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See remark on pdf page 3

NLR CR 94238 C

NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM

NATIONAL AEROSPACE LABORATORY NLR

THE NETHERLANDS

NLR CR 94238 C

ANALYSIS OF ADDITIONAL FLIGHT DATA OF THE DC-10 ACCIDENT AT FARO AIRPORT

by

(Names masked by AvioConsult)

Reviewed by AvioConsult/Lt-Col ret'd Harry Horlings, Flight Test Engineer (USAF Test Pilot School, class 85A), former chief flight test RNLAF and former member of a scientific committee of the NLR, at the request of the lawyers of the victims and casualties of the accident. General conditions apply, which are deposited at the Chamber of Commerce in The Hague.

DFDR and AIDS data that might be required by readers can be found in he Appendices of report: ***The last 80 seconds of Flight MP495***, downloadable in EN and NL languages from: https://www.avioconsult.com/downloads-nl.htm

~~Stg. CONFIDENTIEEL (CONFIDENTIAL)~~

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Incorrect. Stg = staatsgeheim, a military classification.
This report was definitely not State secret confidential; it was made public by including it as Annex 4 in the Portuguese accident investigation report (RvO).

NLR CONTRACT REPORT

CR 94238 C

ANALYSIS OF ADDITIONAL FLIGHT DATA OF THE DC-10 ACCIDENT AT FARO AIRPORT

by

(Names masked by AvioConsult)

This investigation has been carried out under a contract awarded by the Accident Investigation Bureau of the Netherlands Aviation Safety Board, contract number OV/441.

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	nr(s). 33
	nr(s). 34
	nr(s). 35
	nr(s). 36

Not updraft region, but procedural transition from vertical speed mode to CWS in the non-precision approach procedure, requiring level flight for ~10 seconds to intercept the PAPI approach path.

SUMMARY

Some additional flight data from the DC-10 accident at Faro airport was analyzed. Especially flight data (crash) recorder data and data from the cockpit voice recorder were analyzed with respect to flight mechanical aspects. Also additional ACMS data were obtained and analyzed.

variations, not oscillations (have a constant period time)

the command mode (vert. speed) of

The moment where the pilot switched from the autopilot to the control wheel steering mode could be determined more precisely. It showed that the oscillatory behaviour of the aircraft during the approach had already started before this autopilot mode change took place. The main driving factor behind the pitch down motion was the updraft that existed at the moment the aircraft flew through the associated updraft region while leaving a downburst, located at about 1.7 nmi from the runway threshold.

No, the driving factor was the copilot who was inappropriately pushing the pitch control column against the engaged autopilot (AIDS data, RvO Annex 9 figure 9). See the appendices of the ref. mentioned on page 1.

The functioning of the autothrottle system was checked using an elementary engine and autothrottle model, identified from the flight data. It showed that the autothrottle system functioned properly; discrepancies between model-predicted and actually measured power lever positions, which occur near the end of the flight, should be attributable to manual inputs.

This model was not a DC-10 autothrottle model, was not adequate. Elevator input was missing: as soon as the pilot pulls or pushes the elevator control, engine rpm increases or decreases to avoid the airspeed to decrease or increase affecting the flight path.

Analyzing the additional data led to the conclusion that the aircrew was not aware of the very large crosswind component at landing, leading to a traverse landing which, combined with the high sink rate at that moment, could well have led to shearing of the landing gear and subsequent accident of the aircraft. Contributing factors are the information from the tower-reported wind and the on-board navigation system. The latter displayed a wind vector to the crew indicating too small a crosswind component. This is because the sideslip angle is not taken into account in the wind computation in the navigation computer.

Not aware? Ever been in a cockpit during a crosswind landing? A heading of 125° was required during the approach (DFDR data), meaning a 14° wind correction (drift) angle if the airplane was at the 111 approach radial. This would mean a 34 kt crosswind component at an airspeed of 139 kt, higher than the maximum allowed crosswind for a DC-10 on a dry runway. If a runway is that far left in the windscreen, something is wrong, as experienced pilots will realize. At touchdown, the heading was 117° for runway 106°! The crew must have been fully aware.
The traversing landing was also a consequence of the lack of rudder control authority, as the FDR and AIDS data show: near full rudder could not align the airplane with the runway at the current airspeed; therefore, the airplane cannot have approached the runway on the extended runway centerline, otherwise the rudder deflection would have been adequate (designed for over 30 kt crosswind component).
The sink rate was not that high, the initial NLR calculation was 760 ft/min (Draft CR 94xxx page 16; a number that had to be deleted as directed by lead investigator Frans Erhart).
The DC-10 landing gear is equipped with a fuse pin that sacrifices the landing gear in case of large aft forces, to avoid the gear from punctuating the fuel tanks above it in the wing. This pin might have failed; was unknown to the investigators.
The captain read the wind (190°/20 kt) from the navigation system display 10 s before touchdown, a crosswind component is not displayed. The crosswind component of the displayed wind (20 kt) was too large for both a wet (15 kt) and a flooded (5 kt) runway. He should have used this info and initiated a go-around at that time. At that moment, the sideslip angle must have been still very small though, less than 5° (as DFDR data show). The drift angle was larger, due to the large crosswind component. The drift angle is used in calculating the wind, as navigation system manufacturer Collins wrote to RVDL: "The system calculates wind as the vector difference between ground velocity and air velocity". The difference between drift angle and sideslip angle was obvious not known to the writers of this report.

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LIST OF SYMBOLS

A_x	longitudinal acceleration along body X-axis (m/s^2)
A_y	lateral acceleration along body Y-axis (m/s^2)
A_z	vertical acceleration along body Z-axis (m/s^2)
Const	constant in various models
Es_a	specific energy relative to the air (ft) $E_{s_a} = \frac{V_a^2}{2g} + H$
Es_g	specific energy relative to the ground (ft) $E_{s_g} = \frac{V^2}{2g} + H$
g	gravity constant (m/s^2)
H	calculated altitude (m, ft)
H_p	pressure altitude (ft)
H_r	radio-altitude (ft)
K_V, K_{IV}, K_{Vwsh}, K_{udot}	constants ('gains') in autothrottle model
N_1	engine low-pressure spool rpm (%)
N_2	engine high-pressure spool rpm (%)
r	yaw rate (rad/s)
s	Laplace variable
X,Y,Z	aircraft position coordinates in North-East-Vertical reference frame
V	inertial speed (m/s)
V_a	airspeed (m/s, kts)
Y	side force (N)
β	sideslip angle
τ_{AT}	autothrottle #2 time lag (s)
τ_E	engine model time lag (s)
Δ	difference, deviation
ΔV	speed error (m/s, kts)
δ_r	rudder deflection (rad)
δ_T	power lever position (deg)
δ_{Tc}	commanded power lever position (deg)
ζ	damping coefficient

θ	aircraft pitch angle
ω_n	natural frequency (rad/s)

Superscripts

$(\dot{..})$	= d(..)/dt, time derivative

Subscripts

c	commanded
x	north
y	east
z	vertical

ABBREVIATIONS

ACMS	Aircraft Condition Monitoring system
AP	Auto Pilot
AT	Auto Throttles
CAS	Calibrated Air Speed
CVR	Cockpit Voice Recorder
CWS	Control Wheel Steering
FDR	Flight Data Recorder
FMEA	Failure Modes and Effects Analysis
PF	Pilot Flying
PIO	Pilot Induced Oscillations
PNF	Pilot Not Flying
VS	Vertical Speed (mode)
XWC	crosswind component

Was this not called AIDS in the DC-10?

AIDS	Aircraft Integrated Data System
AGL	Above Ground Level
DFDR	Digital Flight Data Recorder
MDA	Minimum Decision Altitude
PAPI	Precise Approach Path Indicator
RvO	Rapport van Ongeval - Accident Investigation Report
WCA	Wind Correction Angle (drift angle)

See comments in ref.1. The used wind model was definitely inappropriate. There was no windshear, there never has been at Faro airport. NLR was not (made) aware of the operation of ATS, and of the way non-precision approaches are conducted, which caused variations that were explained as windshear, up and downdrafts.

1 INTRODUCTION

MP495

On 21 December 1992 Flight ~~MP459~~, a Martinair DC-10, crashed on runway 11 at Faro airport, Portugal, while landing at 07:33 UTC, resulting in total hull loss, as well as 56 casualties and more injured. Because windshear was suspected to have been a major factor, the National Aerospace Laboratory NLR was asked to investigate the windshear situation by the Accident Investigation Bureau of the Netherlands Aviation Safety Board, on behalf of the Portuguese authorities.

The findings were reported in reference 1. In summary it was concluded that windshear (a downburst) had been present, however, it was not a hazardous factor in itself during the approach of the aircraft. Furthermore strong crosswinds were determined to be present at the moment of landing, far in excess of the crosswind limits of the aircraft. A number of recommendations were made, such as requests for additional data from the ACMS, the Flight Data Recorder (FDR) and the Cockpit Voice Recorder (CVR).

was not stated in Ref. 1 (93080)

No. Constant wind during last 80 s of flight: 190/20 kt Is in excess of limits for wet/flooded runway. No sudden increase.

Was changed from "...far in excess of the maximum demonstrated crosswind limits of 30 kt of the aircraft" at request of lead investigator of the NL, Mr. Frans Erhart. 30 kt was the correct limit published for the DC-10 on a dry runway. Limit on wet: 15 kt, on flooded: 5 kt. (On CVR: "runway is flooded").

In section 2.1 an update of the sideslip angle calculation will be given, using updated aerodynamic data delivered by McDonnell Douglas Aircraft Corporation. This sideslip angle is needed in order to calculate the wind vector accurately.

Sideslip angle? Is zero in-flight by yaw damper, except when pilot operates the rudder. Don't you need the drift angle (or wind correction angle) to calculate the wind vector accurately? Sideslip angle and drift angle are not the same.

In section 2.2 the additional raw data from the ACMS will be discussed. New parameters were delivered, such as flight control forces and cockpit control deflections. Also differences between NLR-calculated and ACMS-recorded data will be looked at to see if there are any anomalies in the data. This applies especially to the speed error used by the Autothrottle system and the wind vector.

In section 2.3 a reconstruction of the flight path will be made down to, and including the moment of touchdown (and even after that moment). The altitude versus range from the runway threshold will be integrated with the CVR-data, and models, developed for the engine and the autothrottle system, will be discussed. These will be used to simulate the response of the autothrottle-engine system during the flight, in order to determine if anything peculiar has happened with the autothrottle system.

Finally concluding remarks will be given in chapter 3.

2 ANALYSIS OF THE ADDITIONAL DATA AND DISCUSSION

2.1 Wind calculation with updated aerodynamic data

From McDonnell Douglas Aircraft Corporation the required (proprietary) aerodynamic data were obtained. This data was used to update the various aerodynamic coefficients, which were used in the computations of Reference 1. Of special importance is the value of the side force derivative with respect to sideslip angle β. The updated Y_β value now becomes -5.054 $m.(s^2.rad)^{-1}$. The previous value was -3.87. This means an increase of 30 percent. The side force derivative with respect to rudder deflection ($Y_{\delta r}$) should be -1.922 $m.(s^2.rad)^{-1}$, instead of -0.0102. Finally the side force derivative with respect to yaw rate (Y_r) now becomes 3.408 $m.(s.rad)^{-1}$ instead of 1.34.

should be?
or is?

2.1.1 Sideslip angle reconstruction

Sideslip? When the yaw damper is active, and no rudder control inputs by the pilots, then sideslip is zero. Fig. 1 is not right, impossible. See text in Fig. 1.

Using the updated values given in section 2.1, the time history of the sideslip angle was also updated. A comparison between the "old" and the "new" sideslip angle is given in figure 1. As the figure shows, there are hardly or no differences at all. Because of these very small differences an update was not considered necessary of previously calculated time histories for the wind components, turbulence, etc. Strictly speaking also an update of the windshear models using the calculation process as explained in Ref.1. should be performed. Considering the (very) small differences in the sideslip angle, however, such an update was not required. In summary an update of wind, windshear and turbulence time histories was therefore not required.

analyzed/ computed?

These sideslip data are not correct, cannot be, using common sense. See Fig. 1. The yaw damper is always engaged. The shown sideslip angles would have made the passengers sick.
DFDR data shows that 12.5 seconds before touchdown, the rudder pedals had returned to zero, even a little to the right and the heading returned to 125°. Immediately thereafter, the rudders were pushed left to 95% and the heading decreased from 125° to approx. 112.5°, a change of 12.5°, while Fig. 1 shows a sideslip increase of 25° - impossible. At 6 seconds before touchdown, the rudder deflection was reduced to zero again.

The NLR engineer(s) might not be aware of the difference between sideslip angle (caused by rudder deflection, asym thrust or atmospheric disturbances) and drift angle (caused by the wind - also called Wind Correction Angle (WCA)).

2.2 Raw data inspection and discussion

As result of recommendations made in Ref.1 additional data was provided to NLR for further analysis. This consisted of flight-mechanical data recorded on the Flight Data Recorder (FDR), additional ACMS-data (especially control forces), and transcripted data from the cockpit voice recorder (CVR). A discussion of this data and analysis is presented in the next paragraphs.

Do you mean AIDS data? Annex 9 of the Portuguese report?

DFDR in DC-10 (Digital FDR)

2.2.1 ACMS and Flight Data Recorder (FDR) flight-mechanical data

Thrust was increased to max. for go-around. DFDR data dump shows 4 longitudinal g values, why picked 0.33? Closest was 0.3350, the others 0.2085, 0.1086 and 0,3166.

Why left out data of prior to 07:32:46 ?

a) Longitudinal acceleration A_x (Fig.2a). The longitudinal acceleration from the FDR is shown in figure 2a. The peak in the vertical acceleration (see Fig.2c) was defined to be the moment of touchdown. At that moment the ~~longitudinal acceleration has increased up to about +0.33g.~~ With an aircraft landing mass of 161,000 kg this equates to an accelerating (!) force of about 520 kN. The build-up can be associated with the engines running at full power. Immediately after touchdown a quick oscillation develops, with a period of about 1 second, lasting for about 2 cycles, with an amplitude of about 0.22g. This equates to a fluctuating force of about 350 kN. At about 07:32:54 UTC the acceleration is zero again, only to increase again afterwards. It is suspected that at this moment the aircraft has been damaged to such an extent that it is no longer useful to try to explain what happened.

Thrust was still increasing (DFDR data)

Rele-vant?

Is not UTC, but radar time. Accident occurred at 07:33:20 UTC

DFDR data dump does not show 0.32 g. How reliable is your (ACMS) data?

b) Lateral acceleration A_y (Fig.2b). The lateral acceleration is shown in figure 2b. At touchdown it rather suddenly peaks at +0.32g, after which an oscillation follows, with an amplitude of about 0.5g, with a period of about 1 second also. These accelerations equate to a peak force of about +505 kN, and a fluctuating force of about 790 kN. Since the initial peak force is positive, it indicates that there is the possibility that the right main landing gear may shear off outwards, i.e. towards the right wing tip (i.e. the positive direction for A_y). With the oscillations being both positive and negative, the actual shearing direction depends upon the actual moment the landing gear would shear off. The actual break-up sequence of the right landing gear is influenced by other factors not considered in this report, and a full analysis is therefore left to the structural experts.

RvO Annex 11 shows that the nacelle of engine #3 touched down on the runway 90 m from wheels touch-down. Did you consider fuse pin failure of the right gear due to aft forces? (See comment on page 3).

The heading at touchdown was 112° (DFDR data), the aircraft' path over the ground was in the direction of the runway, as groove and scratches in the as-phalt prove. Hence the crab an-gle was considerable, leading to this lateral acceleration.

DFDR data shows 1.9533 g at landing. Did you notice the increase during the last 2.5 s of flight? Was initiation of go-around.

c) vertical acceleration A_z (Fig.2c). The vertical acceleration clearly shows, in figure 2c, the landing impact load on the aircraft and landing gear. The peak value reached is 1.98g. The implications of this for the structural integrity of the landing gear is left to structural experts.

because the captain initiated a go-around - he pulled the control wheel.

d) pitch angle (Fig.3a). Figure 3a shows the pitch angle time history during the last 3 seconds before touchdown. As shown in this figure the pitch angle increases to about 9 degrees at touchdown. Thereafter it drops to zero increases again, then drops again, and then finally increases again to about 6 deg. Whether this is due to the nose gear compression forces, flexing of the fuselage or other contributions is not known.

These two zero data points were invalid data, refer to the DFDR data dump. Is this relevant? The crash was already a fact.

Is this relevant for the questions asked?

Why not during the last 20 seconds?

e) Bank angle (Fig.3b). Figure 3b shows the time history of the roll (bank) angle. After touchdown the roll angle increases to about 25 deg (right wing down) at 07:32:52 UTC, then drops slightly to 20 deg at 07:32:55 UTC, and then in-creases to a large value of more than 90 deg at 07:32:58 UTC. Apparently the aircraft flips over to the right at this point. At the moment of touchdown the aircraft has a (small) bank angle of about +5 deg (right wing down), i.e. the right main gear touches down first. In view of the crosswind existing at landing this bank angle apparently did not compensate for the left drift of the aircraft.

Would the bank angle history of before the crash not be of more interest?

The deep groove in the asphalt was straight and in the direction of, but on the left side of the runway. The heading at touchdown was 117 deg (runway 106), the difference (wind correction + slip) 11 deg. There was no left drift away from runway heading.

f) heading angle (Fig.3c). The magnetic heading during the ~~entire flight~~ including the portion from the FDR, is shown in figure 3c. After touchdown there is a continuous, sharp increase to beyond 170 degrees. At touchdown there is already a heading misalignment of about 11 degrees with the runway, meaning the aircraft made a traverse landing. The final heading of 170 deg indicates the aircraft turned to the right to an angle almost perpendicular to the runway axis (170 - 106 = 64 deg) before the FDR stopped recording.

only the last 160 s. Why no remark on the large heading 125°?

not relevant

is called crab angle.

Is this required?

Mode reversion? The pilot switched from command mode to CWS, as required during a non-precision approach (the only option at Faro) before reaching 500 ft AGL.

g) Moment of AP-mode reversion with pitch and vertical wind (Fig.4). The moment of mode reversion of the autopilot mode, from the Vertical-Speed (VS)-mode to the control wheel steering mode (CWS) was recorded on the ACMS. The mode reversion occurred at 07:31:57 UTC. In figure 4 this mode reversion is indicated, together with the pitch time history and the vertical wind component Vw_v. The pitch angle has started a downward trend at about 07:31:40

From where? How obtained? Were pilot control force inputs included in the calculation, now?

Frans Erhart required this change; NLR text was "... is too small to ..." - which was a good conclusion.

Was varying, not oscillatory. An oscillation has a constant periodic time.
A phugoid with either the AP engaged and/or the pilot hands on? Sure?

No, not at all likely. This happened because the copilot pushed and pulled pitch control against the AP, refer to AIDS data in Fig. 5. These were inappropriate Pilot Induced variations while under autopilot control. + The (light) turbulence had just started to which ATS responded, causing the thrust increase to which the AP reacted by pitching down to maintain the vertical speed.

The autopilot in vert. speed mode might have been set at a too high ROD at the start of descent (or the head wind was larger than anticipated). Right before the switch to CWS, the pilot noticed being below the PAPI indicated glide path and had to fly level for 10 s to intercept the PAPI. Following this short level flight, the copilot said "PAPI hè" (as excuse, or confirmation). A normal procedure, that can and may not be explained as initiated by a vertical wind component. The writer was obviously not made knowledgeable of non-precision approach procedures.

UTC, i.e. 17s *before* the mode reversion occurs. As is evident from the figure this pitch-down has very likely been initiated by the vertical wind component. This mechanism can be explained by the fact that, with the AP in VS-mode, it tries to maintain a preset vertical speed. When there is an updraft, the AP will pitch down the aircraft in order to recapture the preset vertical speed again.

And what happens when the pilot pulls and pushes on the pitch control with autopilot engaged, as Fig. 5 shows?

The resulting oscillatory motion afterwards has a period of about 35 seconds, which is very close to the calculated phugoid period (Ref.1). The possibility of pilot-induced oscillations (PIO), mentioned in Ref.1, should be ruled out since PIO is related to human visual, vestibular or neuro-motor lags in a tightly controlled situation (high feedback gains), normally at constant speed, where these lags can lead to instability. The resulting PIO oscillatory periods will therefore be in the order of seconds, rather than tens of seconds as is the case here. Nevertheless the divergent oscillatory behavior warrants further investigation, since it may be associated with the use of the CWS-mode *and* autothrottle in ~~heavy~~ turbulence, which may lead to overcontrol.

with varying control forces on the control wheel?

There was no divergent behavior, as DFDR data show.

The turbulence was light, according to the DFDR vertical g data, and i.a.w. the ICAO definition.

Why do you suggest this? The AP (CWS) and AT Systems were well developed feedback and control systems, which can do the job better than humans under these circumstances. The copilot proved not proficient in using these systems.

2.2.2 Cockpit Voice Recorder (CVR) data

If writer and reader understand the non-precision approach procedure.

From the cockpit voice recorder (CVR) the relevant transcripts and remarks were taken and integrated with the altitude profile. This may put the pilot's actions into a better perspective. Further discussion will take place in section 2.3.2. It is noted here that from the CVR it becomes apparent that at time 07:32:39 UTC the wind being reported by the crew is 190/20 kt. This wind may have been taken from the AreaNav. The exact moment of time when the AreaNav was read may however have been earlier. The crew also made some comments about the visibility: at about 250 ft altitude the pilot flying (PF) reported "..*I can't see anything*..", after which the flight engineer reported that the windshield wipers were at 'FAST'. This indicates that the pilot flying was having some problems seeing the runway clearly at that point because of rain. Since he did not report when he could see the runway again it is not known how long this situation lasted, and whether it influenced his judgment about the aircraft's position relative to the runway. The possibility of optical illusions and distortions due to rain and landing in

He should have initiated a go-around at this time, according to the procedures, because he was below MDA. Ask a good pilot to review your report.

can only have been read from the display of the Area Inertial Navigation System (AINS) darkness in a crosswind may contribute to misjudgment by the crew of the aircraft's position.

Are you sure? Did pilots tell you? Should they therefore not have initiated a go-around earlier than they did?

2.2.3 Control forces (PF and PNF)

a) Pitch control forces (PF and PNF) (Fig.5). When the aircraft changes to the Control Wheel Steering (CWS)-mode, the basic function of the flight control system becomes what is known as a "rate command/attitude hold" system. Through the pitch or roll control force the pilot generates a pitch or roll rate command. When the forces are zero then the flight control system maintains the present attitude. In order to see how well this functioned during the Faro landing case, both the control force in pitch and the pitch rate are shown in figure 5. The pitch rate can be seen to correlate with the pitch control force input, indicating that the flight control system functioned properly. Before 07:31:57 UTC there is not much activity, but leading up to the moment of mode reversion ('CWS-on') the PF pitch control force is building up, i.e. the pilot is apparently having his hand on the control column and is exerting a steadily increasing force prior to mode reversion. Again here the divergent, oscillatory nature is noted in the control forces. The PF may have reacted to the nose-down motion due to the updraft while still in the VS-mode, and first to have exerted a nose-up control force on the control column, but after no response of the aircraft, to have decided to take over manually (CWS-mode). There is hardly any activity from the pilot not flying (PNF). Only at the last moment, at 07:32:42 UTC does the PNF provide a small additional nose-up (force) input, apparently in order to aid the PF ~~in flaring~~ the aircraft.

Did the copilot use CWS appropriately?

No divergency observed; was under pilot control.

He himself put the nose down, against the AP.

Wrong. You should have consulted a pilot. It is standard procedure to switch to CWS before descending below 500 ft.

Is normal. At the last moment, the captain took over control of the airplane without informing the copilot (PF) and initiated a go-around. Not noticed the thrust increase from idle (too low!) to max. thrust?

b) Roll control forces (PF and PNF) (Fig.6). Beyond the moment of mode reversion to CWS there is much increased activity of the PF, while there is no activity of the PNF. Only at the last moment, at about 07:32:44 UTC, there is a sudden increase in right roll (force) input from the PNF, with about an equally large left roll (force) input from the PF. This counteracting PF-input is believed to be the reaction force of the PF due to a sudden input by the PNF, since the roll angle rate shows that the aircraft responds at this moment to what the PNF is doing, viz. a roll to the right. The PNF apparently wanted to drop the right wing in an attempt to counteract the drift to the

is normal... only one pilot is steering - has control

Initially also to the right, because the bank angle increased to the left as side effect of full rudder to the left.

The pilot in the left seat, the Capt (was PNF) did not drop the wing to more than 0 deg at this point, as DFDR data show. He was not counteracting the drift, because the heading still was not the runway heading. Why was rudder released? Because the airplane was not on the runway centerline.

left. This ~~one~~-wing-low technique, in combination with the rudder input noted earlier (and also shown in Fig.9), is a prescribed DC-10 crosswind technique. The difference in roll control forces between the PF and the PNF at the end probably caused the CWS-mode to trip, i.e. to be disengaged, leaving the aircraft in a fully manual flying mode. The flare response of the aircraft in this "manual" mode will be quite different than when in CWS-mode, viz such that, certainly at the lower speed at around touchdown, the pitch-up in the flare will be less than expected, if this tripping of the CWS has gone unnoticed by the crew. This may explain the rather short ~~flare~~ that occurred at touchdown (see Fig.3a).

