Michelle E. Bernson
Chief Engineer
Air Safety Investigation
Commercial Airplanes

The Boeing Company
P.O. Box 3707 MC 07-32
Seattle, WA 98124-2207

7 February 2014
66-ZB-H200-ASI-18729

Timothy LeBaron
US National Transportation Safety Board
490 L'Enfant Plaza East
Washington, DC 20594
Sent via e-mail; [redacted]

Subject: Boeing Flight Simulations and FDR Data Analysis – National Air Cargo 747-400 N949CA Takeoff Accident at Bagram AFB, Afghanistan- 29 April 2013

Dear Mr. LeBaron:

A copy of the raw binary FDR data for the subject accident was provided to Boeing by the Afghanistan Ministry of Civil Aviation and Tourism (MOCAT). This letter formally documents Boeing's Simulations and review of the FDR data for inclusion as necessary in the MOCAT Final Report. The requested Boeing FDR data plots, simulation study results and observations are included as an enclosure to this letter.

The information included with this correspondence is controlled under the US Export Administration Regulations (15 CFR Parts 300-799) and has been categorized as ECCN: 9E991.

Please feel free to contact us if you have any questions.

Best regards,

[redacted]

Michelle E. Bernson
Chief Engineer
Air Safety Investigation

Enclosure: Simulations and FDR Analysis

cc: Tim Burtch NTSB
Tom Jacky NTSB
Brian Murphy NTSB

Boeing Flight Simulations and FDR Data Analysis – National Air Cargo 747-400 N949CA Takeoff Accident at Bagram AFB, Afghanistan- 29 April 2013

Summary

A National Air Cargo Group (MUA) 747-400 Boeing Converted Freighter (BCF) [RT075/N949CA] crashed shortly after takeoff from Bagram Air Force Base (OAI), Afghanistan on April 29, 2013. There were no survivors among the 7 crew members onboard. The event is under investigation by the Afghanistan Ministry of Civil Aviation and Tourism (MOCAT) with assistance from the National Transportation Safety Board (NTSB), the Federal Aviation Administration (FAA), National Air Cargo and Boeing. The Flight Data Recorder (FDR) data were provided to Boeing for analysis.

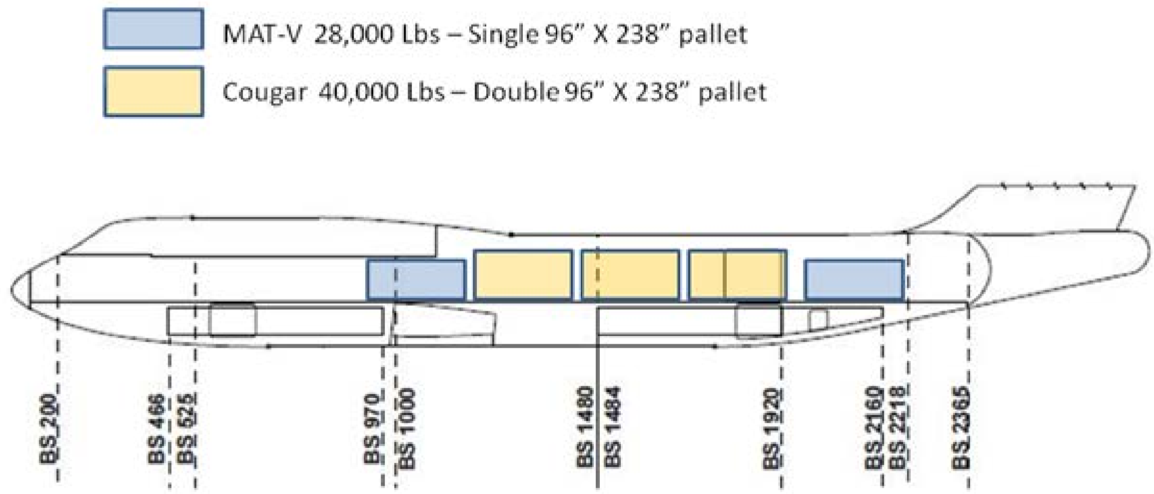
The FDR data show a normal takeoff was performed from OAI, but just after lift-off, the FDR recording stopped with the airplane approximately 33 feet above the ground. Video of the airplane just after lift-off at a low altitude over the runway shows an extremely high pitch attitude before experiencing a stall and impacting the ground at a nose-down pitch attitude. The airplane was carrying five Mine Resistant Ambush Protected (MRAP) vehicles, each weighing at least 28,000 pounds. The available FDR data, Cockpit Voice Recorder (CVR) data, and physical evidence (video, airplane component analysis), with additional support from simulation analysis, suggest that around lift-off, at least one MRAP (aft-most) broke loose of its restraints, shifted aft and damaged the FDR/CVR before penetrating the aft pressure bulkhead. The MRAP's aft movement was determined to have compromised at least Hydraulic Systems #1 and #2 and may have contacted the stabilizer jackscrew assembly. Simulation analysis indicated that an incremental airplane-nose-up stabilizer deflection (stabilizer would have likely deflected Leading Edge [LE] down if it were free to rotate) of 5 units or more could have produced the observed airplane motion. If the stabilizer jackscrew actuator had been displaced downward by the MRAP during takeoff, continued safe flight and landing most likely would not have been possible. An examination of the stabilizer jackscrew occurred on the 15th of January 2014. Results of the examination were inconclusive as to whether displacement of the stabilizer jackscrew from its fuselage mount occurred prior to impact.

Event Report

It was reported in a Multi Operator Message (MOM) by Boeing that a National Air Cargo Group (MUA) 747-400 Boeing Converted Freighter (BCF) [RT075/N949CA] crashed shortly after takeoff from Bagram Air Force Base (OAI), Afghanistan on April 29, 2013. An excerpt from the MOM stated the following:

> *The subject airplane has been involved in an accident while on an international cargo flight from Bagram Air Force Base, Kabul, Afghanistan. The airplane was reported to have crashed after takeoff. Initial reports indicate that the aircraft carried 7 crew members and no passengers and that there were no survivors. Weather was reported to have been daylight conditions with scattered clouds at the time of the event (approximately 1500 hours local).*
>
> *This event is being investigated by the Afghanistan Ministry of Civil Aviation and Tourism (MOCAT). The US is providing assistance to the MOCAT under the guidelines of ICAO Annex 13. Personnel from the US NTSB, US FAA, and Boeing will be dispatched to the scene to assist.*
>
> *The airplane, serial number 25630, Variable RT075, was delivered to a different operator in February, 1993.*

The airplane was delivered in February 1993 to Air France (AFA) and was converted to a freighter in 2007. On April 29, 2013, the airplane was initially flown from Camp Bastion (OAZ), Afghanistan to OAI, and the accident flight was a scheduled flight to Dubai, United Arab Emirates. The flight was a cargo flight that included five Mine Resistant Ambush Protected (MRAP) vehicles: two 12.5-ton (~28,000 pounds) MRAP All-Terrain Vehicles (MAT-V) and three 18-ton (~40,000 pounds) Cougars. The flight from OAZ to OAI represented the first time MUA had carried Cougars (see Graphic 1 for MRAP loading configuration). The crew members consisted of 4 flight crew, 2 mechanics, and 1 loadmaster.



Graphic 1 - MRAP Loading Configuration on RT075

The weather was reported as daylight conditions with scattered clouds at the time of the event (~15:27 local time). Available Aviation Routine Weather Reports (METARs) indicate that around the time of takeoff (15:25 local time), the winds were light (7 knots) from 20 degrees true (north-northeast [NNE]). Special observations were reported at 15:28 and 15:29, indicating that an air mass change occurred that resulted in a 7-degree decrease in temperature and a wind magnitude and direction change (11 knots gusting to 17 knots from 350 degrees true [north-northwest].

The Flight Data Recorder (FDR) data were provided to Boeing for analysis via the National Transportation Safety Board (NTSB). In addition, videos of the event were captured by airport surveillance cameras and an on-ground vehicle dashboard camera (dash cam).

FDR Data Analysis

Time history plots of the pertinent longitudinal and lateral-directional parameters during takeoff roll are attached as Figures 1 through 5. A ground track of the airplane's taxi and takeoff roll is also included as Figure 6. The results from various simulation analyses are presented in Figures 7 through 13. All of the plots are described in Table 1 that follows.

Boeing Flight Simulations and FDR Data Analysis – National Air Cargo 747-400
N949CA Takeoff Accident at Bagram AFB, Afghanistan- 29 April 2013

Table 1 – List of Figures

The FDR data show the airplane configured for a flaps 10 takeoff with a recorded stabilizer setting of approximately -0.85 degrees (3.85 units) [Figure 1]. The recorded takeoff gross weight was approximately 676,000 pounds. However, Boeing Weights Engineering Group analysis indicated the actual gross weight should have been approximately 685,000 pounds when accounting for the pallets and tie-down straps used to restrain the MRAPs. Therefore, a gross weight of 685,000 pounds was used for all subsequent analyses. Maximum takeoff thrust was used (engine N1 = 108 percent). Slight left rudder, on average, was commanded during the takeoff roll to maintain runway centerline (Figure 2).

Fluctuations in computed airspeed were observed during the takeoff roll and were consistent with gusty wind conditions (Figures 3 and 4). Rotation was initiated with a nose-up column input around time 6268.5 seconds, and the airplane rotated to a normal takeoff pitch attitude (Figure 3). The air/ground discrete momentarily changed state to "air" twice before lift-off occurred at approximately time 6274.5 seconds. Valid data end approximately 2 seconds after lift-off (~ time 6276.3 seconds). Additional data were available beyond time 6276.3 seconds (approximately 3.5 seconds), but these data were determined to be invalid and therefore were not included in the plots.

The valid data end with the airplane at 33 feet radio altitude and 171 knots computed airspeed (V2+4) [Figures 3 and 4]. The airplane was pitched at approximately 13 degrees and banked right at approximately 4 degrees. Elevator deflections were around 5-6 degrees Trailing Edge (TE) up when the data end. The last valid recorded wind data indicate the winds were approximately 12 knots from 40 degrees true, which differed in direction from the reported METARs (Figure 4). The left rudder used during the takeoff roll (runway magnetic heading = 27 degrees) was consistent with the recorded wind data (right crosswind).

Figure 5 shows a comparison of the pertinent longitudinal parameters for the takeoffs from OAZ and OAI. Both takeoffs were conducted at flaps 10, but the previous takeoff from OAZ had a lower airplane gross weight and lower thrust setting. In Figure 5, the two takeoffs were aligned approximately around the time of rotation initiation. The takeoffs matched very closely, and both appeared to be normal.

Ground Track

A ground track was generated to show the airplane's path during taxi and takeoff (Figure 6). Runway 03 at OAI has a length of 11,819 feet and a width of 151 feet. Longitudinal and lateral distances were calculated using a combination of inertial data (ground speed, drift angle, heading) and airport information (runway dimensions, etc). The distances were then referenced to the runway based on the airplane's taxi on Taxiway G1 and turn onto Runway 03. These distances are referenced to the airplane Center of Gravity (CG).

