CLOSED-LOOP HIRF EXPERIMENTS PERFORMED ON A FAULT TOLERANT FLIGHT CONTROL COMPUTER

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ABSTRACT

Closed-loop HIRF experiments were performed on a fault tolerant flight control computer (FCC) at the NASA Langley Research Center. The FCC used in the experiments was a quad-redundant flight control computer executing B737 Autoland control laws. The FCC was placed in one of the mode-stirred reverberation chambers in the HIRF Laboratory and interfaced to a computer simulation of the B737 flight dynamics, engines, sensors, actuators, and atmosphere in the Closed-Loop Systems Laboratory. Disturbances to the aircraft associated with wind gusts and turbulence were simulated during tests. Electrical isolation between the FCC under test and the simulation computer was achieved via a fiber optic interface for the analog and discrete signals. Closed-loop operation of the FCC enabled flight dynamics and atmospheric disturbances affecting the aircraft to be represented during tests. Upset was induced in the FCC as a result of exposure to HIRF, and the effect of upset on the simulated flight of the aircraft was observed and recorded. This paper presents a description of these closed-loop HIRF experiments, upset data obtained from the FCC during these experiments, and closed-loop effects on the simulated flight of the aircraft.

INTRODUCTION

Transport aircraft of the future will need to have higher levels of performance in order to improve efficiency, reduce operational costs, and achieve air transportation goals in the next century. Increased performance will be accomplished through advanced design of the airframe configuration (such as wing-body structure, control surface definition, propulsion system, etc.) as well as the flight control system (including control laws, flight control computers, pilot/system interfaces, and all related components). High-level aircraft performance will include advanced requirements for aerodynamics (such as supersonic cruise velocities, high-level maneuverability, etc.), safety and security, environmental compatibility, and affordability. In order to achieve advanced aerodynamic performance, the open-loop stability requirements of future aircraft may have to be drastically reduced, and the airframe itself will be lighter and, hence, more flexible. Thus, in order to achieve desired closed-loop performance and safety of the aircraft, there will be an increased requirement for active controls (such as stability augmentation, gust load alleviation, and flutter suppression). Navigation and air traffic control considerations may also become more automated within the control system to accommodate satellite guided flight in an advanced air traffic management system that could support free flight. Thus, there will be increasing numbers of complex and highly integrated airframe systems. Such systems will be flight-critical, since the flight of the aircraft will depend on reliable operation of these systems.

The problem of verifying the integrity of control computers in adverse, as well as nominal, operating environments is a key issue in the development, validation, certification, and operation of critical control systems for advanced aircraft. An adverse operating environment of particular concern relative to validation and certification of critical systems is caused by electromagnetic disturbances. Sources of electromagnetic disturbances include lightning, High Intensity Radiated Fields (HIRF) caused by RF transmitters and radars, personal electronic devices carried onto the airplane, and electromagnetic incompatibilities of equipment installed on the aircraft. These threats can cause common mode errors or upsets in critical systems whose fault tolerance is achieved through redundancy.

The current state-of-the-art in electromagnetic environment (EME) effects testing is to perform full-scale aircraft testing as well as laboratory tests on aircraft computers. Full-aircraft tests are performed with the aircraft situated on the ground and equipment powered on during exposure to electromagnetic energy. These tests are extremely expensive to perform and, since they are static, do not provide a means of validating system performance over the operating envelope required for flight. Current laboratory test methods for EME susceptibility of avionics equipment primarily consider the use of a GTEM test cell or an anechoic chamber. The disadvantage of this approach is that the equipment is tested at very few angles of incidence relative to the impinging field. Therefore, worst case conditions may not be represented during tests. In addition, these laboratory tests are primarily open-loop and static at a few operating points over the performance envelope of the equipment and do not consider system level effects. Therefore, current test methods (full-aircraft and laboratory tests) do not provide a means of validating system performance over the operating envelope required for flight, and do not reflect operation in adverse flight conditions such as clear air turbulence or wind shear.

A process is currently under development at the NASA Langley Research Center that provides a comprehensive systems level assessment approach for evaluating the effects of electromagnetic disturbances on critical control computers [1]. The motivation for the assessment process is to provide a guideline for certification compliance demonstrations of complex and highly integrated critical systems to requirements for operation in EME, such as lightning and HIRF [2] - [3], and to requirements for fault containment that would ensure continued safe flight and landing of the aircraft [4] - [7]. The assessment process is a combination of analysis, simulation, and tests. This process is comprehensive because it addresses the following issues: (i) closed-loop operation of the controller under test, (ii) real-time dynamic detection of controller malfunctions that occur due to the effects of electromagnetic disturbances caused by lightning, HIRF, and electromagnetic interference and incompatibilities, and (iii) airframe systems effects relative to the stage of flight, flight conditions, and required operational performance.

Experiments to demonstrate this process and collect data to characterize upset modes are performed on flight critical control computers in the HIRF Laboratory and the Closed-Loop Systems Laboratory at NASA Langley. The HIRF Laboratory consists of 3 Mode-Stirred Chambers and 1 GTEM Test Chamber [8]. The advantage to performing tests in Mode-Stirred Chambers is that the equipment is subjected to fields at all angles of incidence simultaneously, so that worst case conditions are represented during testing. Having 3 mode-stirred chambers enables testing of distributed systems. Through the development of distributed Mode-Stirred Chamber test techniques in the HIRF Laboratory, state-of-the-art methods for EME testing will be improved.

The Closed-Loop Systems Laboratory consists of a flight simulation computer, a real-time monitoring system, data acquisition computers, and a bulk cable injection test station. The flight simulation computer simulates aircraft dynamics, engines, sensors, actuators, and atmosphere (including winds, gusts, and turbulence). One testbed that is used in this research is a military flight control computer. During testing, the flight control computer is placed inside one of the mode-stirred chambers of the HIRF Lab and is interfaced to the flight simulation computer in the Closed-Loop Systems Lab. Electrical isolation is achieved via fiber optic interfaces for the analog signals, discrete signals, and 1553 data bus. Closed-loop test methods are part of the assessment process currently under development at NASA Langley to provide a comprehensive systems level assessment approach for evaluating the effects of electromagnetic disturbances on flight critical control computers for advanced future aircraft. This represents a significant improvement to the state-of-the-art in electromagnetic effects testing methods.

This paper reports on the initial series of closed-loop HIRF experiments performed on a fault tolerant flight control computer. Section 2 describes the experiments. Section 3 presents some representative data collected during these experiments. Concluding comments are presented in Section 4.

EXPERIMENT DESCRIPTION

The objective of the HIRF experiments was to collect as much closed-loop upset data as possible under several varying conditions for research purposes. Data collected will form the basis of a comprehensive data base for characterizing upset phenomena in aircraft control computers, and in the mathematical modeling required for the design of upset detection and accommodation algorithms. The equipment under test was an RF-hardened military quad-redundant flight control computer (FCC). The FCC was programmed to execute B737 Autoland control laws, placed inside a mode-stirred test chamber in the HIRF Lab as shown in Figure 1, and interfaced to a B737 Autoland flight simulation in the Closed-Loop Systems Lab, shown in Figure 2. The B737 simulation includes the aircraft, engines, sensors, actuators, and atmosphere. The equations of motion in the simulation used in these experiments were based on linear models of the aircraft dynamics. Electrical isolation between the FCC and the flight simulation computer was achieved through fiber optic signal conversions.