When in CWS, pull to pitch attitude, then release control to maintain the pitch. When in manual, pull to pitch attitude, then maintain control force to maintain the pitch attitude. Pilots are looking outside, they respond to airplane motions and if no adequate response, they continue pulling. Not quite different. The captain had increased the thrust for go-around at this moment, was no flare.

In the draft: "(i.e. pitch up to about 9 degrees)". Deleted by Frans Erhart.

2.2.4 Control displacements

was not a good piloting technique using CWS , was it?

a) Control column displacement (Fig.7). After the mode reversion to CWS-mode there is an increasing trend in control column displacement activity (it is the result of the pilot force inputs acting through the CWS). At the moment of mode reversion there is an aft (i.e. nose-up) input, which agrees with the aircraft pitch angle having dropped due to the updraft. Evidently, the closer the aircraft gets to the ground the greater the variations in control column displacements become. Also here the divergent oscillatory character noted earlier in the pitch control forces can be observed.

don't see divergent, it's pilot against CWS. You should use more realistic scales. Prior to CWS, did you notice the inputs by the copilot? He should have used the vertical speed wheel of the AP.

b) Control wheel displacement ~~(Fig.8). There is hardly any activity in roll up to the moment of mode reversion to CWS. Noteworthy is the large right roll input at about 07:32:43 UTC.~~ Apparently this control wheel displacement follows the roll force input of the *PNF* and not that of the PF. This PNF-input came so quickly that due to the reaction time of the PF he apparently counteracted the PNF input.

In CWS, the control forces by the captain take precedence over the forces by the copilot. The captain should have said "my controls."

in the command mode of

c) rudder pedal displacement (Fig 9). During the portion of flight on the AutoPilot (AP), there is no activity at all. Noteworthy is the large rudder pedal input at about 07:32:40 UTC. An almost full left rudder pedal input is given, apparently in an attempt to line up the aircraft's longitudinal axis with the runway centerline.

And why already rudder input from 07:32:10? Did you include the resulting sideslip in your calculations?

not required either, the yaw damper takes care.

And, was this line-up successful? No, why not? Why not analyzed this?
The rudder obviously had no control power to align the airplane with the runway, while it was designed for 30 kt crosswind. The reason? The airplane approached at a too large heading of 125°, not on the 111° radial, not on the extended runway centerline either, and never made it to the (extended) runway centerline, don't you agree?

2.2.5 Specific energy and energy rate

General. The aircraft energy state is the sum of potential and kinetic energy. When dividing by the mass of the aircraft, the resulting energy is called "specific" energy, i.e. the energy per unit mass. When referencing specific energy to the inertial frame, the resulting specific energy is named Es_g, the specific energy *relative to the ground*. When referencing it to the air it is named Es_a. When studying the energy state of the aircraft one may be able to investigate the effect of thrust variations and external effects on the aircraft (e.g. rain, turbulence), and hence to check the functioning of the autothrottle system for example.

Word "other" was deleted by Frans Erhart

During a "normal" steady descent, the specific energy *rate* of the aircraft is constant and equal to the rate of descent, and the specific energy state shows a linear decrease during descent. Deviations from these linear "trends" may be interesting, since they will be induced by thrust variations and external influences, such as wind variations, rain effects, etc. Both for the specific energy relative to the ground and to the air this linear trend was therefore determined. For the landing at Faro this trend was -563 ft/min for Es_g, and -685 ft/min for Es_a. For a 3 deg glide path, flown at 144 kts (airspeed), this rate should be -760 ft/min. So the average sink rate during this landing was a little bit less than was required for a 3 deg glide path. The fact that relative to the air the average energy rate is greater (in absolute sense) than when relative to the ground, can be explained by the fact that on average there must have been a headwind-to-tailwind shear. This has been substantiated by the wind analysis in Ref.1.
After removal of the linear trends mentioned above the deviations of the specific energies from these trends may show any effects of wind influence, etc. In case of a pure phugoid motion these deviations should be zero, since in a phugoid motion there is (theoretically) no energy lost and therefore an exchange of kinetic and potential energy will take place.

5.2% at Faro, according to the approach chart

Less? Avg airspeed was less than 144 kt

shear, or just a larger head or tail wind component?

Is this analysis still valid if the pilot pushes and pulls on the controls? Account for transition AP to Manual?

correction of a non-precision approach path (page 13) does show effects.

a) Specific energies (Fig.10a). The deviations in specific energies are shown in figure 10a. The average deviation in both Es_g and Es_a is zero. Also the difference between the deviation in Es_g and in Es_a is zero on average. This means that the autothrottle system, which provides the energy input to

The ROD to be set in the autopilot depends on the headwind component, might have been 750 ft/min. The descent from 2000 ft down to 500 ft (might be in the clouds) must be below the 5.2% (3°) to be able to intercept the PAPI 5.2% (3°) glide path visually from below by flying straight and level for some time at 500 ft, which actually occurred. Did you calculate with these two approach segments?

Why was the heading (DFDR) during the last 80 s nearly constant 125, apart from sideslip induced by the copilot with rudder from 40 s before touchdown?

Yes, there were manual inputs, to the control column being the elevator control. As AIDS data show, the copilot almost continuously pushed and pulled on the elevator control (against the autopilot). The position of the elevator is fed back to the autothrottle system. When the pilot pulls the control only a bit, the ATS responds by increasing the thrust. Some people would call this aggressive, but this is designed to ensure adequate thrust increase to prevent the decrease of airspeed during the approach at low altitude while maintaining the glide path, or when initiating a go-around. In addition, the ATS increases the airspeed with 5 kt if gusts are above a certain internal threshold. Hence, both the (light) turbulence and the copilot caused the thrust changes and airspeed variations, and therewith energy state. The 5 kt speed changes, as shown by the DFDR data, of course also have effect on the approach path and autopilot response for maintaining the vertical speed before CWS was engaged.

maintain the energy level, is functioning well. Obviously the autothrottle system tries to maintain airspeed.

As figure 10a shows, both the deviation in Es_a and in Es_g show essentially the same time history, apart from "turbulent" variations having a zero mean. The wind influence on energy deviation appears to be relatively small. During the portion of flight in CWS-mode the energy deviations are *NOT* zero as expected during a phugoid oscillation, but are varying, with peaks of ±100 ft and -50 ft. Apparently the autothrottle system is providing additional inputs during this oscillatory motion, which causes the energy balance to be both on the plus and minus side. This could indicate a sluggish autothrottle system that has some time delay in keeping the airspeed constant, or else there have been manual inputs. Because of the "control" exerted during this portion of flight the assumption that the motion observed is a phugoid oscillation does no longer hold.

Then, why wrote about this in the first place?

After 07:32:40 UTC the deviation in specific energy (both relative to air and to the ground) becomes more and more negative. This is due to the fact that the power levers were retarded, with a resulting loss of energy. The loss in Es_a is greater than in Es_g, which is due to the decrease in the headwind component. At touchdown the loss in Es_a is -200 ft. This means that, when the airspeed would have been kept constant (at 144 kts), the aircraft would have been 200 ft too low, or, when at the proper altitude, the airspeed would have been too low by about 16 kts (with an airspeed of 144 kts as reference).

?? What are you saying? The approach airspeed set in the ATS window was 139 kt, being the threshold speed, 5 kt too low for the approach. During gusts, the ATS increased the airspeed to 144 kt temporarily, as shown by DFDR data. Throttles were closed at 150 ft.

b) Specific energy rates (Fig.10b). The average energy rate should be equal to the rate-of-descent in constant wind conditions. Both the energy rate relative to the air and to the ground is shown in figure 10b. Numerical differentiation causes quite some oscillations, especially in the rate in Es_a after the mode reversion to the CWS-mode. On average the energy rates oscillate around their respective mean approach values, given earlier in this section.

In the draft CR 94xxx, the mean approach value presented was "760 ft/min". This was changed upon remark by Frans Erhart to "given earlier in this section".

c) kinetic and potential energy components (Fig.11). The energy deviations calculated under point a) above are the sum of *potential* and *kinetic* energy deviations. In case of a perfect autothrottle system the speed will be held constant, and then the total energy deviations will consist of only potential energy deviations. In case there is no autothrottle at all, then there will

May be, but an excellent ATS (DC-10) will increase the airspeed 5 kt during gusts to increase the airspeed safety margin during the approach. The engine thrust then increases or decreases the energy levels.
You forget to mention inappropriate pilot inputs. The NTSB wrote in their letter that is attached to the accident report: "Once the autopilot was disengaged, CWS with ATS remained; functions which were inappropriately used by the fllght crew"

provided the thrust settings are not changed, is it?

be an exchange between potential and kinetic energy, such as exists in a phugoid. Apparently this was not the case, because energy deviations were observed in the oscillations (see Fig.10a). Hence the question is how much of the total energy deviation is made up of kinetic energy, and how much is potential energy. So, why are you including this analysis in the first place.

The potential energy deviation ΔH was calculated by subtracting a linear trend with time from the calculated altitude time history. The respective kinetic energy deviations were then calculated by subtracting this potential energy deviation from the respective total energy deviations ΔEs_a and ΔEs_g. The result is shown in Fig.11, where both the potential energy deviation as well as the kinetic energy deviations are given. It can be observed that the kinetic energy deviation relative to air is relatively constant, up to about 07:31:40 UTC. Thereafter variations can be seen to appear, however, they are all mostly on the positive side. This corresponds with the functioning of the autothrottle and gust compensation system, keeping variations in kinetic energy "on the safe side". Noteworthy again is the drop in this kinetic energy deviation relative to air after 07:32:40 UTC, while at this time there is no decrease in potential energy deviation (rather an increase). This is due to the effect of closing the power levers. Too early, by the copilot.

2.2.6 Differences between reconstructed data and recorded (ACMS) data

In reference 1 it is explained how various programs at NLR were employed to reconstruct the flight path and to calculate the wind vector in 3 dimensions. In order to see how well these programs performed, and to check whether no anomalies occurred in these calculations, in this section a comparison will be shown between the calculated and the measured variables of interest. The variables looked at more closely will be the altitude profile, the (air)speed error used by the autothrottle system, the difference in the wind vector calculated and as recorded on the ACMS and the vertical speed.

2.2.6.1 Altitude profile

In figure 12 the difference between the calculated altitude (from a Kalman filter process) and the measured radio-altitude and baro-altitude (as recorded on the ACMS) are given. The differences are normal and well within

allowable errors. The Kalman filter process contains several assumptions about the magnitude of the error sources, and the differences are well within these limits. The higher above the ground, the greater the altitude error may be in this filter. Maximum altitude difference is at the beginning of the data run, where the Kalman filter-smoother "thinks" it is 60 ft higher than the baro- or radio-altitude. The figure shows that nothing special is happening. At 07:32:40 UTC and later there are two negative peaks in $H\text{-}H_p$ of about -40 ft. This would mean a static pressure lower than expected. Other error sources are suspected, e.g. ground effect, time delays in the pneumatic lines and/or in the measurement and/or recording system, sideslip, etc. Insufficient data is available to provide an in-depth analysis.
It is noted furthermore that the difference between calculated and *radio-*altitude is minimal at around touchdown.

Elevation of the runway taken into account?

2.2.6.2 Speed error

The ACMS system recorded the speed error, a signal used by the autothrottle system. It has also been calculated by NLR. A comparison is given in figure 13. No difference between the ACMS-speed error and the calculated speed error is seen. Noteworthy is the large, negative trend in speed error at the end of the data, which is due to the power levers having been closed.

2.2.6.3 Wind vector time history

How calculated? Where is data from? Why peak in Fig 14 at :40?

Was not the airplane location!

a) difference in windspeed (Fig.14). The (differences between the) calculated windspeed and the windspeed from the AreaNav system (recorded on the ACMS) are shown in figure 14. Also the mean wind and gust as recorded by the Faro meteo-office are shown. Up to 07:31:40 UTC there are no real differences. After this moment several times it can be observed that the ACMS-windspeed lags the calculated windspeed, and also is about 20 kts less when at the end. It will be shown later-on (Fig.16) that this difference is almost entirely due to the sideslip angle, which has been taken into account in the wind calculation (Ref.1), but which has not been included in the AreaNav wind computations (nor in any wind calculations on board aircraft computers). The AreaNav-wind just before 07:32:40 UTC is about the same as the *gust* recorded

Did you notice the differences in time between the UTC, radar and meteo clocks? Did you correlate?

You mean drift angle?
Wind causes drift, rudder causes sideslip. The always engaged yaw damper maintains sideslip zero, otherwise the pax start vomitting in turbulence.

Are this AIDS data? The AIDS recording quit 3 sec before touchdown. So where are these data from?

You should have conducted a heading/drift angle analysis as presented in report: The last 80 s of flight MP495. (see page 1)
Why was the heading constant during the last 80 s of flight (except during rudder input)?

Are you sure that ACMS recorded wind data? Schematic Diagrams do not prove wind data from the INS systems to ACMS, AIDS or DFDR. So where are these data from?

by Faro, thereafter the AreaNav-wind is even less than the *mean* recorded wind.

?

Why, NLR, did the mean required heading to get to the airport not change up to the instant of touchdown? Did the pilots follow the prescribed approach procedure?

b) difference in wind direction (Fig.15). The (difference between the) wind direction calculated (Ref.1) and recorded on the ACMS (calculated by the AreaNav computer) is shown in figure 15. Also the wind direction as recorded by the meteo-office at Faro is shown. Generally the ACMS and the NLR-wind direction agree quite well in terms of trend, although differences of the order of 10 degrees do occur. Both are better than the meteo-wind direction recorded, which is about 20 degrees less at the moment of touchdown than calculated.

Was not at the same location as the airplane!

How can you be that sure? Fig 14 shows AINS wind 214 deg just prior to touchdown, and a meteo wind of 190 deg. Where are these data from? Not from the accident report. Time clocks correlated? Do you observe any changes in the DFDR data that supports your analysis?

c) correlation of windspeed error with sideslip angle (Fig.16). The windspeed error is defined as the difference between the NLR-calculated windspeed and the windspeed recorded ~~on~~ the ACMS. Most, if not all of this windspeed error is a crosswind error because of the wind direction.

Why is the "windspeed recorded on the ACMS" not presented in the accident report?

From a simple analysis one can derive that a correlation must exist between the error in the crosswind component XWC and the sideslip angle. If Δ denotes the deviation, or error, then ΔXWC is about equal to the airspeed V_a times the sideslip angle, or mathematically: $\Delta XWC = V_a * \beta$. When there is a sideslip angle β of about 10 deg, i.e. ~0.2 rad, then the error in the crosswind component would be $\Delta XWC = 144 * 0.2 \approx 28$ kts!.

Only in the calculation, not in the real world. Is 28 kt a realistic error? No. something is wrong here.

Do you consider sideslip angle and drift angle to be the same? It's not. (Cross)wind causes drift, not sideslip. See remark in Fig. 14.

The correlation between windspeed error and sideslip angle is shown in figure 16. It can be seen that there is an almost one-on-one relationship between the windspeed error and the sideslip angle. In mathematical terms it is said that the correlation between windspeed error and sideslip angle is reaching unity (the calculated correlation coefficient r = 0.915 in this case). Any sideslip angle β not accounted for in wind calculations would result in an error in the crosswind of 14 kts per 0.1 rad (5 deg) sideslip angle.

Don't believe this analysis. Compare to DFDR heading data. And look at rudder inputs. This analysis is bad.

Fig 16 shows sideslip angle Beta while no rudder input. Cannot be correct.

Lijst 2 Tab 3f, pdf page 6: Letter of AINS manufacturer Collins to RVDL:
"The system calculates wind as the vector difference between ground velocity and air velocity". Effect sideslip Beta? No, is called drift angle.
Pilots apply a wind correction angle, not sideslip, to compensate for (cross)wind (except during landing).

2.2.6.4 Vertical speed

A vertical speed had been recorded on the ACMS. This variable is derived from the barometric pressure module within the aircraft, and should indicate the vertical speed as displayed on the vertical speed indicator (VSI). It may be valuable to compare this variable with the vertical speed as obtained from

Was the vertical speed as indicated on VSI indeed recorded?

CADC?

The indication on a VSI doesn't change very fast, not as presented in fig. 17. Indication is always rather smooth.

Fig 17 shows a vertical speed change in 2 s from +625 to -2625 ft/min just prior to touchdown. Is this realistic for a 161.400 kg body on a 5.2% glide slope? Radalt data does not confirm this. Just crunching numbers? Inappropriately been differentiating discrete data?

the calculation process (i.e. Kalman filter-smoother) performed at NLR (Ref.1). The intent of the Kalman filter-smoother combination employed is to obtain a good estimate of the vertical, inertial speed, since this component is needed in order to get a good estimate of the vertical wind component. The comparison is shown in figure 17. As is evident the two agree, albeit that there are quite some variations in the ACMS-values due to atmospheric disturbances. Both indicate a strong reduction in sink rate at about 07:31:50 UTC, i.e. before the mode reversion to CWS, which is due to the updraft of the downburst flown through before.

The copilot pushed on the control wheel from 07:31:20 against autopilot (see pitch force/angle) and brought it back to neutral at this time. Is definitely not an updraft.

Noteworthy is the inertial vertical speed at touchdown, which reaches a value of -966 ft/min.

Radalt data show less. In the draft of this report, § 2.2.5 b, NLR mentioned 760 ft/min.

2.3 Flight path reconstruction

From the available FDR data, the flight path, in terms of X, Y, Z, and the inertial speed components was calculated down to the moment of touchdown, and even after that moment. Of special interest is the final segment beyond the ACMS-data range, in order to see if anything special happened there that could explain what went wrong during the very final segment of flight.

How accurate is this? DFDR provides radalt data and heading, so why calculate and therewith introduce errors?

2.3.1 Altitude profile

The (X,Y,Z) position calculated is that of the center of gravity of the aircraft.
For the analysis the touchdown point was defined to be at 392m from the runway threshold, and 22m left of the centerline of the runway. The downwind distance of 392m is taken from runway markings left behind by the aircraft. The lateral displacement is taken from indications that the center body landing gear touched down on the left runway shoulder, between the runway edge lights and the adjacent grass area.

The grooves and scratches in the runway asphalt were in the direction of the runway. Was there lateral displacement on-going, or did the airplane approach from the left side (given the large heading) and did not quite reach the runway centerline?

The accelerometer signals generally need corrections for bias. If this were not done than large drifts can show up in the calculated positions. The vertical channel is the one most prone to these drifts. For the vertical acceleration this bias was determined by integrating the accelerations twice to yield a vertical height trace. By correlating it with the radio-altitude

DFDR presents several lat, long and vert. g data streams, which ones did you use, and why? Are these data accurate enough?

for the same segment of flight the (constant) bias term could be established, and the resulting flight path could be updated/corrected. This process at the same time also provided the vertical, inertial speed. The result of the flight path reconstruction, in terms of vertical speed for example, has already been used in figure 17. The height, or altitude, will be shown together with the cockpit voice recorder data shown in the next section.

This cannot be correct. Number crunching, nothing to do with reality. You differentiate (d/dt) discrete data, is that allowed? No, is not a good engineering practice, is it? Refer to note on top of page 21. Also refer to remark with Fig. 17

2.3.2 Combined CVR-flight path

The transcripts from the Cockpit Voice Recorder are shown with the altitude profile together in figure 18.
Concerning *flight visibility* it can be observed that the crew had the runway in sight at about 1000 ft. Later however, at about 900 ft, the sound of windshield wipers indicate there was rain. After the PF reported he was going to change to CWS-mode (at 650 ft), the PNF confirmed this , but immediately remarked something about the runway (*"ok, hé, the runway is..."*). Although unintelligible, possibly the PNF momentarily lost sight of the runway, or noted any other condition about the runway. At about 250 ft the PF also reported not being able to see the runway, after which the flight engineer remarked that the windshield wipers were at fast (speed). Apparently at this point the PF lost sight of the runway. How long this moment lasted, and whether the PNF did have the runway in sight, is not known at this moment, nor is it certain to what extent this may have affected the PF's judgment about his position relative to the runway. The PNF was also coaching the PF as to speed control and altitude control. which is standard procedure.
Concerning *turbulence* no remarks were made as to the severity level, other than that earlier in the flight the crew made remarks about the bad weather to be expected at Faro. The turbulence was only light i.a.w. ICAO definitions.
Although not shown in figure 18 the PNF reported the *AreaNav-wind* to the PF at a late moment in the flight, viz. at 07:32:39 UTC, which was about 8 seconds before the start of the kettle tones. He reported a wind of 190 deg with 20 kts. The actual crosswind component was 20 kt, too high for a wet runway (max. 15 kt), much too high for a flooded runway (max. 5 kt).
Nowhere along the flight path are there any verbal indications from the cockpit of an impending disaster. No, but several safety calls, that are required during a non-precision approach, were not made by the crew. These calls are required to avoid disaster.

You didn't answer the question in § 2.3 on "what went wrong during the very final segment of flight".
Refer to the paper on this subject on www.avioconsult.com/downloads-nl.htm

2.3.3 Engine and auto-throttle response

From N_1, N_2 and power lever position data a simplified engine and autothrottle (AT) model was derived for the FARO-landing. Purpose of these models is to be able to reconstruct missing signals, to better predict certain dynamic behavior, and to understand better the dynamic power lever response which occurred at FARO. This was done to investigate whether the observed power levers closure at 07:32:40 UTC was caused by the autothrottle system itself.

A detailed analysis and implementation will allow one to study more accurately the dynamic behavior of the system. By including elements of the AT-system in model form allows one to simulate the total system as accurately as possible, and to perform failure modes and effects analysis (FMEA). This may allow one to determine the possible cause for the power levers being retarded before landing. Such a detailed modeling is the subject of a separate study.

Incl. feedback from elevator?
And the gust filter in ATS?

The simplified engine model used here has been derived in Appendix A. In Appendix B two autothrottle models have been derived. The models were "tuned" or matched using a selected data set. Since it is suspected that manual inputs were made somewhere at the final moment, i.e. after about 07:32:20 UTC, only data up to this moment were used in fitting these models.

2.3.3.1 Engine model fit

In Appendix A a simple engine model is derived. Initially a first order model was assumed but the difference between model and data contained dynamic effects which required an improved order of modeling. Therefore a second order dynamic model was assumed to exist between the transfer of power lever inputs to N_2 rpm. The match of this model with the actual data is given in figure 19. A very good match has been achieved.

Also in Appendix A a model is derived for the relationship between N_2 and N_1 rpm (the low-pressure spool rpm). A direct, linear relationship has been assumed to exist. The model fit is shown in figure 20, where N_1 rpm response from the model is shown along with the actual data. Again a very good fit has been achieved. Generally one may state that the engine model derived here is good enough for the purpose of being used in conjunction with an autothrottle model.

2.3.3.2 Autothrottle model fitting

A generic autothrottle model has been derived and applied to the Faro data, in order to study the possibility of premature closing of the power levers by the autothrottle system. A detailed modeling of the system is underway, and will be reported elsewhere. In this report a simplified modeling technique will be applied which is believed to be adequate to show whether such a retardation of the power levers can occur or not, on the condition that there are NO failures in the system.
The general structure of the control law of a DC-10 type autothrottle system is depicted in figure 21. A speed error signal ΔV is derived from the difference between "bugspeed" V_{bug} and actual airspeed V_a. In order to quicken the engine response, i.e. to take into account the fact that the engines need a certain time to respond to power lever position commands δ_{Tc}, a "lead" time is required. This is normally achieved by also feeding back the time derivative of the speed, udot, which equals the longitudinal acceleration minus the gravity component, compensated by pitch angle. Since it is power lever position rate that is controlled, the time derivative of these signals have to be taken. The equations are given in the Appendix.

??

Measuring a speed change would take too long if close to the ground a go-around is initiated. Therefore elevator position feedback.

Furthermore two versions of modeling are assumed. For the autothrottle #1 model a direct relationship is assumed to exist between power lever position rate commands and actual power lever position rate. In version 2 a servo system is assumed to exist between the rate commands and the position rates. This may be equated to (electric) servo-motors driving the power levers to their commanded speed. The performance of both autothrottle models will be shown in the following sub-sections.

2.3.3.2.1 Autothrottle #1 model and fit

This autothrottle model has no servo lags included in the dynamics that drive the power levers. Only a very simple feedback law is implemented, as

An other, more important (dynamic) input to the autothrottle system is the left inboard elevator position; refer to DC-10 Schematic Diagram 22-31. When the pilot pulls or pushes the control column, the elevators move and the feedback to the AT results in an immediate in- or decrease of the engines' rpm. Respons to airspeed only would be way too slow, and result in unexpected altitude loss and incidents if the altitude is low. DFDR data show this rpm response to pitch control inputs frequently during the last 70 seconds of flight.
The AT System also includes a gust filter that increases the airspeed with 5 kt at the onset of gusts above a certain internal threshold, to increase the speed safety margin during the approach. An autothrottle system model without these and the other inputs is not a valid model.

discussed in Appendix B, where power lever position rate $\dot{\delta}_T$ is a direct function of speed error, the higher-frequency variations in CAS and the longitudinal time derivative udot, used to "quicken" the autothrottle response. The AT response in the DC-10 is "quickened" by feeding back elevator control. Refer to remark bottom previous page.