The ground track was created in order to determine the location of the airplane at rotation initiation and at lift-off. These airplane locations were then compared with the locations of the airplane parts found on and near the runway (discussed below in Physical Evidence Discussion Section) to determine if they were consistent. The calculated data show that rotation was initiated approximately 4700 feet beyond the runway threshold, just after passing Taxiway E (Figure 6). Lift-off occurred approximately 6400 feet beyond the threshold, and the valid data end around 6860 feet beyond the threshold, just prior to passing Taxiway C. The location of ground impact is also shown in Figure 6. The airplane impacted the ground near the end of the runway, approximately 600 feet to the right of the runway centerline.

Cockpit Voice Recorder (CVR) Findings

The CVR also stopped recording around the time the FDR recording stopped. The last three statements recorded on the CVR were: 1) "Rotate", 2) "Positive climb, gear up", and 3) "Keep on that … (sounds like wing, weight, or wheel)."

Physical Evidence Discussion

Video

Since the FDR data end just after lift-off, additional sources of information were used to investigate the sequence of events that led to this accident. The first source of additional information was an on-ground vehicle dash cam that captured the airplane in the air just after lift-off. The video shows the airplane at a low altitude with an extremely high pitch attitude over the runway before exhibiting motion consistent with an aerodynamic stall. The airplane then rolled/yawed to the right before impacting the ground at a nose-down pitch attitude, resulting in a large explosion.

In addition, airport surveillance video was provided as part of the investigation. Cameras situated at various locations around the airport property show the airplane's impact with the ground from different angles. These videos show that the airplane's body gear and nose gear were extended at impact, but the wing gear were raised. Given this information, it was suspected that Hydraulic System #1 had been compromised (controls body/nose gear) and that Hydraulic System #4 was working (controls wing gear).

On-site Findings

Below is a brief summary of some of the findings from the on-site investigation:

- Engines show high Revolutions Per Minute (RPMs) at impact
- Runway sweep found parts on runway near lift-off zone and all along flight path (see Graphic 2)
- Many of the parts on the runway were associated with Hydraulic System #2, so Hydraulic System #2 was suspected to have been compromised at or after lift-off (for reference,

Hydraulic System #2 tubing passes through the main cabin floorboards and through the bottom of the aft pressure bulkhead)

- Fire consumed most of the airplane, but the tail section, including the aft pressure bulkhead, was not thermally damaged
- Hydraulic System #4 was also assumed to be working based on the position of the recovered wing landing gear actuator position

Additionally, there were several findings associated with the aft pressure bulkhead, the aft-most MAT-V, and the remaining stabilizer structure. There was a tire imprint towards the center apex of the aft pressure bulkhead. It aligned with the location of the MAT-V spare tire that is situated at the rear of the vehicle (refer to Graphic 3 and 4). Graphic 3 shows a picture of the back of a MAT-V, a picture of the actual tire imprint on the aft pressure bulkhead, and a depiction of the tire relative to the cargo hold and aft pressure bulkhead. Another piece of evidence was the presence of orange paint marks on the rear side of the aft-most MAT-V (see Graphic 4). The orange paint on that structure appeared to match the orange paint from the FDR encasing. A depiction is shown in Graphic 4 that approximates the dimensions (including rear spare tire) of the aft-most MAT-V and its location within the cargo hold. Given the FDR/CVR recording failure, the discovery of airplane parts in the lift-off zone, the orange paint transfer from the FDR, and the spare tire imprint on the aft pressure bulkhead, this evidence supports the conclusion that at least the aft-most MAT-V broke loose from its restraints and moved aft during lift-off.

With the evidence that an MRAP broke loose and penetrated the aft pressure bulkhead, the investigation then focused on what other systems or structure may have been compromised. Based on the on-site findings and video evidence, Hydraulic Systems #1 and #2 were believed to have been compromised while Hydraulic System #4 was believed to have been functioning. Hydraulic System #3's status was unknown. System experts do not believe that the flight control cables were jammed or compromised, mostly due to the distance between the top of the MAT-V and the crown of the airplane (flight control cables pass along top of the fuselage through the top of the aft pressure bulkhead). The aft-most MAT-V was discovered to be wrapped in rudder control cables on the ground, but this was believed to have occurred at ground impact as the vehicle penetrated the top of the fuselage.

Boeing Flight Simulations and FDR Data Analysis – National Air Cargo 747-400
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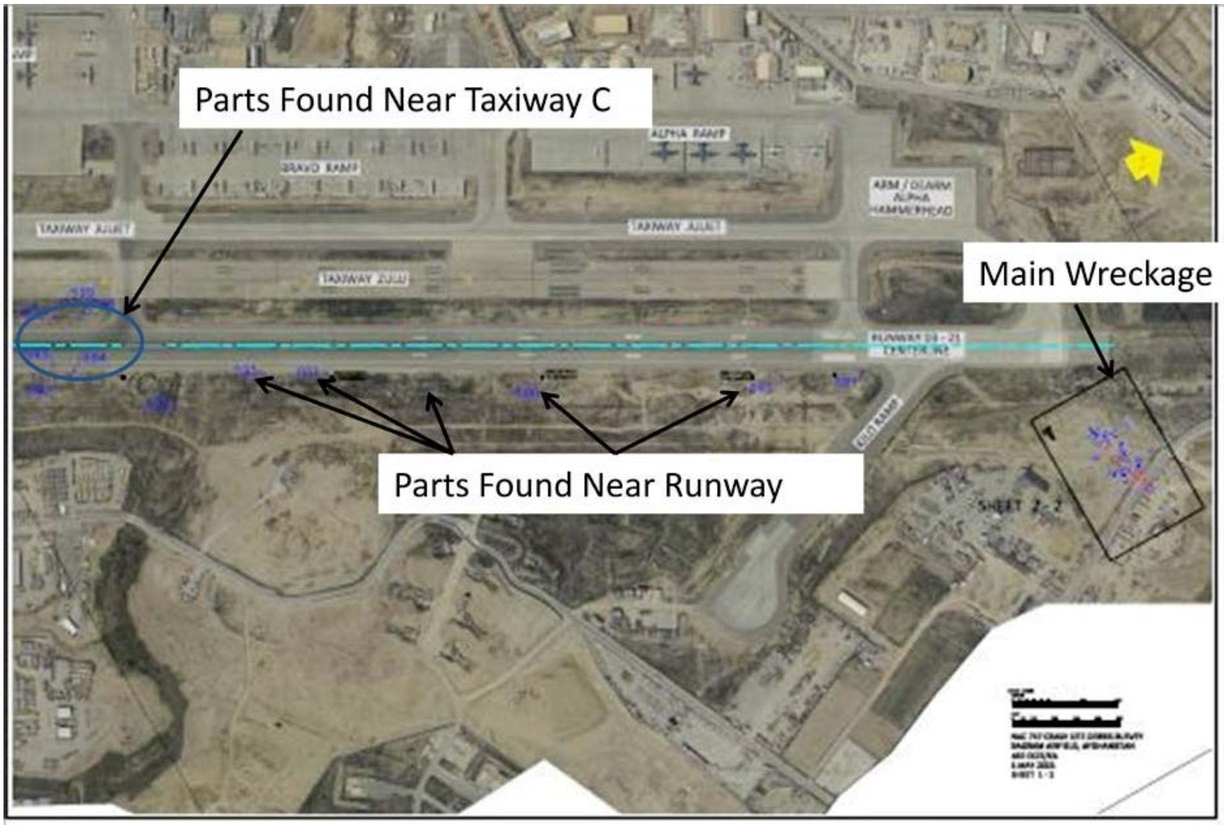

Graphic 2 – Location of Parts Found On or Near Runway

Graphic 3 – Spare Tire Imprint

The stabilizer and surrounding structure was mostly intact following the accident. The measured jackscrew nut travel was consistent with the recorded takeoff stabilizer position of approximately 4 units (-1 degree). However, the jackscrew was sheared on its lower end (2 feet above the floorboards), and there were witness marks (noted as metal on metal gouge marks) on the gimbaled nut collar fitting. Visual analysis at the NTSB structures laboratory could not conclude what caused the jackscrew to shear. A more detailed analysis of the jackscrew took place in January 2014 at the Boeing Equipment Quality Analysis (EQA) laboratory in Seattle, Washington, but the analysis was inconclusive as to whether the jackscrew was sheared prior to ground impact.

Simulation Analysis

Due to the absence of FDR data throughout the majority of the event flight, simulation analyses were used to explore possible scenarios that may have led to the accident. A simulation match of the FDR data during the takeoff roll and lift-off was generated, and a single hypothetical scenario of a CG shift (to simulate a MRAP shifting aft) was also generated based on this simulation match. In addition, other possible scenarios were analyzed involving varying CG shifts, hydraulic system failures, and flight control failures.

The 747-400 desktop simulation was used to re-create the takeoff from OAI and perform several case studies. The simulation offers flexibility in being able to drive the simulation control positions with FDR data or use mathematical pilot models to produce the desired airplane state/flight path. The simulation is a six degree of freedom non-linear model that has been updated to match flight data. A mathematical pilot applies inputs to track a specified parameter(s) (e.g. heading) in an attempt to minimize the error between the flight data and simulation.

Simulation Match

The simulation was initialized on the ground with similar initial conditions (e.g. altitude, speed, etc.), control inputs, and throttle inputs to the recorded FDR parameters. Instead of the recorded gross weight, the calculated gross weight of 685,000 pounds (discussed above in the FDR Data Analysis Section) was used for the simulation gross weight. The Boeing Weights Engineering Group also performed an independent calculation of the CG position using the best available information for cargo and fuel, and this value (31.7 percent) was used in the simulation. The simulation was driven with the FDR stabilizer position, elevator deflection, control wheel position, rudder pedal, and throttle resolver angles. A mathematical pilot model was used on the elevators and rudder pedal to match the pitch attitude and heading/ground track angle, respectively. The simulation winds were driven with a constant wind magnitude and direction of 15 knots and 355 degrees, respectively, as determined by a combination of available METARs and a calculated wind profile.

The majority of the resulting match was very close (Figures 7 and 8). However, during the last 3 seconds, the simulation parameters deviated from their FDR counterparts, most notably in pitch attitude, longitudinal acceleration, and radio altitude (Figure 7). Some deviations were also observed during the takeoff roll in some of the lateral-directional parameters, but this was most likely due to variations in the on-ground wind profile that could not be determined due to the difficulty in calculating winds on the ground (Figure 8).

A hypothetical scenario was generated using this simulation match as a baseline (Figure 9). At time 6272 seconds, a CG shift was simulated that represented a scenario where the aft-most MRAP shifted to the stabilizer jackscrew. The Boeing Weights Engineering Group calculated that the CG would be 34.9 percent with the vehicle at that position. Starting at time 6272 seconds, a CG shift from 31.7 percent to 34.9 percent was ramped in over 3 seconds, where it was then maintained at 34.9 percent until the simulation was terminated one second later. The resulting simulation results matched better in pitch attitude, longitudinal acceleration, and radio altitude than the baseline results. These results support the previously stated hypothesis that the aft-most vehicle broke loose and shifted aft, most likely during the timeframe analyzed here.

