National Transportation Safety Board
Office of Research and Engineering
Washington, D.C. 20594

Airplane Performance Study

Specialist's Report of Investigation
Timothy Burtch

A. ACCIDENT

Location:	Denver, CO
Date:	December 20, 2008
Time:	0018 GMT (6:18 pm MST)
Airplane:	Boeing B-737-500, N18611
NTSB Number:	DCA09MA021

B. GROUP

Chairman: Timothy Burtch
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C. SUMMARY

On December 20, 2008, at 1818 mountain standard time (MST), Continental Airlines (CAL) flight 1404, a Boeing 737-500 (registration N18611), equipped with CFM56-3B1 engines, departed the left side of runway 34R during takeoff from Denver International Airport (DEN). The scheduled, domestic passenger flight, operated under the provisions of Title 14 CFR Part 121, was enroute to George Bush Intercontinental Airport (IAH), Houston, Texas. There were 37 injuries among the passengers and crew, and no fatalities. The airplane was substantially damaged and experienced a post-crash fire. The weather observation in effect at the time of the accident was reported to be winds at 290 and 24 knots (kt) with gusts to 32 kt, visibility of 10 miles, a few clouds at 4000 feet and scattered clouds at 10,000 feet. The temperature was reported as -4 degrees Celsius. The tower reported winds of 270˚ and 27 kt with the take-off clearance.

D. DETAILS OF PERFORMANCE STUDY

The performance study describes the airplane motion during the accident sequence based on the available data sources. This includes airplane position, speed, and attitude derived from the Flight Data Recorder (FDR), Denver Airport Movement Area Safety System data (AMASS), data obtained from various weather information services, and data collected during the on-scene portion of the investigation.

Select FDR Parameters

The FDR was an L-3 Communications Fairchild Model FA2100 FDR. It was configured to record 64 12-bit words, or parameters (i.e. altitude, airspeed, etc), every second. The grouping of the 64 words every second is called a sub-frame, and words can be repeated within a sub-frame to obtain sample rates of greater than 1 Hz. Additional details on the FDR and a complete list of recorded parameters can be found in the Flight Data Recorders Specialist's Factual Report.

Select data from the FDR are plotted in Figures 3 through 9. Figure 3 contains the pilot inputs throughout the take-off roll, the excursion through the grass adjacent runway 34R, and the crossing of Taxiway WC. The data end when the airplane was just north of Taxiway WC. This point approximately corresponds with a 3g spike in vertical load factor recorded on the FDR and likely resulted from a drop-off north of Taxiway WC. According to on-scene witness marks, this is also the point where the airplane lost both main landing gear and began to slide on its engine nacelles. See the inset in Figure 1 and Figure 2.

Figure 4 includes FDR parameters for the engines. Engine performance was normal for take-off until just after the airplane departed the runway[1] and before the Captain made the call to reject the take-off at 18:18:21MST. (All times are MST unless otherwise noted.) As shown in the figure, the airplane departed the runway at approximately 110 kt calibrated airspeed (KCAS) and reached a maximum airspeed of 120 kt KCAS[2]. The airplane decelerated to about 90 KCAS before the FDR stopped recording just north of Taxiway WC at 18:18:27.

Figures 5 through 9 indicate that control continuity existed in both the yaw and pitch axes. The data also show that the control surfaces responded to the pilot's commands as expected and that the airplane responded to the control inputs as predicted. Little or no time delay could be detected between the pilot's rudder pedal commands and rudder movement. The same is true of column position and elevator.

Figures 8 and 9 show an expanded scale of the pilot's inputs and the resulting airplane response for the time around the airplane's excursion off of the runway. Figure 8 shows that the proper airplane control wheel for a left crosswind was input just after 18:18:07. At this time, approximately 30° of left-wing-down (LWD) wheel and about 0.75° of airplane-nose-up (ANU) column were input. Five to ten degrees of airplane-nose-right (ANR) rudder had already been input by this point. While not recorded, the performance study assumed that no nose wheel tiller

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[1] Based on available data, the airplane departed the runway at approximately 18:18:17 where the figures indicate the cockpit area mike (CAM) recorded the "sound of increasing background noise".

[2] For the accident take-off, Continental reported the following V speeds: V_1 = 137 KCAS, Vr = 140 KCAS, and V_2 = 146 KCAS. Climbout was to be done at V_2 + 15 KCAS or 161 KCAS.

inputs were made beyond this point in the take-off attempt because the pilot likely would have already transitioned from the tiller to the rudder pedals as the primary means for directional control. (Boeing indicates that the B-737-500 rudder becomes effective between 50 kt and 60 kt airspeed.) However, the pilot did report using nose wheel steering again as the airplane approached the left side of the runway in a final attempt to keep the airplane on the concrete.

Irrespective of the winds that were present during Continental flight 1404's take-off attempt, select FDR data shown that the airplane was capable of tracking the runway centerline. The airplane largely tracked the centerline until approximately 18:18:13 when the FDR rudder deflection went from 24° ANR to a near neutral position and the wheel transitioned from 20° LWD to over 80° of right-wing-down wheel (RWD).[3]

FDR Accelerometer Integration

The FDR integration is shown in red in Figure 1. It was necessary to perform an integration because the position data recorded on the FDR lacked the precision to accurately place the airplane on the runway. The AMASS data, on the other hand, is accurate and is recorded every second at Denver International Airport. However, AMASS position for Flight#1404 does not exist beyond the point the airplane departed the runway. An integration was required for an accurate ground track beyond the AMASS range and up until the FDR stopped recording. In addition to providing a ground track for the accident airplane, integrating the FDR accelerometer data also provided the proper context for the cockpit voice recorder (CVR) comments and a set of accelerometer biases for the wind extraction effort. The CVR comments are show in yellow in Figure 1. The wind extraction is discussed below.

The AMASS data and the measurements taken during the on-scene portion of the investigation, besides providing an accurate position for Continental flight 1404 while the airplane was still on the runway, were used to determine the constants of integration and the accelerometer biases. The integration effort required an initial velocity and position to anchor the results. The AMASS and on-scene measurements provided these constants of integration. Additionally, the AMASS and measurements provided the necessary boundary conditions to extract the accelerometer biases. Most accelerometers have an error bias, and, as a result, the resulting velocity and position will drift as the error is integrated over time. The degree to which velocity and position drift is a measure of accelerometer quality, and the growth over smaller time periods is typically negligible. In the case of Continental flight 1404, the take-off accident lasted less than a minute. The accelerometer biases that minimized the error between the computed ground path and the given boundary conditions were as follows:

$$\Delta n_x = 0.045378 \text{ g's}$$
$$\Delta n_y = -0.005564 \text{ g's}$$
$$\Delta n_z = 0.006420 \text{ g's}$$

Finally, a trapezoidal integration scheme was used. This result of using a trapezoid instead of a rectangle is better coverage for the "area under the curve" and, as a result, less integration error.

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[3] The pilot reported after the accident that he was concerned about the airplane rolling over the embankment adjacent the runway and that he added RWD aileron to help prevent this from happening. However, the AMASS data and FDR integration in Figure 1 show that the airplane was still close to the runway centerline when the RWD wheel was introduced by the pilot at about 18:18:13.

The final integrated position and speed is shown in Figure 19 as a function of time, and the integrated altitude never varied more than ±10 ft from the recorded airport elevation.

Wind Extraction Results

Winds were considered as a factor in the Denver accident. As a result, an effort was made to extract the winds present during the accident sequence using both measured FDR and predicted airplane performance data. It is possible to estimate the winds that were present for the accident given the pilot inputs and the airplane response recorded on the FDR, as well as accurate performance models for the B-737-500. The NTSB and Boeing independently estimated the accident winds, and a summary of the results are presented here.

NTSB Wind Estimate

The NTSB wind extraction used a validated B-737-500 simulation[4] and applied the biases from the FDR accelerometer integration to the accelerations recorded on the FDR. These accelerations, along with the FDR pilot controls, were then used as inputs to a kinematic extraction (or "inverse simulation") to back out the sideslip angle, pitch angle, center of gravity elevation, nose wheel steering angle, and, ultimately, the wind speed and direction as a function of time[5].

The wind extraction was dependent on an accurate ground model and, as a result, the NTSB B-737-500 simulation checkout included both standalone ground model as well as integrated checkout data. In addition, since the ground model used was not valid for unapproved surfaces, there are no extraction results presented for the time after Continental flight 1404's nose wheel departed the runway.

The NTSB's wind extraction results for the accident are shown with FDR magnetic heading in Figure 10 as a speed and absolute direction. The same winds are shown with the FDR recorded rudder in Figure 11 as a speed and a relative direction off of the airplane nose. The short dashed portions in the figures represent intervals where a wind extraction solution could not be mathematically determined.

The NTSB estimated that winds for the accident varied between 30 kt and 45 kt out of the west, almost a straight crosswind for Denver's runway 34R. A peak gust of 45 kt was extracted at about the same time the 24°ANR rudder input was returning to a near neutral position and about 1.5 seconds after the first recorded skid marks. This is in comparison to the Low Level Wind shear Alert System (LLWAS) at the Denver airport which recorded a ten-second average wind of 40 kt approximately two minutes prior to the accident and 34 kt around the time of the accident. (This was for LLWAS sensor #2 located closest to the departure end of runway 34R. A detailed discussion of the LLWAS data can be found in the Meteorological Factual Report and

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[4] The NTSB 737-500 model matched all of the simulation check cases provided by Boeing to within acceptable tolerances. Gear model check cases and select gear forces for limited sideslip angles were provided by Boeing to assist in validating the gear model used in the NTSB analysis. As per Boeing's instructions, the NTSB 737-500 aerodynamics model was developed using 737-200 drag and directional derivatives and 737-300 lift curves. The tail arms were scaled for the proper tail effectiveness, and the appropriate engine and ground reaction models were used. While the NTSB B-737-500 simulation did not include an increment for winglets, Boeing analysis using predicted winglet effects for the B-737-500 showed that the winglets have a neglible effect on airplane crosswind performance. More details on the B-737-500 winglet effect can be found in Attachment 1: CAL 737-500W Accident, Boeing Simulation Activities, March 2009.

