techniques described earlier in this report in an effort to quantify the accuracy of the kinematic analysis / simulator back-drive methodology

Data for a "Roll Rate Reversal" maneuver with large wheel inputs was provided to the analyst by another member of the group, in a blind test of the procedure. The data included the equivalent seven motion parameters (pitch, roll, heading, vertical and longitudinal acceleration, airspeed and altitude) at the same sample rates as were available from the USAir 427 FDR. The data were analyzed and given back to the supplier for comparison with the flight test measured wheel and rudder position, sideslip angle, and angle of attack. The results, shown in Figure A-1, are generally quite good. (Note: The physical control wheel can exceed 100 degrees deflection but reaches its aerodynamic effectiveness limit at about 85 degrees, agreeing well with the predicted results.)

An unexplained apparent time lag of about 0.2 seconds in the predicted wheel deflection will require further analysis.

Note: Additional validation work, with data involving adverse and favorable combinations of wheel and rudder, will be done as flight test data become available.

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Wheel and Rudder Prediction Test Case (Seq. No 4913)

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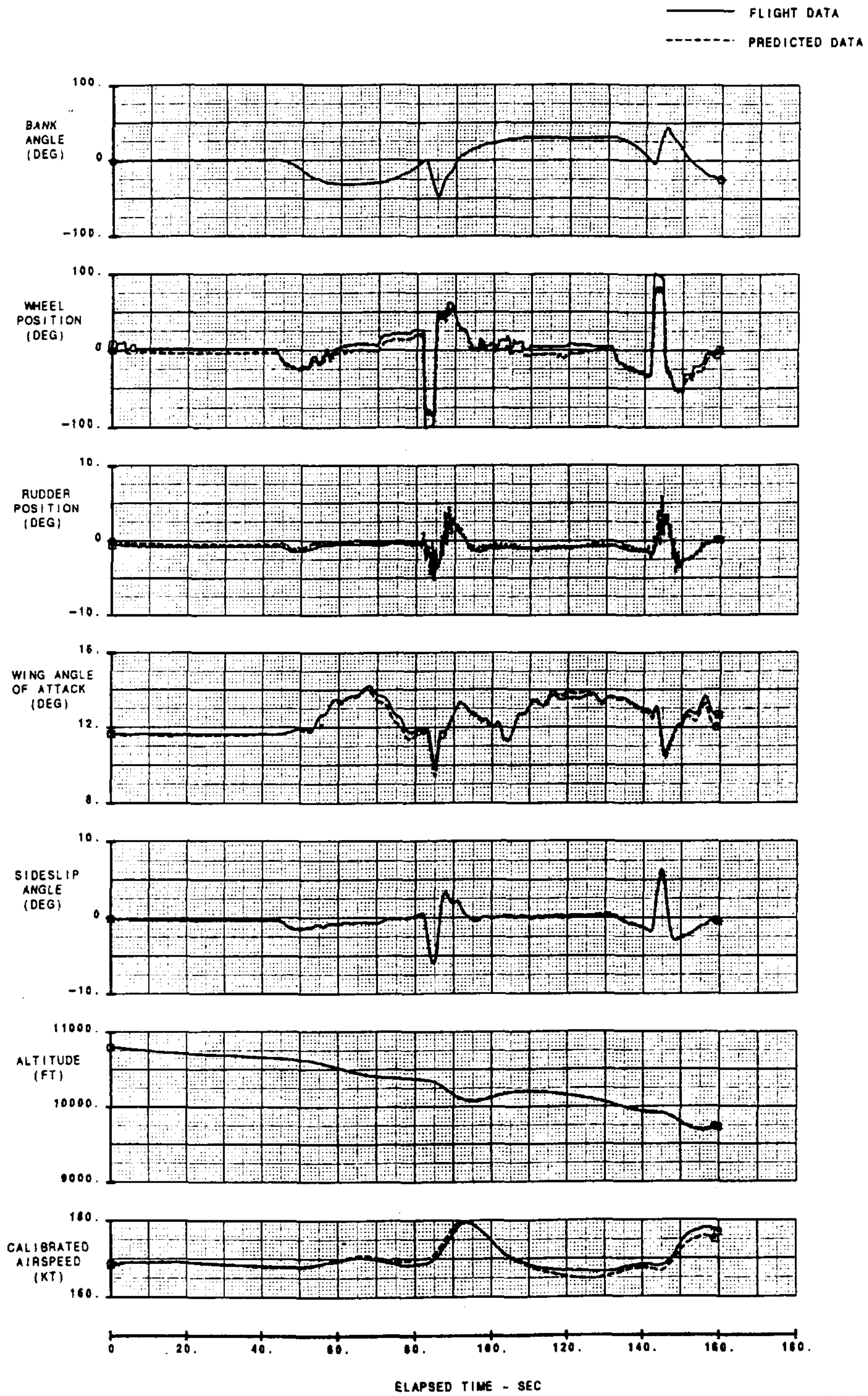

FIGURE A-1