Additional Simulation Analysis – Hydraulic Failures and CG Shift

With physical evidence supporting a scenario in which the MRAP(s) shifted and hydraulic systems compromised, additional simulation analysis was performed to assess the impact of combinations of the possible contributing factors. For the purpose of this discussion, the MRAPs are numbered 1 through 5, beginning with the aft-most MRAP and moving forward. A total of 20 cases were simulated, and these cases are described in Table 2 that follows:

Table 2 - Simulation Scenario Summary

Case #	CG Shift	Hydraulic Systems Failed
1	MRAP #1 shift to stabilizer jackscrew (34.9 %)	None
2	MRAP #1 shift to stabilizer jackscrew (34.9 %)	System #1
3	MRAP #1 shift to stabilizer jackscrew (34.9 %)	Systems #1 and #2
4	MRAP #1 shift to stabilizer jackscrew (34.9 %)	Systems #1, #2, and #3
5	MRAP #2 shift to MRAP #1 shifted position (40.5 %)	None
6	MRAP #2 shift to MRAP #1 shifted position (40.5 %)	System #1
7	MRAP #2 shift to MRAP #1 shifted position (40.5 %)	Systems #1 and #2
8	MRAP #2 shift to MRAP #1 shifted position (40.5 %)	Systems #1, #2, and #3
9	MRAP #3 shift to MRAP #2 shifted position (46.6 %)	None
Case #	**CG Shift**	**Hydraulic Systems Failed**
10	MRAP #3 shift to MRAP #2 shifted position (46.6 %)	System #1
11	MRAP #3 shift to MRAP #2 shifted position (46.6 %)	Systems #1 and #2
12	MRAP #3 shift to MRAP #2 shifted position (46.6 %)	Systems #1, #2, and #3
13	MRAP #4 shift to MRAP #3 shifted position (51.5 %)	None
14	MRAP #4 shift to MRAP #3 shifted position (51.5 %)	System #1
15	MRAP #4 shift to MRAP #3 shifted position (51.5 %)	Systems #1 and #2
16	MRAP #4 shift to MRAP #3 shifted position (51.5 %)	Systems #1, #2, and #3
17	MRAP #5 shift to MRAP #4 shifted position (56.0 %)	None
18	MRAP #5 shift to MRAP #4 shifted position (56.0 %)	System #1
19	MRAP #5 shift to MRAP #4 shifted position (56.0 %)	Systems #1 and #2
20	MRAP #5 shift to MRAP #4 shifted position (56.0 %)	Systems #1, #2, and #3

To cover all possible scenarios, it was decided to simulate CG shifts due to all 5 MRAPS moving aft (MRAP #1 shifts to the stabilizer jackscrew, MRAP #2 shifts to MRAP #1 shifted position, etc) and various hydraulic system failure combinations. Since the status of Hydraulic System #3 was unknown, as a hypothetical scenario, Hydraulic System #3 was also assumed to been compromised in five of the cases. As a "baseline," five cases were simulated with no hydraulic failures.

Table 3 below contains a brief summary of critical flight control surfaces/systems and the hydraulic system(s) that control each:

Table 3 - Flight Control and Hydraulic System Summary

Flight Control Surface/System	Hydraulic System(s)
Left Outboard (LOB) Aileron	#1 and #2
Left Inboard (LIB) Aileron	#1 and #3
Right Inboard (RIB) Aileron	#2 and #4
Right Outboard (ROB) Aileron	#3 and #4
Spoilers 1/4/9/12	#3
Spoilers 2/3/10/11	#2
Spoilers 5/6/7/8	#4
LOB Elevator	#1
LIB Elevator	#1 and #2
RIB Elevator	#3 and #4
ROB Elevator	#4
Upper Rudder	#1 and #3 (Yaw Damper #3)
Lower Rudder	#2 and #4 (Yaw Damper #2)
Normal Stabilizer Trim	#2 and #3
Normal Elevator Feel	#2 and #3

In each scenario, the simulation airplane was configured consistent with the event airplane near the last valid FDR data point. The initial airplane configuration was as follows:

- Gross weight = 685,000 pounds
- CG = 31.7 %
- Altitude = 50 feet Above Ground Level (AGL)
- Computed airspeed = 177 knots (V2+10)
- Flaps 10
- Stabilizer Position = 4 units
- Gear Down
- Engine N1 = 108 %

The simulation airplane was then trimmed at this configuration, resulting in a trimmed pitch attitude of 16.2 degrees. No atmospheric effects were modeled, and the airplane's configuration (flaps, gear, and thrust) did not change during the simulated time period. In addition, the stabilizer was fixed at the takeoff position setting during the simulated time period. At time zero, the CG shift, hydraulic failure (if any), and full nose-down column were stepped in and then a free response time history was generated. It was assumed that the crew immediately commanded full nose-down column upon experiencing the rapid pitch-up. The intent of this simulation was to determine whether sufficient nose-down pitching moment capability was available from the column input (including effects from any floating control surfaces) to arrest the nose-up pitching moment from a particular CG shift and hydraulic failure scenario. The simulation was terminated when either zero degrees pitch attitude was reached or when 60 seconds had elapsed (for reference, the accident airplane was approximated to be in the air for 30 seconds). The metric used to quantify the results from this simulation analysis was "Time to Zero Pitch Attitude" (i.e. how long did it take the airplane to reach zero degrees pitch attitude) [Figure 10].

When the hydraulic systems that control a particular control surface are failed, some surfaces (for this simulation, elevators and ailerons) move to their float position based on airplane configuration and atmospheric conditions. The simulation spoilers did not float most likely due to restriction from their lock-down mechanisms, this would be expected on the event airplane as well. Table 4 (on the next page) summarizes the positions of the critical control surfaces that affected pitching moment during this simulation analysis (**Note:** Analysis assumes full nose-down column input; positive (+) control surface movement is TE-down).

The results from this analysis are displayed in Figure 10 in the form of a three-dimensional bar chart. A supplemental plot is also included that shows the pitch attitude time history for each case (Figure 11). In Figure 10, the CG shifts are shown along the horizontal axis and the hydraulic failure scenarios are shown along the depth axis. The vertical axis shows the "Time to Zero Pitch Attitude" in seconds, and the table at the bottom of Figure 10 displays the exact values in seconds. The majority of the cases (13 out of 20) attained zero degrees pitch attitude within 10 seconds (Figures 10 and 11). Case #17 reached zero degrees pitch attitude in just under 30 seconds. One interesting observation to note is that the cases with the three failed hydraulic systems reached zero degrees pitch attitude faster than the cases with two failed hydraulic systems. This occurred because the LIB aileron floated to close to its maximum TE-up deflection (-18.5 degrees), resulting in more nose-down pitching moment with Hydraulic System #3 failed.

There were six cases where pitch attitude and pitch rate were not controllable. These cases are denoted with arrowheads in Figure 10 and with different, colored line types in Figure 11. Case #11 and #18 never reached zero degrees pitch attitude, but the simulation airplane also never pitched to a stall attitude either (Figure 11). These cases developed a divergent pitch oscillation where the airplane pitched up and down as airspeed slowed and increased, respectively. These two cases are marked with an "NS" in Figure 10, which indicates that in those two cases, the airplane did not stall within the simulated time period.

Table 4 – Summary of Simulation Elevator and Aileron Surface Deflections

Hydraulic System Status	Flight Control Surface(s)	Deflection (degrees)
All Systems Operating	Outboard Elevators	+17
	Inboard Elevators	+15
	Ailerons	0
System #1 Failed	LOB Elevator	+1.15
	ROB Elevator	+17
	Inboard Elevators	+15
	Ailerons	0
System #1, #2 Failed	LOB Elevator	+0.85 to +1.15 (depending on CG)
	ROB Elevator	+17
	LIB Elevator	-0.022 to +0.014 (depending on CG)
	RIB Elevator	+15
	LOB Aileron	-10.7
	LIB/RIB/ROB Aileron	0
System #1, #2, #3 Failed	LOB Elevator	+0.85 to +1.15 (depending on CG)
	ROB Elevator	+17
	LIB Elevator	-0.022 to +0.014 (depending on CG)
	RIB Elevator	+15
	LOB Aileron	-10.7
	LIB Aileron	-18.5
	RIB/ROB Aileron	0

Cases #15, #16, #19, and #20 all exhibit a rapid pitch-up leading to an aerodynamic stall (Figure 11). These cases are marked with an "S" in Figure 10. These cases represent the scenarios where either four or five MRAPs shifted aft and at least Hydraulic Systems #1 and #2 had failed. All of these cases closely replicated the pitch-up observed in the dash cam video and at one point in the investigation represented the best candidates for the most likely accident scenarios. However, after analyzing all of the available evidence, the investigation could not establish whether more than one MRAP (aft-most) shifted aft. From Figures 10 and 11, a single MRAP shift to the stabilizer jackscrew with any combination of hydraulic system failures resulted in a controllable scenario. The outcome of this analysis, considering a single MRAP shift, indicated that another source of nose-up pitching moment was required to replicate the airplane pitch attitude observed in the dash cam video. With an elevator control cable restriction or jam ruled unlikely by the investigation, the focus shifted to the stabilizer jackscrew and stabilizer control surface.

Additional Simulation Analysis – Stabilizer Movement Scenarios

Investigators considered that the damage incurred by the stabilizer jackscrew and surrounding structure could have occurred pre-ground-impact due to impact from the aft-most MRAP during lift-off. Based on the fracture location of the stabilizer jackscrew, it was determined that the stabilizer structure would have rotated Leading Edge (LE) down, resulting in an airplane nose-up pitching moment. Two possible scenarios relative to stabilizer movement were selected for analysis: 1) the stabilizer rotated LE-down and was fixed in that position, restricted by either the MRAP or other airplane structure, and 2) the stabilizer was free to float, and rotated to different positions based on its own weight and air loads.

A stabilizer trade study was conducted using the desktop simulation. These scenarios were similar to the simulation scenarios discussed in the previous section, except this analysis focused on a single MRAP CG shift to the stabilizer jackscrew. Again, full nose-down column was commanded at time zero, and either a Hydraulic System #1/#2 or #1/#2/#3 failure scenario was simulated. Various stabilizer positions beyond 4 units in the airplane nose-up direction were analyzed, and the resulting free-response time history for each case was evaluated.

For the case with three hydraulic systems failed, a stabilizer position of at least 9 units was sufficient to result in an uncontrollable pitch-up (Figure 12). Larger stabilizer deflections resulted in a more rapid pitch-up. An additional stabilizer trade study was performed with only Hydraulic Systems #1 and #2 failed. This hydraulic system failure scenario was determined to be the most likely accident scenario, based on available evidence. Similar to the results in Figure 12, a stabilizer position of at least 9 units was sufficient to result in an uncontrollable pitch-up.