The result of "simulating" the autothrottle in this simple way results in a power lever position rate time response as given in figure 22a, and of power lever position in figure 22b. The match is very good for the position rate and the position. After 07:32:35 UTC the calculated power lever rate becomes positive, whereas the data becomes negative and peaks at -9 deg/s. This exceeds the maximum rate at which the autothrottle system can move the power levers, hence suggesting a manual override.

At 07:32:20 UTC the calculated position of the power levers is more forward than actually measured (30 deg instead of 25 deg), and after 07:32:45 UTC starts to increase to about 60 deg. Because power lever position <u>rate</u> has been matched with the data, it is possible that small differences in position may arise due to the integration process, causing an accumulation of errors. The position data clearly shows that the model would have increased the power on the engines by moving the power levers full forward, rather than reducing them to idle (0 deg).

Pitch went down, hence power levers went aft. From 32:42 pitch went up, to which the AT would have responded if not kept close. Due to the idle rpm at the time the captain increased the throttles, the engine spool-up took too much time for preventing a touchdown. Following the touchdown, the spoilers deployed while throttles were forward (system error?), making a go-around impossible.

<u>2.3.3.2.2</u> Autothrottle #2 model and fit

The second autothrottle system has a servo lag included in the mechanism that drives the power levers. This results in a lag in the time response of the power levers when commanded to a certain rate, and makes it harder for the system to follow quickly varying command signals. The reasons behind this modeling are explained in Appendix B.

throttle lever command?

The (matched) position <u>rate</u> is shown in figure 23a, and the power lever position is shown in figure 23b. The model has been matched for data up to 07:32:20 UTC. Only after 07:32:35 UTC the calculated rate increases to +4 deg/s, whereas the data shows a drop to -9 deg/s. Thereafter, at 07:32:45 UTC, they are the same for one moment, only to diverge from one another again. It is suggested, looking at the encircled area, that the pilot manually retarded the power levers from this point onwards. It is conceivable that he has been misled by the retarding action of the autothrottle system into believing that the system was retarding the power levers to idle, and he

Is it really? An ATS does not retard below 55% rpm above 50 ft AGL

No, the captain grabbed the throttles and moved them forward to initiate a go-around. The AT System would also have increased engine rpm because the captain increased the pitch control.

"helped" the AT doing so. After he let go of the power levers at 07:32:40 UTC, they immediately started to move forward again to a rate of +3.5 deg/s at 07:32:43 UTC, where the AT-modeled position rate coincides with the data; after this point they were again retarded, either manually or by the autothrottle system, to a rate of -2 deg/s, which is the retardation rate of the AT-system during the flare.

There was no retardation, as DFDR rpm data prove, because the captain initiated a go-around.

The second autothrottle model includes a "lag" of 1.2 seconds. Looking at the power lever position rates, knowing that there are less systematic errors remaining in the residuals of this model than of the first AT-model (App. B), the second model seems to perform slightly better. Also, especially where the manual inputs are believed to have been made (07:32:35 UTC), the second model shows better the likely moment where the human intervened. Otherwise there is not much difference between both AT-models in their general character and final response. Due to small differences in position rates, the position of the power levers shows a larger difference between model 2 and the data than is the case for model 1. Both models, however, do NOT indicate a reduction or retardation of the power levers as measured after 07:32:40 UTC. Although a detailed analysis can only establish whether there have been any malfunctions in the autothrottle system, the results here indicate that the autothrottle system did not function abnormally, and manual inputs are suspected to have been made to retard the power levers, since the power lever position rate exceeds 6 deg/s.

Many concluding remarks were not discussed in the report.

3 CONCLUDING REMARKS

what were the questions?

In view of the questions set out to be answered, and the results obtained and discussed, the following concluding remarks can be made:

switch

- The moment where the mode ~~reversion~~ was made from the autopilot Vertical Speed mode to the control wheel steering mode, occurred 17s later than the onset of the pitching oscillation. This onset coincides with the updraft of the downburst, which may have acted as a "trigger" mechanism to start this motion. The autopilot, operating in VS-mode,

No up- and down drafts occurred at all. Was because ROD set in Autopilot was too high as often happens and is intentional to avoid ending up above PAPI glide path. Level flight was required to intercept the PAPI glide path. Is normal procedure.

light turbulence. Had nothing to do with oscillations!
Had nothing to do with the mode switch either, which is standard during a non-precision approach, and has to be achieved prior to reaching 500 ft AGL (refer to AOM). During a non-precision approach the airplane needs to be in manual (CWS) control.

Not the autopilot, but the copilot pushed the pitch control, disturbing autopilot control. See Fig 7 before CWS on: this line should be straight under autopilot control. Pitch control while autopilot engaged should be by the vertical speed wheel on the Autopilot panel, not by pushing the control

reacted to this onset by pitching down the aircraft in order to try to maintain the preset vertical speed.

DFDR data does not prove divergent oscillatory longitudinal motions, only airspeed variations due to the gust filter in the AT System after onset of (light) turbulence and inappropriate pitch control by the copilot.

o The oscillatory behavior, previously called a PIO, is in fact neither a PIO in the traditional sense, nor is it a classical phugoid motion. The divergent, oscillatory longitudinal motion observed to start at 07:31:40 UTC requires further investigation as to the underlying causes.

?

There were variations, not divergent though, because the copilot interfered with the autopilot and, following the switch to CWS, also with this mode. The NTSB agreed. No further investigation required.

and decreasing airspeed

"strongly" was used here in the draft version, but had to be changed to "directly" by Frans Erhart

o The abrupt short flare maneuver, in combination with the high vertical speed at touchdown (due to closure of the power levers) might be the result of the unintentional mode reversion from CWS to fully manual flight control mode, taking into account the difference in flare technique between CWS and fully manual flight mode.

hardly any difference ...

Was there a flare maneuver? The captain initiated a go-around.

Sideslip angle? When? Or do you mean drift angle? Was crosswind displayed/used? No, just the wind (190/20)? At that moment there was <5° sideslip angle. NLR does not discuss the sideslip from 07:32:10 (DFDR data)

o The AreaNav's displaying less than the actual crosswind component is directly related to the sideslip angle during the flight. Considerably large sideslip angles occurred. These are not taken into account by algorithms used on-board to calculate the wind vector. This generally results in an error in the calculation of the crosswind component. At an airspeed of 140 kts each 5 degrees sideslip angle equates to 14 kts under-estimation of the crosswind component.

2 s prior to reading the wind data, the sideslip was zero (DFDR data). The captain read the wind data, not drift angle.

o Contributing factors to the under-estimation of the actual crosswind at touchdown are:

What does it make you say extreme crosswind? Evidence?

Was there? No, the line of touchdown was straight as proven by the grooves in the asphalt of the runway.

a) The crew could not be warned for the crosswind since this extreme crosswind occurred rather suddenly only just prior to touchdown.

b) From the available meteo-wind data this sudden extreme crosswind condition could not be predicted.

It wasn't there. It never occurred prior to touchdown.

c) The AreaNav also indicated too benign a situation. In an on-board system not including the sideslip angle in the calculations will lead to an under-estimation of especially the crosswind component.

??

An on-board system cannot calculate the sideslip angle, only the drift angle.

d) The non-precision VOR/DME approach made judgment by the crew of the crosswind more difficult since the aircraft was not lined up early with the runway centerline.

The system calculates wind as the vector difference between the ground velocity and the air velocity. (NTSB, Lijst 3 tab 3F, fax of Collins); the angle between the vectors is the drift angle. A sideslip (by rudder or asym. thrust) doesn't change the flight path over the ground immediately. The max. approved crosswind component for a DC-10 of 30 kt results in a 13 deg drift angle at 139 kt IAS. Rudder is designed to achieve this. DFDR data show 6° heading change following delta r from 40 to 12 s before landing, then increasing linearly from 125° again with 12° at 5 s before landing following near full rudder.So, where is this error from?

Has nothing to do with non-precision approach. A good indication, as all pilots know, is the required wind correction (drift) angle during the flight towards the airport. The heading during the last 80 seconds was 125°. If at the 111° approach radial, a WCA of 14 deg would result - caused by a 35 kt crosswind, way too large for both a flooded or wet runway. Hence, the approach was at a larger radial than 111° and not on the extended runway centerline either. The rudder was not capable of aligning the aircraft with the runway from this large angle/ approach radial (DFDR data).

Less if radalt data used, and less in draft of this report (760 ft/min.)

which is normal with a crosswind from the right.

o The touchdown data shows clearly that the aircraft made a traverse landing; it touched down right wheels first. The crabbing angle at touchdown was about 11 degrees, at a sink rate of 966 ft/min. Judgment of the structural integrity of the landing gear under those landing conditions is left to structural experts.

MDA confirmed to the NTSB that the gear will not fail at a ROD of 1014 ft/min at max. LW (NTSB Aircraft Accident Report DCA97MA055). The crab angle might have caused the fracture, or the fuse pin might have failed and sacrified the gear.

The used AT model was not of DC-10

o There are indications of lags in the Auto-Throttle system. Although it is felt that this is not the cause of the accident, it could be a factor contributing to the instability of the approach.

No lags, but a copilot who was interfering with the elevator, the pitch control to which the autothrottle responded immediately, and the NLR not being aware of the elevator feedback to the autothrottle system, and of the gust filter in the autothrottle system.

o The improved calculation of the sideslip angle, using proprietary aerodynamic data from McDonnell Douglas Aircraft Corporation yielded no significant change in sideslip angle time history, wind, windshear, windshear models, etc.

drift angle?

o Differences between NLR-calculated flight path and flight-mechanical data and those derived or measured by the ACMS are insignificant, apart from the wind components calculated by NLR.

Analysis of DFDR and AIDS heading and other data leads to a significant different flight path than meant here. Refer to report 'De last 80 seconds of flight MP495' on the Faro page of www.avioconsult.com.

4 REFERENCES

1. (Name masked by AvioConsult) , Windshear analysis using flight data from the DC-10 crash at Faro airport. NLR CR 93080 C, 1993.

DFDR Factual Report not used?