The frequency and power level of the EM field generated in the test chamber was 550 MHz and approximately 575 V/m, respectively. In order to meet the objective of the experiments, it was necessary to have the ability to consistently induce upset in the controller at a relatively low power level. Therefore, the signal filters of the controller were removed during testing. It should be stressed that these experiments were performed to collect upset data for a research program, and were not performed to evaluate the susceptibility of the controller to HIRF. The FCC with its signal filters removed was determined to be vulnerable to upset at this frequency and power level during initial open-loop experiments [9]. Each Autoland flight constituted a separate test, and a total of 150 flights were conducted. Conditions that varied were wind turbulence and duration of HIRF exposure.

The 150 flights were conducted in three groups of 50. The values of approximately 200 parameters were stored at each data frame during each simulated flight. For each group, the FCC received HIRF exposure for 10 seconds in 25 of the flights, and for 180 seconds in the remaining 25 flights. During the first group of 50 Autoland flights, the aircraft was not subjected to winds or gusts. Figure 3 shows plots of 6 parameters for the no wind case with the nominal condition of no HIRF exposure. Plot (a) is the altitude of the aircraft in feet versus its horizontal distance in feet from the runway. The aircraft position is initialized at an altitude of approximately 1500 feet and a horizontal distance from the glideslope of approximately 8000 feet. In this landing simulation, the aircraft flies straight and level to the glideslope, engages the glideslope, tracks the glideslope, and flares. In simulations with lateral winds, crab and decrab maneuvers are also included. The simulation ends with the aircraft approximately 10 feet above the runway, and does not include touchdown or weight on wheels. The location of the lines around the glideslope are fixed for all plots and shown to facilitate comparison of flight path from plot to plot. Plot (b) is the lateral displacement of the aircraft in feet from the glideslope versus horizontal distance in feet from the runway. Plot (c) is the voted throttle command in degrees versus the horizontal displacement of the aircraft in feet from the runway. Plots (d) - (f) are the pitch, roll, and yaw of the aircraft in degrees versus the horizontal distance in feet from the runway. All plots in this paper follow this format.

During the second group of 50 flights, the aircraft was subjected to heavy clear air turbulence that occurred identically in each flight. Figure 4 shows 6 plots of the repeatable clear air turbulence case for the nominal condition of no HIRF exposure. These 6 plots are directly analogous to plots in Figure 3.

In the final group of 50 flights, the aircraft was subjected to heavy clear air turbulence that occurred pseudo-randomly in each flight. Figure 5 shows 6 plots of a typical example of the pseudo-random clear air turbulence case for the nominal condition of no HIRF exposure.

CLOSED-LOOP HIRF DATA

A series of closed-loop HIRF experiments were performed on a quad-redundant flight control computer as described in Section 2. Conditions that varied in these experiments were wind turbulence and duration of HIRF exposure. The occurrence of upset was very repeatable at the frequency and power level used, and with the line filters removed from the input/output connectors of the controller. However, the manifestation of HIRF effects on the controller were not the same for each flight per test case. Reasons for this include: (1) the initiation/termination of the HIRF excitation was not synchronized with the controller; (2) observed effects depend on the number of channels affected in the quad-redundant controller. Data from 1 flight for each test case is shown.

No Wind Case

During the first group of 50 Autoland flights, the aircraft was not subjected to winds or gusts. The varying parameter was the duration of the HIRF exposure.

Finite Duration HIRF Exposure In this group of experiments, the FCC received HIRF exposure for 10 seconds in each of 25 flights. The 10 second exposure began approximately when the glideslope was being engaged, but was not synchronized with the flight. Figure 6 shows data plots of a flight with no winds and 10 second HIRF exposure. The disturbance to the throttle command caused by the field is evident in plot (c) by the noisy data that occurred between approximately 30000 and 28000 feet from the runway. Lateral displacement from the runway occurs from about 29000 to 26000 ft. from the runway, but settles out once the HIRF is removed. This indicates that the lateral control system was not permanently affected (i.e., upset) for the duration of the flight. However, plot (d) indicates that pitch control of the longitudinal control system was upset for the duration of the flight. This is evident by the continual increase in the pitch of the aircraft, even after the field was turned off. At approximately 14000 feet from the runway, the pitch of the aircraft reached 30 degrees. In the simulation used for these tests, execution ends if the pitch of the aircraft exceeds +30 or -15 degrees.

Continuous HIRF Exposure In this group of experiments, the FCC received HIRF exposure for approximately 120-160 seconds in each of 25 flights. This represented essentially continuous exposure once the glideslope had been engaged. Figure 7 shows data plots of a flight for the no winds case with continuous HIRF exposure. Again, the disturbance is evident in the throttle command shown in plot (c). It can also be seen in plot (c) that the throttle command essentially remained fixed at about 30 degrees for the duration of the flight, which is incorrect. Plot (b) shows that the aircraft was displaced to the right of the correct flight path for the duration of the flight, sometimes by as much as 50 feet. At the end of the flight, during the flare maneuver, the aircraft should pitch up and the throttle should be decreased so that descent continues. For this flight, an extreme pitch up occurs, as seen in plot (d). Since the throttle command was fixed, as shown in plot (c), the aircraft does not continue its descent, but essentially takes off as shown in plot (a) at approximately 1000 feet from the runway. The roll and yaw of the aircraft, shown in plots (e) and (f), show some relatively minor disturbances.

Repeatable Clear Air Turbulence Case

During the second group of 50 Autoland flights, the aircraft was subjected to heavy clear air turbulence that occurred identically in each flight. Wind occurred at a 45 degrees northeast direction, with a speed of 20 knots and gusts of 6 ft/s. Repeatability was accomplished by reseeding the random number generators used in the wind and gust models with the same number at the beginning of each flight. Therefore, the varying parameter for this group of experiments was again the duration of the HIRF exposure.

Finite Duration HIRF Exposure In this group of experiments, the FCC received HIRF exposure for 10 seconds in each of 25 flights. The 10 second exposure occurred once the glideslope had been engaged. Figure 8 shows data plots of a flight for the case of repeatable clear air turbulence with 10 second HIRF exposure. Plot (a) shows that the aircraft successfully tracked the glideslope, but did not correctly flare and end up at approximately 10 feet above ground as seen in plot (a) of Figure 4. Plot (b) of Figure 8 shows that the aircraft is displaced to the right of the runway by approximately 40 feet at the end of the flight. Plot (c) shows that the throttle command was essentially fixed for the duration of the flight, even after the HIRF exposure ended. The throttle command was also not diminished, as it should have been, during flare. Plot (d) shows that the pitch of the aircraft was more negative than what would occur nominally, as seen in Figure 4, plot (d). Since the pitch of the aircraft was not positive during flare, the constant throttle did not cause the aircraft to take off as seen in Figure 7 plot (a). However, the aircraft overshot the point at which it should have had an altitude of 10 feet. The roll and yaw of the aircraft shown in plots (e) and (f) do not show any remarkable deviations.