The stabilizer would have had to move approximately 5 units (degrees) LE-down (airplane nose-up) from the takeoff stabilizer position of 4 units to reach a configuration where the available flight control surfaces could no longer counter the nose-up pitching moment. An approximate calculation was performed to determine the equivalent amount of LE stabilizer movement in inches. A simple right triangle approximation from the stabilizer hinge line was used to calculate the amount of LE travel at the root. The distance from the stabilizer hinge line to the LE at the root is approximately 185.75 inches. A stabilizer deflection of 5 degrees is approximately equivalent to 16 inches of LE travel. The displacement of the LE at the root can also approximate the displacement of the sheared stabilizer jackscrew and surrounding structure.

Analysis was also performed for possible stabilizer float scenarios. With no air loads and a small angle of attack, the stabilizer would rotate LE-down under its own weight. The stabilizer CG is approximately 2 feet forward of the stabilizer hinge line. If the stabilizer were free to float, the combined moments from the stabilizer structure weight and the air loads would result in a LE-down rotation. The moments do change depending on elevator deflection, which was an unknown. Some sample configurations and their corresponding stabilizer hinge moments are provided below (positive (+) is LE-up/airplane-nose-down):

1. Takeoff stabilizer position (4 units) and CG (31.7 %), All hydraulic systems operating, zero column command, elevators near neutral deflection (OB = 0.786 degrees, IB = -1.2 degrees), stabilizer hinge moment = **-15,113.6 foot-pounds**
2. Takeoff stabilizer position, CG shift to 34.9 % (equivalent to 1 MRAP shift to stabilizer jackscrew), Hydraulics Systems #1/#2/#3 failed, full nose-down column command (float positions on left elevator panels, full nose-down deflections on right elevator panels), stabilizer hinge moment = **-152,002.6 foot-pounds**
3. Takeoff stabilizer position, CG shift to 34.9 %, Hydraulics Systems #1/#2/#3 failed, zero column command (LOB elevator = 0.85 degrees, LIB elevator = -1.78 degrees, RIB elevator = -3.94 degrees, ROB elevator = -1.94 degrees), stabilizer hinge moment = +**7370 foot-pounds**

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Neutral elevator deflection and any TE-down (airplane-nose-down) elevator deflection would result in airplane nose-up motion due to the stabilizer rotating LE-down. Therefore, if the stabilizer was free to float and the crew commanded nose-down column, it would have exacerbated the pitch-up moving the airplane further into a stall condition.

Conclusion

It was not possible to determine with absolute certainty the contributing factors that led to this accident due to the loss of the FDR data during the accident takeoff. However, the available FDR/CVR data and physical evidence (video, airplane component analysis and other data), with additional support from simulation analysis, indicate that the most likely scenario involved at least one MRAP (aft-most) breaking loose of its restraints shortly after takeoff rotation, shifting aft and damaging the FDR/CVR, before penetrating the aft pressure bulkhead. The MRAP’s aft movement compromised at least Hydraulic Systems #1 and #2 and may have contacted the stabilizer jackscrew actuator assembly, shearing the jackscrew actuator from its fuselage attach points. If the stabilizer jackscrew actuator had been liberated from its attach points on the fuselage by the MRAP, the horizontal stabilizer control system would most likely have been compromised to the point that continued safe flight and landing would not have been possible.

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LONGITUDINAL PARAMETERS

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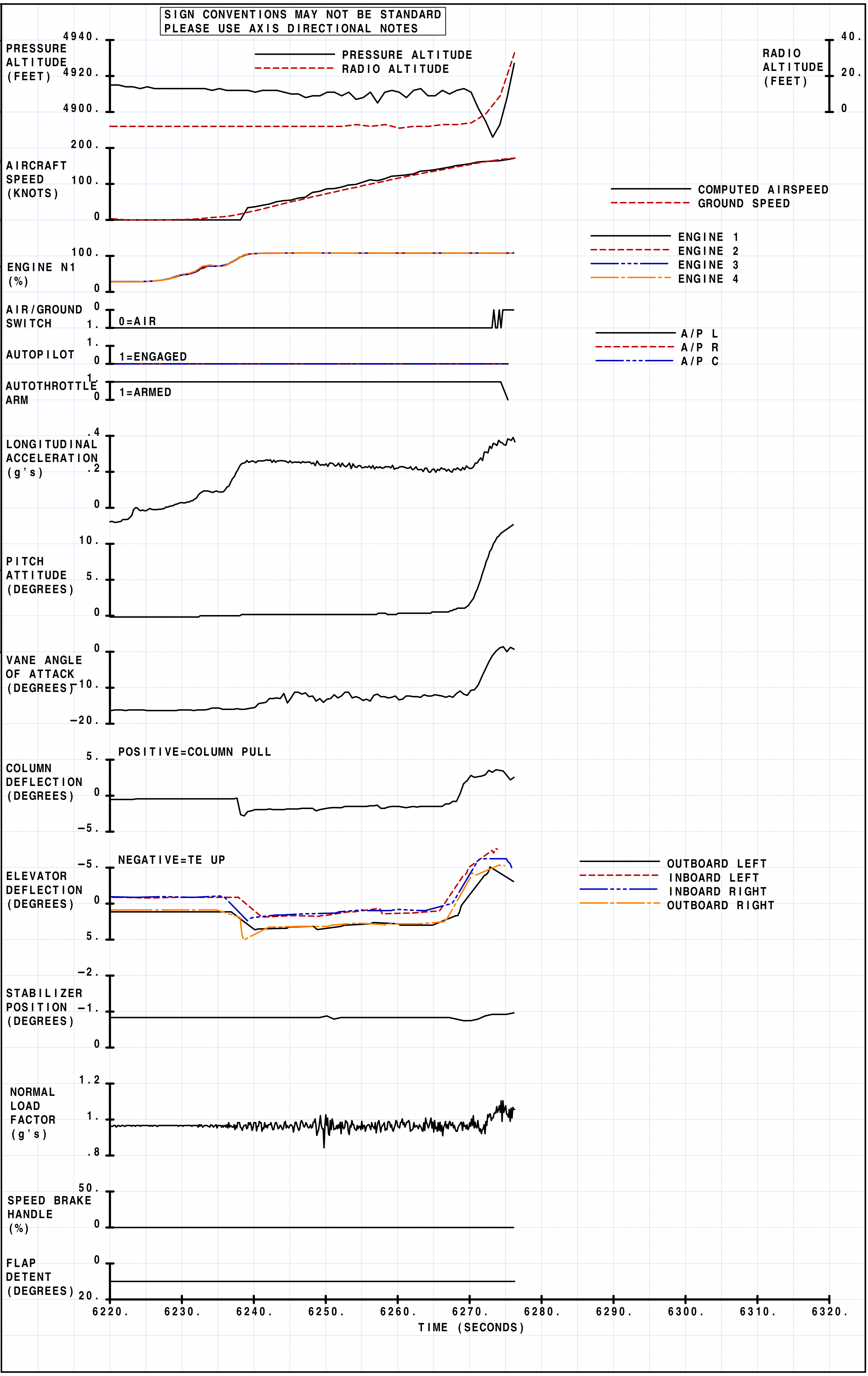

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RT075

FIGURE 1

PAGE

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LATERAL-DIRECTIONAL PARAMETERS

FIGURE 2 | RT075

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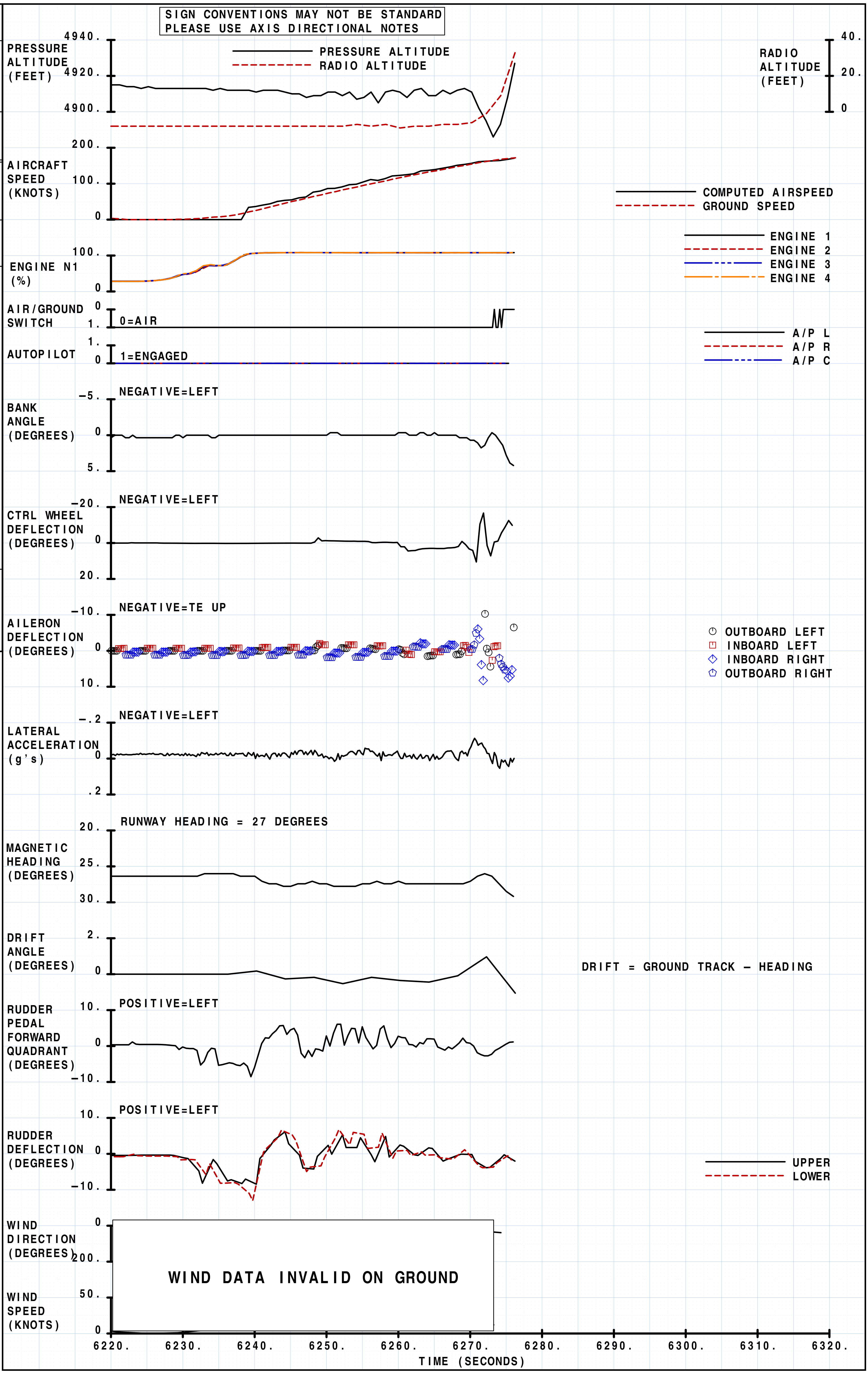

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LONGITUDINAL PARAMETERS, ROTATION ZOOM