[5] Winds were calculated from the extracted sideslip angle, the FDR airspeed, and the FDR groundspeed.

Addendum.) Approximately 3.5 seconds after the first recorded skid marks, the calculated drift angle grew rapidly. As a result, the confidence in the estimated wind beyond approximately 18:18:14 is reduced.

In addition to the accident winds, the nose wheel steering angle was also estimated using the FDR measurements and the NTSB B-737-500 simulation. The extracted steering angle is shown with FDR rudder in Figure 12. The nose wheel angle is commanded by either rudder pedal or tiller on the B-737. Assuming the crew of Continental flight 1404 did not input tiller around 18:18:12, the extracted steering angle would be expected to more closely mirror the rudder (as it did at time 18:18:07). This discrepancy is likely due to limits in the accuracy and availability of FDR data (e.g., drift sensitivity discussed below), skidding, and other limits in the ground and aerodynamic models used in the extraction. Despite this discrepancy, the large right nose wheel steering angle in the last three seconds of the extraction suggests that significant right tiller was input by the pilot as the airplane diverged from the runway centerline. While the tiller input may have slowed Continental flight 1404's departure from the runway, the final tiller input had little effect on the airplane's track, likely due to the high airspeed at this point in the take-off.

Finally, the NTSB considered a sensitivity study to determine the effect of small errors in FDR drift and lateral load factor on the extracted wind solution. FDR drift and lateral load factor are shown in Figures 13 and 14, respectively. Since the bias on n_y is known and accounted for as a result of the integration, only the sensitivity with respect to drift angle was considered further. The extraction sensitivity to drift angle was run with a $\pm 0.5°$ tolerance-band on drift angle to determine the effect of small errors possibly present in the FDR data. The drift angle sensitivity is shown in Figures 15 through 17 for wind direction, wind speed, and nose wheel steering angle, respectively.

Boeing Wind Estimate

Boeing independently estimated the winds, and a more detailed description of Boeing's analysis is contained in Attachment 2[6]. As noted earlier, checkout showed that the performance models used in both the NTSB and Boeing extractions were similar at the check case conditions. However, the methods used to estimate the accident wind in the two extractions were significantly different.

To estimate the winds, Boeing first bracketed a wind solution by using FDR airspeed and ground speed. Boeing then combined the results of two "point-by-point" methods: one method that varied the winds to match FDR lateral load factor, airspeed, and ground speed ("n_y method") and another method that varied the winds to match FDR yaw acceleration derived from an optimal curve fit of FDR heading, airspeed ,and ground speed ("rdot method"). Finally, Boeing slightly modified the average wind solution to fall within the LLWAS reported winds. The hand-tailored average produced a slightly better match in their B-737-500W[7] time history simulation.

Because nose wheel parameters are not recorded on the FDR, Boeing assumed two degrees of right nose wheel tiller up to approximately 60 KCAS in their time history simulation. This speed

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[6] "Supplement to Boeing Wind Analysis CAL 737-500 (PT811) Runway Excursion Accident at Denver (DEN)", November 2009.
[7] "W" for winglets.

occurs at about 18:18:04 on the accident take-off or just before the pilot applied the proper control wheel for a left crosswind (at 18:18:07 as mentioned earlier). Boeing felt that this tiller profile was most reasonable, and it did produce a better match with the FDR ground track in their time history simulation. Boeing's "point-by-point" methods assumed no tiller input and a nose wheel angle based solely on FDR rudder pedal. However, the pilot of Continental flight 1404 reported and the skid marks suggest that additional tiller was input as the airplane departed the runway. As a result, during the last three to four seconds, the Boeing wind extraction solution is not valid, and Boeing has substituted a constant wind value instead. (Note: The NTSB extracted nose wheel steering angle as part of its wind solution. As a result, the NTSB extraction did include nose wheel steering angles of approximately ± 5° above 60 KCAS. This approach does capture the pilot's final nose wheel input.)

All of Boeing's methods produced similar results above an airspeed of approximately 60 kt. The final winds extracted by Boeing for the accident are shown with the NTSB results in Figure 18 as a speed and magnetic direction. Boeing reported the accident winds as gusting out of the west at 25 kt to 40 kt, and the results aligned well with the LLWAS sensor data[8]. The final Boeing wind solution produced a very good match with the FDR recorded heading and resulted in small differences in other parameters – namely drift, lateral load factor, and rudder deflection. Bank angle differed from the FDR recorded value by one to two degrees because bank angle was an output in Boeing's forward[9] time history simulation. However, Boeing used FDR bank angle in the "point-by-point" methods discussed previously, and Boeing's final wind solution is largely based on these methods. The time history simulation was used only to refine the point-by-point results.

Finally, Boeing performed a sensitivity study similar to that of the NTSB's to determine the effect of small errors in FDR drift and yaw acceleration on their extracted wind solution. The results of the sensitivity study can be found in Attachment 2.

As the FDR data also suggest, Boeing concluded that the airplane was capable of handling the winds it encountered during the take-off that evening. It was not until the rudder recorded on Continental flight 1404's FDR went to a near neutral position that the airplane diverged from the centerline and departed the runway.

Continental Airlines Boeing 737-500 FFS Models for Crosswind Training

The use of rudder control in the Continental flight 1404 accident prompted the NTSB to investigate the training models used for flight crew crosswind training. Continental Airlines uses a B-737-500 Full-Flight Simulator (FFS) in their Houston facility for all crosswind training.

The Continental B-737-500 FFS does not include a winglet increment. However, as discussed earlier, Boeing analysis has shown the winglet effect on airplane handling qualities to be minimal.

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[8] The average peak wind speed from the two methods used by Boeing was about 45 kt, the same peak wind extracted by the NTSB. However, after considering the reported LLWAS winds, Boeing modified their wind solution and a peak of 40 kt resulted.

[9] With the "inverse simulation" mentioned earlier, FDR accelerations and bank angle are inputs. This is one advantage of using the inverse method.

While no problems were identified with Continental's FFS airplane performance models, a problem with the simulator atmospheric model was found: no gusts are included below a 50 ft altitude (above ground level). See Attachment 3[10] for details. This means that flight crews training in the Continental FFS will only be exposed to a steady-state wind and no gusts during take-off and landing. This is a problem if the FFS is the sole means for training crosswinds to Continental flight crews; the first time that crews will be exposed to gusty winds in the 737-500 will be in the actual airplane.

Boeing 737-500 Crosswind Guidance to Operators

The NTSB also investigated the testing and analysis used by Boeing to provide crosswind guidance to operators. As specified in the Code of Federal Regulations (CFR), Boeing is not required and does not set a crosswind limit for any of its airplanes. Instead, through analysis, Boeing has shown that the B-737 is controllable in a 40 kt crosswind on a dry runway. Boeing actually demonstrated a 35 kt crosswind for the B737-300. Similarly, APB demonstrated 22 kt for the wingleted B-737-500W. However, none of these crosswinds are considered limiting. Subsequently, Continental has chosen 33 kt as a crosswind limit for all of its B-737 models.

Another potential shortcoming with Continental's crosswind operations is that the 40 kt crosswind provided by Boeing to operators as guidance for the B-737 is based on analysis using a steady-state wind only. It too does not include gusts or account for dynamics with a pilot-in-the-loop. As can be seen by all of the wind profiles extracted for the accident, none are steady in nature.

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[10] "Analysis of the Simulation of Wind Effects Continental Airlines B-737-500 FFS", July 2009.