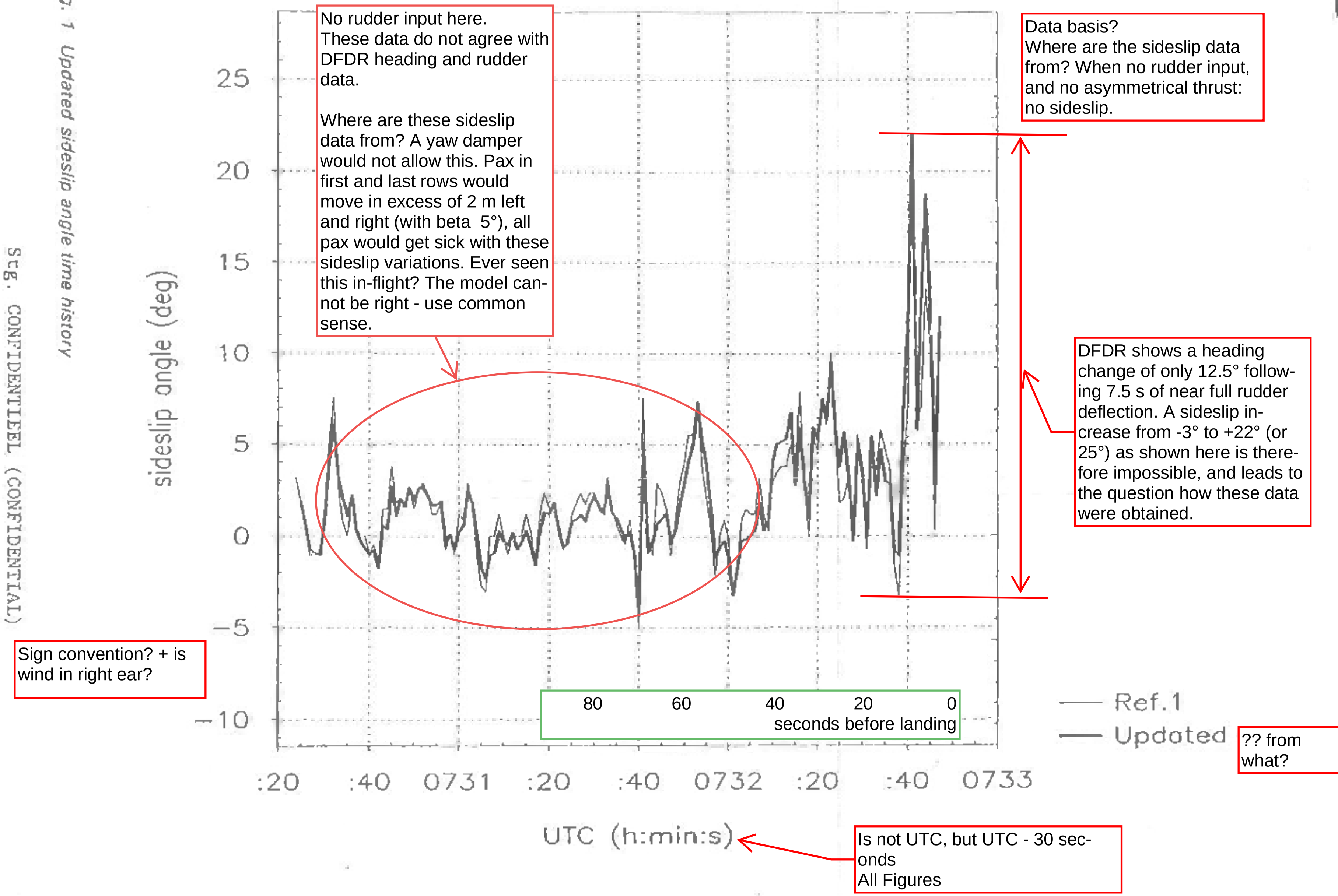


Fig. 1 Updated sideslip angle time history

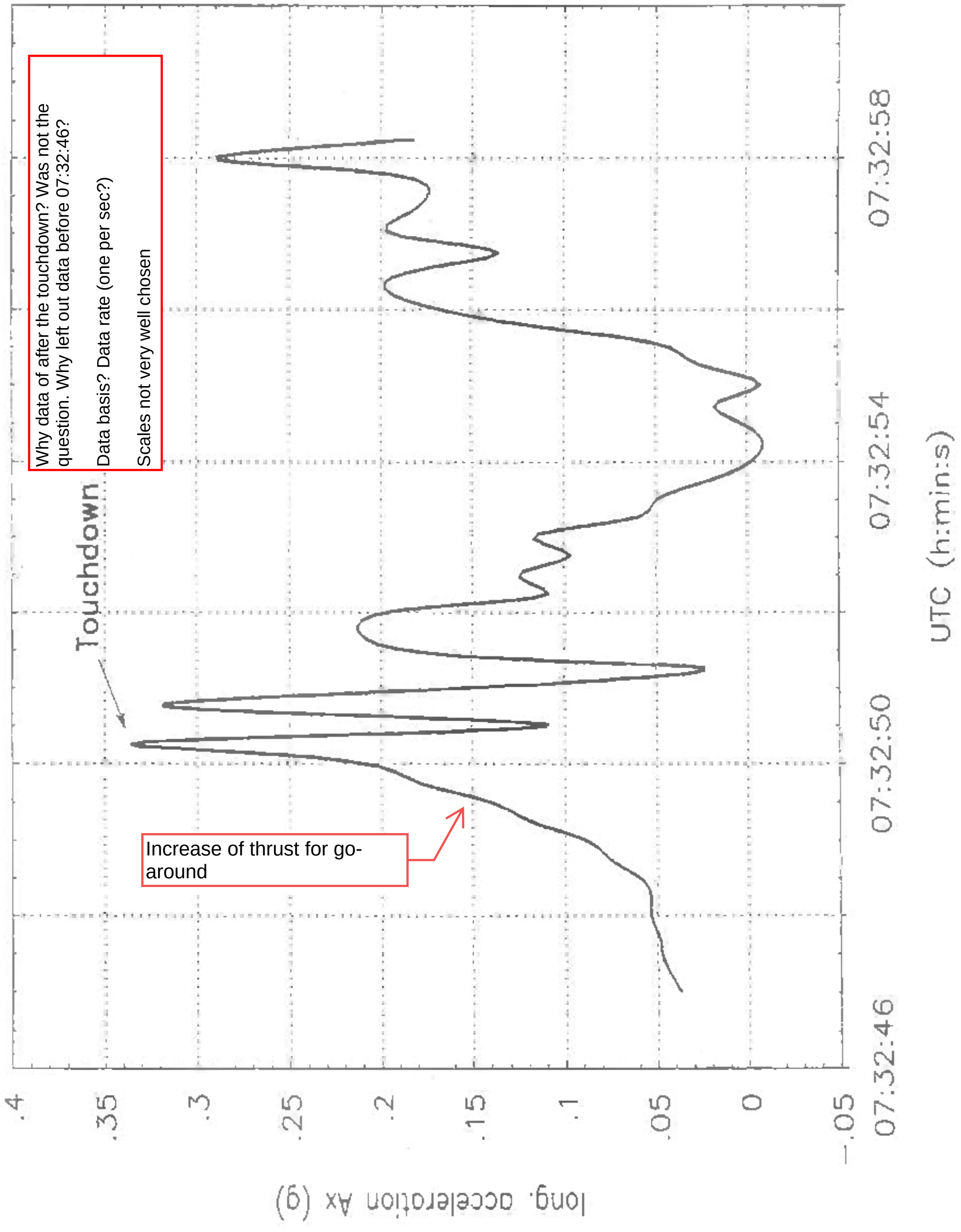


Fig. 2a Longitudinal acceleration from FDR

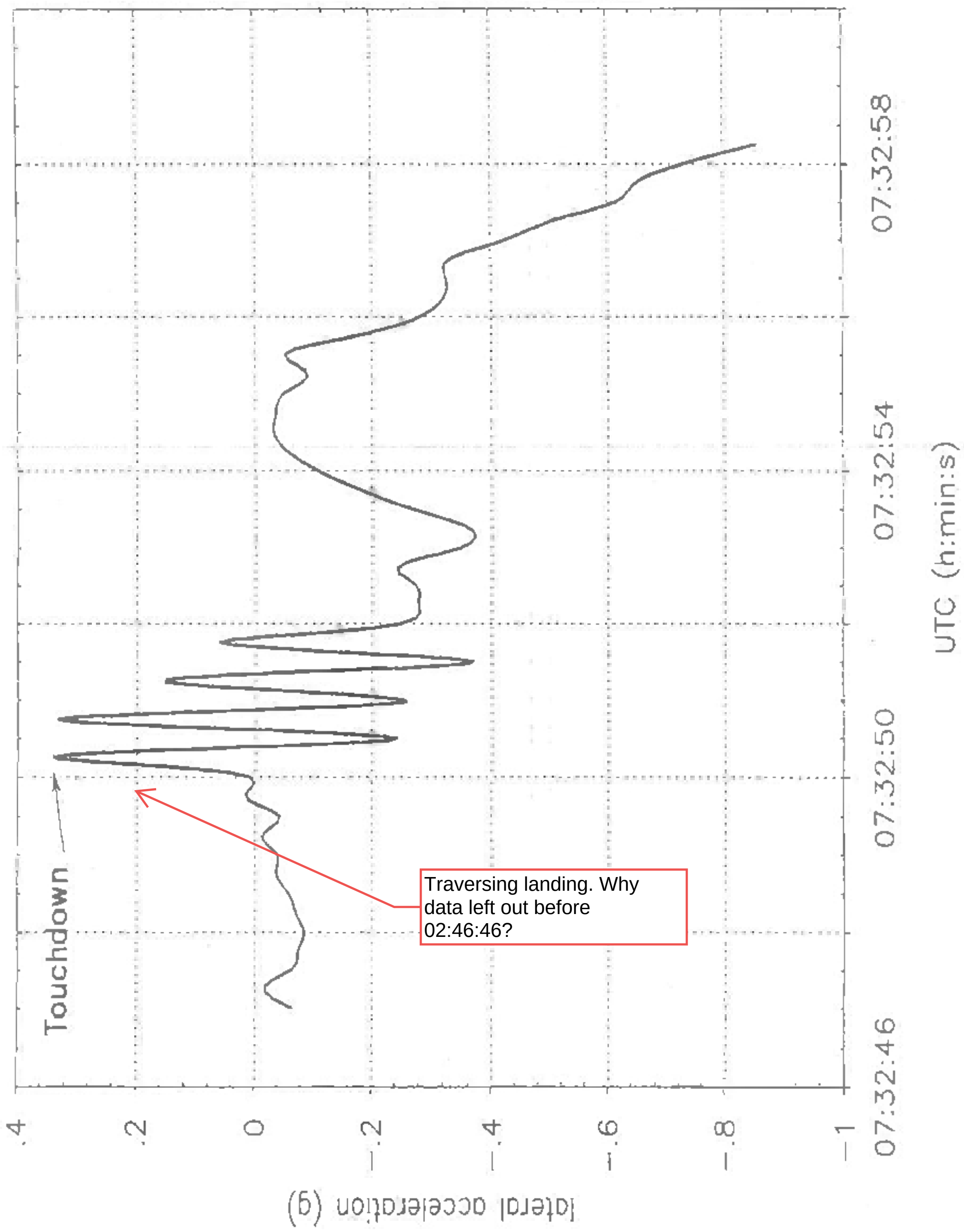


Fig. 2b Lateral acceleration from FDR

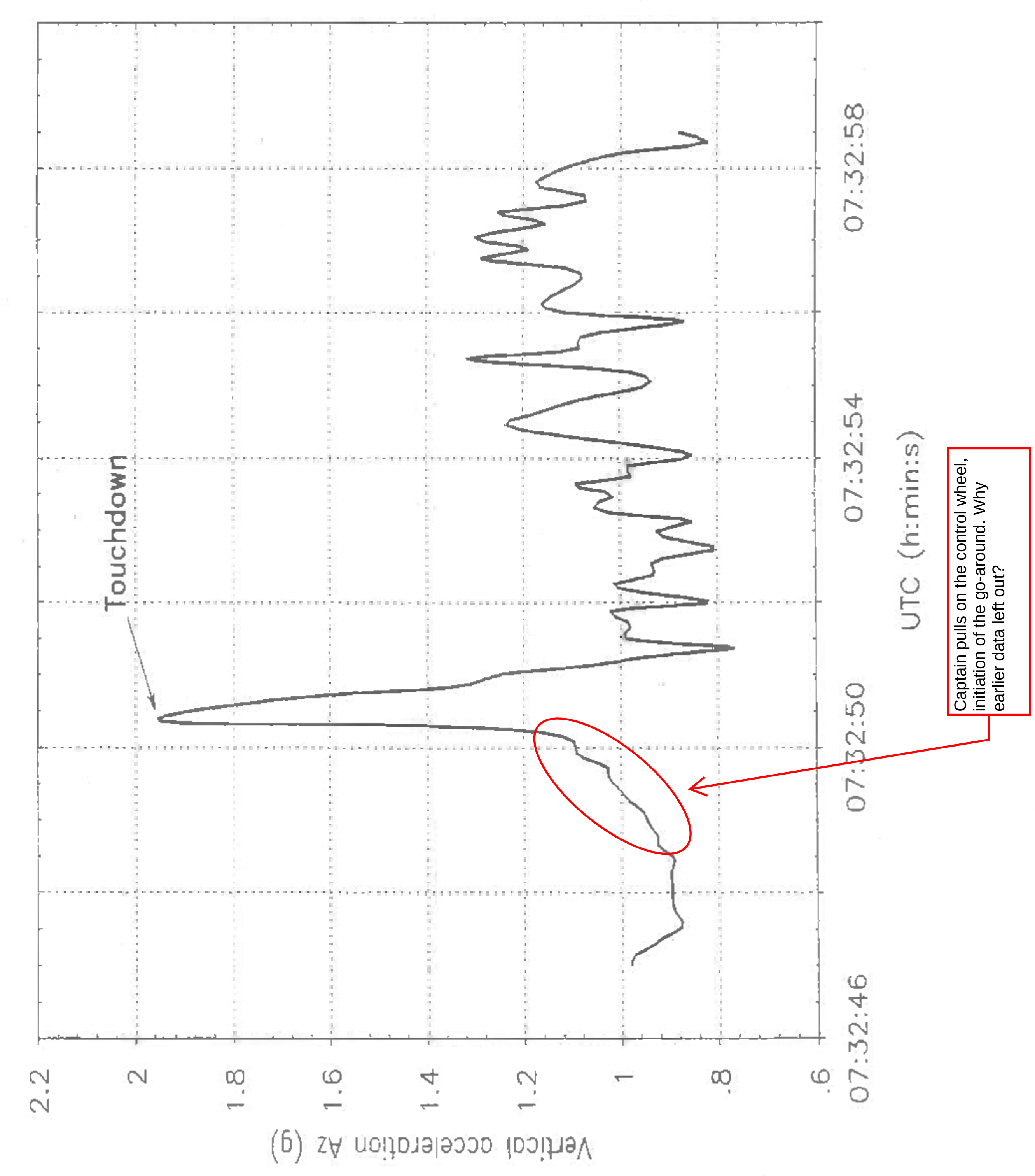


Fig. 2c Vertical acceleration from FDR

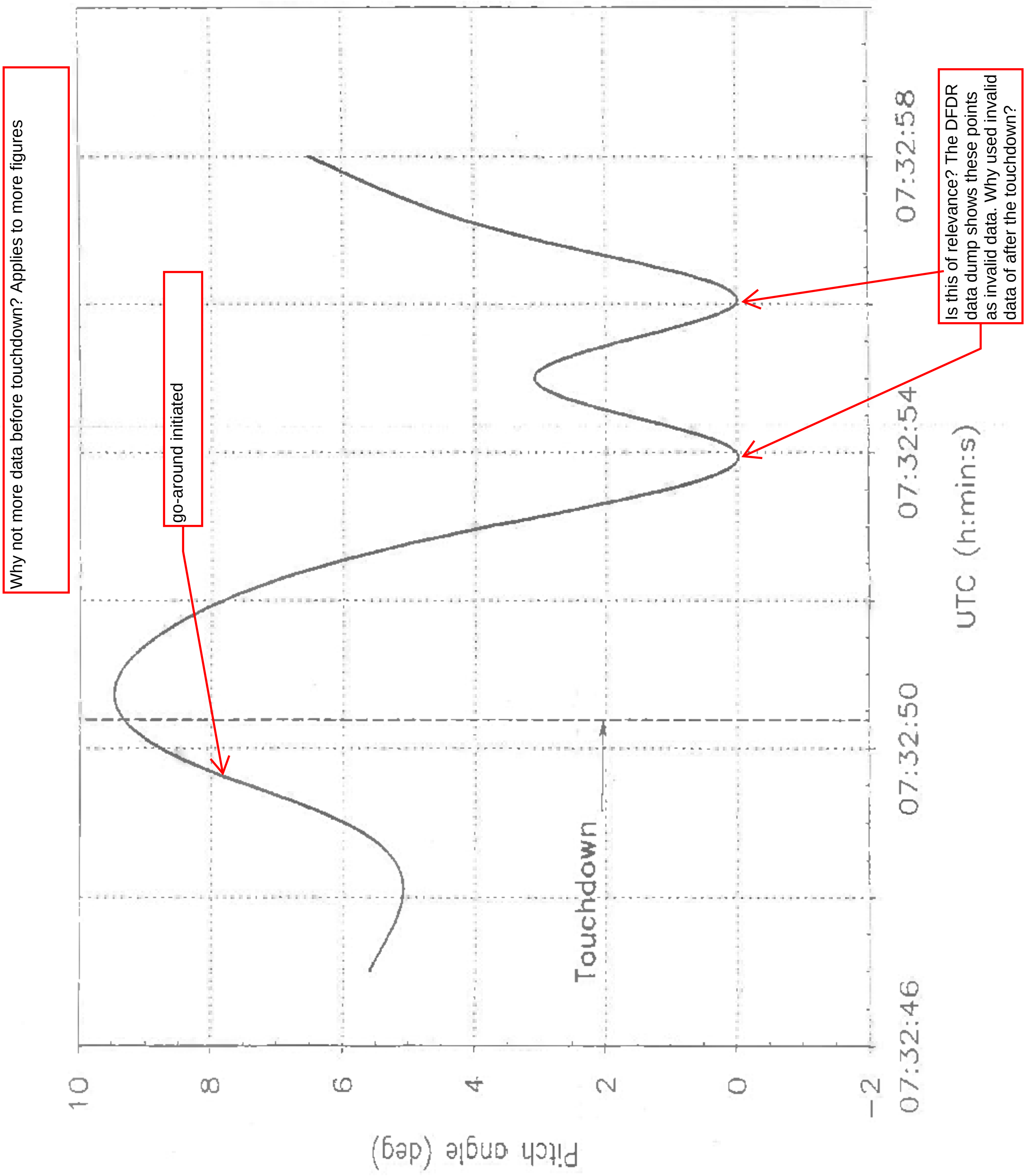


Fig. 3a Pitch attitude from FDR

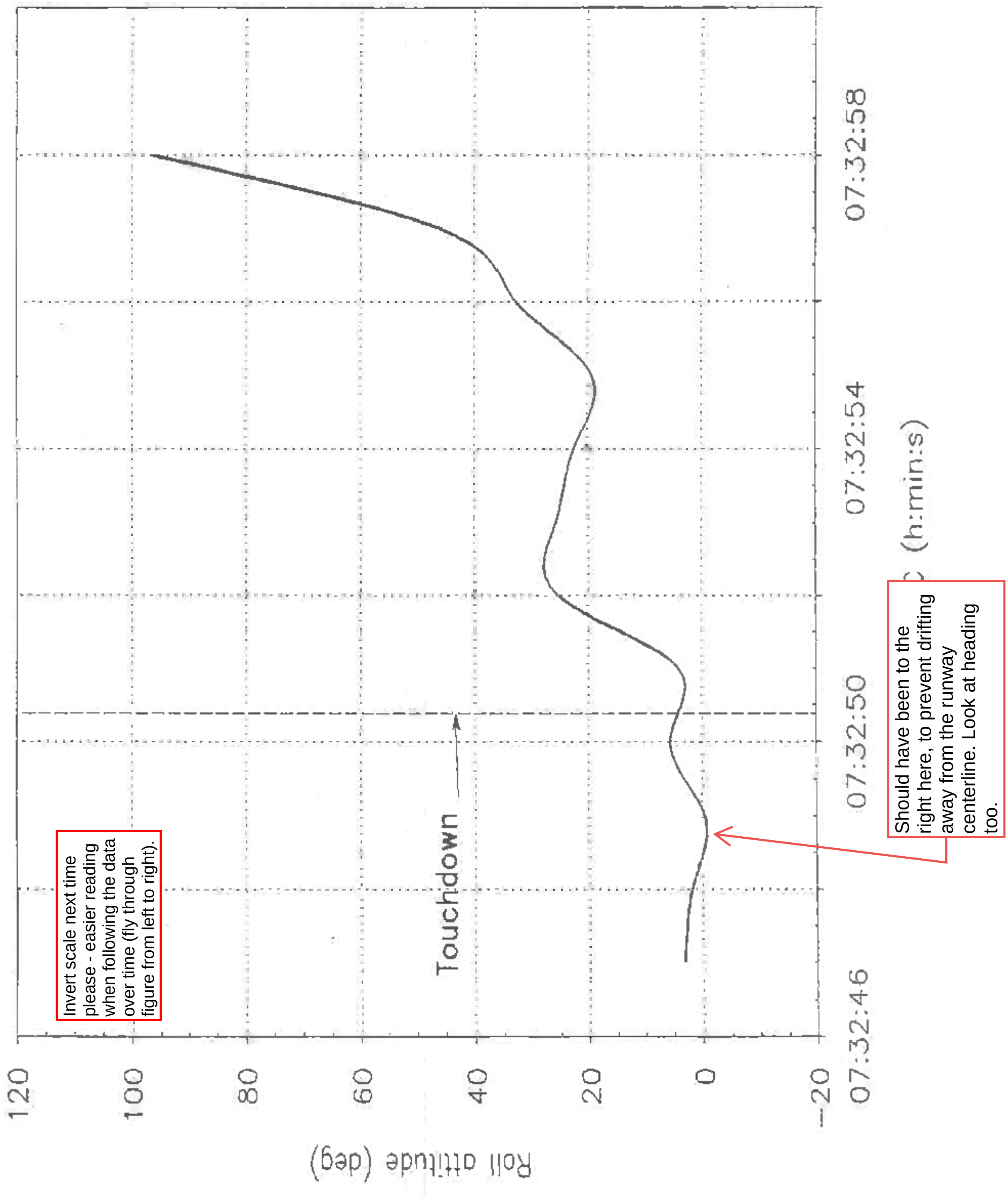


Fig. 3b Roll attitude from FDR

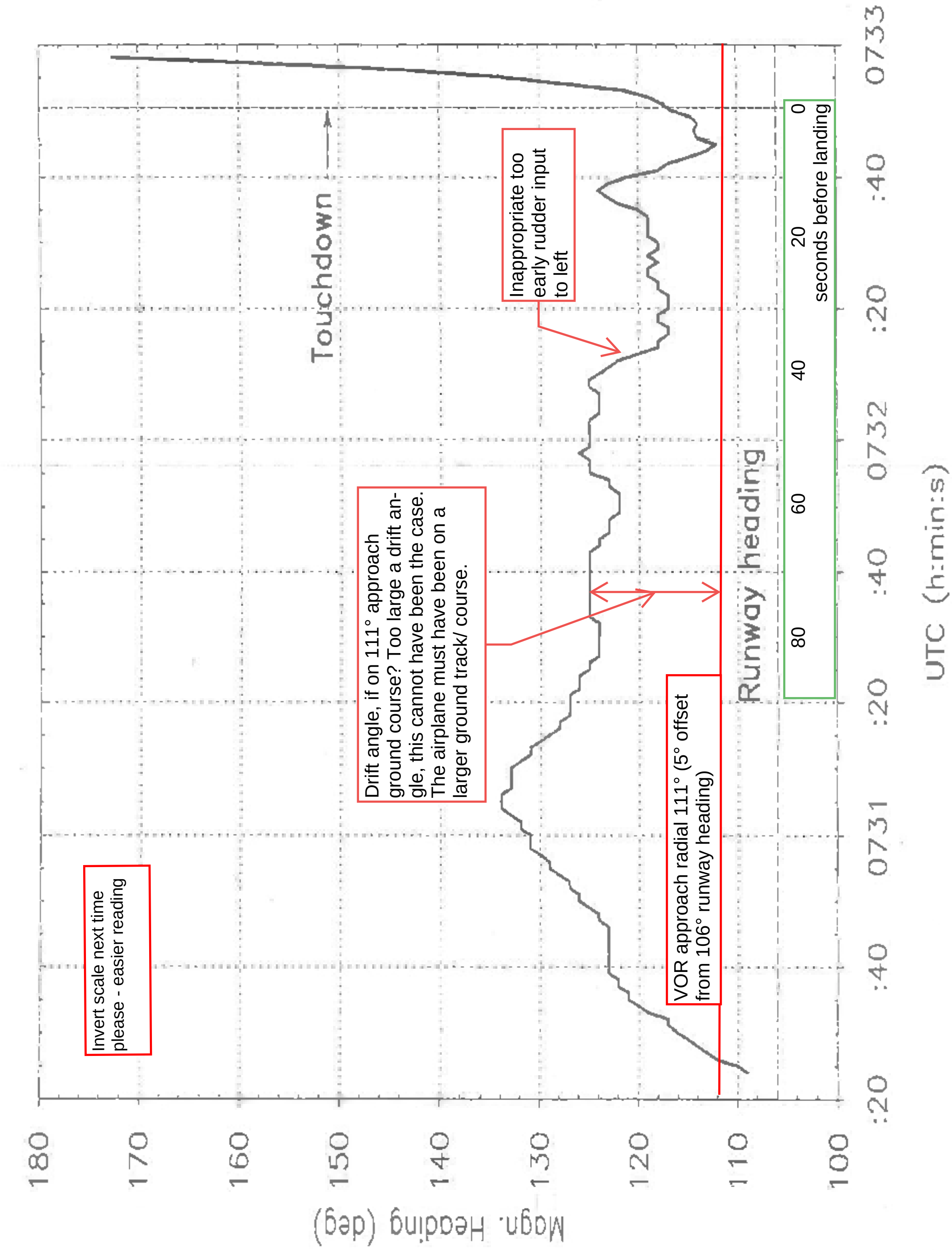


Fig.3c Magnetic heading during flight

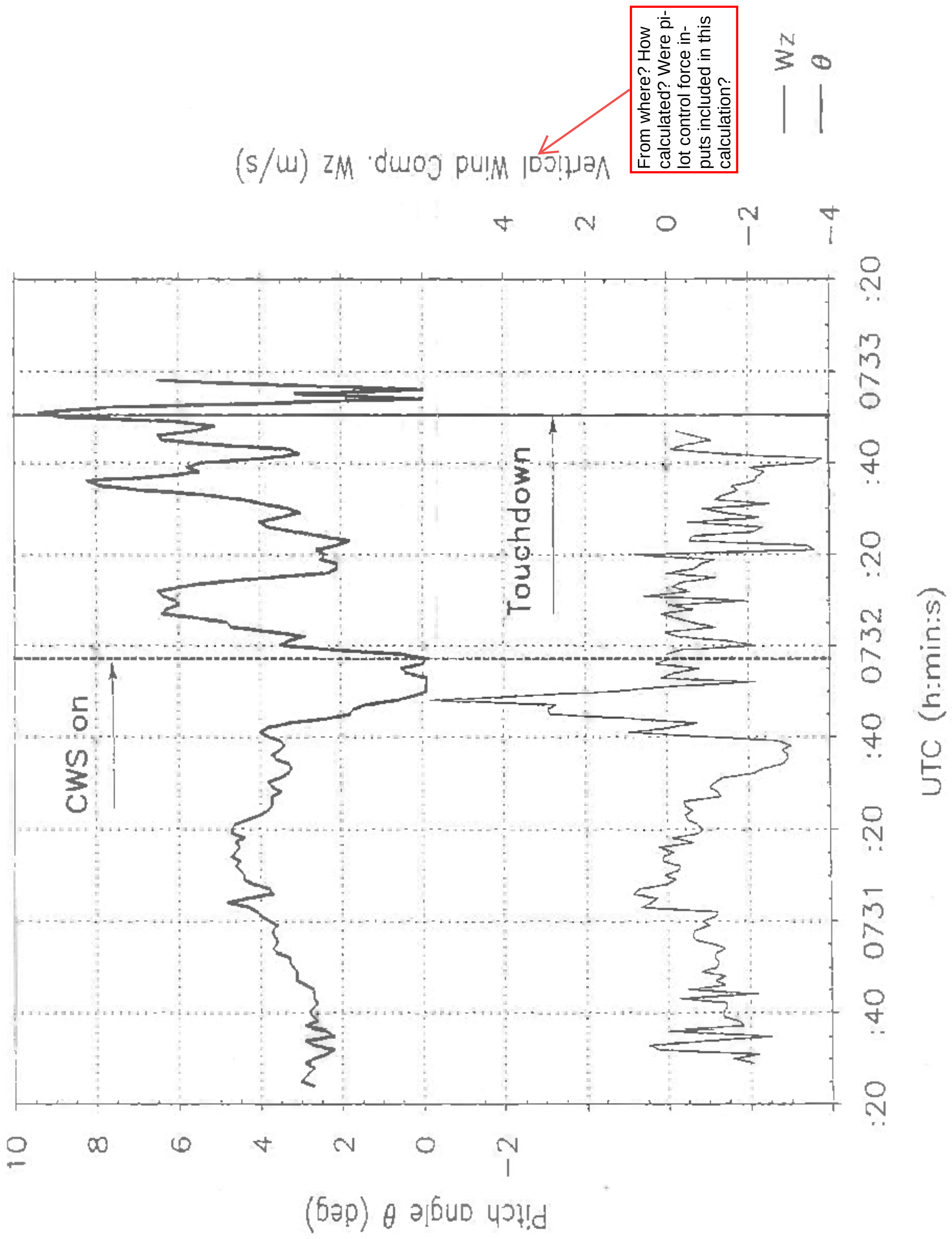


Fig. 4 Mode reversion from Autopilot to CWS, pitch angle and vertical wind

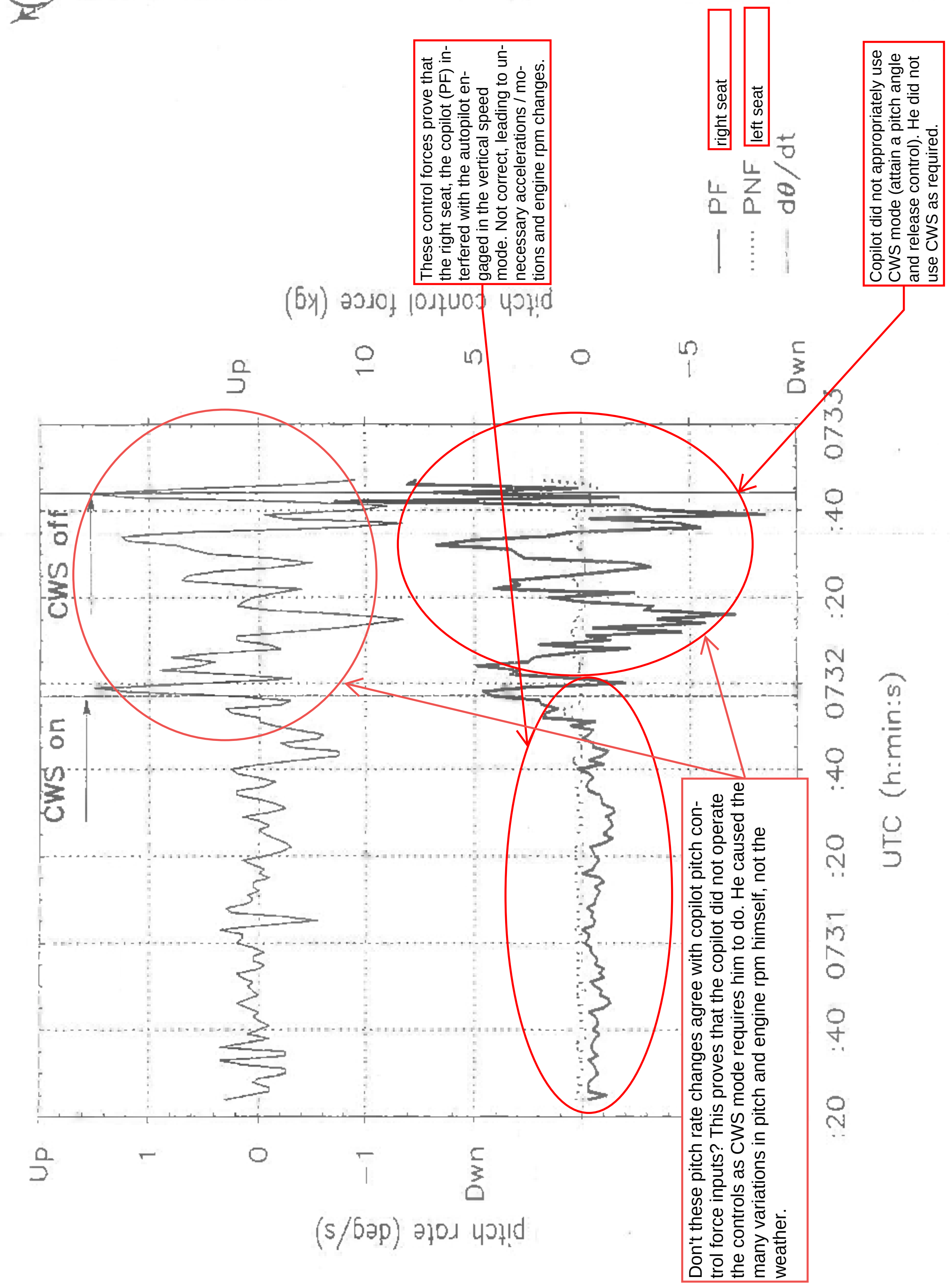


Fig. 5 Pitch control forces, and pitch rate, for Pilot flying (PF) and Pilot not flying (PNF)

Better to say: left seat, right seat

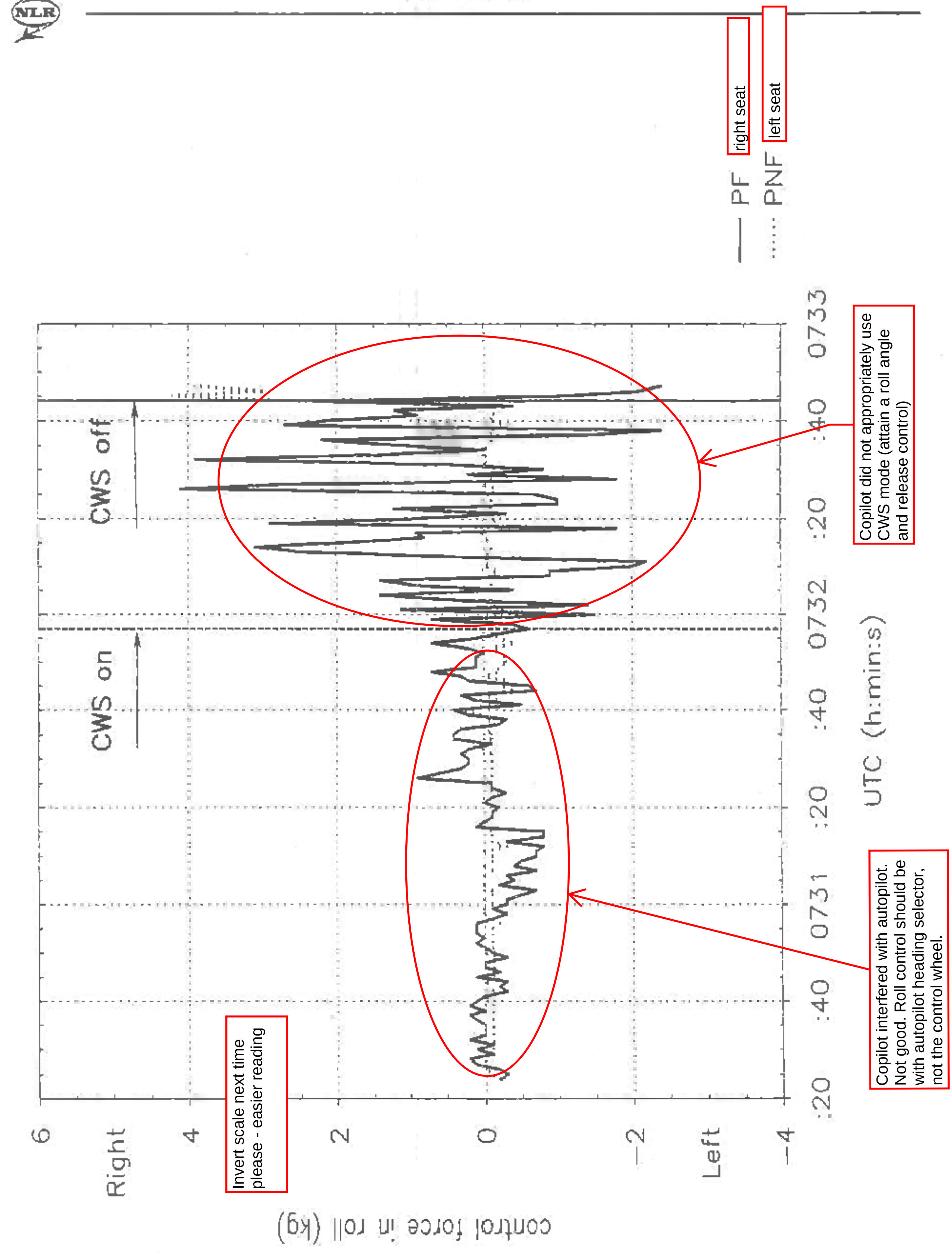


Fig. 6 Roll control forces of Pilot flying (PF) and pilot not flying (PNF)