Continuous HIRF Exposure In this group of experiments, the FCC received HIRF exposure for 120 - 160 seconds in each of 25 flights. This represented essentially continuous exposure once the glideslope had been engaged. Figure 9 shows data plots of a flight for the case of repeatable clear air turbulence with continuous HIRF exposure. Plot (c) shows that the throttle command was incorrectly fixed for the duration of the flight, once the HIRF exposure was initiated. Plots (a), (b), (d), (e), and (f) all show catastrophic deviation from the flight path and normal aircraft attitude that occurred once flare was initiated. Plot (d) shows an abnormally high increase in pitch at approximately 1000 ft. from the runway. Since the throttle command did not decrease, as it should have during flare, the aircraft flew up from the correct flight path, as shown in plot (a). At this point, plot (b) shows that the aircraft was displaced in excess of 50 ft. to the right of the runway. The negative yaw initiating in plot (f) at about 2000 ft. from the runway indicates an attempt by the controller to correct for the lateral displacement, but as seen in plots (b) and (f) an over-correction occurs. Plot (e) shows that at about this time, the aircraft also started to roll abnormally. In plot (d), the pitch of the aircraft decreases extremely sharply at the runway, causing the aircraft to decrease in altitude, as shown in plot (a). The simulation stops when the lower pitch limit of -15 degrees is reached. At this point, the aircraft is more than 40 ft. to the left of the runway, and has a negative pitch, roll, and yaw that caused it to move in a backward direction as shown in plot (a).

Pseudo-Random Clear Air Turbulence Case

During the third group of 50 Autoland flights, the aircraft was subjected to heavy clear air turbulence that occurred pseudo-randomly in each flight. Wind occurred at a 45 degrees northeast direction, with a speed of 20 knots and gusts of 6 ft/s. Pseudo-random occurrence of the turbulence was achieved by reseeding the random number generators used in the wind and gust models with a different number at the beginning of each flight. Therefore, the varying parameters for this group of experiments were wind conditions and the duration of the HIRF exposure.

Finite Duration HIRF Exposure In this group of experiments, the FCC received HIRF exposure for 10 seconds in each of 25 flights. The 10 second exposure occurred once the glideslope had been engaged. Figure 10 shows data plots of a flight for the case of pseudo-random turbulence and 10 s. HIRF exposure. This flight is similar to the flight of Figure 6. In this flight, the pitch shown in plot (d) continues to increase, even after the HIRF exposure ends. The simulation stops once the pitch reaches the 30 degree limit. At this point, the aircraft is displaced to the left of the runway by approximately 20 ft., as shown in plot (b). The roll and yaw of the aircraft, shown in plots (e) and (f), do not show remarkable deviation from the nominal case shown in Figure 5.

Continuous HIRF Exposure In this group of experiments, the FCC received HIRF exposure for 120-160 seconds in each of 25 flights. This represented essentially continuous exposure once the glideslope had been engaged. Figure 11 shows data plots of a flight for the case of pseudo-random turbulence and continuous HIRF exposure. Plot (b) shows that the aircraft was displaced to the right of the correct flight path from about 31000 to 2000 feet from the runway. At about 1000 feet from the runway, the lateral position had been corrected. Plot (c) shows that the decrease in the throttle command occurred prior to flare at approximately 4000 ft. from the runway. Plot (d) shows that the aircraft pitched excessively during flare, causing the aircraft to fly up off of the correct flight path at approximately 1000 ft, from the runway, as shown in plot (a). At approximately this time, the aircraft began to roll, as shown in plot (e) and its lateral position began deviating to the right of the glideslope as shown in plot (b). At the end of the flight, the aircraft yawed as shown in plot (f), and was displaced to the right of the runway in excess of 50 ft., as shown in plot (b).

COMMENTS AND CONCLUSIONS

A total of 150 Autoland flights were made during a series of closed-loop HIRF experiments performed on a quad-redundant flight control computer (FCC) at the HIRF Laboratory and Closed-Loop Systems Laboratory at the NASA Langley Research Center. The FCC was programmed to execute B737 Autoland control laws, placed inside a mode-stirred chamber, and interfaced to a B737 Autoland flight simulation. The objective of the experiments was to collect as much closed-loop upset data as possible under several varying conditions for research purposes. Conditions that varied were wind turbulence and duration of HIRF exposure. The values of approximately 200 parameters were stored at each data frame during each simulated flight. The occurrence of upset was very repeatable at the frequency and power level used, and with the line filters removed from the input/output connectors of the FCC. However, the manifestation of HIRF effects on the controller were not the same for each flight per test case. Reasons for this include: (1) the initiation and termination of the HIRF excitation was not synchronized with the controller; (2) observed effects depend on the number of channels affected in the quad-redundant controller. The data showed that induced upset in the FCC due to the HIRF exposure did cause the simulated aircraft to deviate catastrophically from the desired flight path. This data is the only known closed-loop HIRF upset data in the US aerospace industry.

Data collected in these initial experiments will form the basis of a comprehensive data base for characterizing upset phenomena in aircraft control computers, and in the mathematical modeling required for the design of upset detection and accommodation algorithms. Future experiments will include a B737 flight simulation based on nonlinear aircraft dynamic models. In addition, experiments with other flight control computers and aircraft simulations, as well as additional hardware in the loop, are planned.

ACKNOWLEDGMENTS

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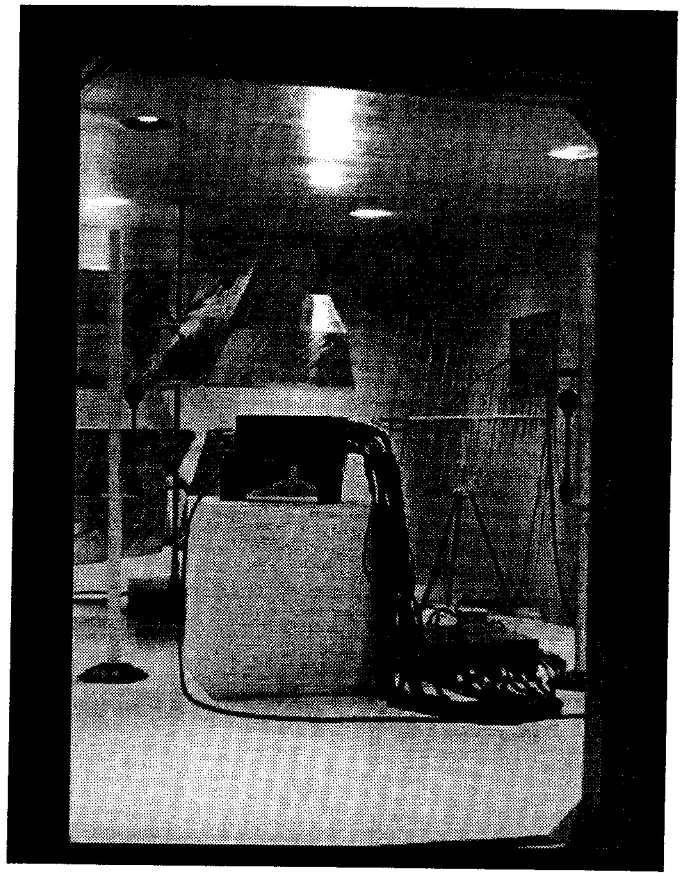