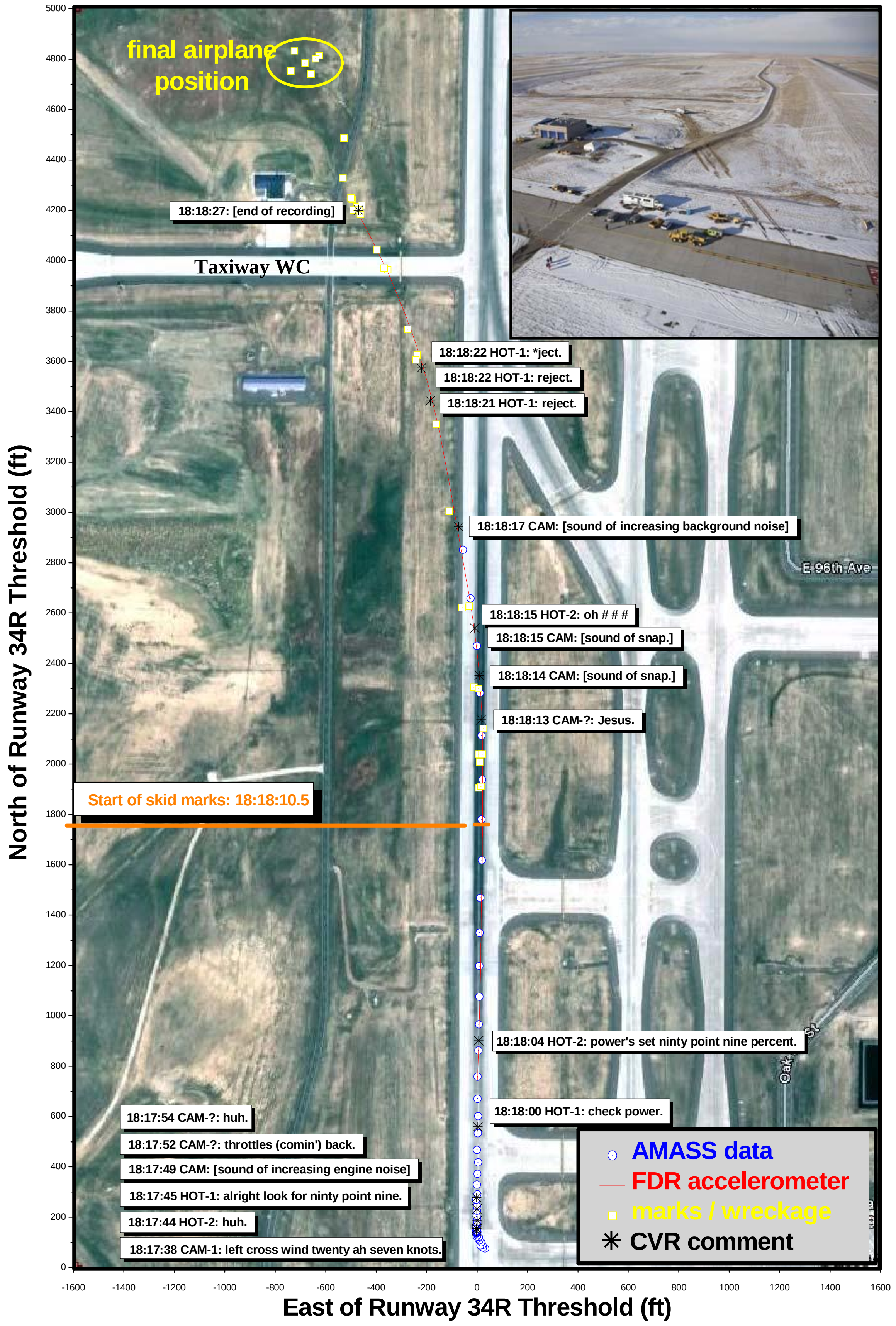

Figure 1: Accident Scene Overlay Including Ground Path and CVR Comments

Figure 2a: Gear and Engine Nacelle Tracks Appear North of Taxiway WC

Figure 2b: Looking South at Drop-Off North of Taxiway WC

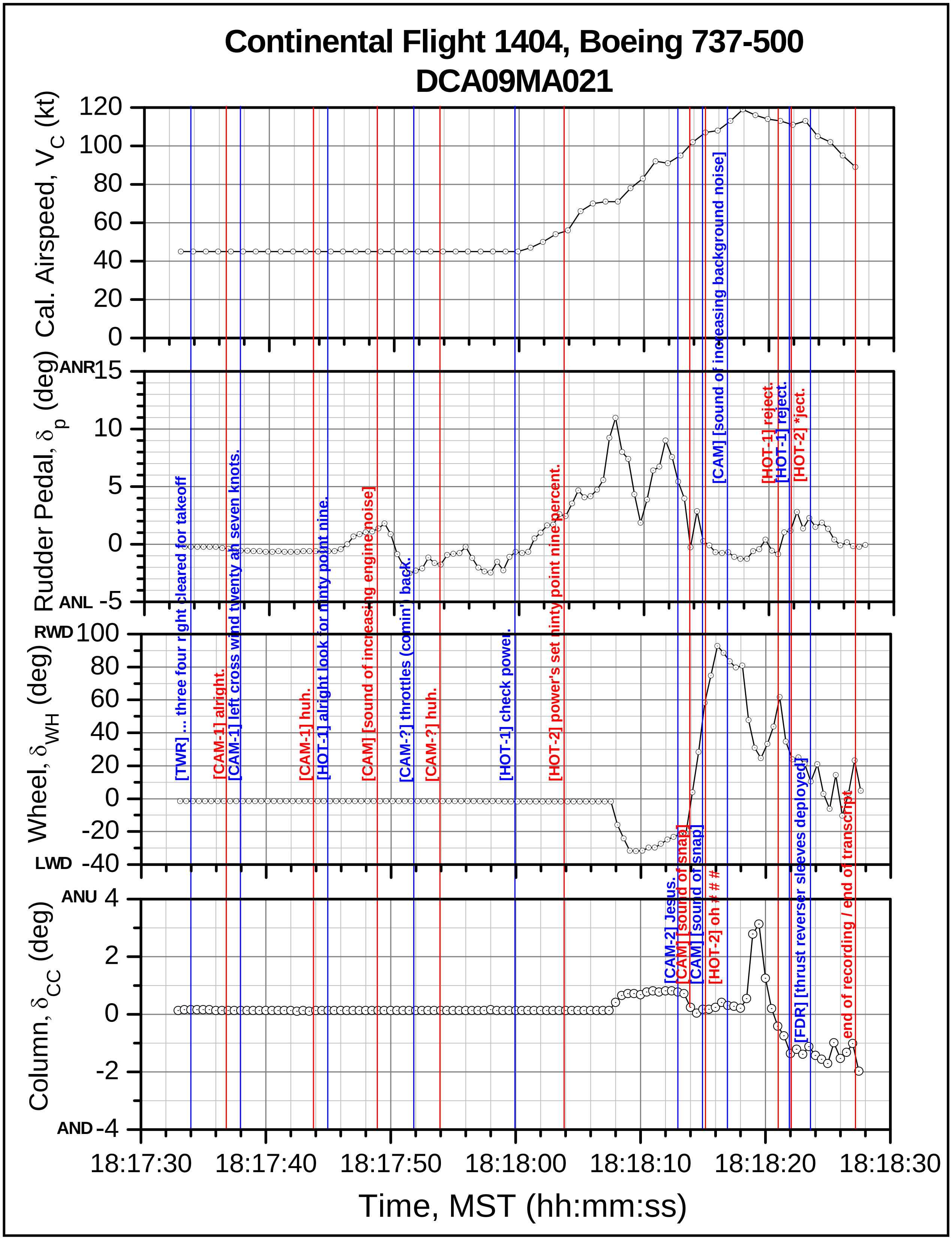

Figure 3: Pilot Inputs