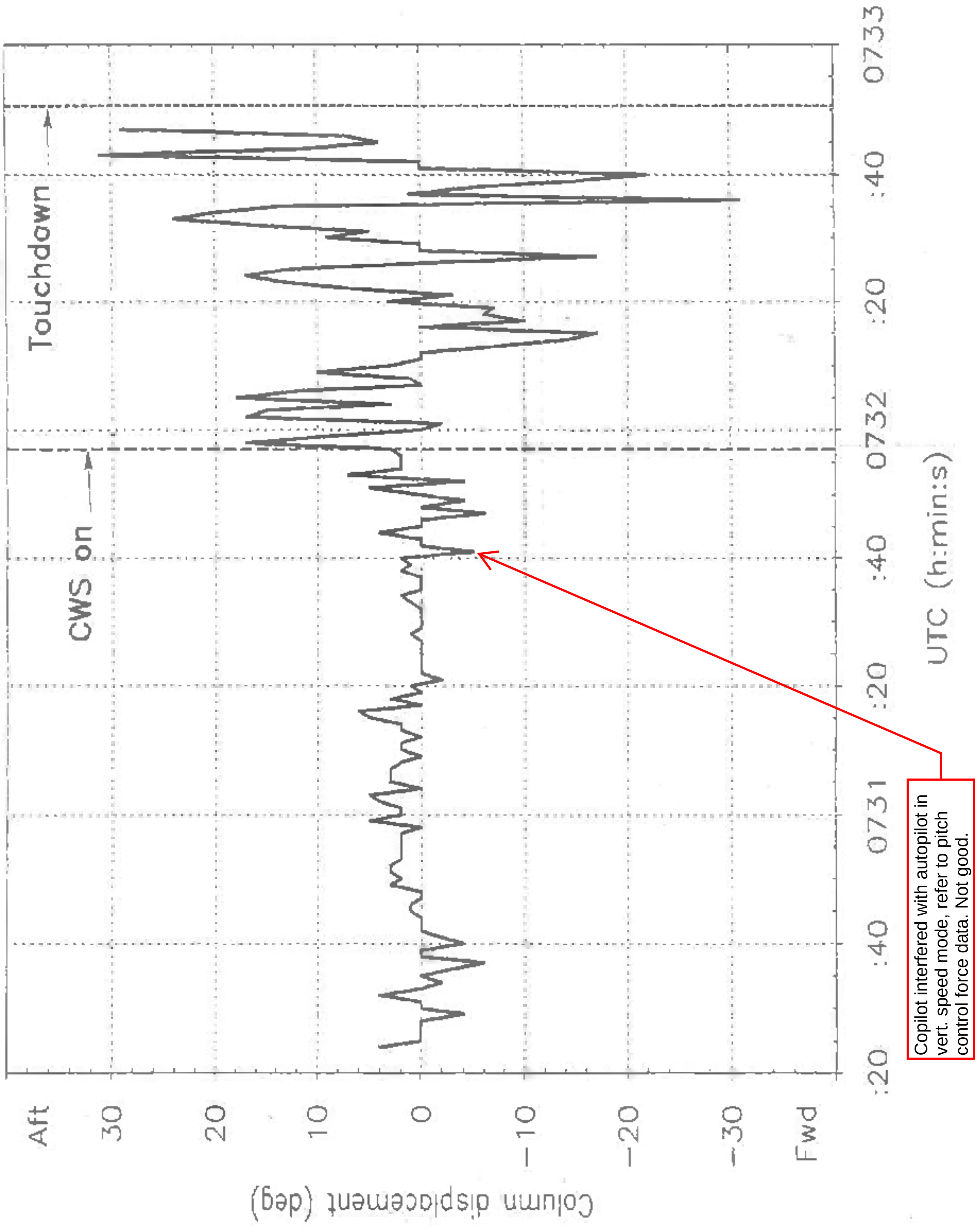


Fig. 7 Control column (pitch) displacement

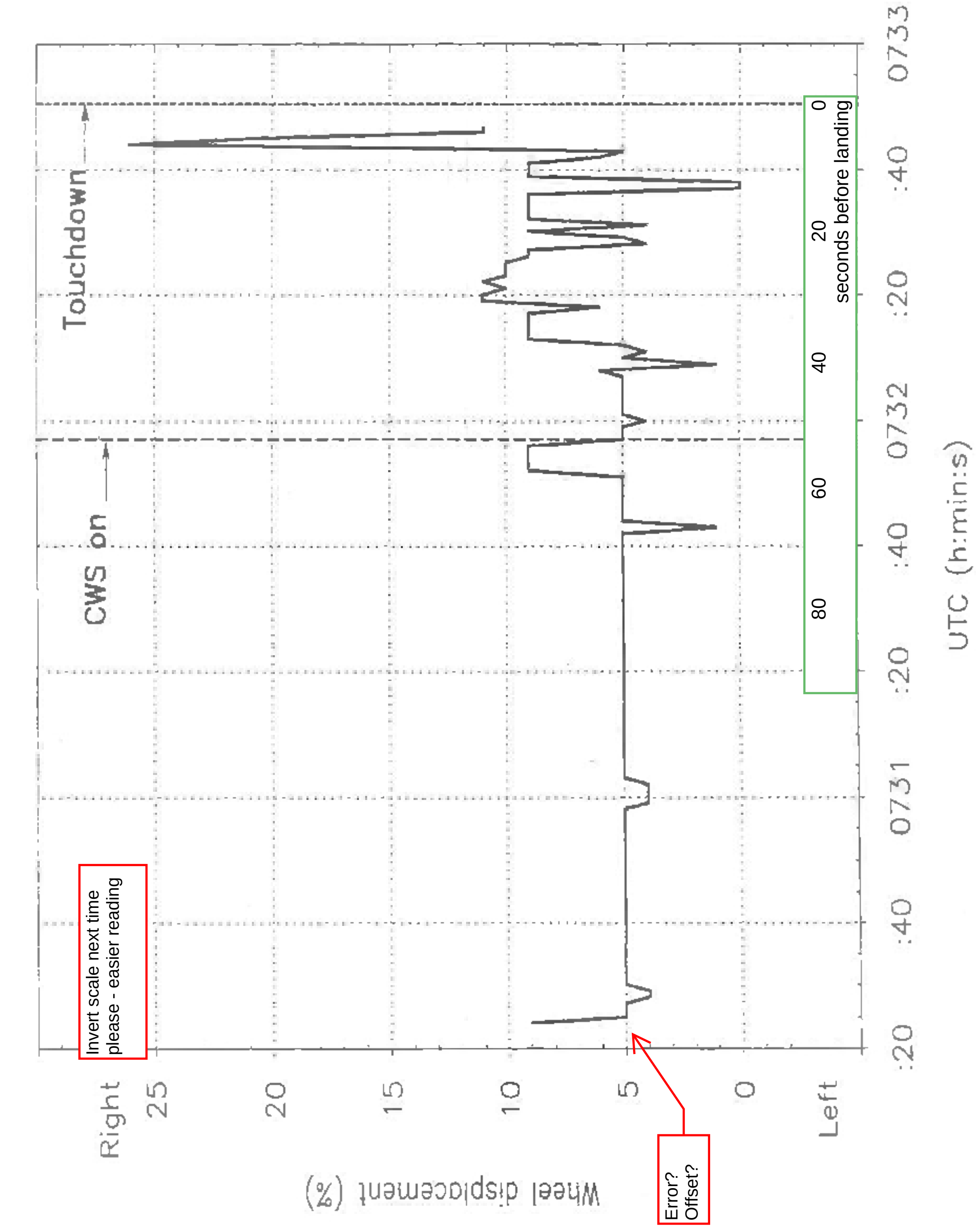


Fig. 8 Control wheel (roll) displacement

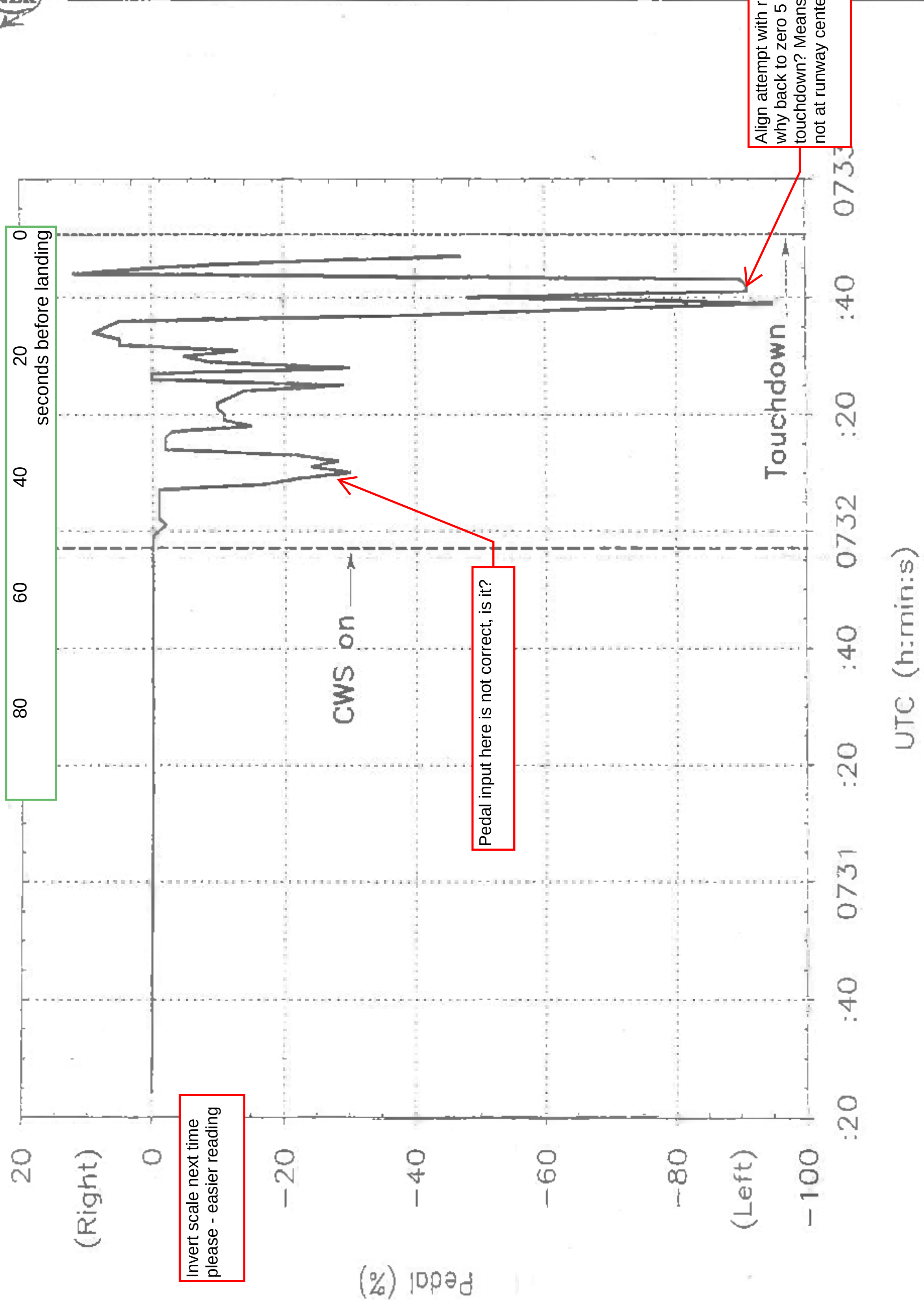


Fig. 9 Rudder pedal displacement

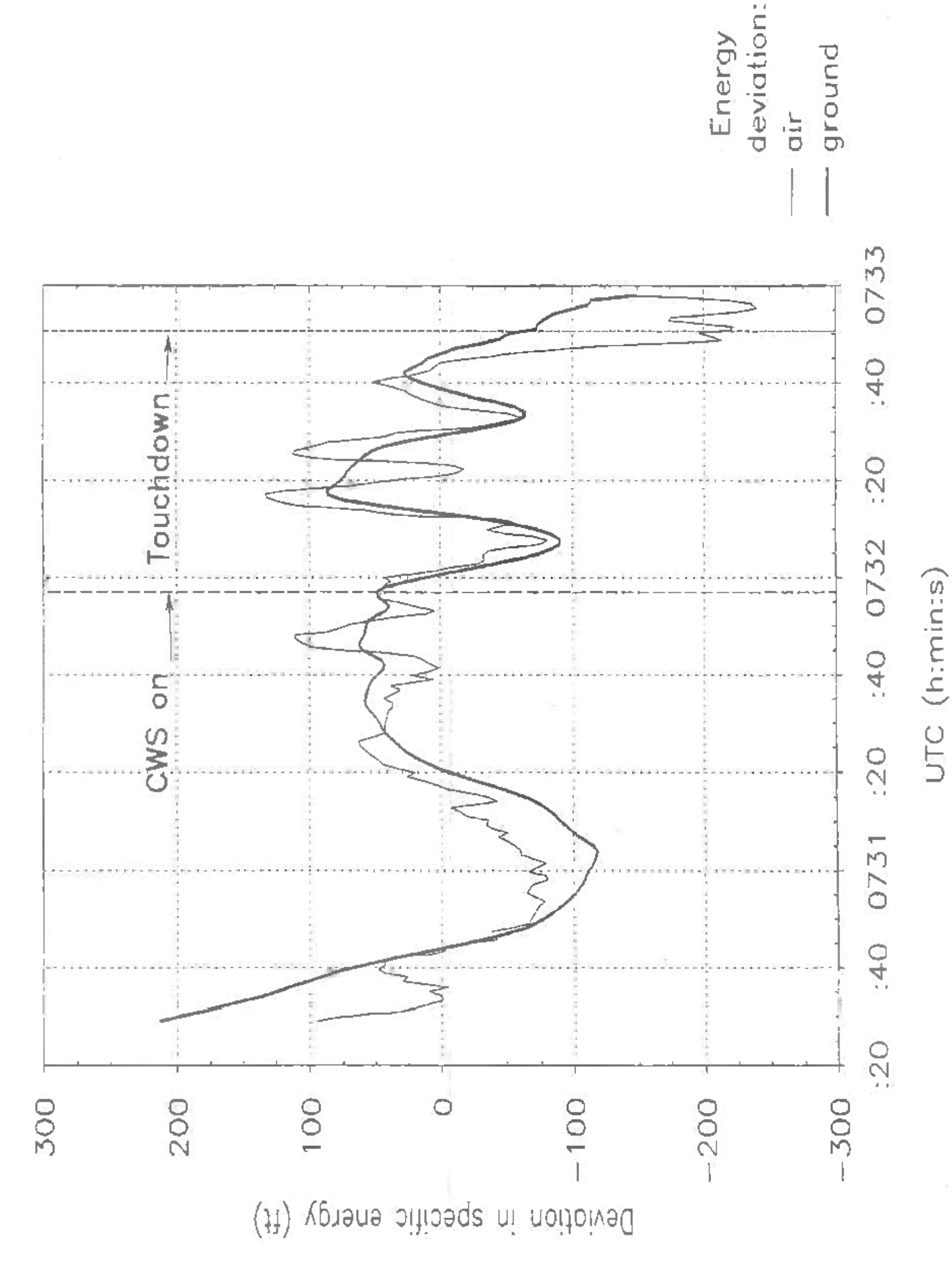


Fig. 10a Specific energy deviations from trend during flight

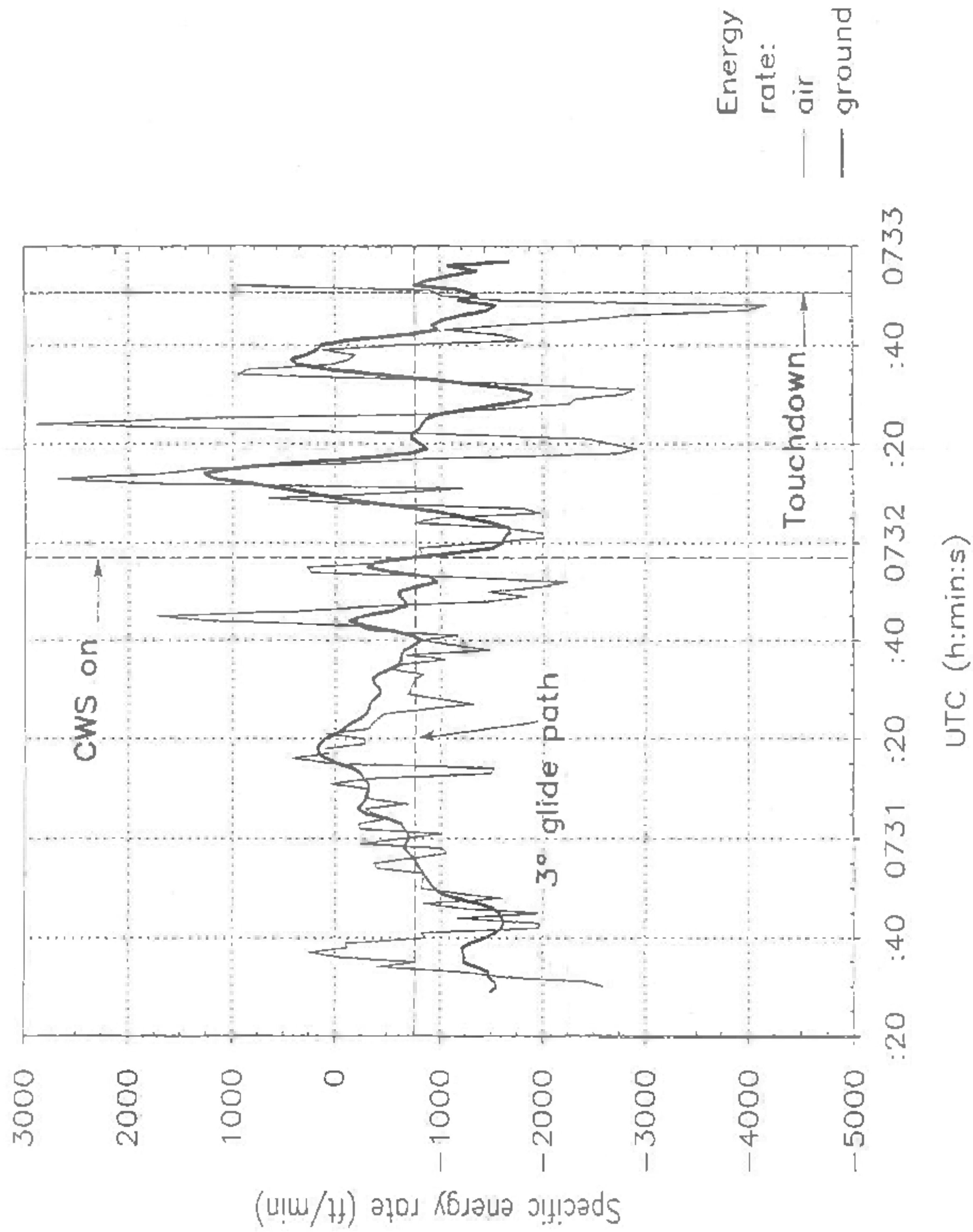


Fig. 10b Specific energy rate during flight

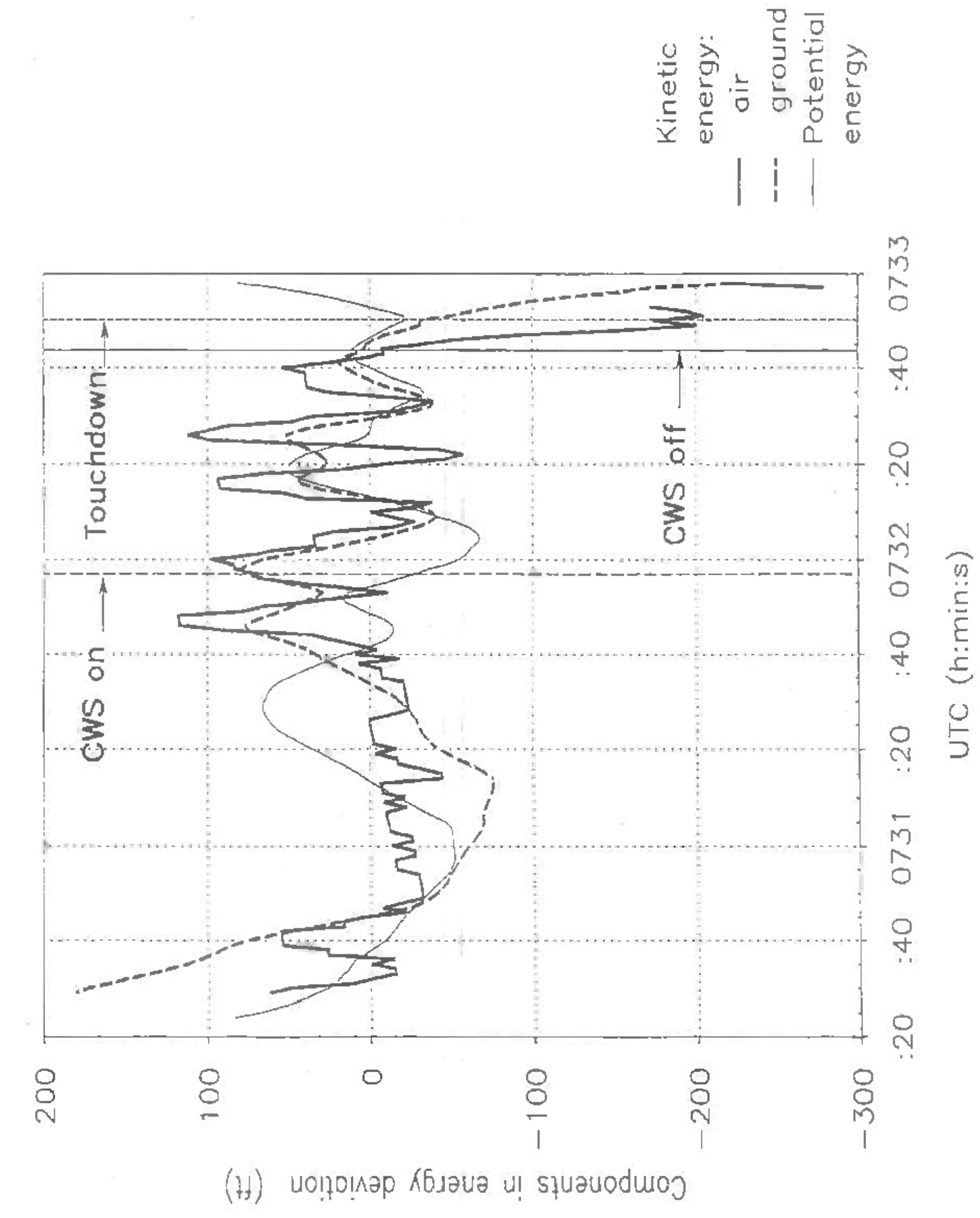


Fig. 11 Potential and kinetic energy deviation components in total energy deviation

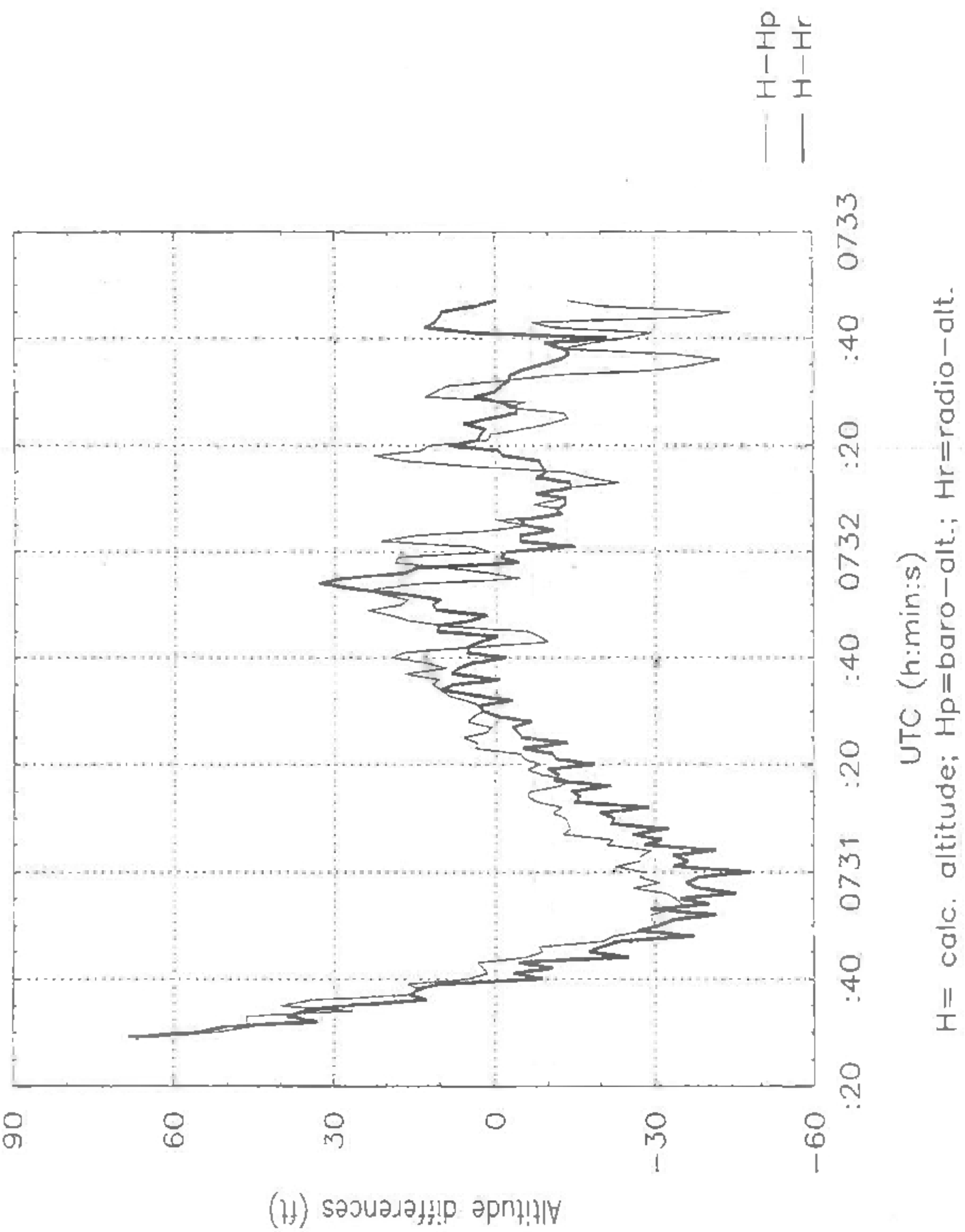


Fig. 12 Deviations between calculated (i.e. Kalman-filtered) altitude, baro- and radio-altitude