RT075

FIGURE 3

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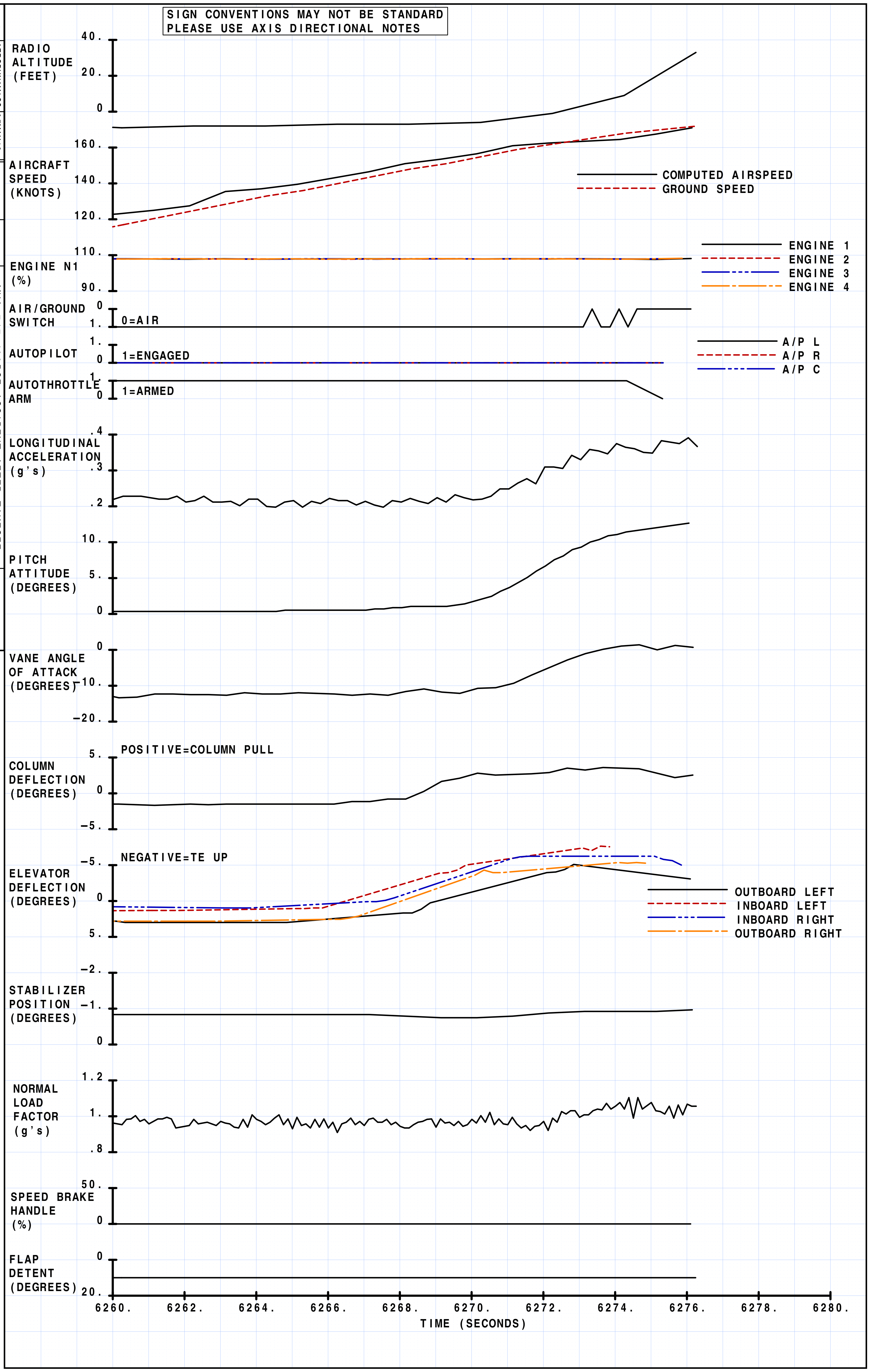

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LATERAL-DIRECTIONAL PARAMETERS, ROT ZM

FIGURE 4

RT075

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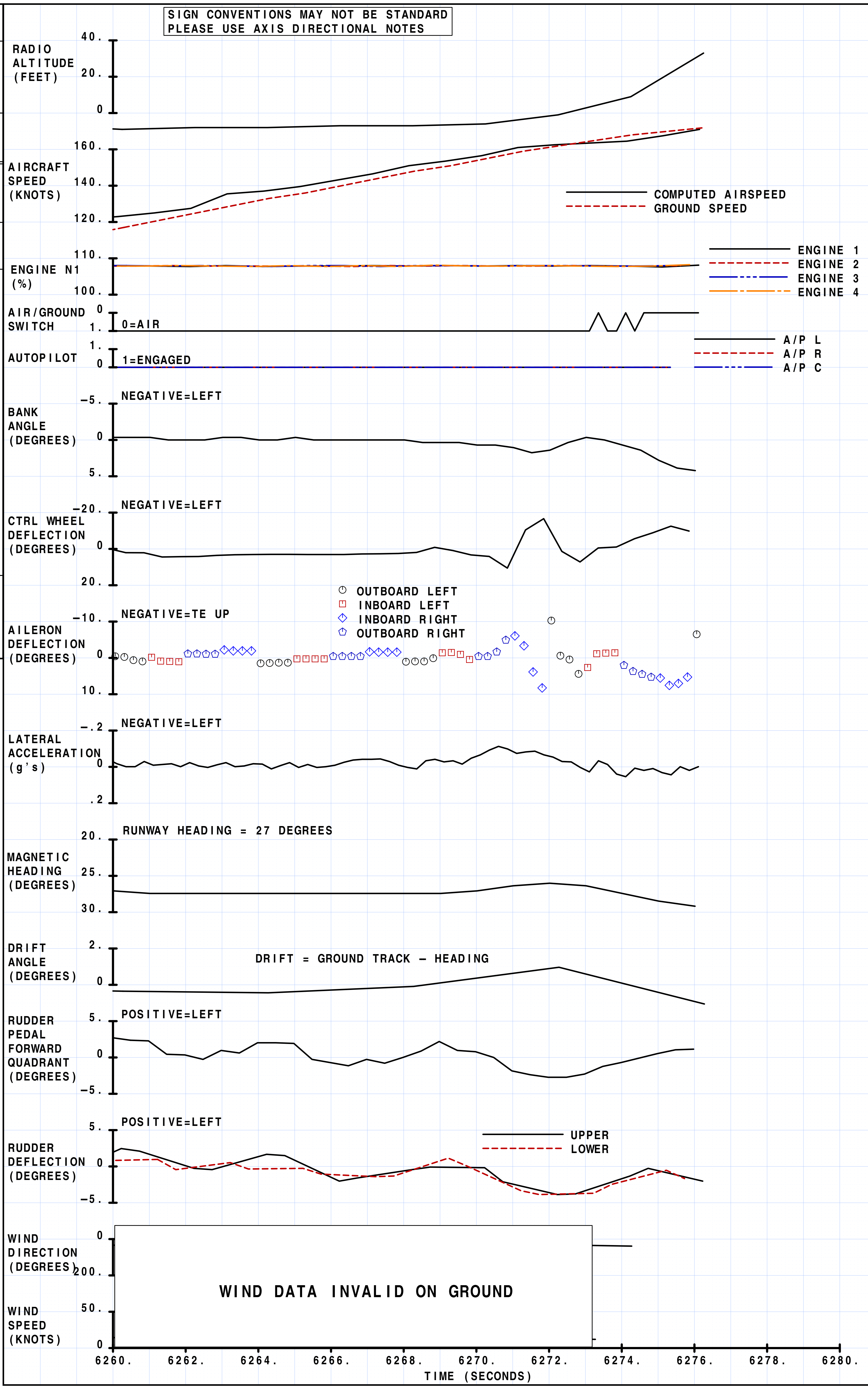

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LONGITUDINAL PARAMETERS, TAKEOFF COMP

RT075

FIGURE 5

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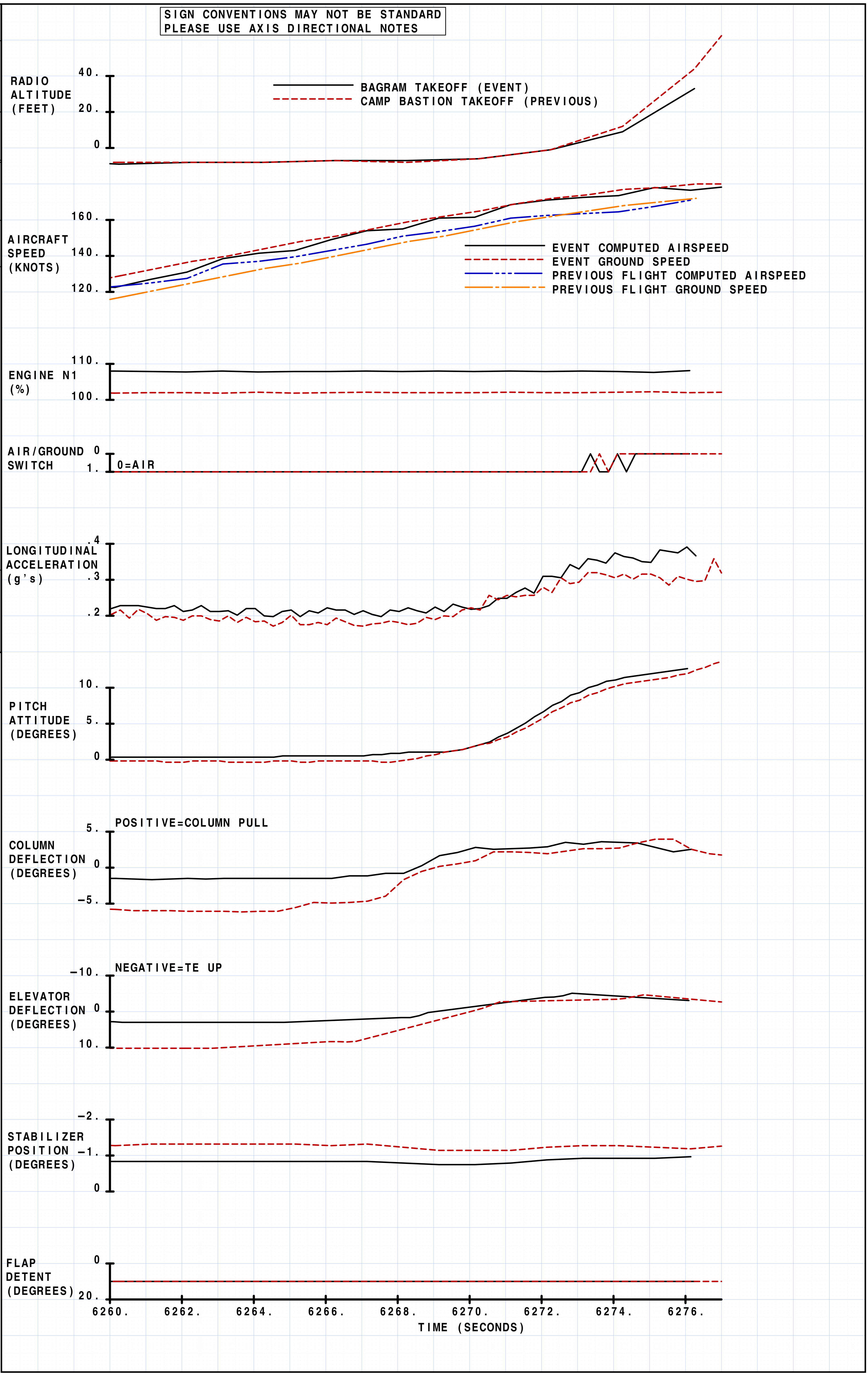