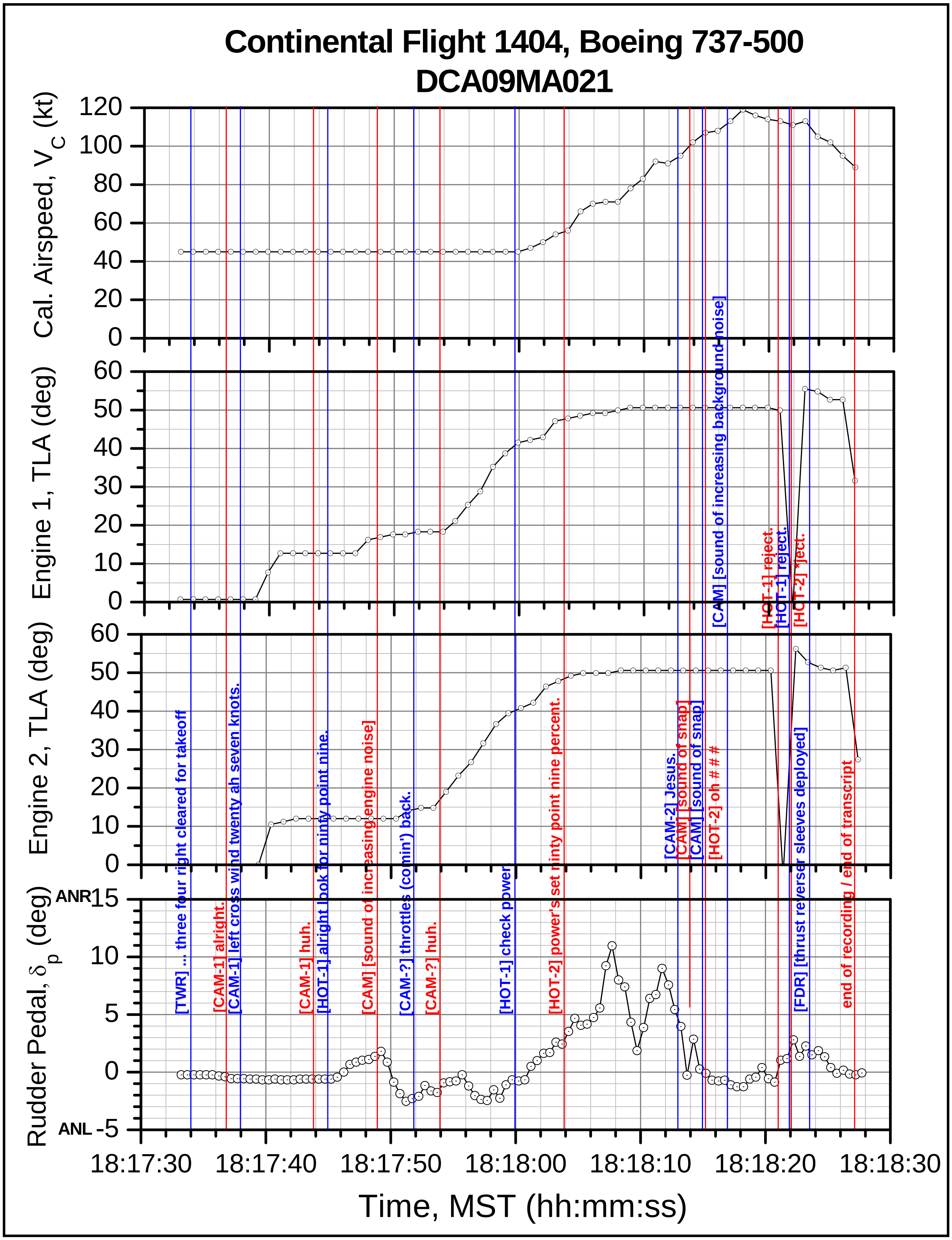

Figure 4: Engine Operation

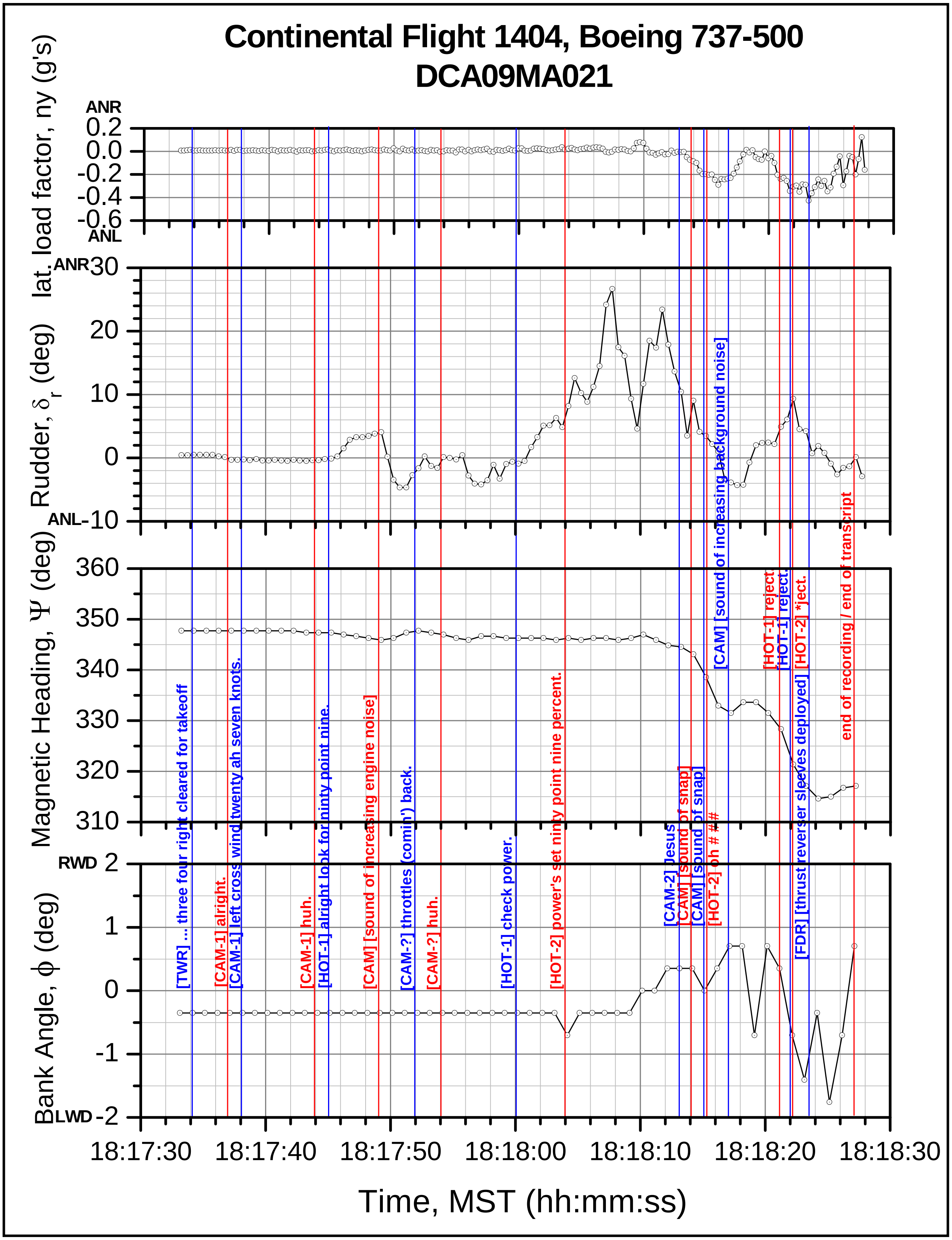

Figure 5: Magnetic Heading

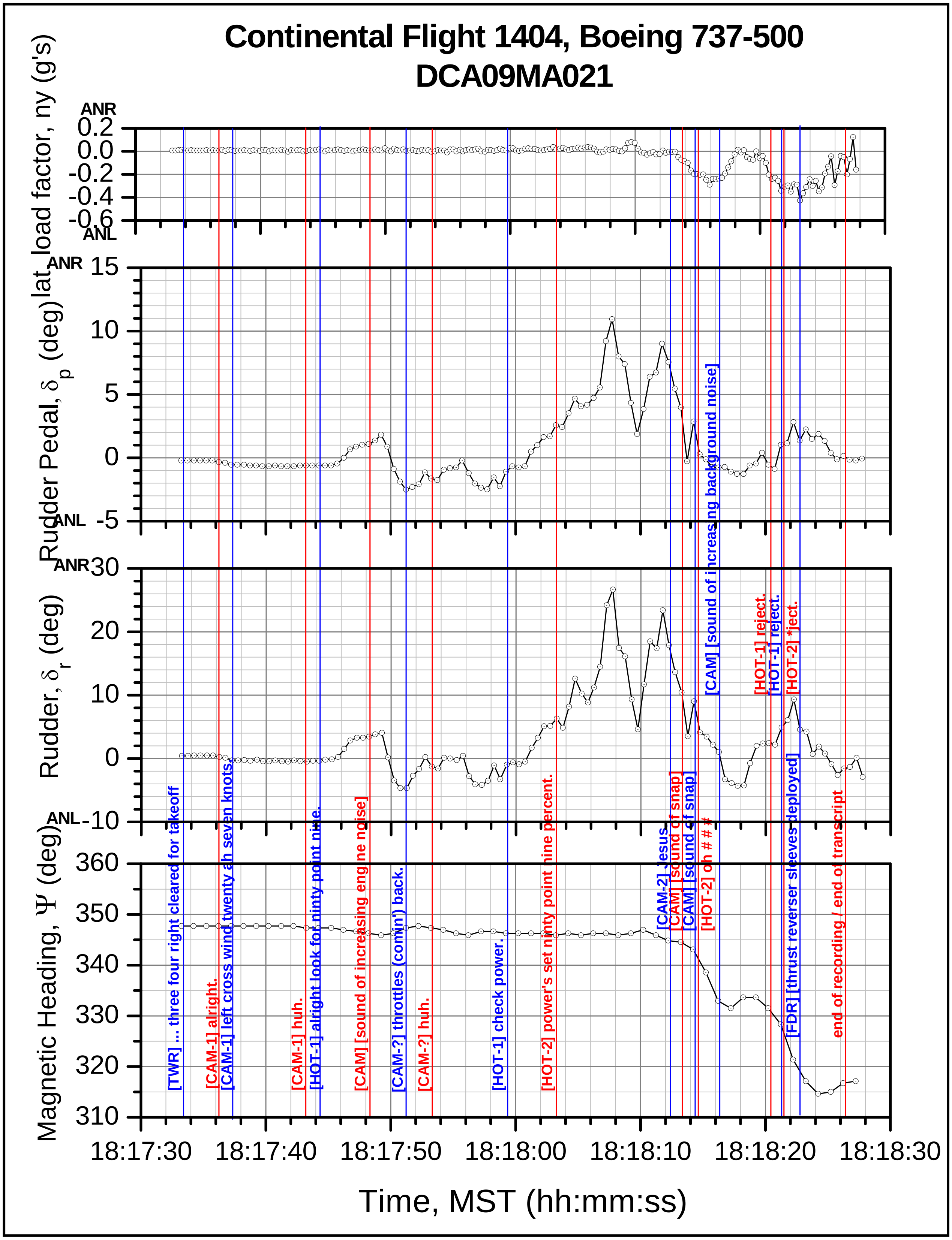

Figure 6: Yaw Continuity

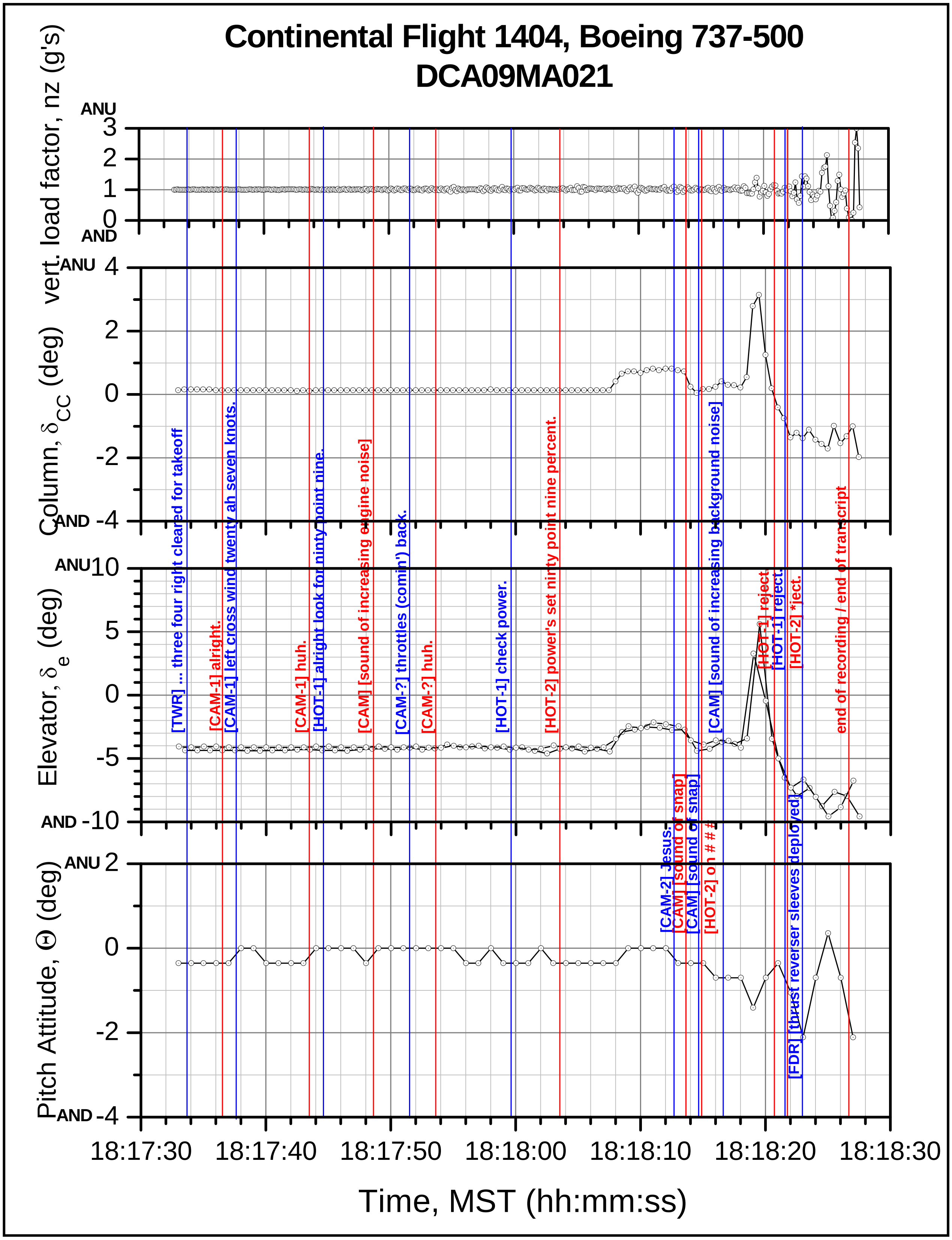

Figure 7: Pitch Continuity