Figure 1: Flight Control Computer in Mode-Stirred Reverberation Chamber

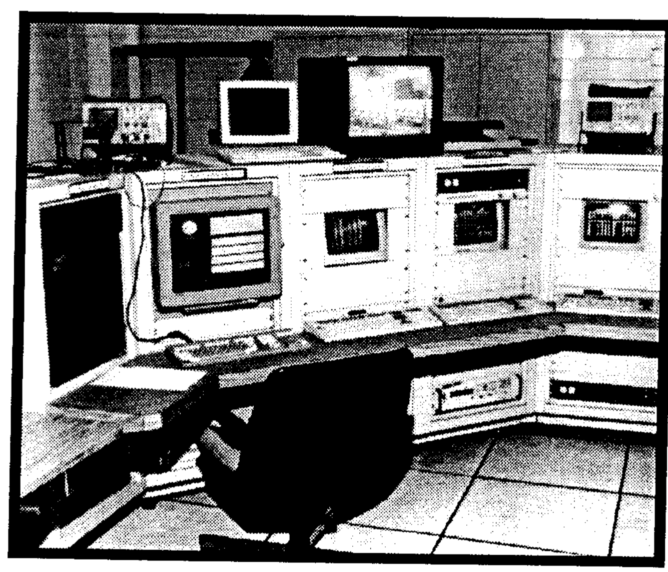

Figure 2: Flight Simulation Computer in the Closed-Loop Systems Lab

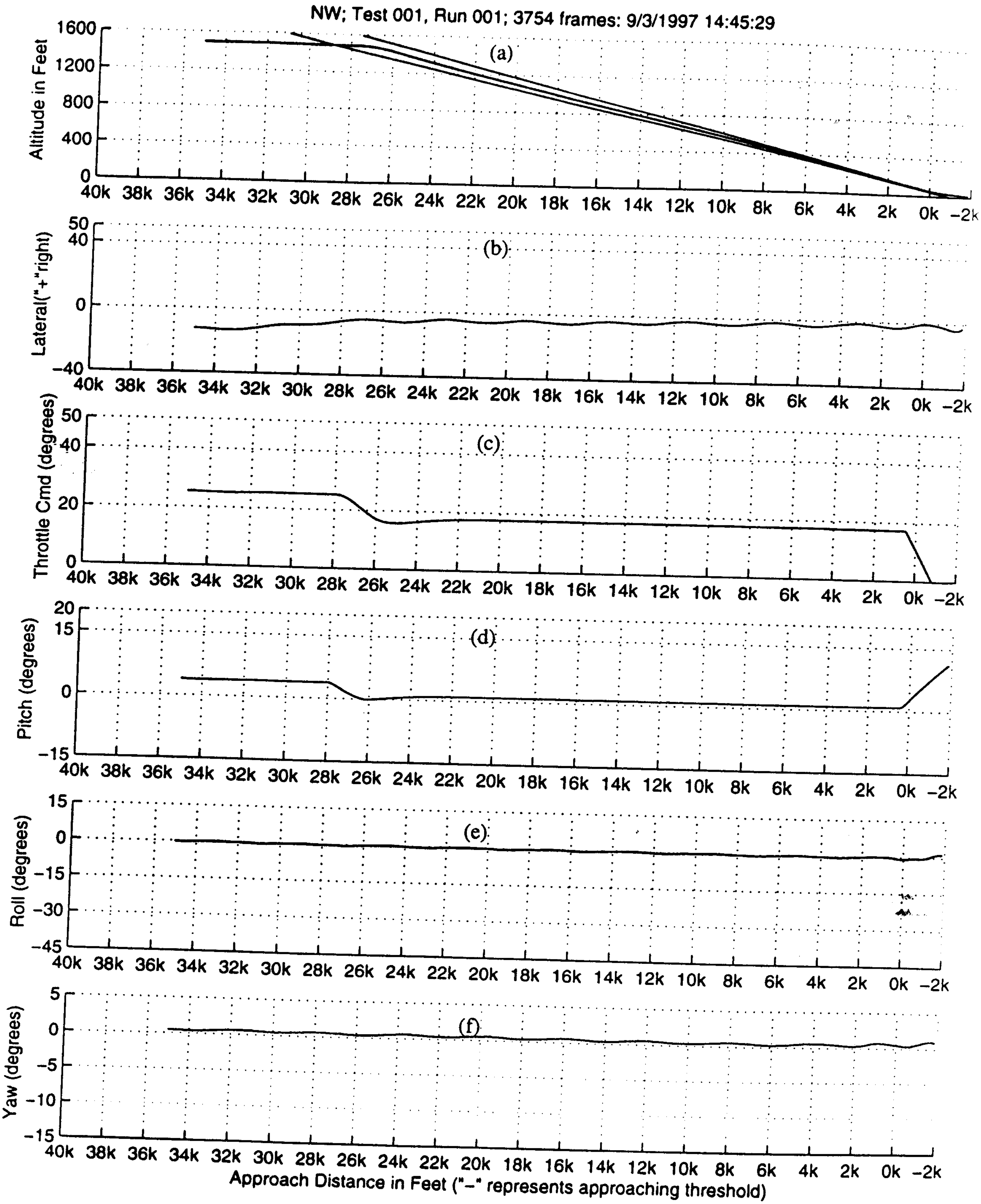