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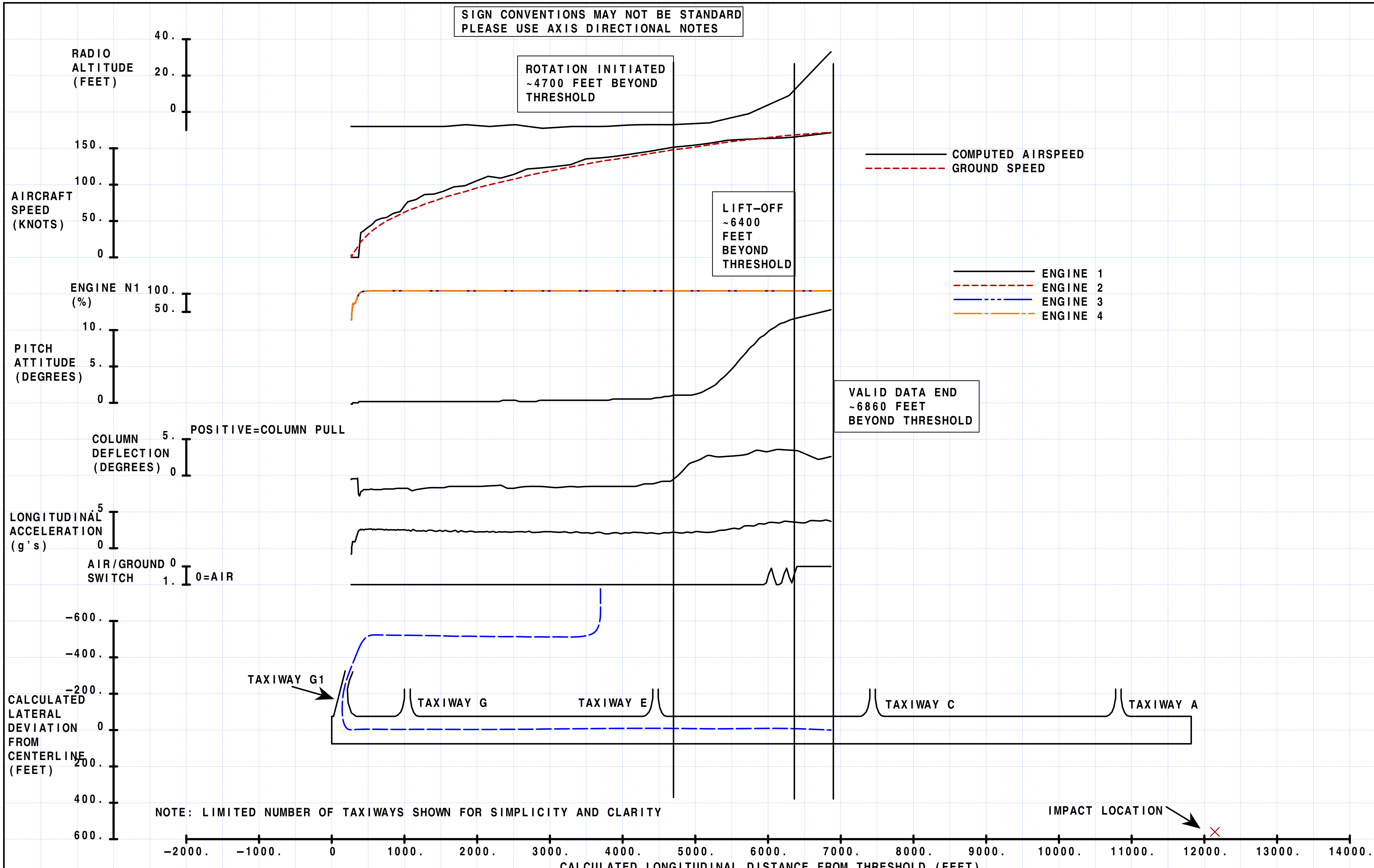

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LONGITUDINAL PARAMETERS, SIM MATCH TO

FIGURE 7 RT075

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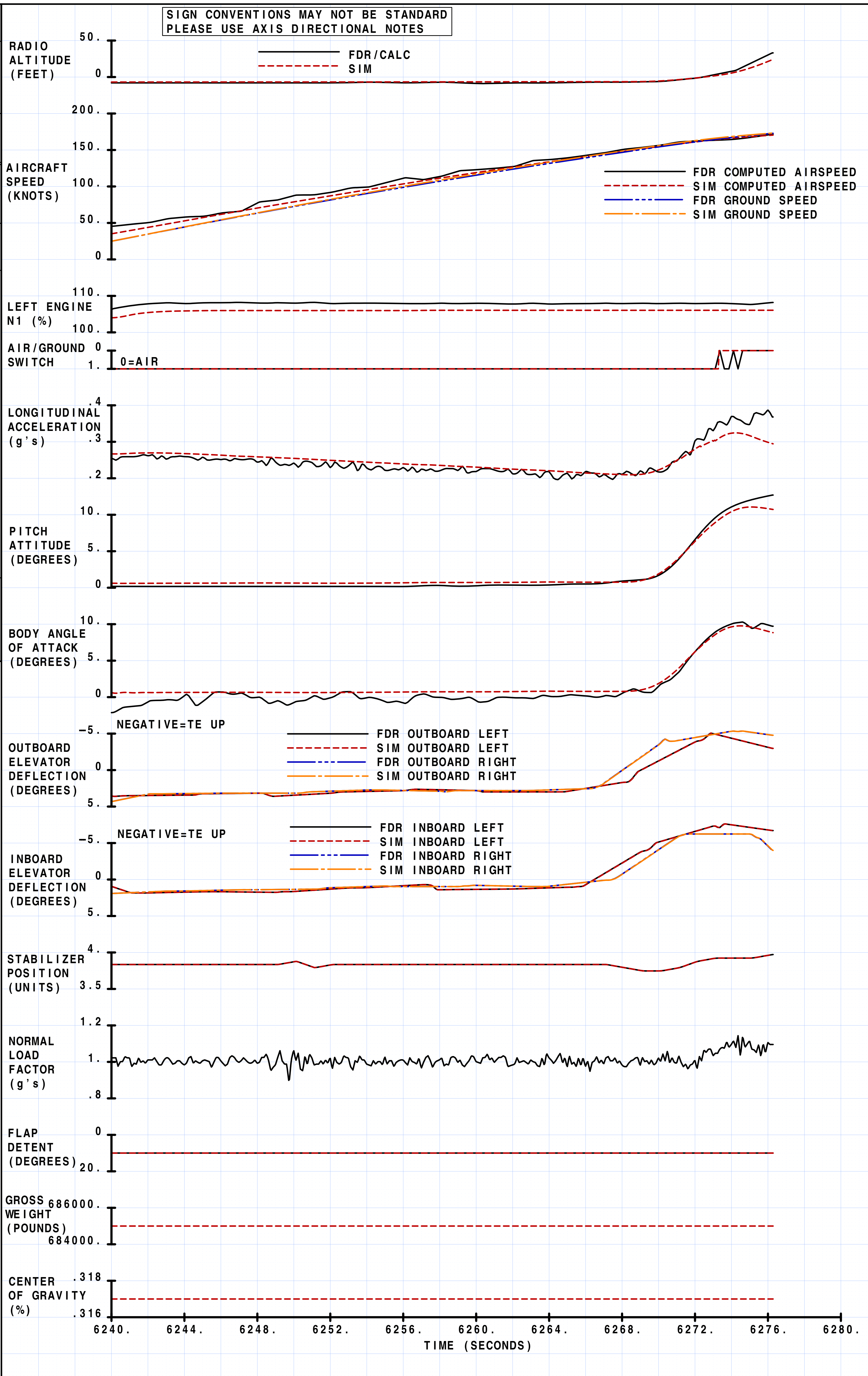

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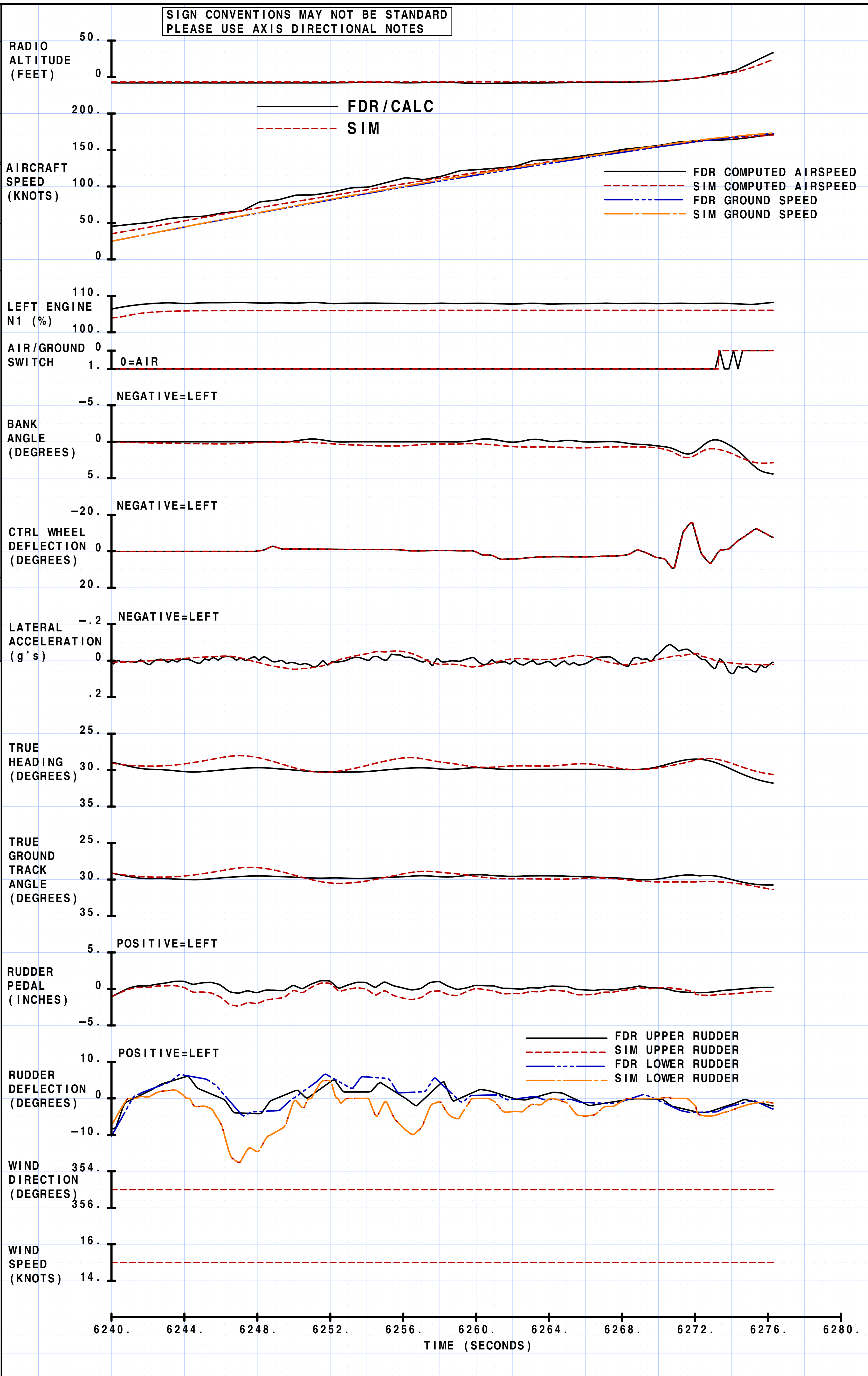