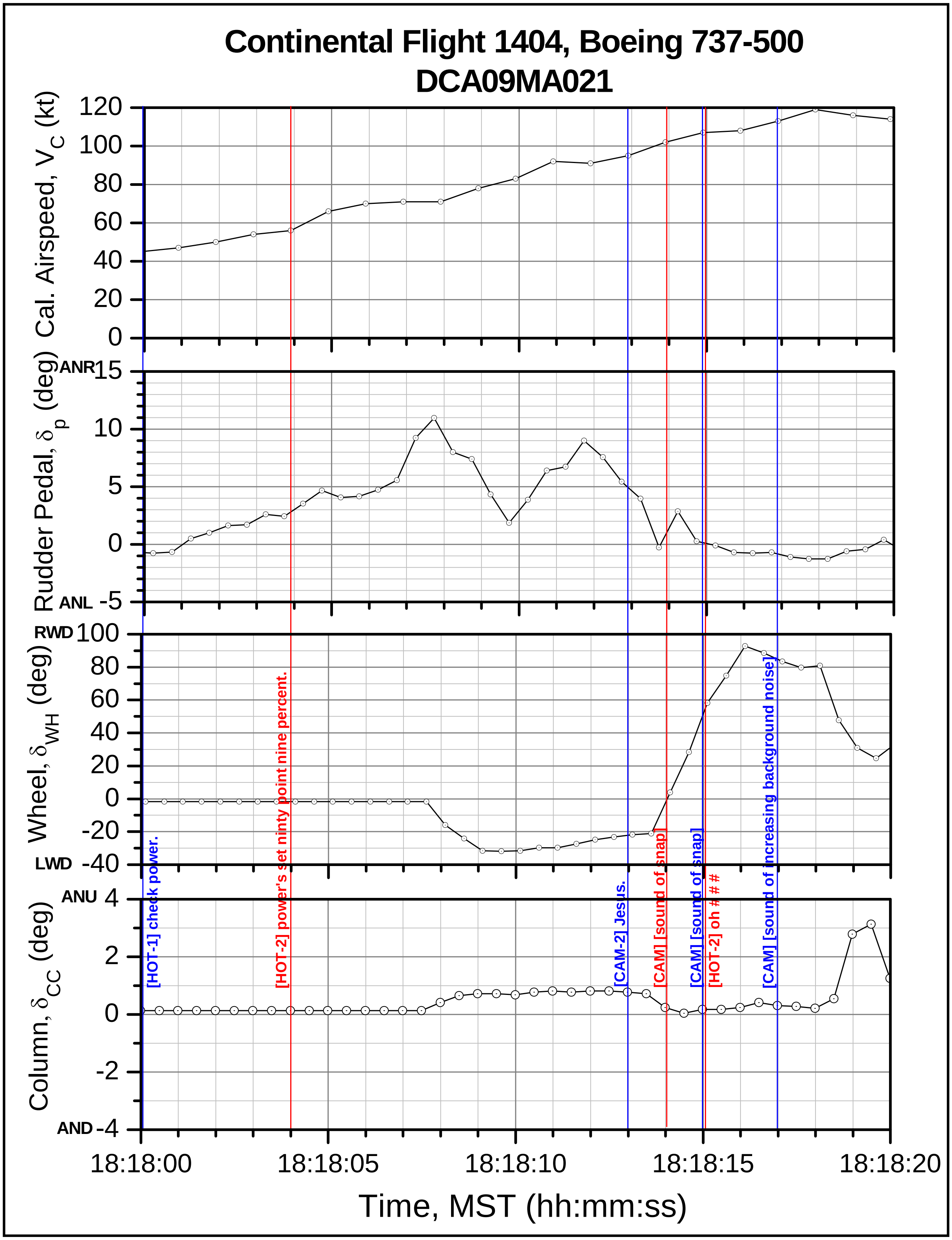

Figure 8: Pilot Inputs Around Excursion

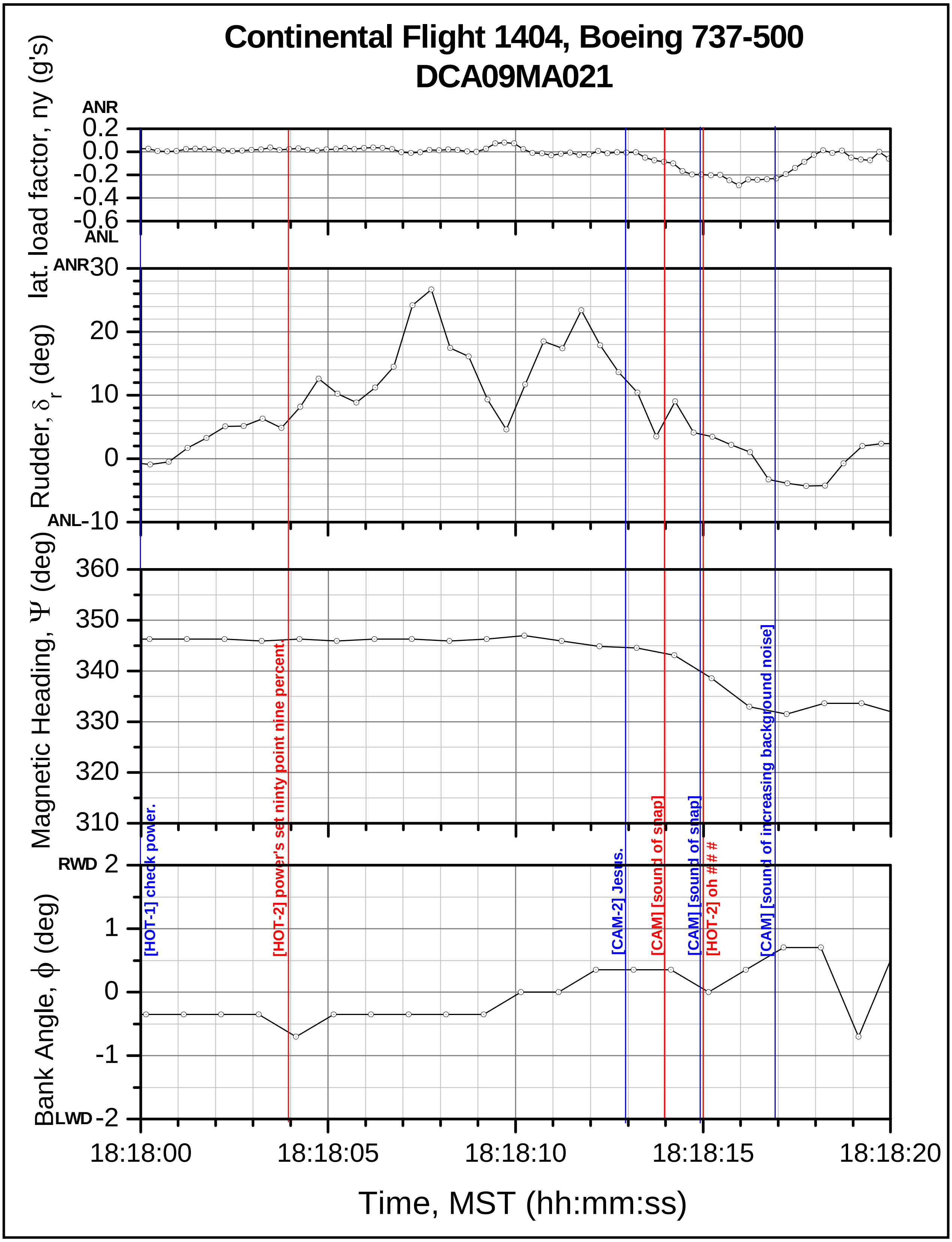

Figure 9: Magnetic Heading Around Excursion

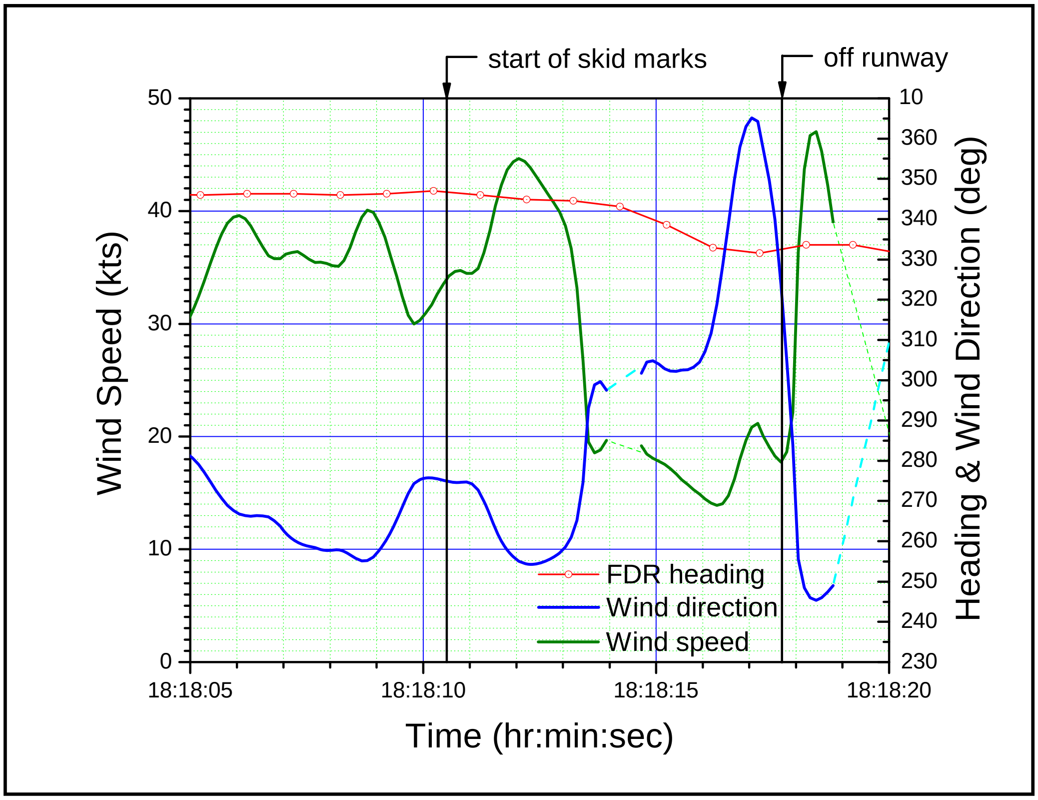

Figure 10: NTSB Extracted Wind Speed and Absolute Direction

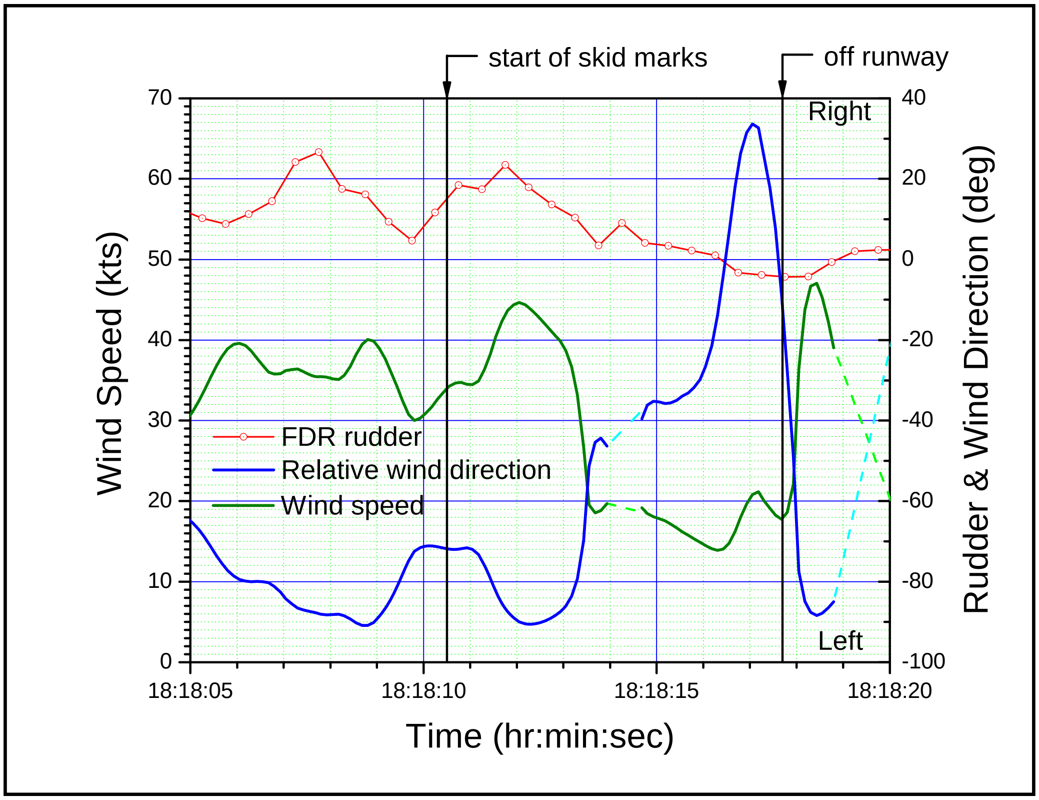