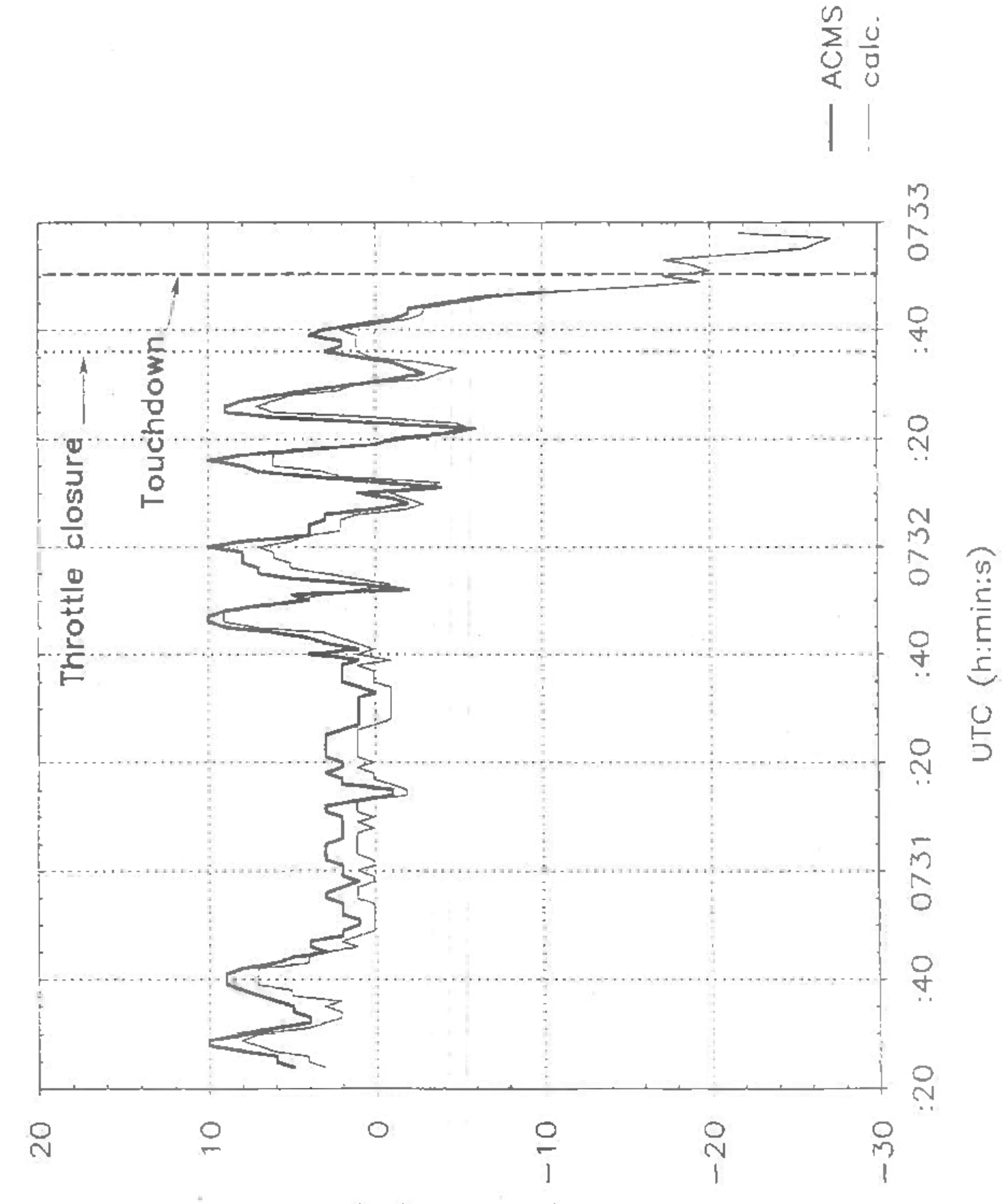


Fig. 13 Speed error calculated and as recorded on the ACMS

At the airport, not at airplane location!

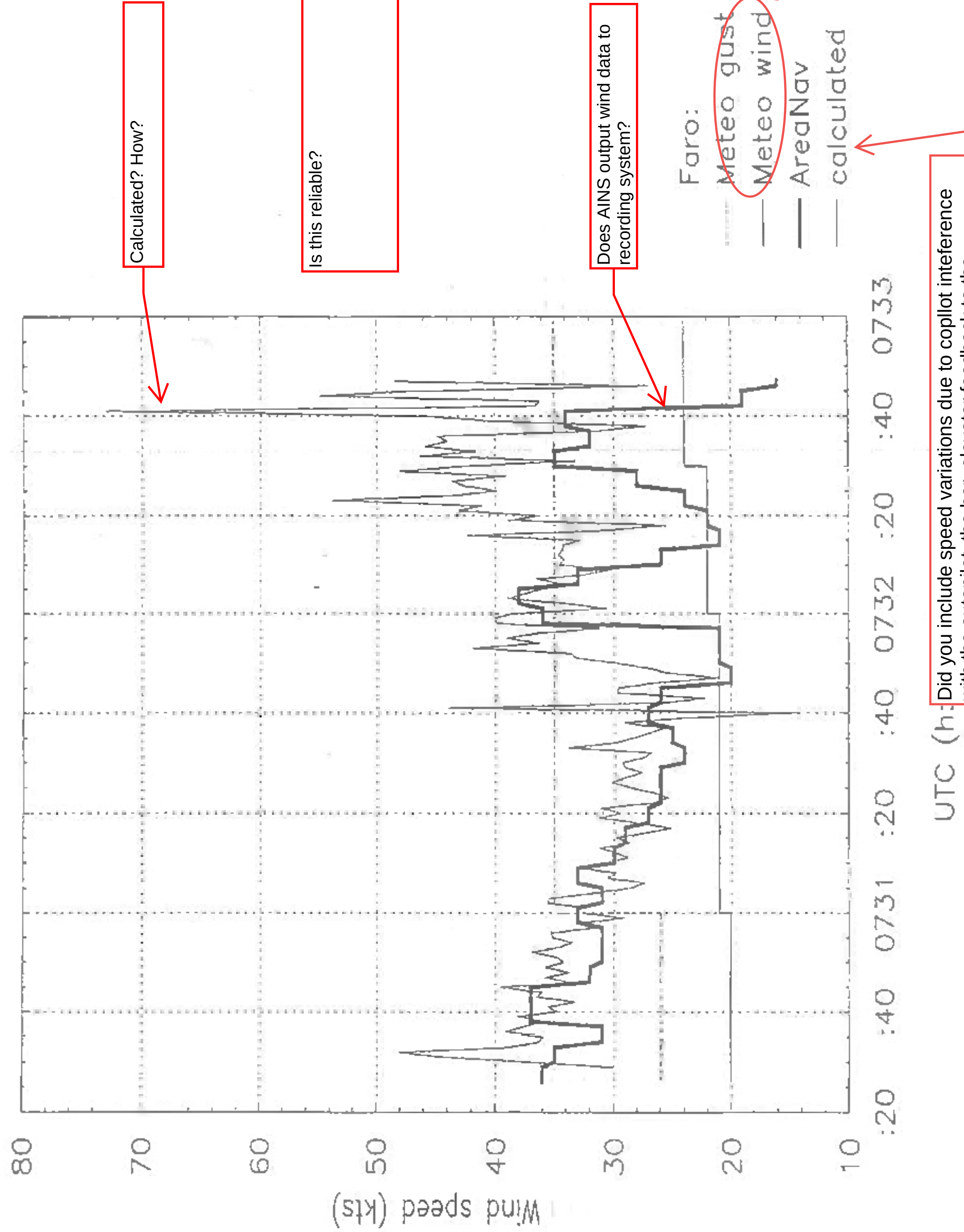
Meteo clock deviated from radar time, from UTC as well! Did you take this into account?

Calculated? How?

Is this reliable?

Does AINS output wind data to recording system?

Did you include speed variations due to copilot inteference with the autopilot, the hor. elevator feedback to the autothrottlesystem?



was "estimated" in the draft report, but changed by Frans Erhart.

Fig. 14 Difference in windspeed calculated and recorded by the AreaNav

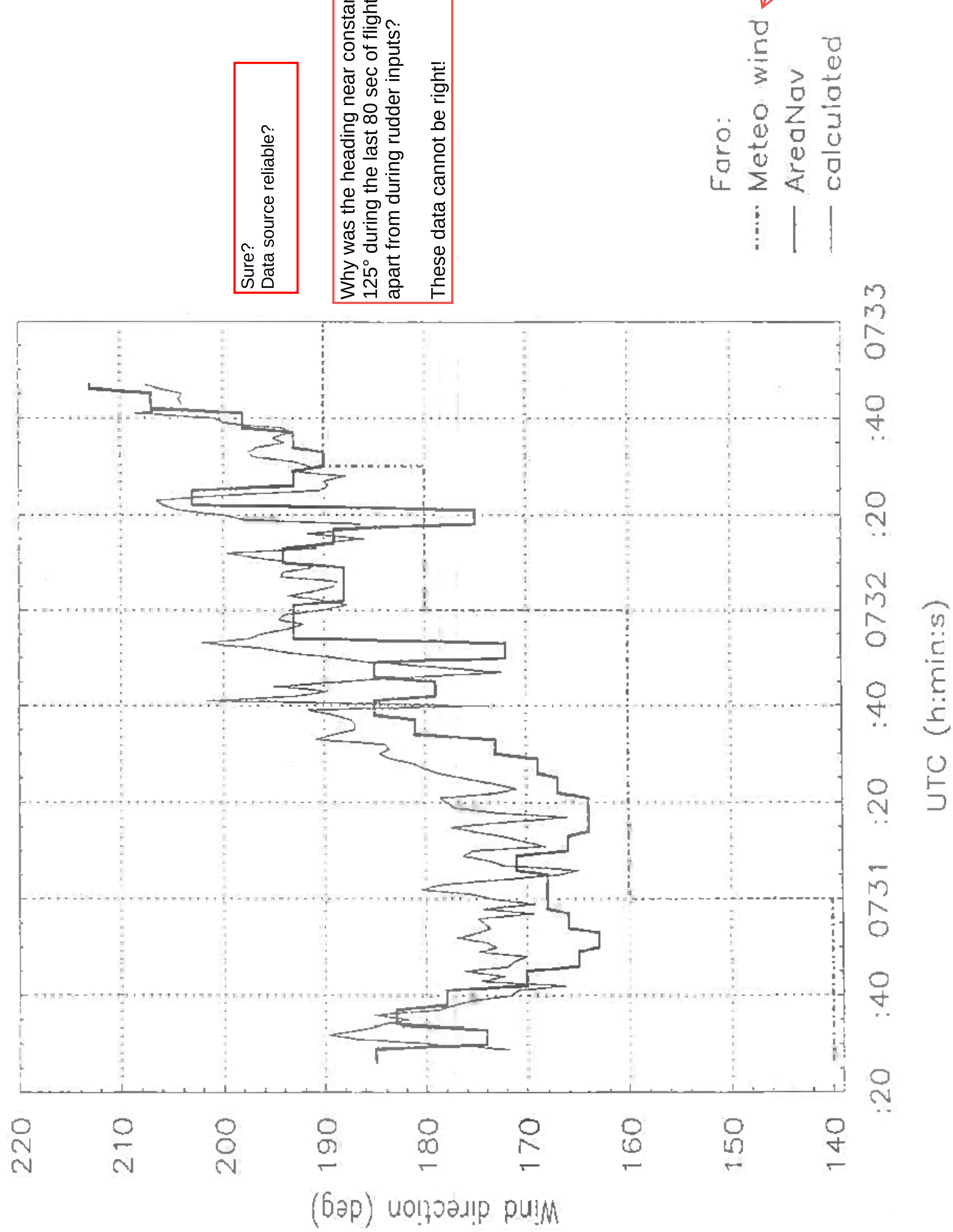
At the airport, not at airplane location!

Meteo clock deviated from radar time, from UTC as well! Did you take this into account?

Sure?
Data source reliable?

Why was the heading near constant 125° during the last 80 sec of flight, apart from during rudder inputs?

These data cannot be right!



was "estimated" in the draft report, but changed by Frans Erhart.

Fig. 15 Difference in wind direction calculated and recorded by AreaNav

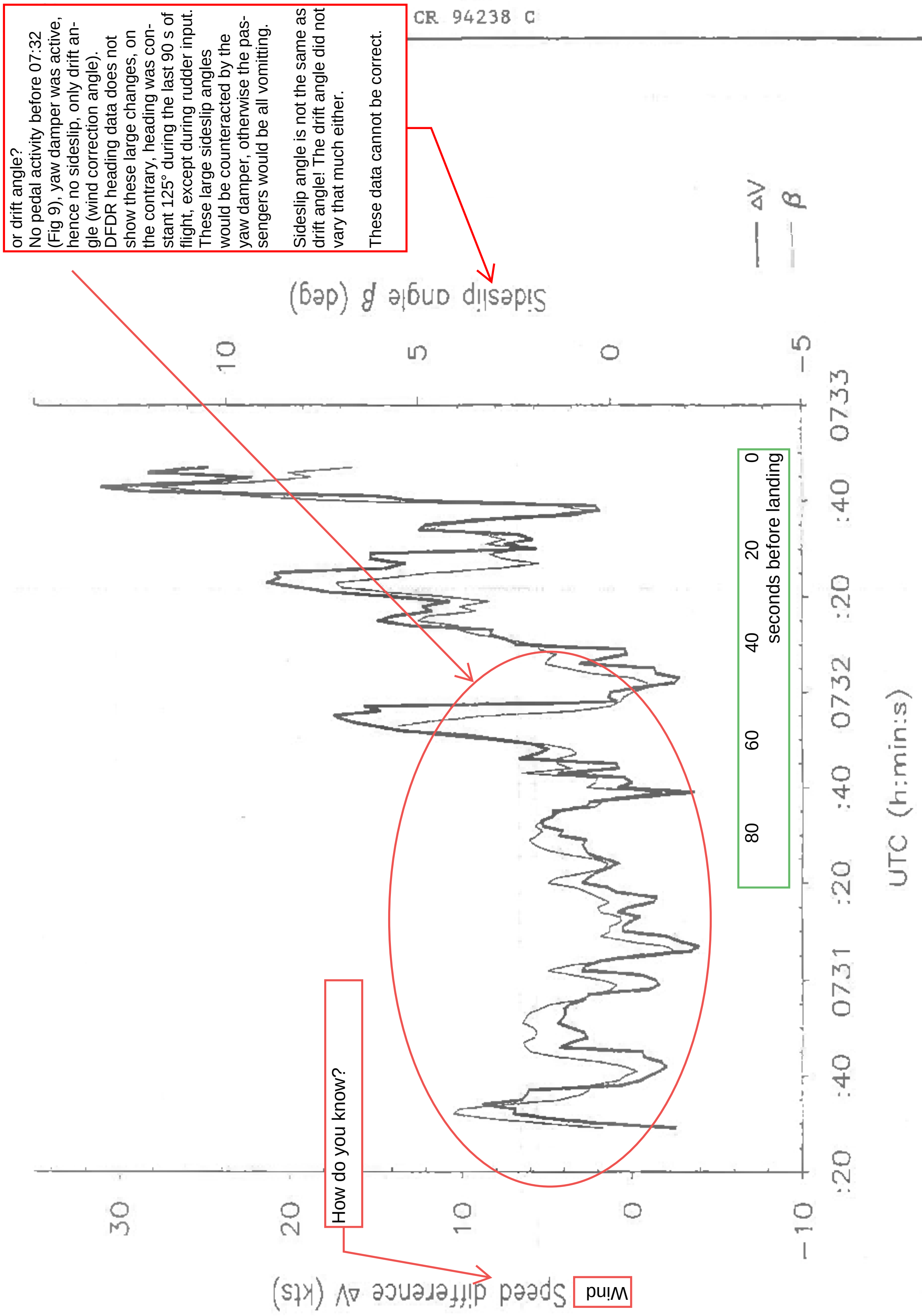
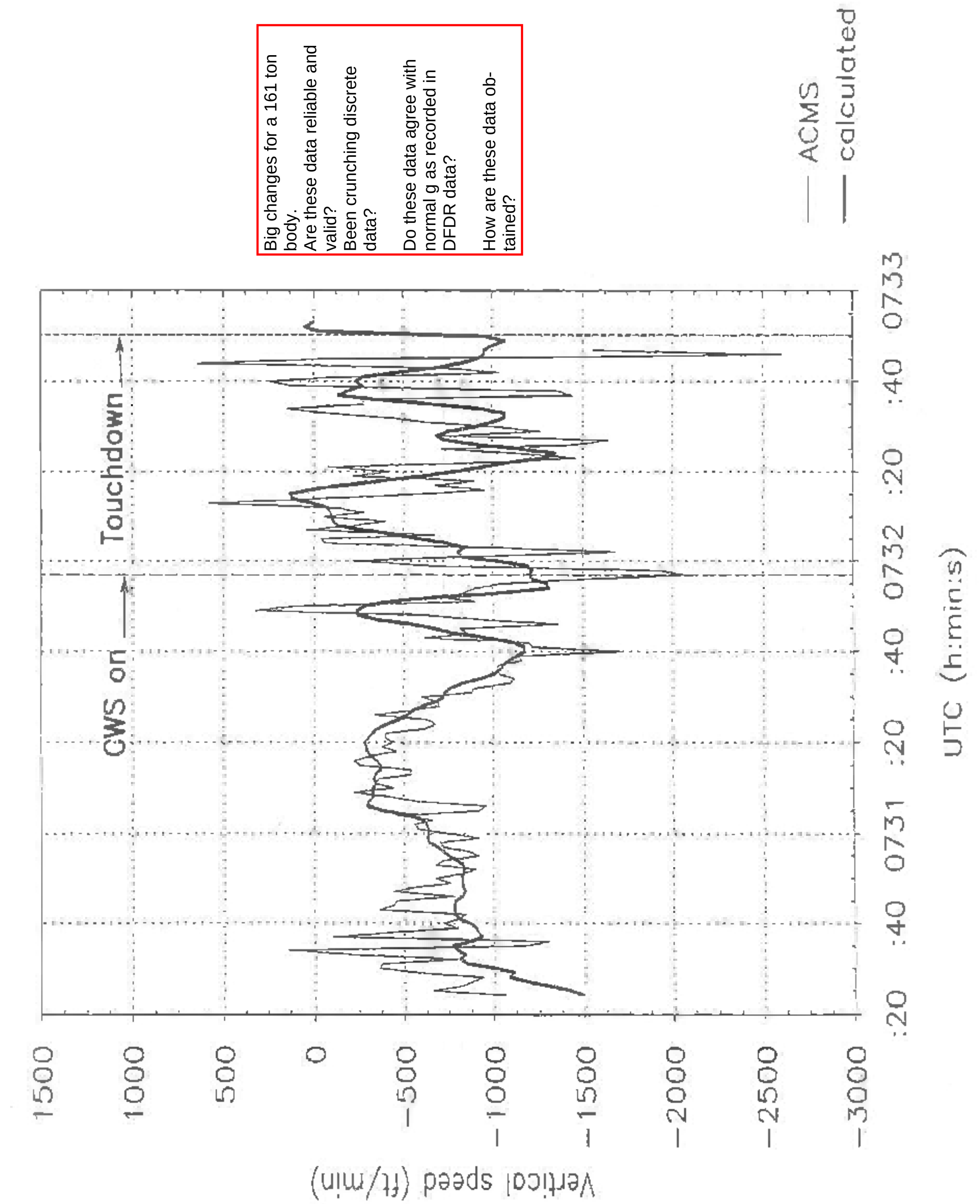


Fig. 16 Correlation between sideslip angle and difference in windspeed



was "estimated" in the draft report, but changed by Frans Erhart.