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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LAT-DIR PARAMETERS, SIM MATCH TO

RT075
FIGURE 8
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MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- TIME-ALIGNED FDR DATA
LONG PARAMETERS, SIM MATCH W/ CG SHIFT

FIGURE 9

RT075

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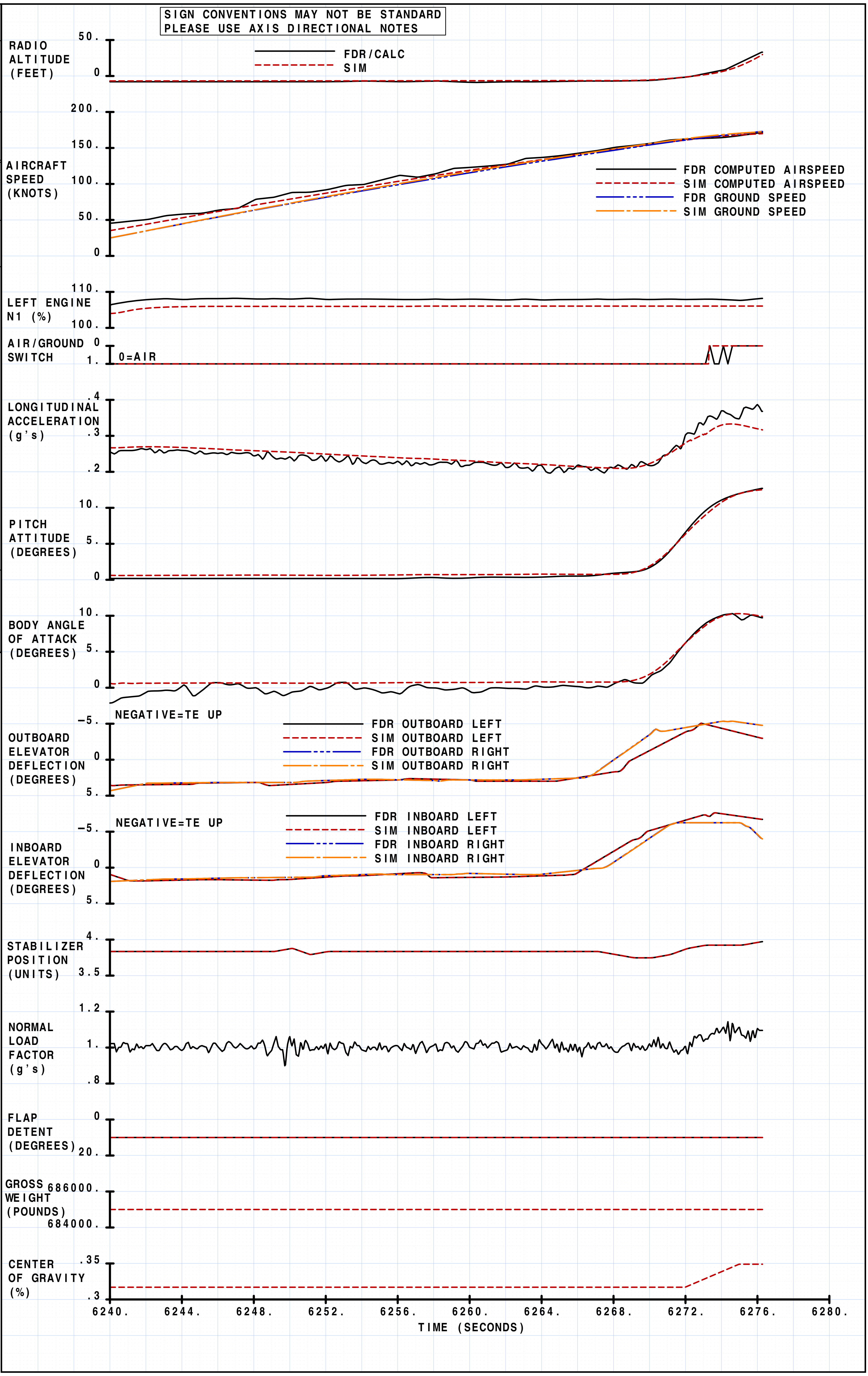

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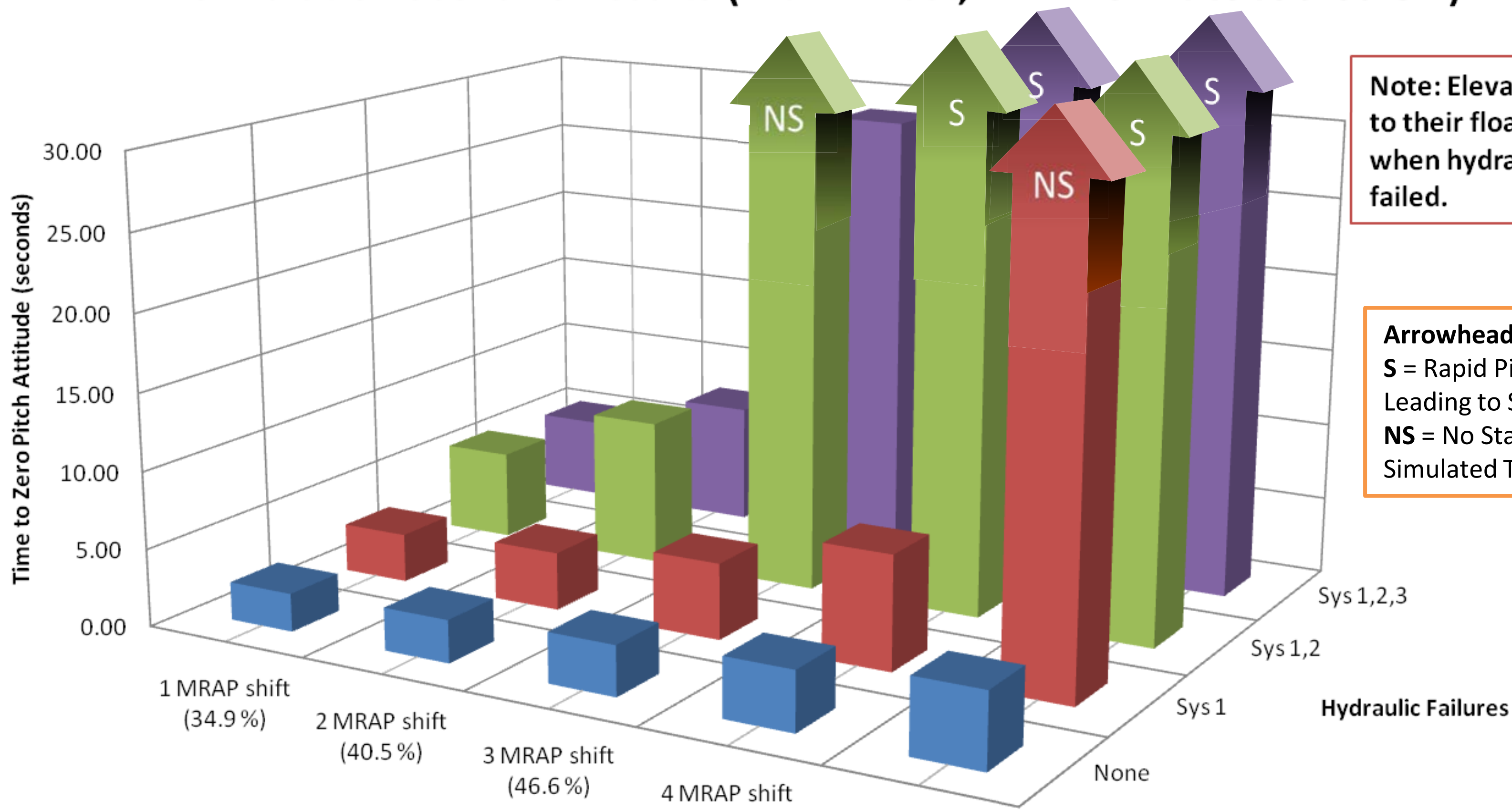
Simulation Scenario Results (Max Thrust, MRAP Shift to Jackscrew)



Note: Elevators move to their float position when hydraulics are failed.

Arrowhead Legend:
S = Rapid Pitch-up Leading to Stall
NS = No Stall Within Simulated Time Period

Thrust = 108 % Engine N1

	1 MRAP shift (34.9 %)	2 MRAP shift (40.5 %)	3 MRAP shift (46.6 %)	4 MRAP shift (51.5 %)	5 MRAP shift (56.0 %)
None	2.46	2.75	3.22	3.81	4.76
Sys 1	3.14	3.74	4.92	7.36	NS
Sys 1,2	5.73	9.46	NS	S	S
Sys 1,2,3	5.24	7.76	28.77	S	S