Figure 11: NTSB Extracted Wind Speed and Relative Direction

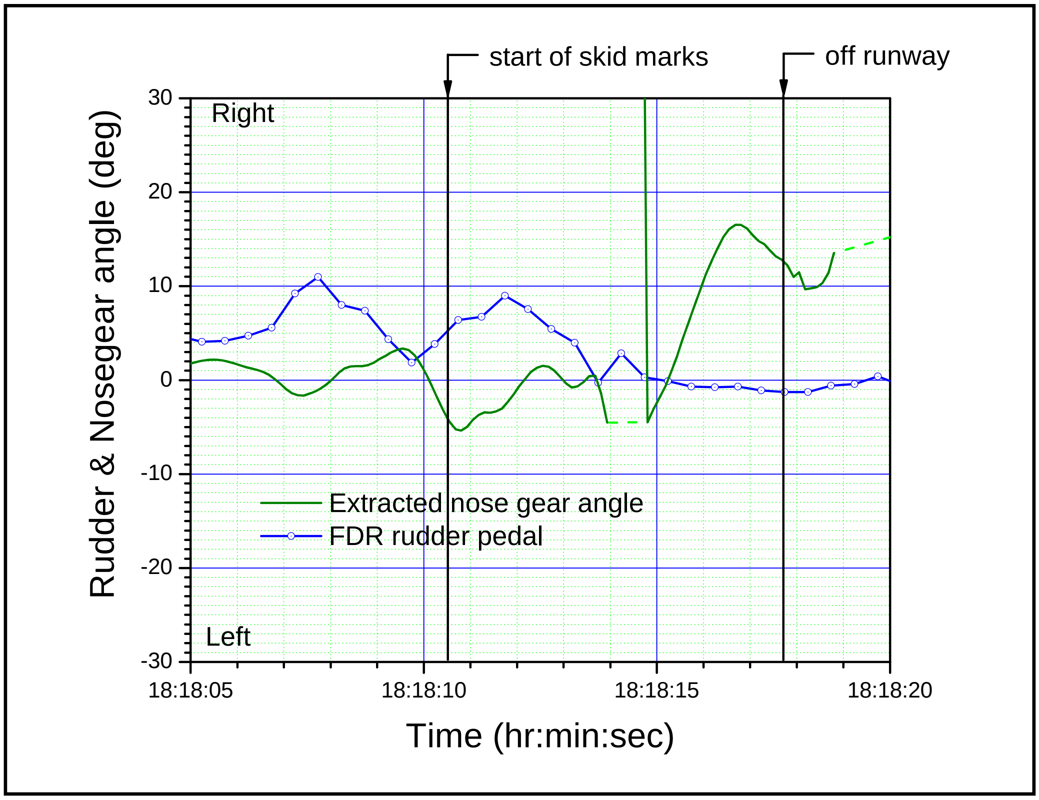

Figure 12: NTSB Extracted Nose Wheel Steering Angle

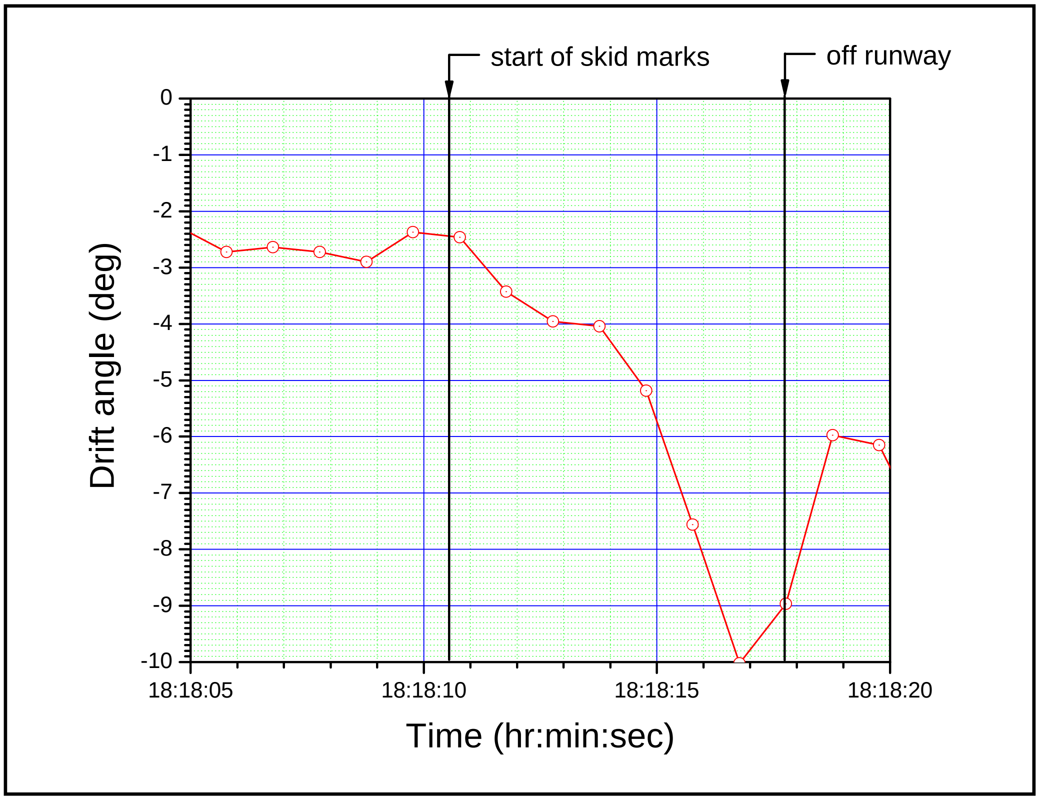

Figure 13: FDR Drift Angle = ground track - heading

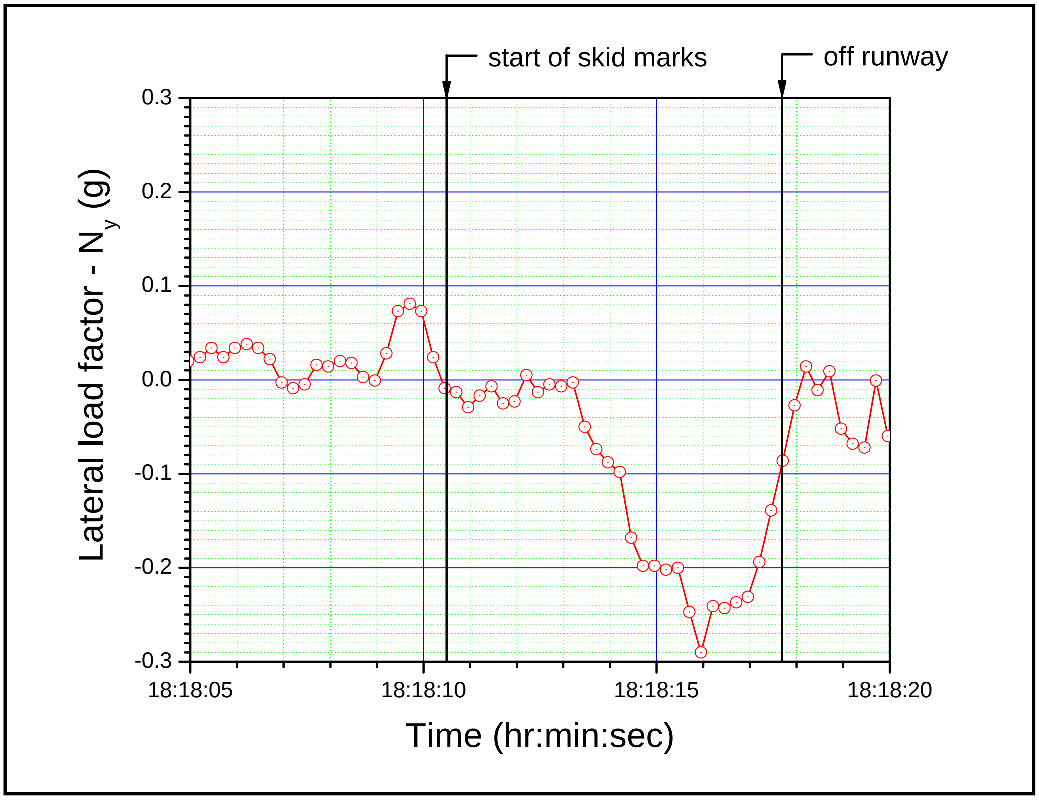