Fig. 17 Vertical speed calculated and as recorded on the ACMS

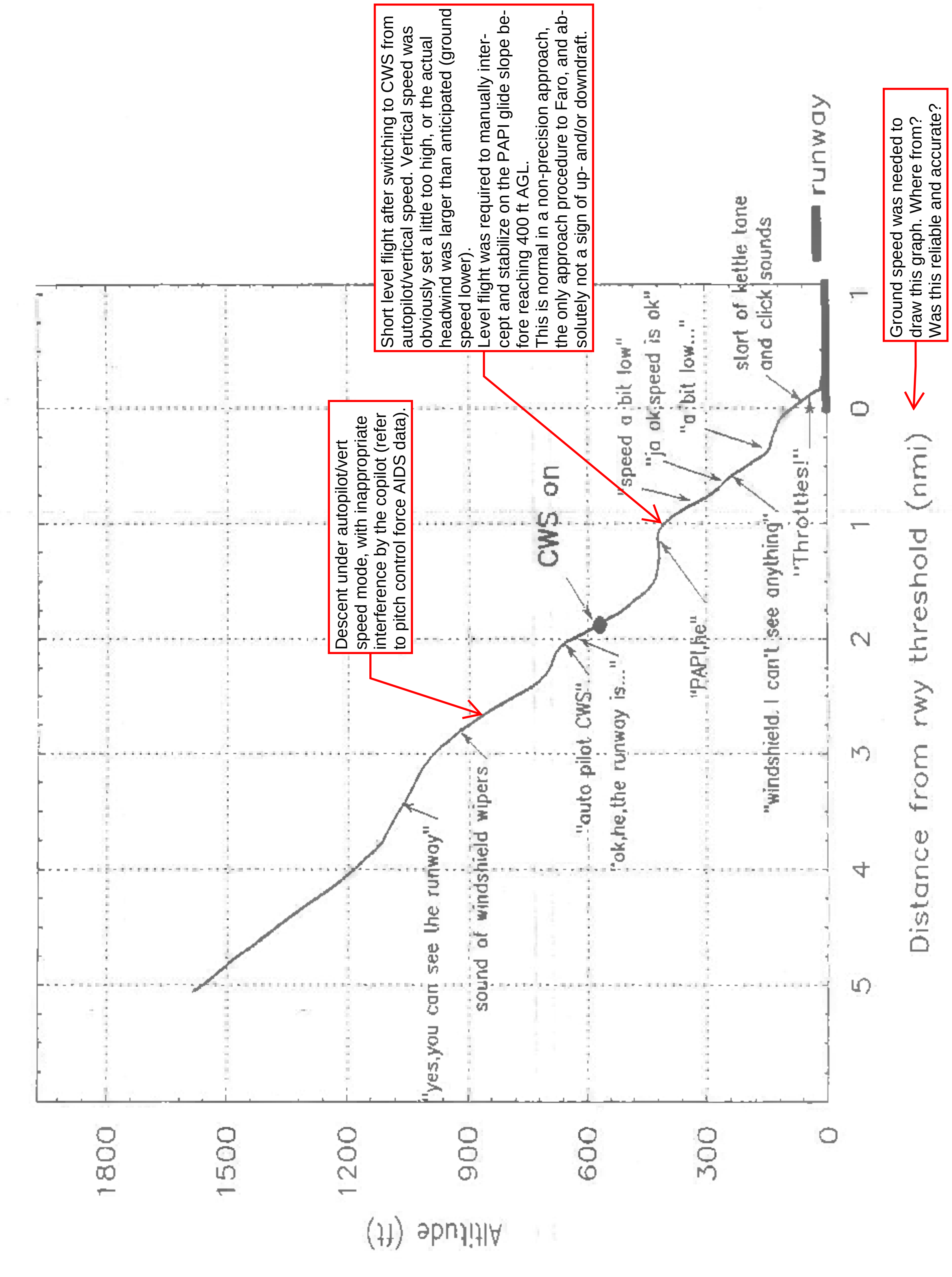


Fig. 18 Altitude profile with transcripted CVR data

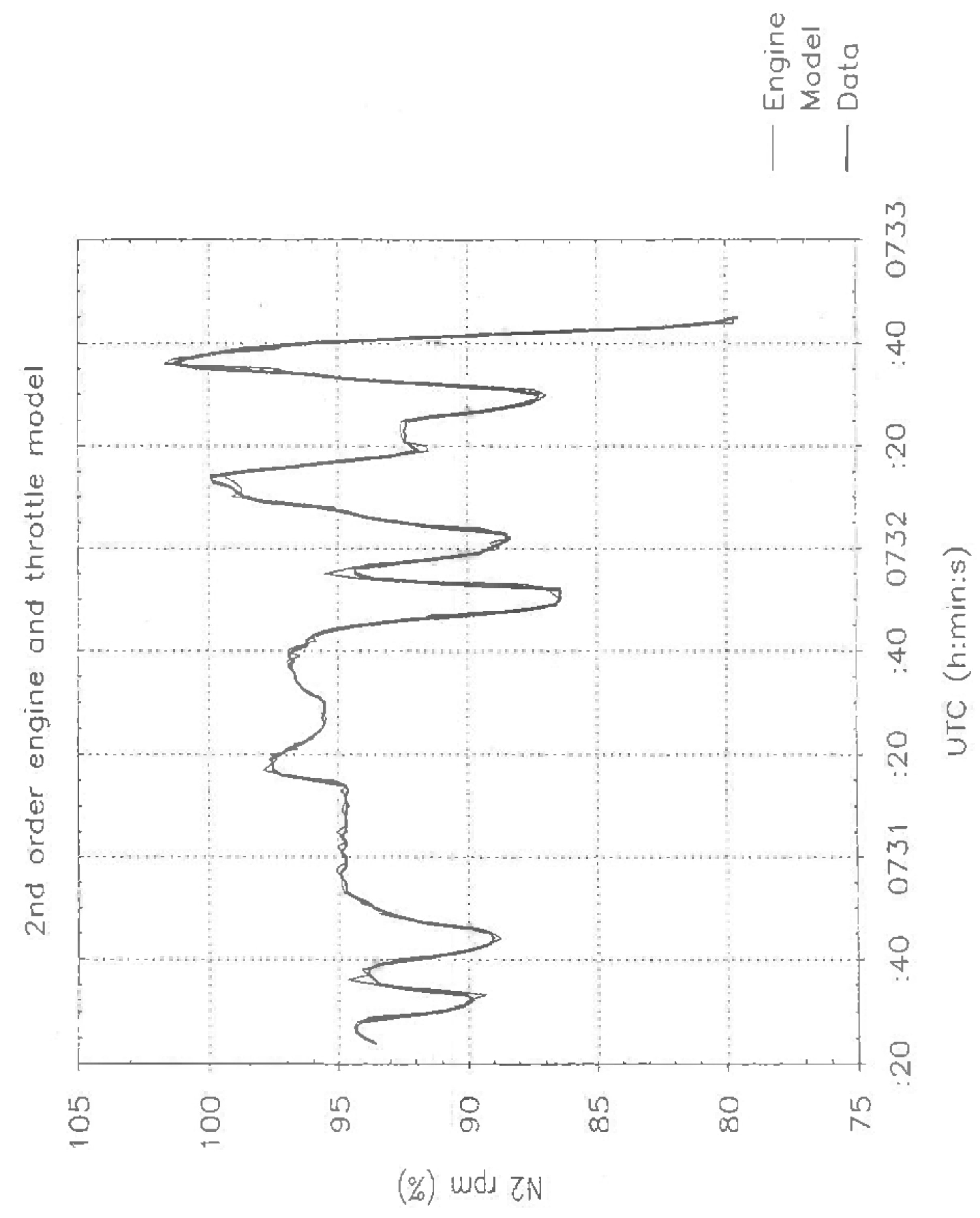


Fig. 19 Match of N_2 between engine model and data

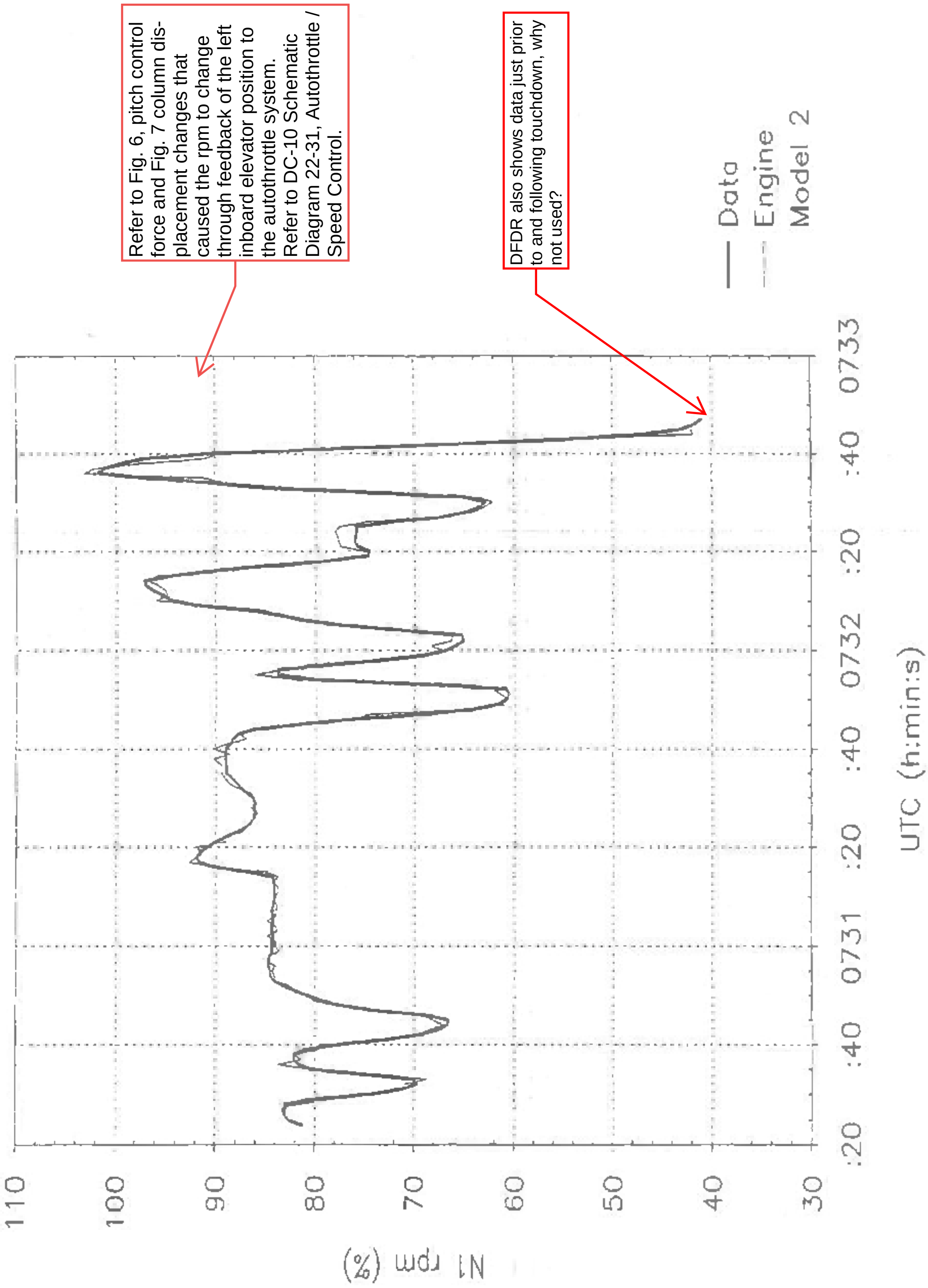
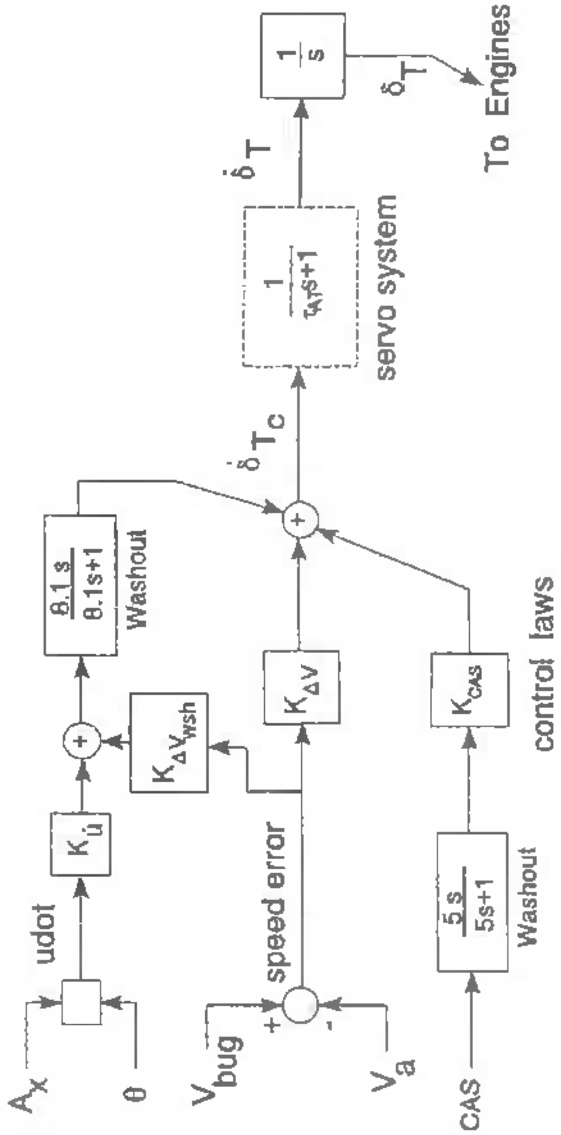


Fig. 20 Match of N_1 between engine model and data



Left inboard Elevator position and other inputs not shown.

Gust filter not included.

This is not a DC-10 autothrottle model.

Fig. 21 Diagram of control laws of "typical" ~~DC-10~~ autothrottle system

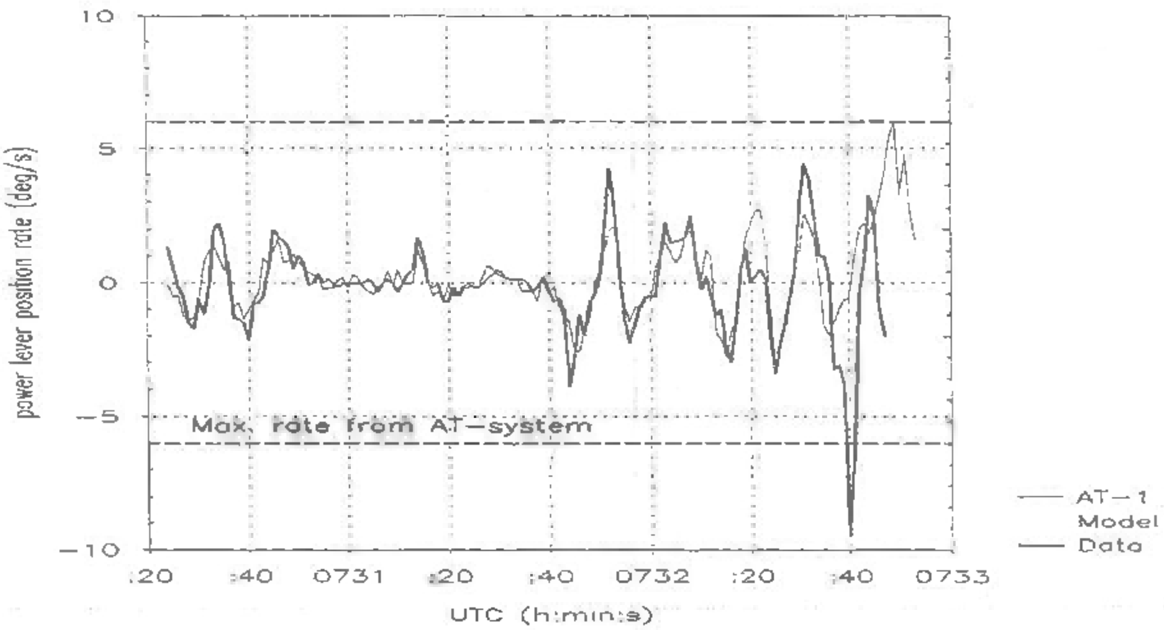


Fig. 22a Comparison of autothrottle #1 model power lever rate with actual data

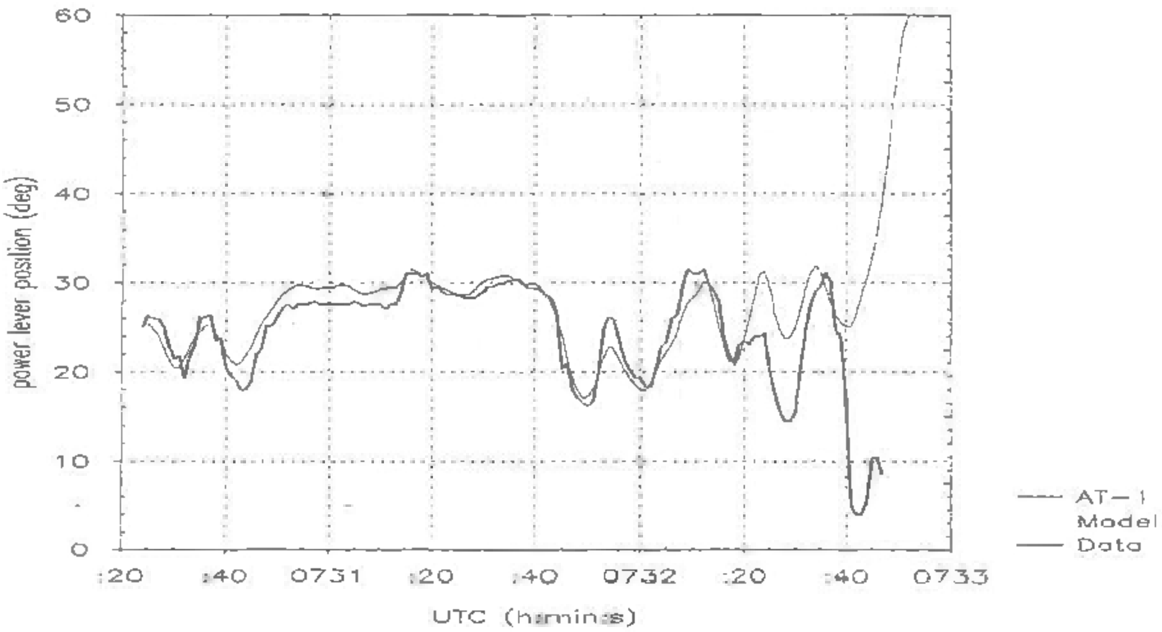


Fig. 22b Comparison of autothrottle #1 model power lever position with actual data

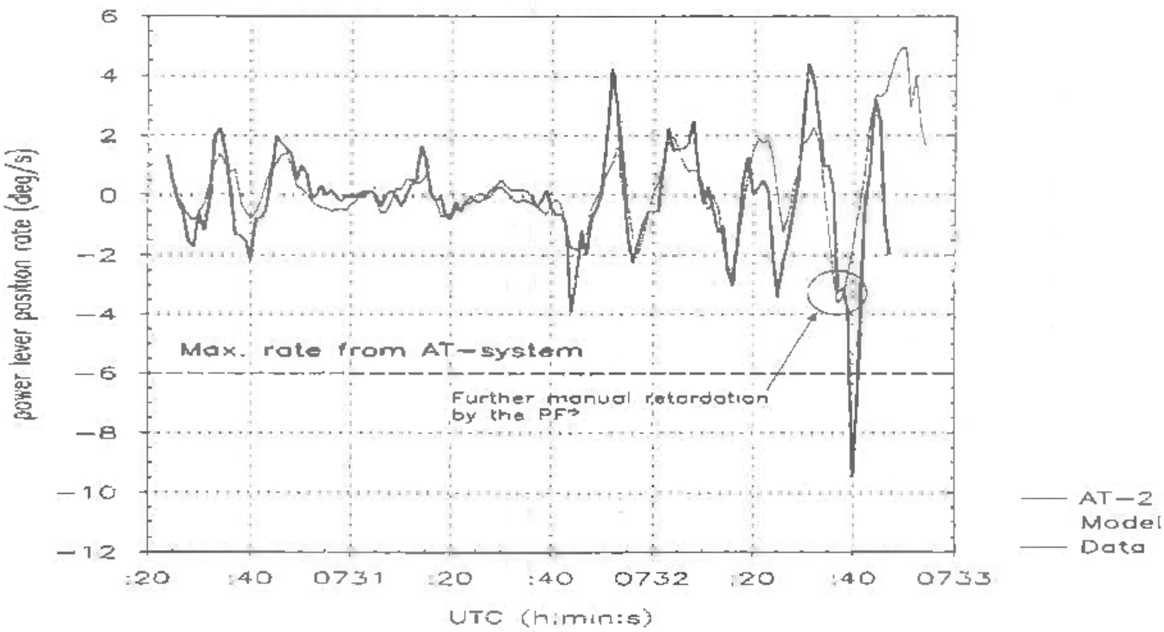


Fig. 23a Comparison of autothrottle #2 power lever rate with actual data

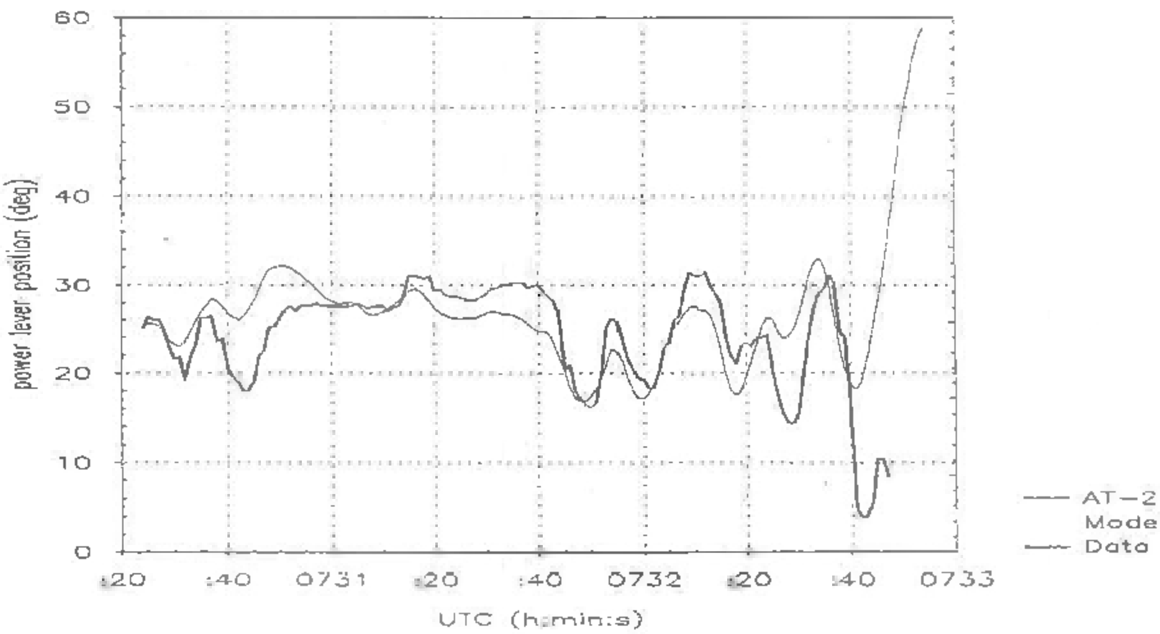


Fig. 23b Comparison of autothrottle #2 power lever position with actual data

APPENDIX A Engine model estimation and fitting

A.1 General

The engine consists of a low-pressure spool with rpm N_1, and a high-pressure spool, with rpm N_2. The time history of both these rpms is given in figure A1 for the landing approach at Faro. Mathematical models will be fitted to both these rpms.

A.2 High pressure spool rpm N_2

Initially a first-order dynamic model was assumed to exist between power lever position δ_T and engine N_2 rpm (the high pressure spool), of the following form:

$$\tau_E . \dot{N}_2 + N_2 = b . \delta_T \tag{A.1}$$

When this equation is put in discrete form, one gets:

$$N_2(i+1) = e^{-\Delta t/\tau_E} . N_2(i) + b . [1 - e^{-\Delta t/\tau_E}] . \delta_T(i) \tag{A.2}$$

A linear regression was made on this equation to determine the unknown terms. The regression, which turned out to be significant (in statistical terms), yields the following equation:

$$N_2(i+1) = 0.5716 N_2(i) + 0.3265 \delta_T(i) + 31.95 \tag{A.3}$$

from which one can derive the appropriate values:

$$\tau_E = 1.79 \text{ s} \tag{A.4a}$$

$$b = 0.762 \quad (\text{rpm}/^\circ) \tag{A.4b}$$

An idea about the accuracy of the regression is obtained by looking at the residuals between N_2-calculated and measured. These residuals are given in figure A2. The rms value is 0.84 % rpm, with a maximum N_2 rpm error of about 4% rpm. Most of the residuals occur after 07:31:40 UTC, which is because of greater activity of the power levers after this time. The serial correlation is 0.682, which indicates there are dynamic processes in the residuals, which are still unaccounted for. In order to improve this a second order dynamic model is assumed to exist, of the form:

$$\ddot{N}_2 + 2\zeta\omega_n\dot{N}_2 + \omega_n^2 N_2 = b.\delta_T \qquad (A.5)$$

When putting this in discrete form one gets:

$$N_2(i+1) = A.N_2(i) + B.N_2(i-1) + C.\delta_T(i) + D.\delta_T(i-1) \quad (+Const) \qquad (A.6)$$

where A, B, C and D are expressions containing ζ, ω_n and Δt (time step size). When a regression is made on this equation, a statistically very significant regression could be made, with as result:

A = 1.34044;
B = -0.53312;
C = 0.247314;
D = -0.131784;
(Const = 15.138).

This equates to a damping coefficient ζ of 0.61 and a natural frequency ω_n of 0.515 rad/s.
The residuals of this model are shown in figure A3. The serial correlation is now -0.0164, i.e. negligible. This is also shown by the figure, when compared with figure A2. The rms value is now 0.59 % rpm, with a maximum error of 2.8 % rpm.