Figure 3: B737 Autoland with No Winds and No HIRF Exposure

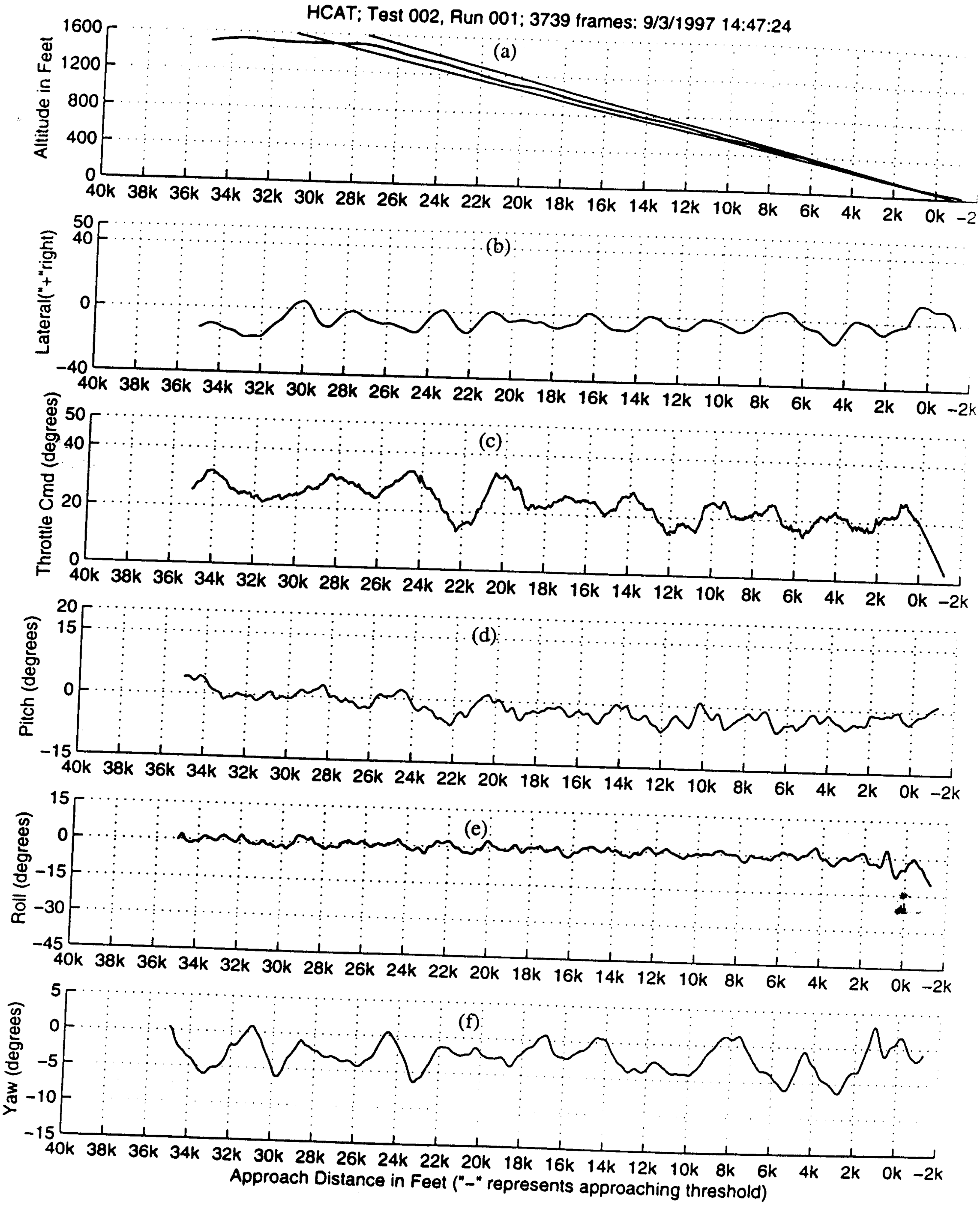

Figure 4: B737 Autoland with Repeatable Turbulence and No HIRF Exposure

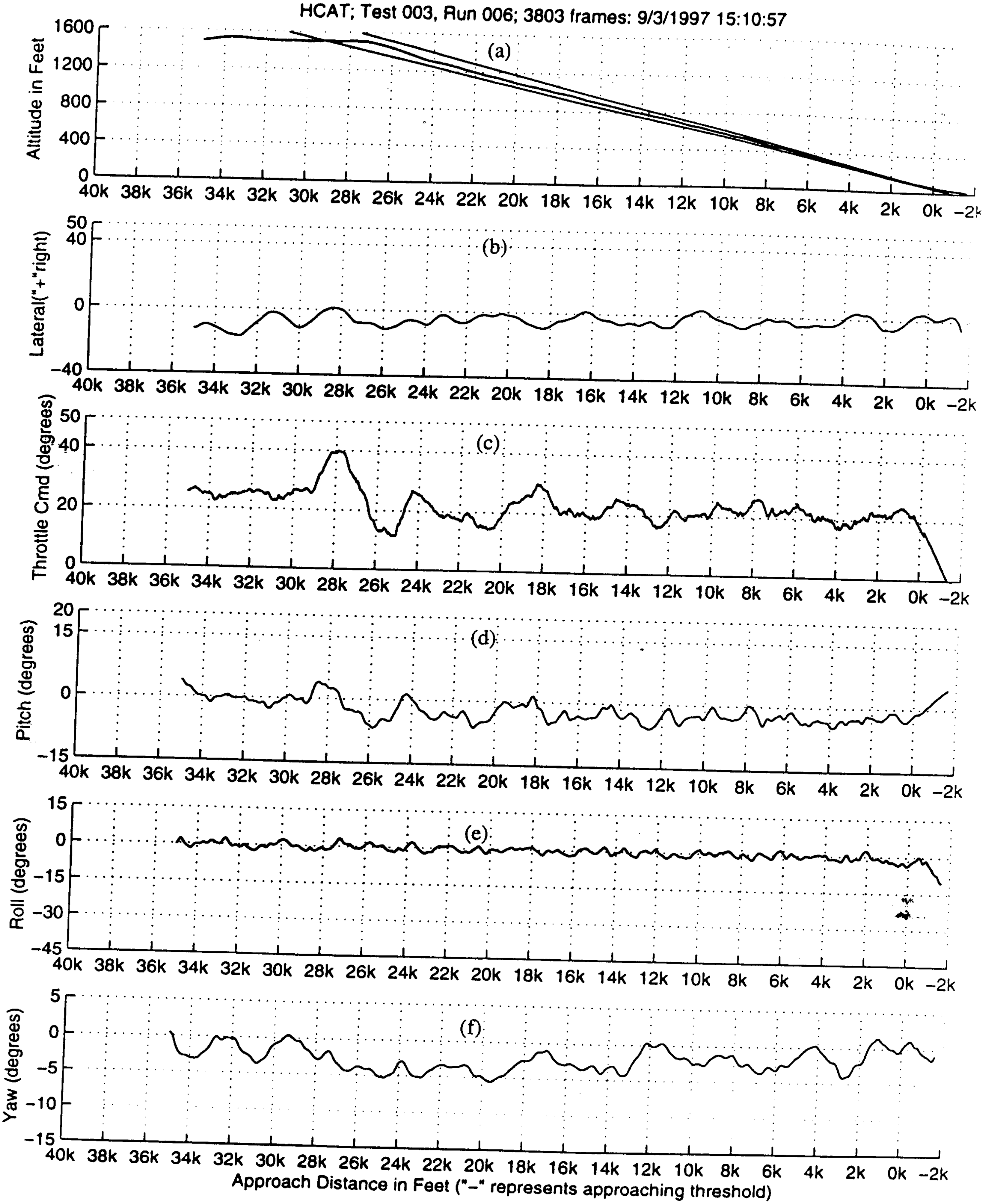

Figure 5: B737 Autoland with Pseudo-Random Turbulence and No HIRF Exposure