Figure 14: FDR Lateral Load Factor

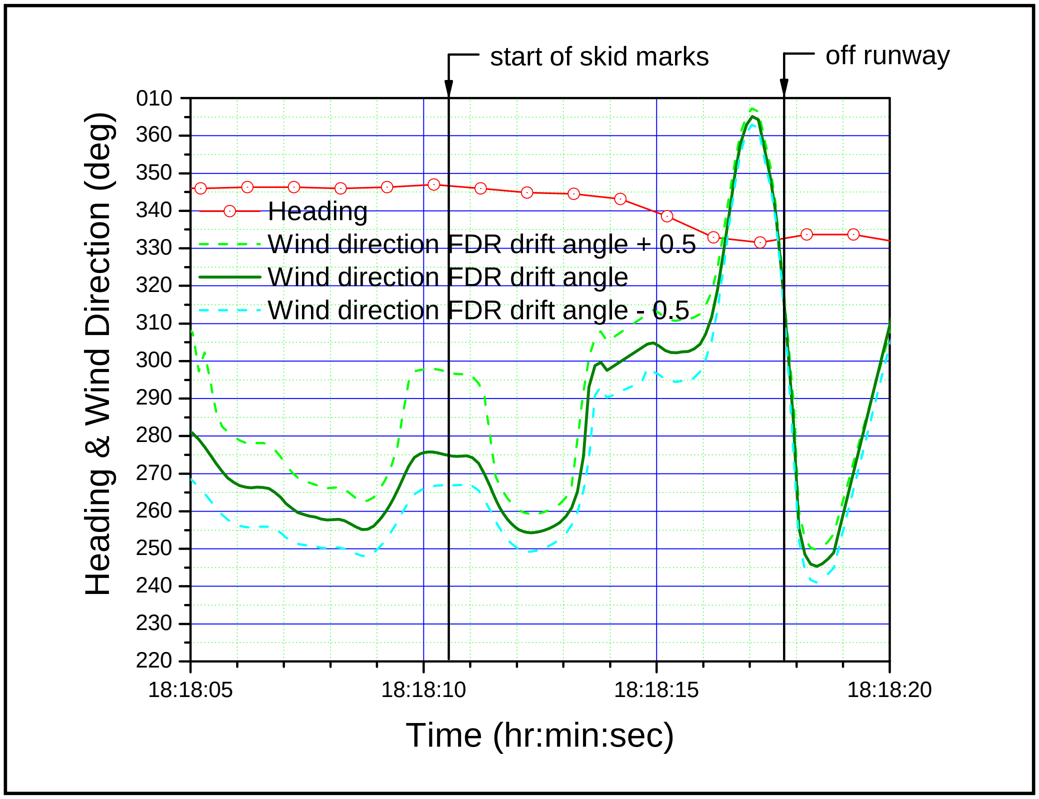

Figure 15: Effect of FDR Drift Angle Error on Extracted Wind Direction

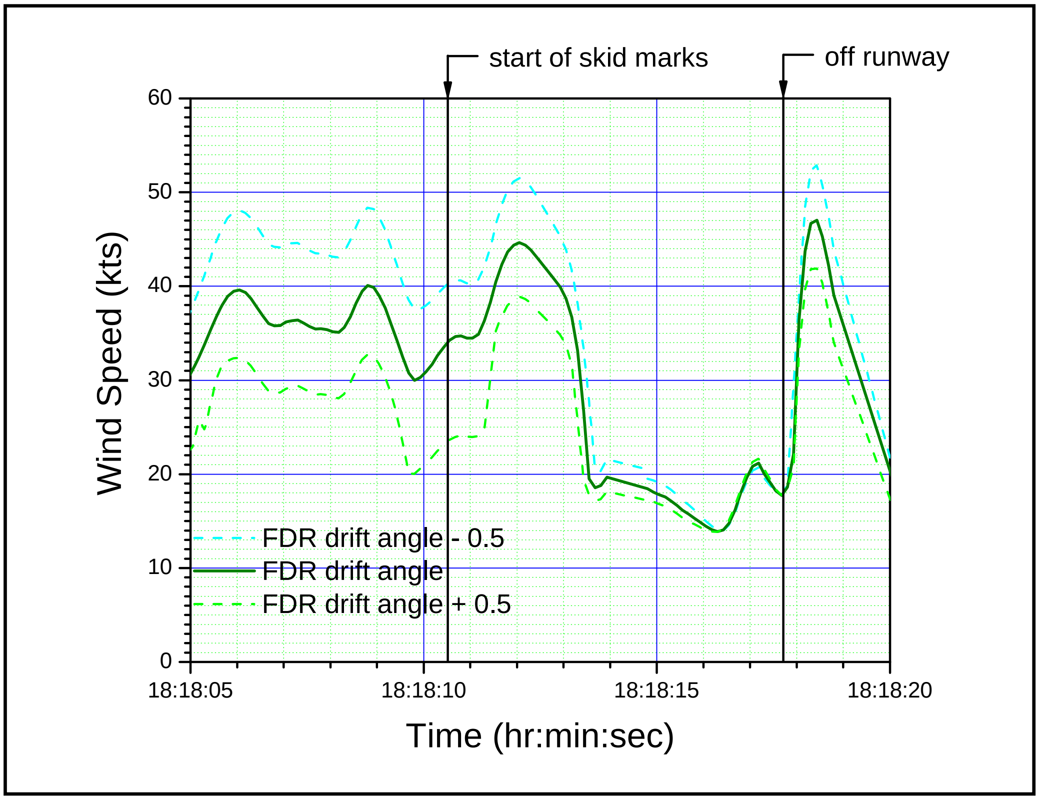

Figure 16: Effect of FDR Drift Angle Error on Extracted Wind Speed

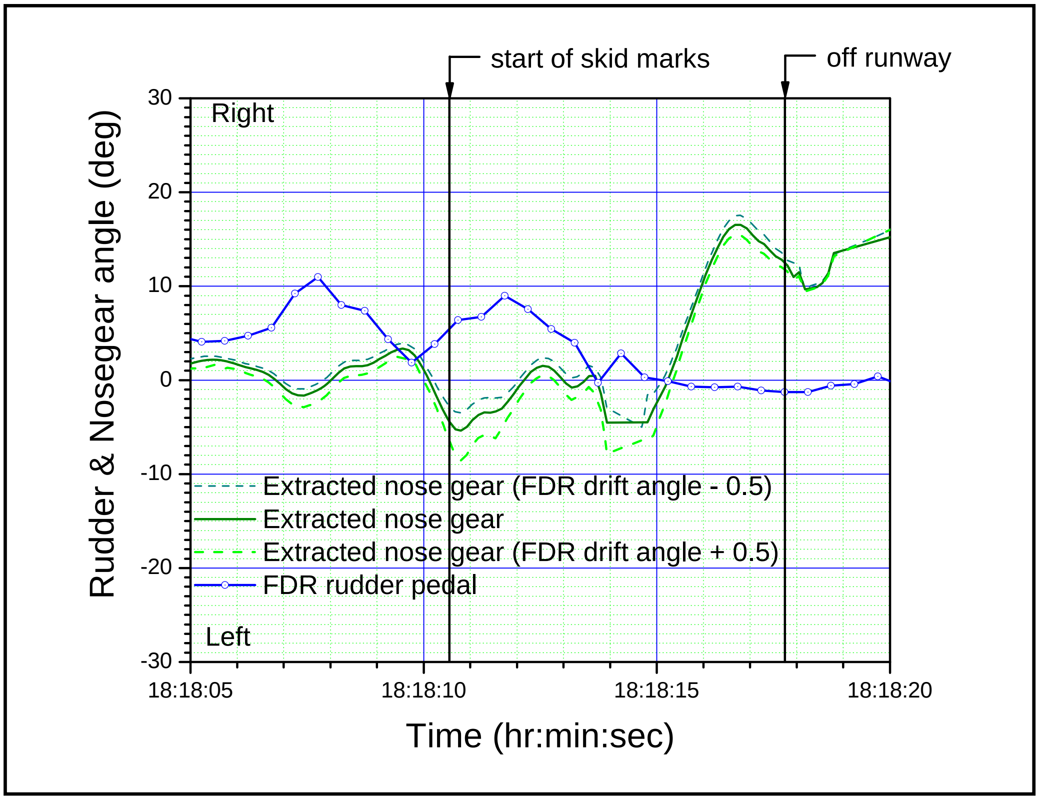