A.3 Low pressure spool N_1

A first order model might be assumed to exist for N_1 also, but the time constant will be too small generally, because of the sampling rate, to allow this model to be identified properly. Hence a direct relationship is assumed to exist between N_2 and N_1. This is of the form:

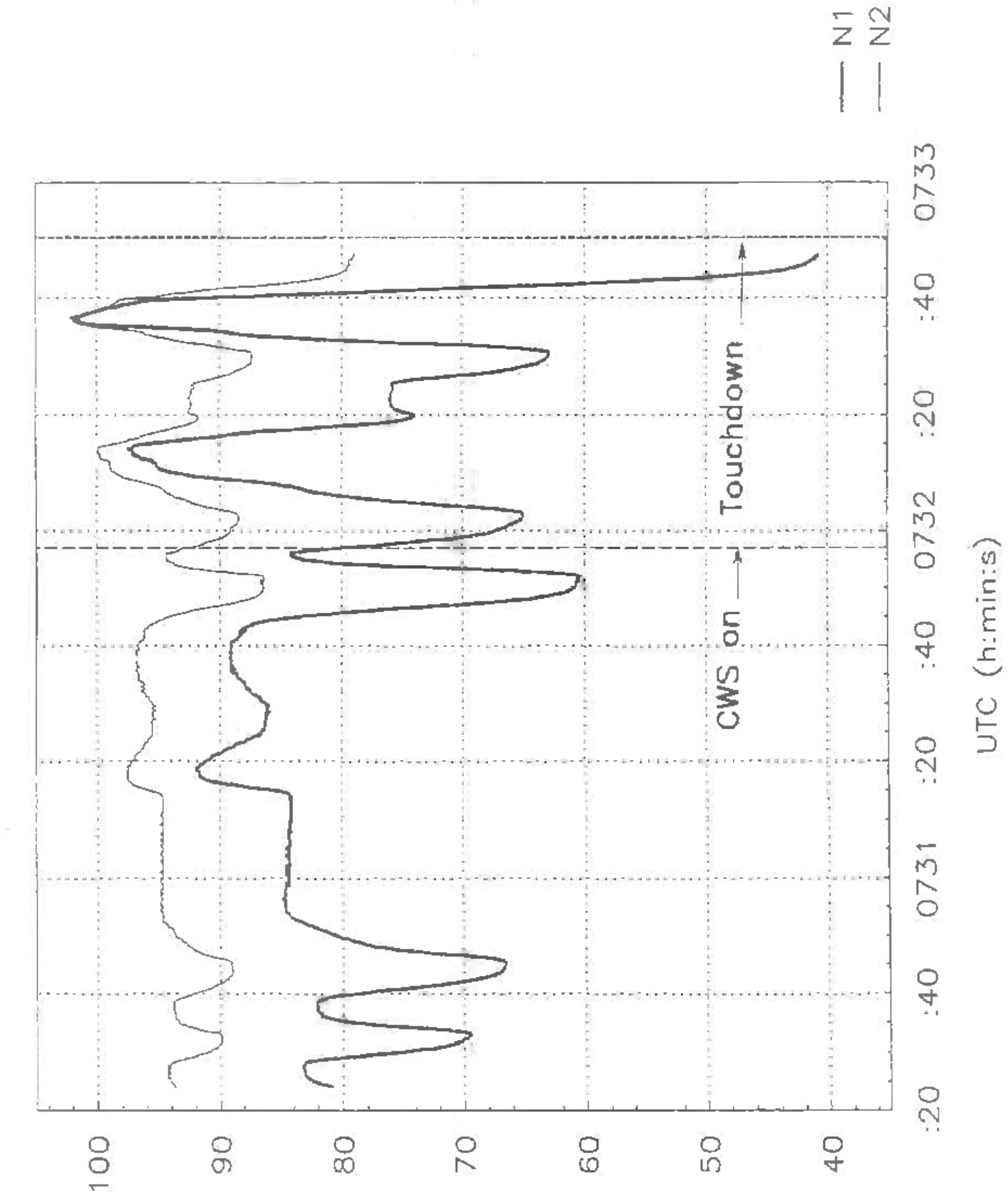
$$N_1(t) = A.N_2(t) + B \tag{A.7}$$

A significant regression could be made, where the following values for A and B were found:

A = 2.784;

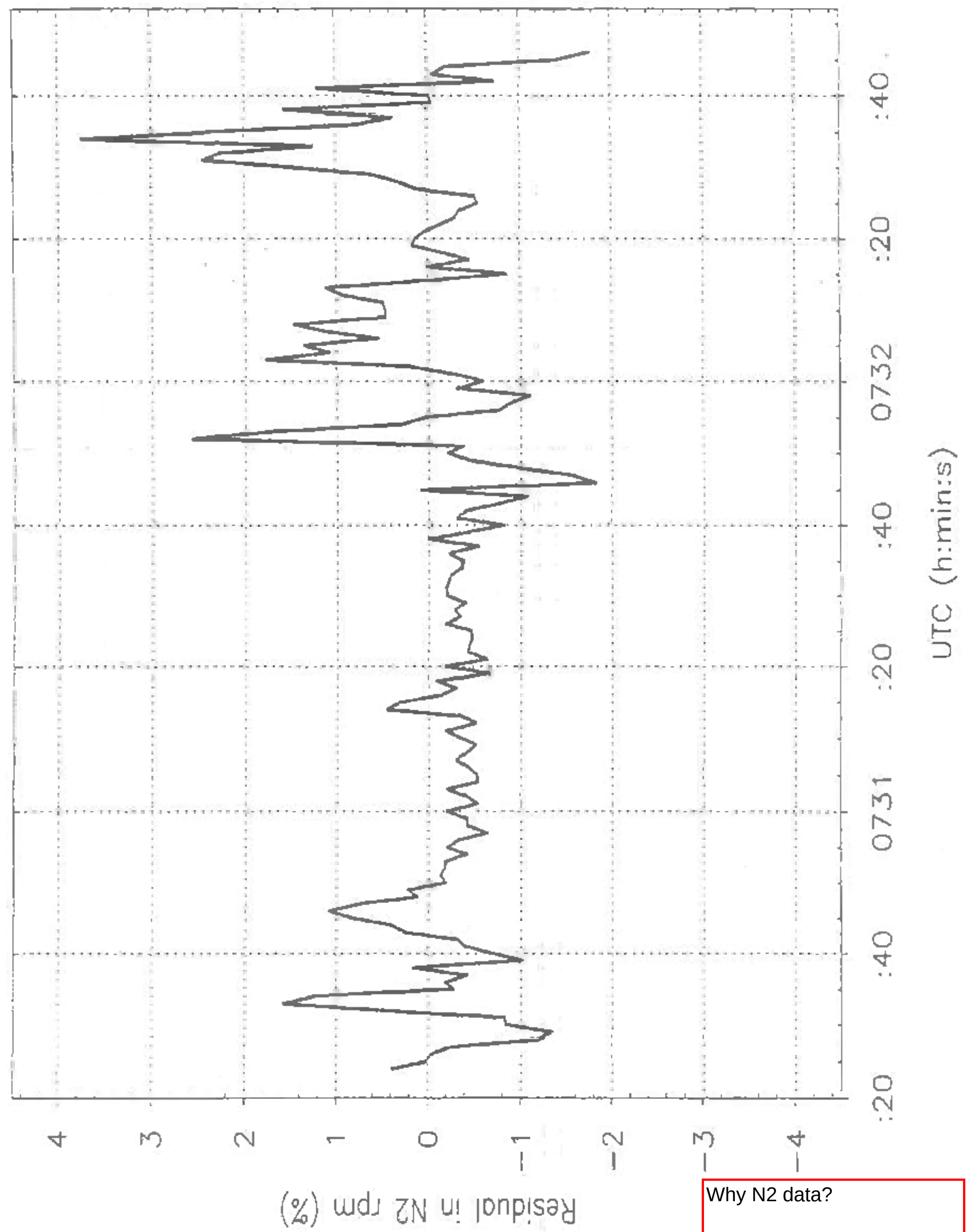
B = -179.82.

The "goodness-of-fit" of this regression can be observed by inspecting the residuals, see figure A4. A good fit has been obtained: the rms value is 1.02 percent rpm, with a maximum deviation of 3.9 percent rpm. The overall good fit is partly attributable to the fact that the greatest response that occurs is a <u>de</u>crease in rpm, which behaves much more like a first order response than a thrust (rpm) <u>in</u>crease. The serial correlation is 0.616, so an improvement in dynamic modeling can be made. Due to the sampling rate this could not be achieved, however.



Refer to Fig. 20 for comments

Fig. A1 Time history of N_1 and N_2 rpm



Why N2 data?

Fig. A2 Residuals between first-order engine model-predicted and measured N_2 data

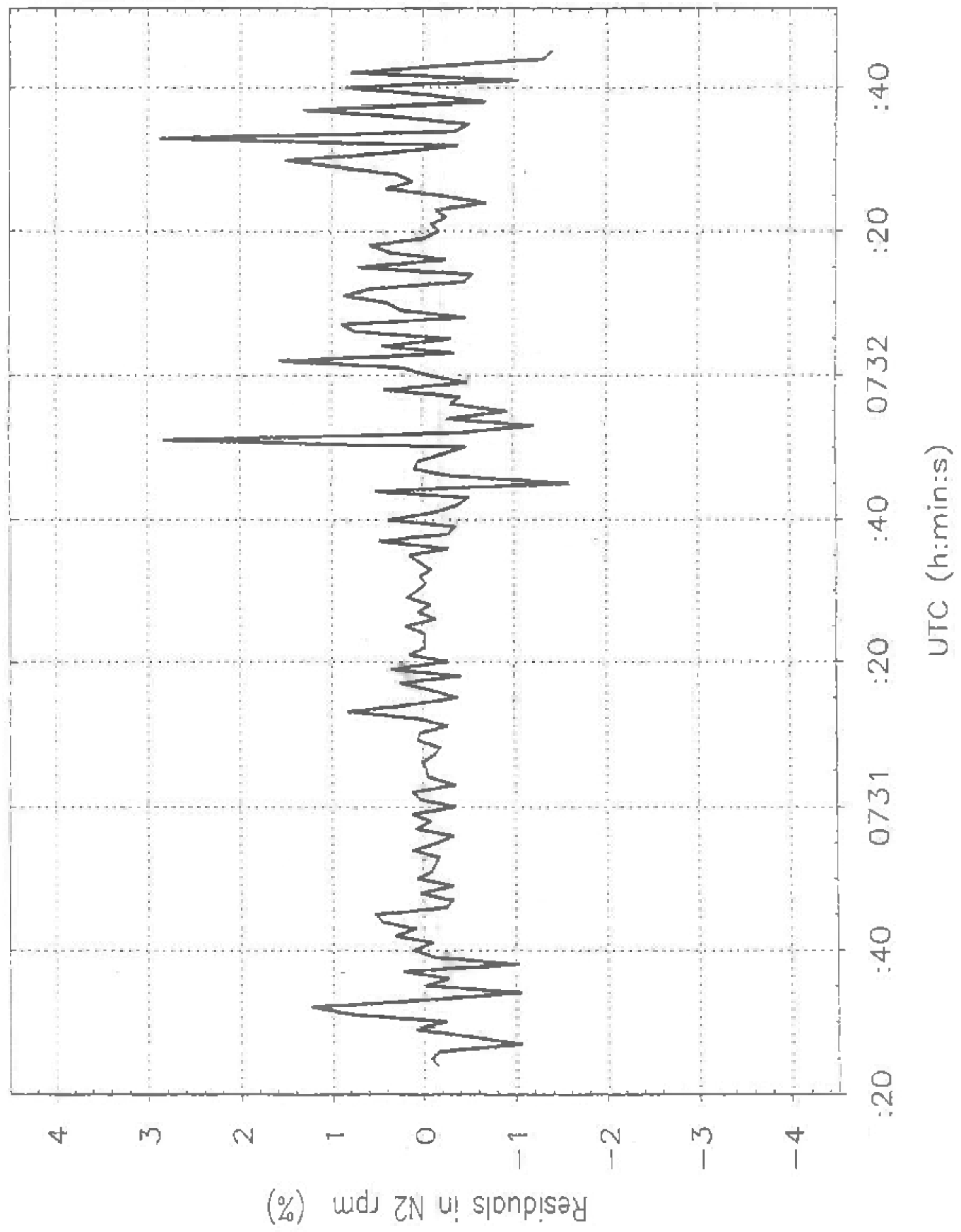


Fig. A3 Residuals between 2nd-order engine model-predicted and measured N_2 rpm

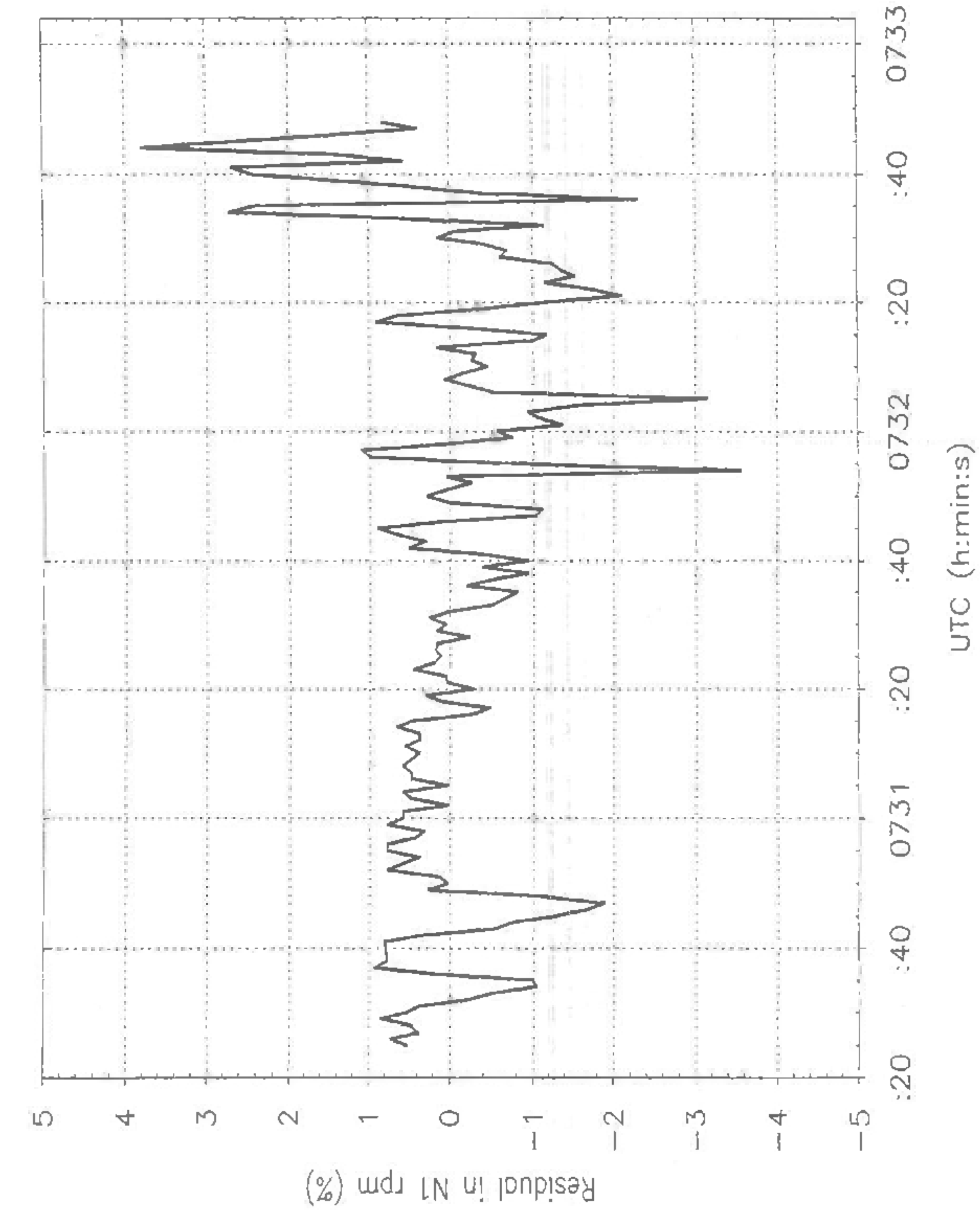


Fig. A4 Residuals in N_1 rpm between engine-model predicted and measured data

And more variables, such as left inboard elevator position that changes as the autopilot or pilot changes the pitch attitude, AOA, pitch and roll angles, stabilizer and elevator position, radalt, normal and long. acceleration, etc.
Refer to DC-10 SD 22-31.

Plus: if normal g exceeds a threshold, airspeed is increased 5 kt (= gust filter). This happened 4 or 5 times during the last 70 s of flight.

APPENDIX B Autothrottle models and fitting

B.1 General

Generally the autothrottle function is to maintain airspeed at a preset value. It does so principally by feeding the airspeed error, i.e. the difference between a preset value and the actual value of airspeed, back to the engine power levers. An airspeed loss should cause an increase in power lever position. To account for the lag in engine response, not only the airspeed error, but also a time derivative term is used in the feedback loop for quickening the autothrottle response. This term, called udot (which is the longitudinal total acceleration), is derived from the longitudinal acceleration A_x (a specific force) and the longitudinal component of gravity due to pitch angle. In other words:

Elevator position feedback results in a faster engine response than udot. Using Udot would take too long to have effect, for instance to prevent touchdown if a go-around during the approach at low altitude would be initiated by pulling the control wheel (pitching up).

$$udot = A_x - g\sin\theta \tag{B.1}$$

Throttles should increase immediately to avoid losing airspeed. This happened at Faro because the throttles were kept close and engine rpm was too low, near idle.

Several levels of complexity in autothrottle modeling can be employed. In this Appendix two models are identified, viz. autothrottle #1-model with no servo system lags in the rate positioning of the power levers, and autothrottle #2-model, where servo system lags in the power lever rate positioning are included. Both models are described in the next sections. For applying the identification process to the data (i.e. regression analysis), a partial data set is used, viz. up to time 07:32:20 UTC. There are suspicions that after this time manual power lever inputs were made. In order to increase the accuracy of the model fit these data should not be included.

Which one is DC-10?

B.2 Autothrottle #1

Did NLR not use the DC-10 autothrottle model?

For modeling the autothrottle #1 model a simple relationship is assumed to exist between the power lever commanded position δ_{Tc}, the airspeed error ΔV and the variable udot. There are no power lever servo system lags involved. To prevent the airspeed from building up, also the time integral of the speed error is used.

From Eq.(B.1) and the above statement, assuming a linear relationship, one can derive:

Delta e (elevator position) and other inputs are missing. This analysis is therefore incomplete and not further reviewed.

$$\delta_T = K_V.\Delta V + K_{IV}\int\Delta V.dt + K_{udot}.(A_x - g\sin\theta) + Const \qquad (B.2)$$

From manuals describing the DC-10 autothrottle system it is known that power lever position <u>rate</u> is controlled, so the time derivative is taken of Eq.(B.2), which, after taking the Laplace transform, results in:

$$\dot{\delta}_{T_c}(s) = K_V s.\Delta V(s) + K_{IV}\Delta V(s) + K_{\dot{u}} s.\dot{u}(s) \qquad (B.3)$$

where $\dot{u} = A_x - g\sin\theta$. To avoid high-band noise from driving the system, both the first term and the third term are low-pass filtered with a first order filter with time constants of 5s and 8.1s respectively, yielding:

$$\dot{\delta}_{T_c}(s) = K_V.\frac{5s\Delta V(s)}{(5s+1)} + K_{IV}.\Delta V(s) + K_{\dot{u}}.\frac{8.1s\dot{u}(s)}{(8.1s+1)} \qquad (B.4)$$

In reality the DC-10 autothrottle system has a slightly different control law (apart from the non-linear components), see figure 21:

Gust filter?

$$\dot{\delta}_{T_c} = K_V.\frac{5s.CAS(s)}{(5s+1)} + K_{IV}.\Delta V(s) + K_{\dot{u}}.\frac{8.1s\dot{u}(s)}{(8.1s+1)} + K_{V_{wo}}.\frac{8.1s\Delta V(s)}{(8.1s+1)} \qquad (B.5)$$

Still incomplete

This control law states that the commanded power lever position rate depends upon the "higher frequency" variations in CAS (the 5s/(5s+1) term is a wash-out filter), the airspeed error ΔV, and the "higher frequency" variations in the longitudinal derivative udot and ΔV (again here the term 8.1s/(8.1s+1) is a wash-out filter). Furthermore there is a direct transfer of the commanded rate to the actual rate as follows:

$$\dot{\delta}_T = \dot{\delta}_{T_c} \tag{B.6}$$

A regression analysis was applied to the data, using Eq.(B.5) and (B.6). The regression, which was highly significant in statistical terms, yielded the following values:

K_V = -0.65839 deg/m.
K_{TV} = -0.01883 deg/(kt.s) = -0.03660 deg/m (n.s.).
K_{udot} = -1.22826 deg.s/m.
K_{Vwsh} = -0.06565 deg/(kt.s) = -0.12761 deg/m (n.s.).

The indication 'n.s' stands for non-significant (in statistical terms).
These values are used in the Autothrottle #1 model to generate the power lever position rate time response during the flight, as function of speed error ΔV (calculated from the ACMS data), washed-out CAS and udot.
The quality of the model fit can be obtained by looking at the difference between the calculated (auto)throttle position rate and that derived from the measured positions (for the data stretch used). This difference, or residual, is shown in figure B1.
The serial correlation of the residuals is 0.273. This means there is some time dependency in the data, which is still unaccounted for. The airspeed error ΔV was calculated based on an approach speed of 144 kts (i.e. Vref+5). The rms value of the residuals is 0.71 deg/s, with a maximum difference of about 2.5 deg/s in power lever position rate.

B.3 Autothrottle #2

Not a DC-10 autothrottle model either, is it?

In the case of the autothrottle #2 model, it is assumed that there is a servo lag between the commanded power lever position rate and the actual power lever motion. It turned out from inspecting the data that there was a correlational lag of 1s or more between δ_{T_c} and ΔV and udot, which led to this assumption made here.
With the servo-driven autothrottle model the following, linear dynamical model is assumed to exist between the transfer of commanded to actual power lever position rate:

$$\tau_{AT}\dot{\delta}_T + \delta_T = \delta_{T_c} \tag{B.7}$$

This model is used in conjunction with that of Eq.(B.5) to drive the power levers. A statistically significant regression (i.e. data fit) could be made, which resulted in the following values for the parameters in Eq.(B.5) and (B.7):

τ_{AT} = 1.25 s.
K_V = 0.34868 deg/m (n.s.).
K_{IV} = -0.02808 deg/(kt.s) = -0.05458 deg/m (n.s.).
K_{udot} = -4.03734 (deg.s)/m.
K_{Vweh} = -0.43255 deg/(kt.s) = -0.84081 deg/m.

The quality of this regression is shown in figure B2, where the residual in power lever position rate is given. Compared to figure B1 the residuals in autothrottle #2 are much the same as those of autothrottle #1. The serial correlation however, is now 0.154. It means that the autothrottle #2 model fits the dynamic response of the power lever position rates a little better than autothrottle #1 model does. The rms value of the residuals is 0.68 deg/s, with a maximum difference in power lever position rate of 2.6 deg/s. These numbers are very similar to those of autothrottle #1 model. As figure B2 shows the residual for the second model shows a little more low-frequency variations for the first part of the time history, whereas for the second part the first model shows some low-frequency variations.

Overall it is hard to say which autothrottle model is better; judging by the time history of the power lever position it looks like the autothrottle #1 model is better (see Fig.22a). From the good fit of the autothrottle #2 model in terms of power lever position *rate* there are indications that there may be a time delay ('lag') of the order of 1.25s in the rate positioning of the power levers.

These are not DC-10 autothrottle data. This should have been made very clear by the engineer!
No elevator and gust filter contributions?!

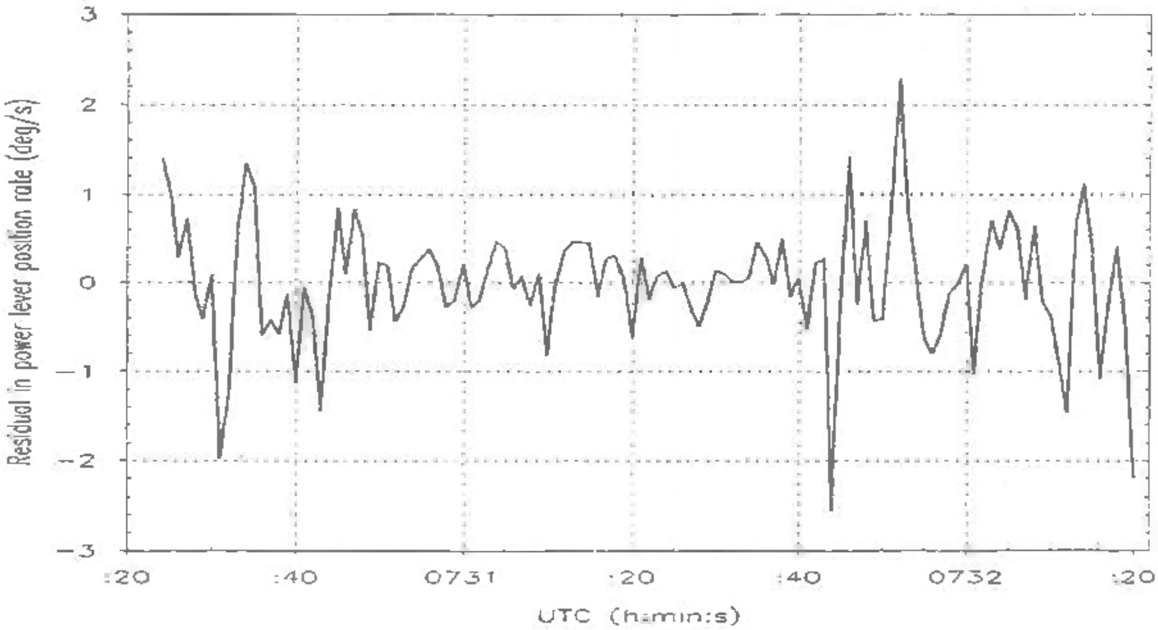


Fig. B1 Residuals in power lever position rate between autothrottle #1 model-predicted and measured data

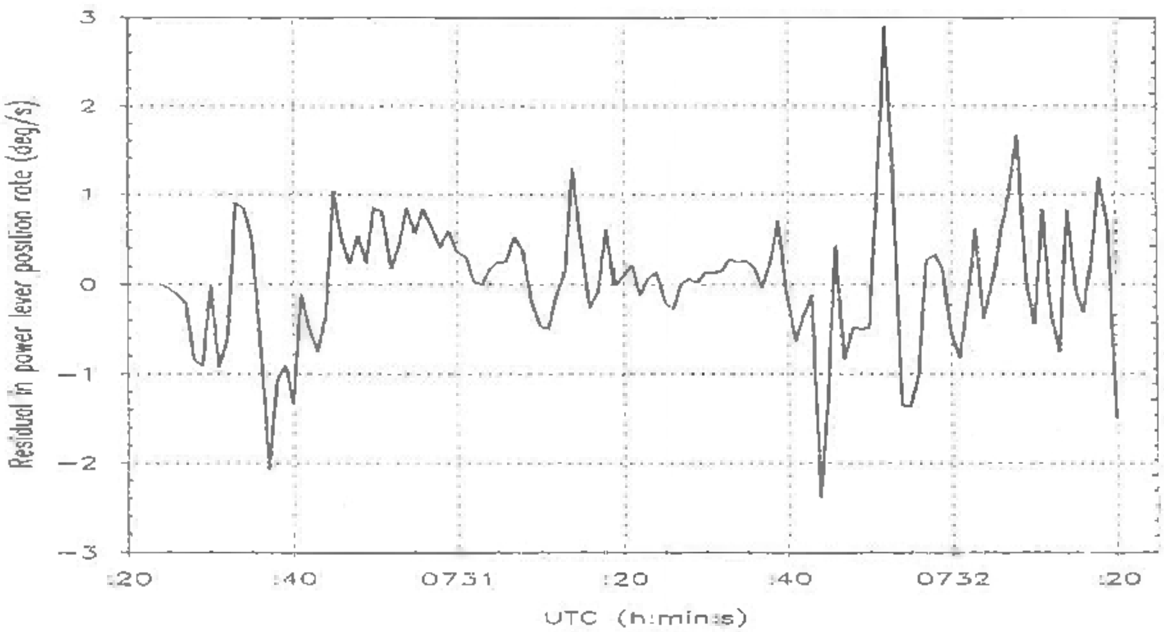


Fig. B2 Residuals in power lever position rate between autothrottle #2 model-predicted and measured data