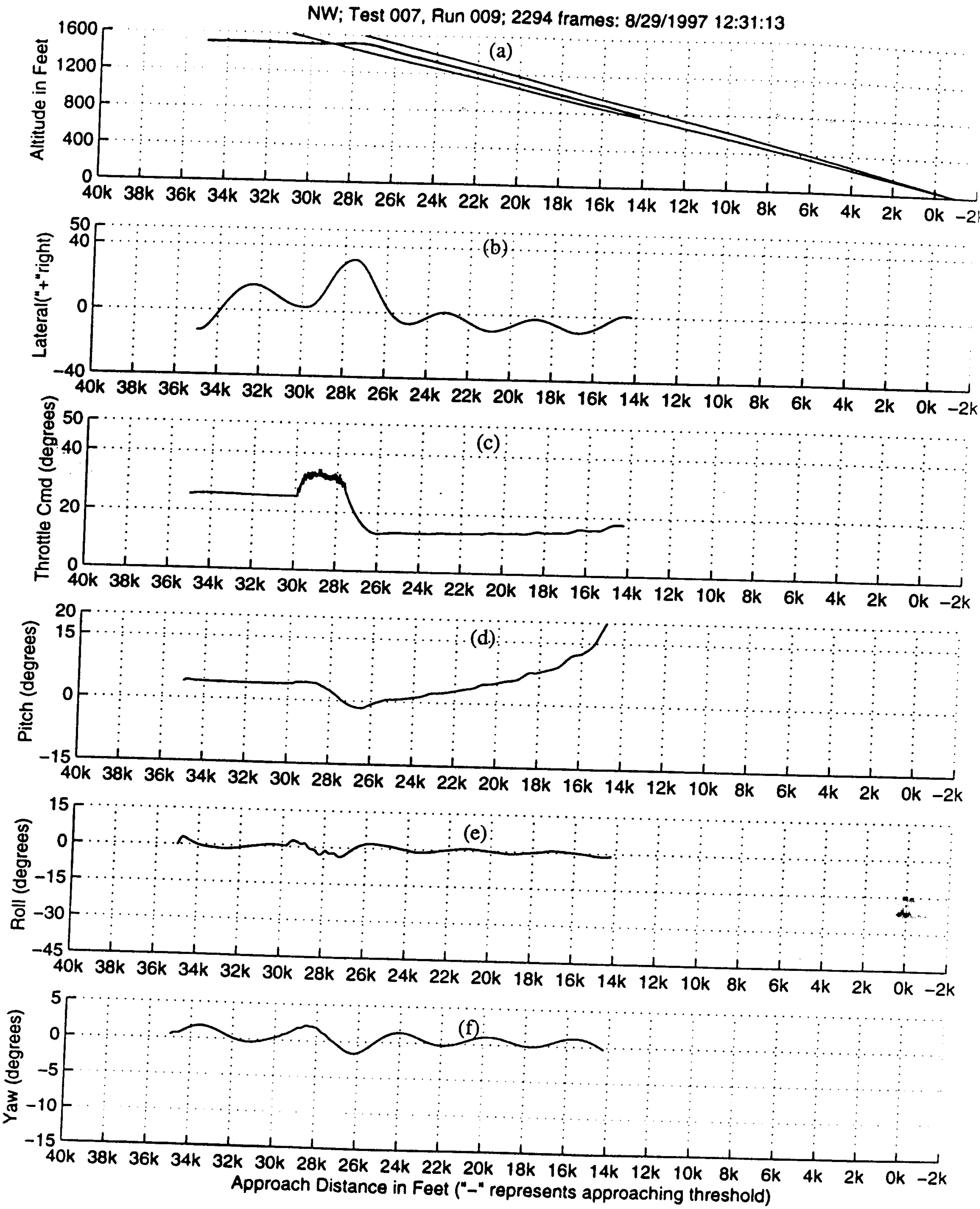

Figure 6: B737 Autoland with No Winds and 10 s. HIRF Exposure

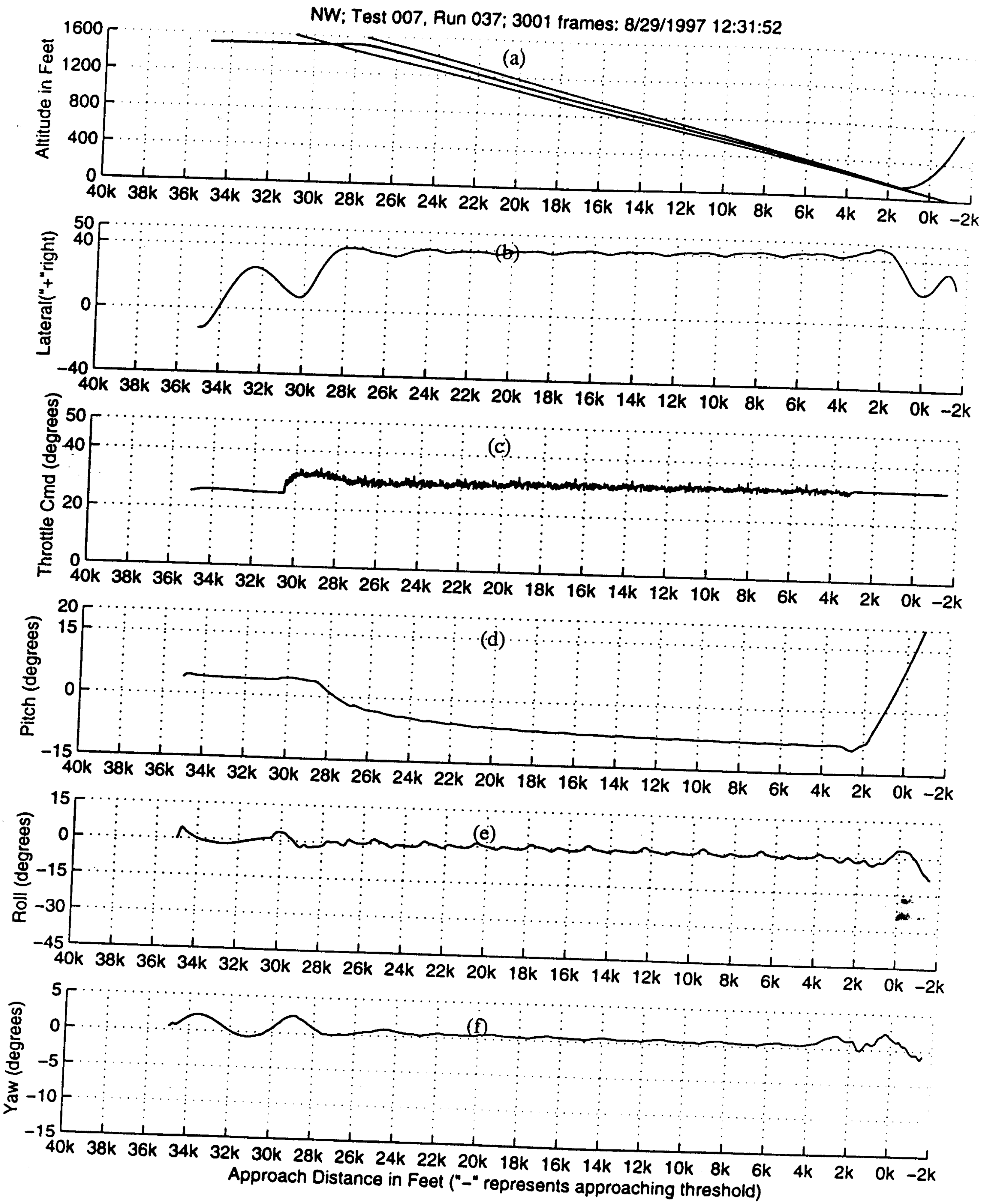

Figure 7: B737 Autoland with No Winds and Continuous HIRF Exposure