Figure 17: Effect of FDR Drift Angle Error on Extracted Nose Wheel Steering Angle

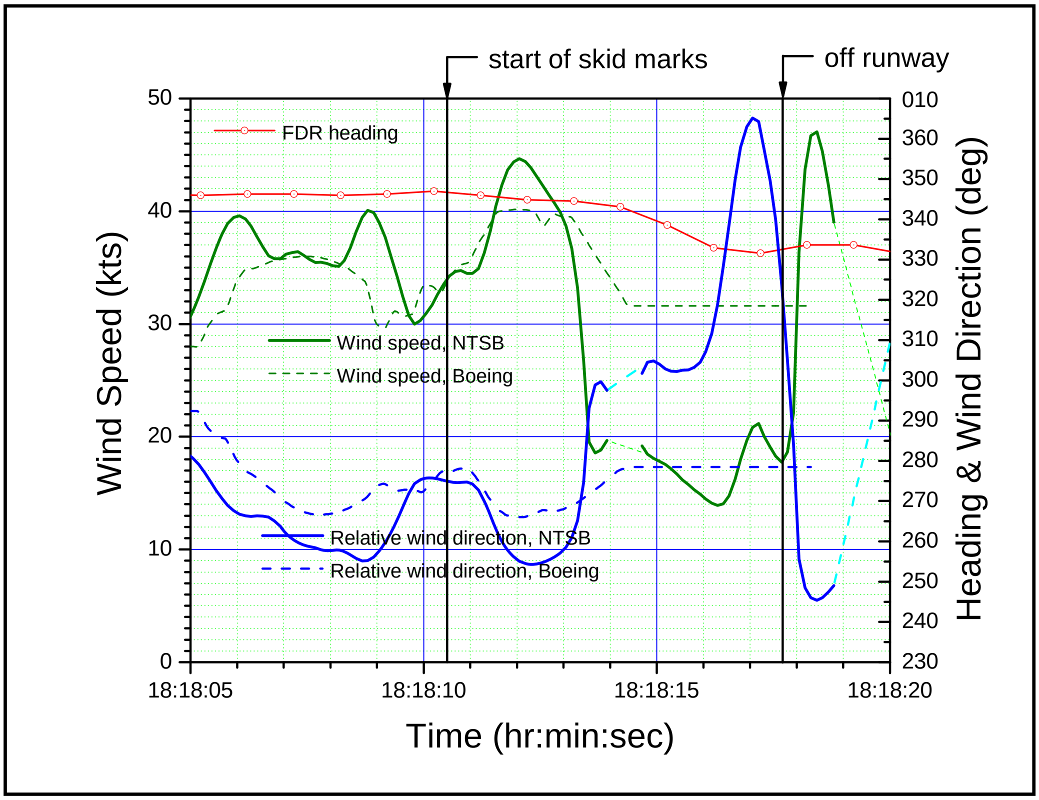

Figure 18: Boeing and NTSB Extracted Wind Speed and Magnetic Direction

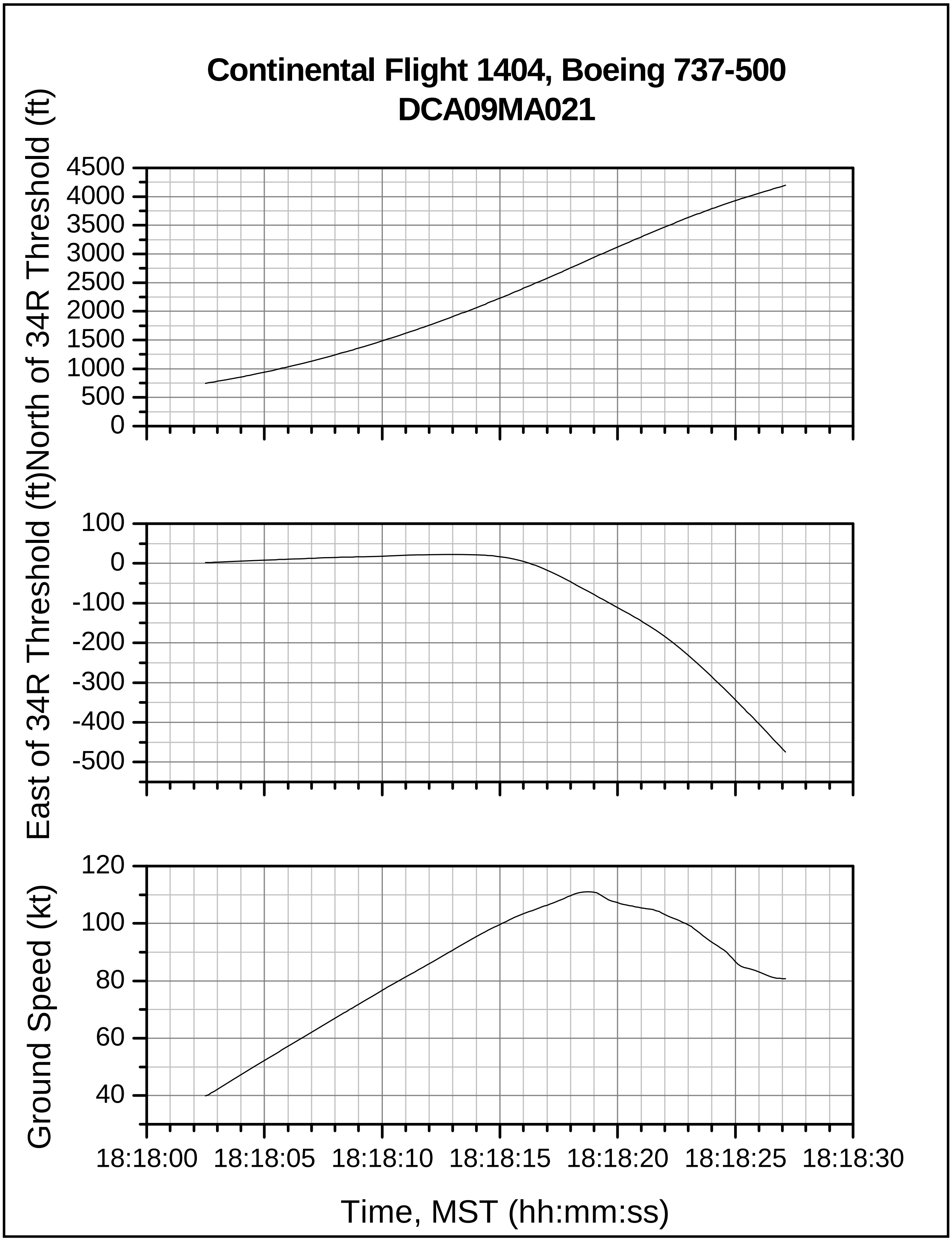

Figure 19: Final Integrated Position and Speed Relative to Runway 34R Threshold