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APPD					BOEING PROPRIETARY

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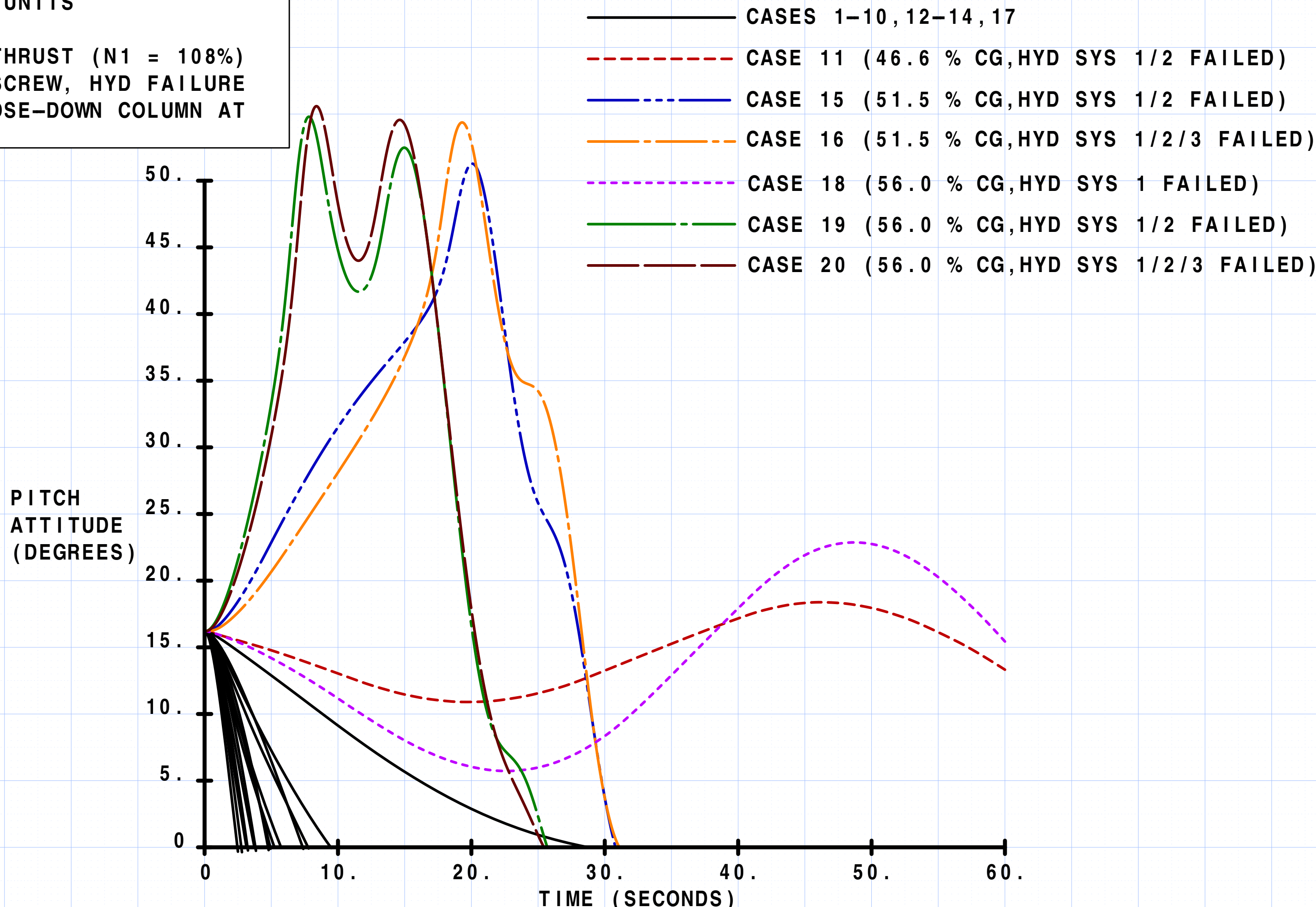
INITIAL AIRPLANE CONFIGURATION:
GROSS WEIGHT = 685,000 LBS
CG = 31.7 %
PRESSURE ALTITUDE = 4950 FEET
COMPUTED AIRSPEED = 177 KNOTS (V2+10)
PITCH ATTITUDE = 16.2 DEGREES
FLAPS 10
STAB SETTING = 4 UNITS
GEAR DOWN
MAXIMUM TAKEOFF THRUST (N1 = 108%)
CG SHIFT TO JACKSCREW, HYD FAILURE (IF ANY), FULL NOSE-DOWN COLUMN AT TIME ZERO



MUA 747-400BCF ACCIDENT AFTER TAKEOFF
29APR13 -- SIMULATION DATA
CG SHIFT/HYD FAILURE STUDY, PITCH ATT.

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FIGURE 11
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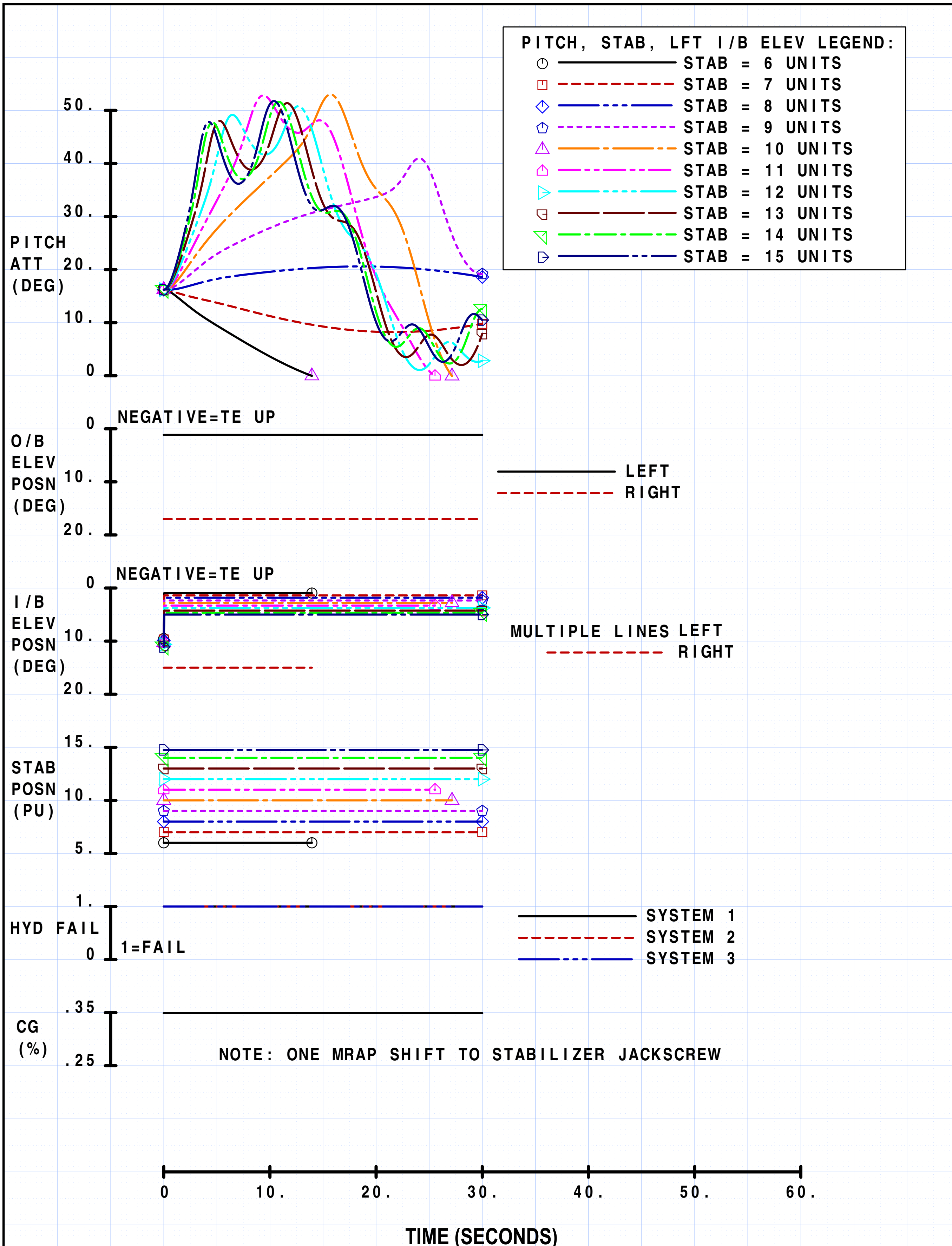

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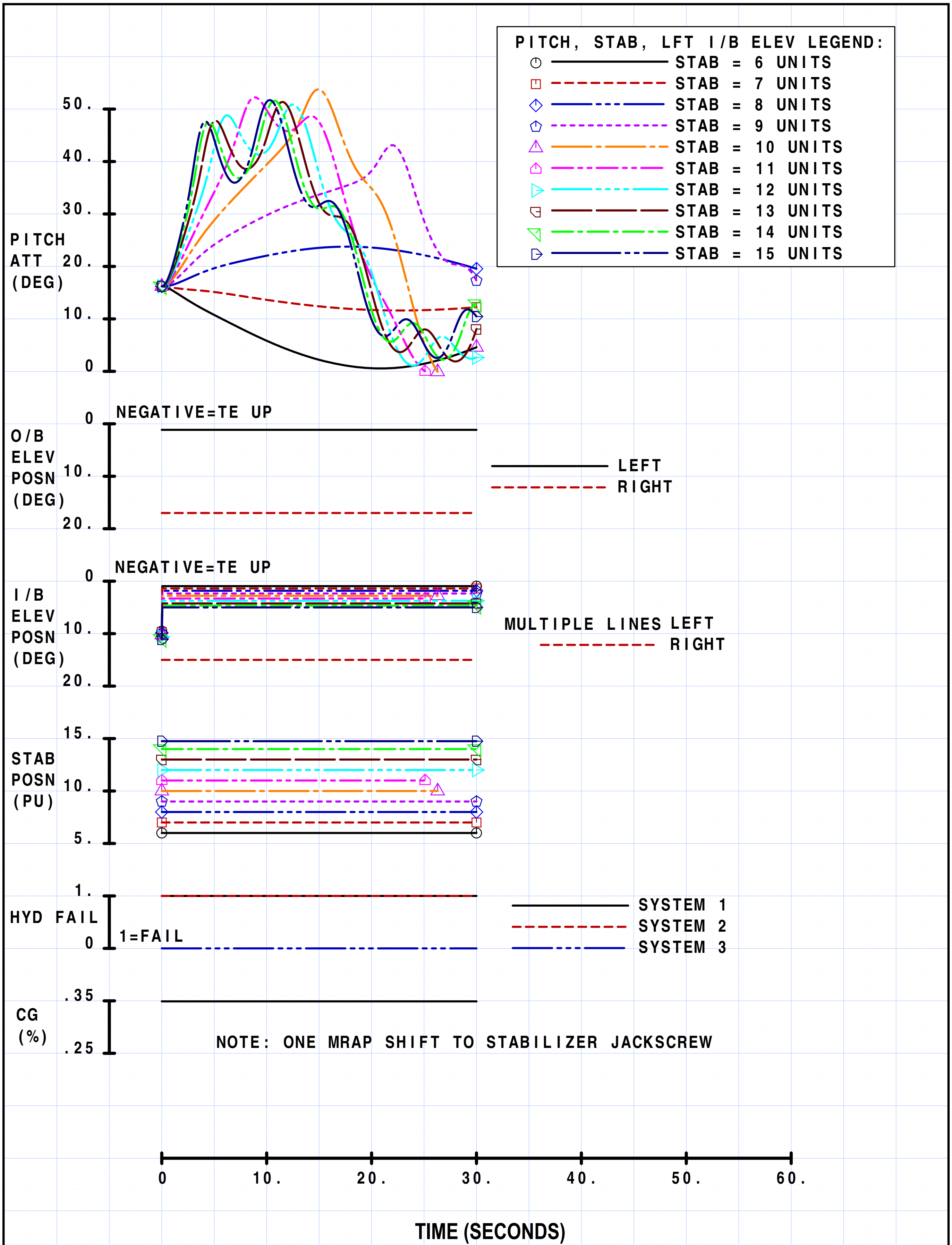

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