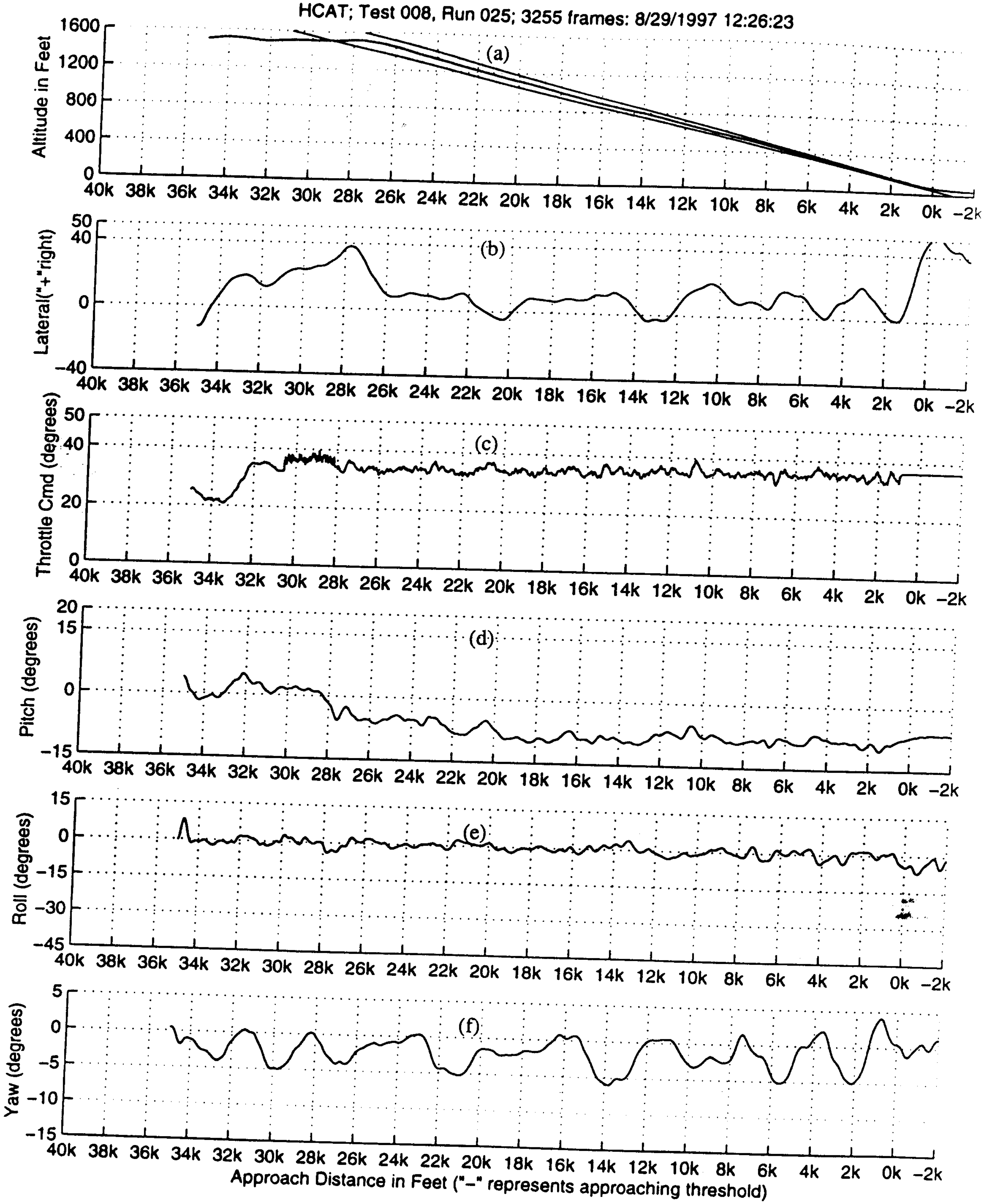

Figure 8: B737 Autoland with Repeatable Turbulence and 10 s. HIRF Exposure

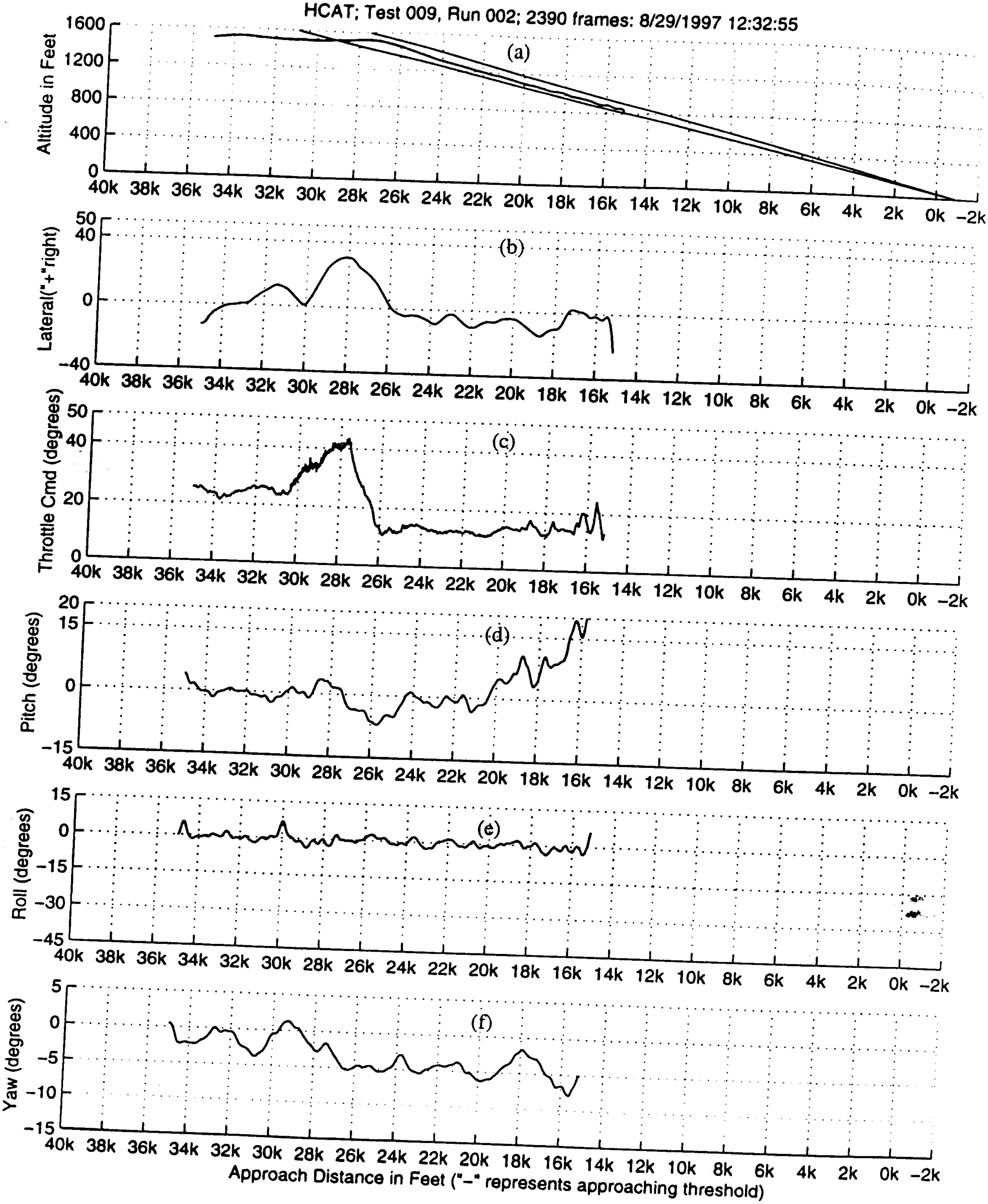

Figure 10: B737 Autoland with Pseudo-Random Turbulence and 10 s. HIRF Exposure

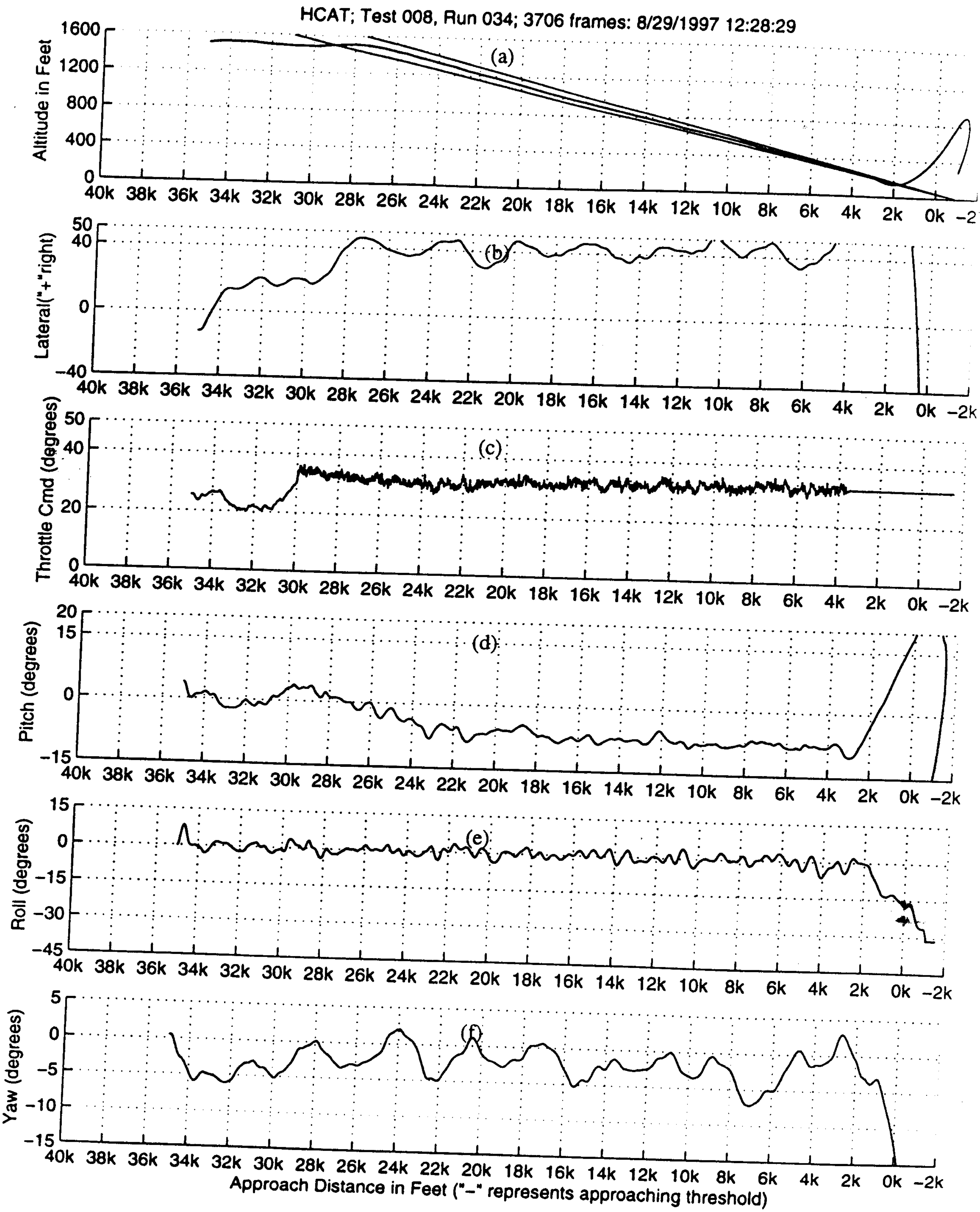

Figure 9: B737 Autoland with Repeatable Turbulence and Continuous HIRF Exposure

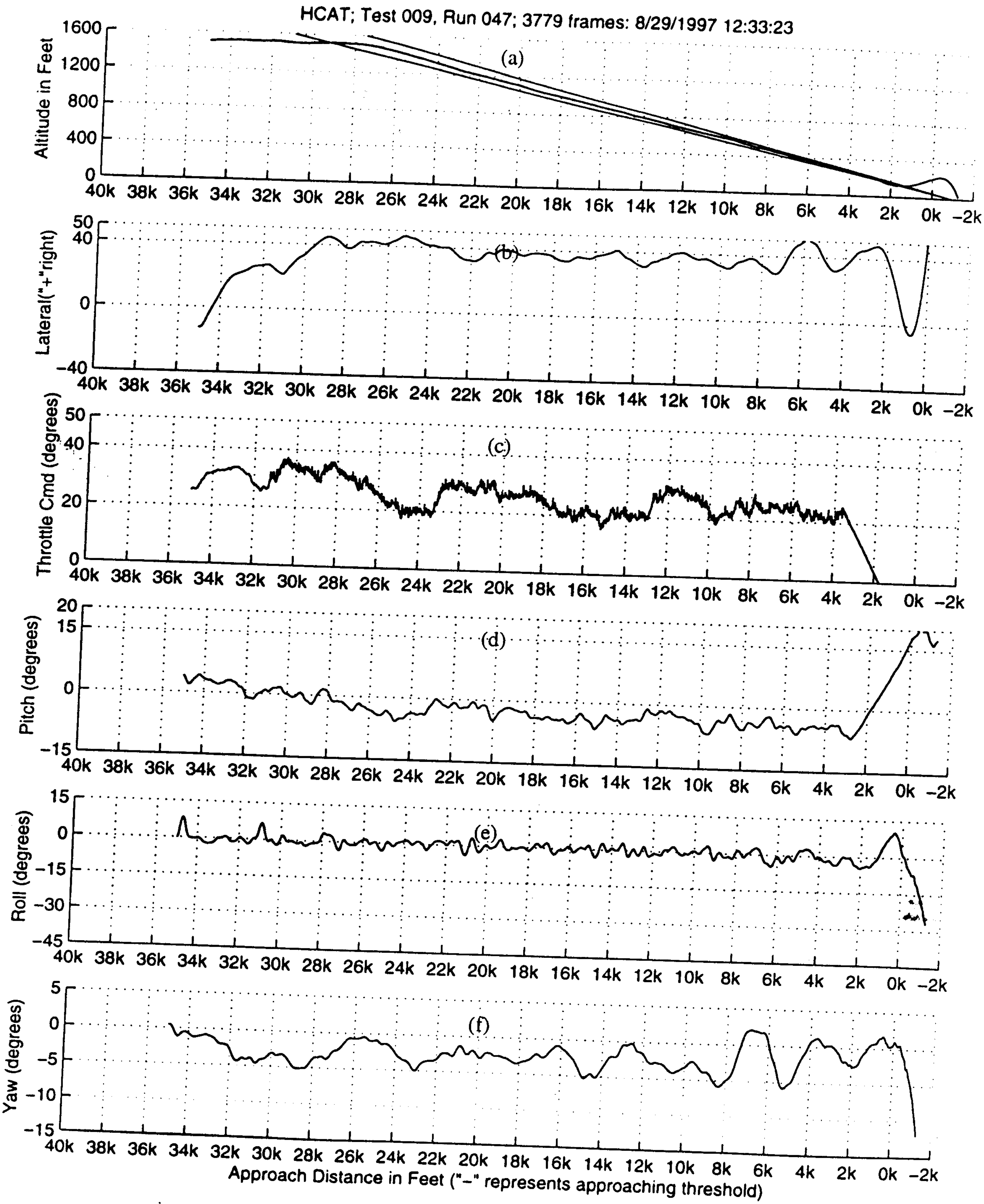

Figure 11: B737 Autoland with Pseudo-Random Turbulence and Continuous HIRF Exposure