NATIONAL TRANSPORTATION SAFETY BOARD

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Study of Autopilot, Navigation Equipment, and Fuel Consumption Activity Based on United Airlines Flight 93 and American Airlines Flight 77 Digital Flight Data Recorder Information

by John O'Callaghan and Daniel Bower, Ph.D.

A. SUBJECT AIRCRAFT

Location:	Arlington, VA
Date:	September 11, 2001
Time:	09:38 AM Eastern Daylight Time
Flight:	American Airlines Flight 77
Aircraft:	Boeing 757-200, registration: N644AA
NTSB#:	DCA01MA064

Location:	Shanksville, PA
Date:	September 11, 2001
Time:	10:03 AM Eastern Daylight Time
Flight:	United Airlines Flight 93
Aircraft:	Boeing 757-200, registration: N591UA
NTSB#:	DCA01MA065

B. GROUP

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C. SUMMARY

This document describes information obtained from the Digital Flight Data Recorders (DFDRs) of the subject aircraft concerning the use of the airplane autoflight and navigation systems both before and after the hijacking events, and presents fuel on board calculations based on the DFDR fuel flow data.

D. AUTOFLIGHT SYSTEMS DESCRIPTION AND ACTIVITY

Numerous parameters on the DFDRs record the status of various autopilot modes and navigation equipment settings. Analysis of these parameters provides some indication of the way the autopilot and navigation equipment was used by those operating the aircraft, both before and after the hijackings.

The Boeing 757 autopilot can control both the vertical movement of the airplane (climbs, level flight, and descents), as well as its horizontal movement (direction of flight). In addition, the autothrottle automatically controls the engine thrust required for different maneuvers. Taken together, the autopilot and autothrottle comprise the “autoflight” system. The manner in which the autoflight system maneuvers the airplane is governed by different autopilot and autothrottle “modes.” In some modes, the autoflight system obtains all the information it needs to fly the airplane from the Flight Management Computer (FMC), which has been pre-programmed (or re-programmed in flight) by the flight crew to fly the desired route at the desired altitudes and speeds. In other modes, the autoflight system obtains required information from the Mode Control Panel (MCP), a set of controls on the instrument panel with which the crew specifies desired headings, altitudes, speeds, and climb or descent rates. In general, more crew interaction is required when the autoflight system is operated from the MCP than from the FMC, because with the MCP each change in flight condition must be initiated by a crew input on the MCP, whereas changes in flight condition can be pre-programmed into the FMC and so will occur automatically in modes that use the FMC for input.

The Flight Director is an instrument that provides pitch and roll guidance to the pilot when flying manually, by displaying “command bars” on the Attitude Direction Indicator (ADI), which is an electronic version of an artificial horizon. The pitch and roll commands issued by the Flight Director, if followed by the flying pilot, will result in a flight path identical to the flight path that would be flown by the autopilot itself. This flight path is a function of the autopilot mode, and the programming of the FMC or values set in the MCP. The autoflight system calculates the pitch and roll maneuvers that will result in the desired flight path; with the autopilot on, the autopilot executes these pitch and roll maneuvers itself. With just the Flight Director on, the system only provides control input guidance to the pilot, and the pilot must make the control inputs, or the airplane will not follow the desired flight path. The Flight Director and autopilot can both be on at the same time, or each can be on independently.

<u>AAL 77 Autoflight Activity</u>

Figure 1 shows a time history of the various autopilot and autothrottle modes engaged on Flight 77, from takeoff from Dulles airport to the end of the DFDR data at impact with the Pentagon. Also shown in the Figure are the values of speeds, altitudes, headings, and Mach that the airplane flew. The values set in the MCP by the pilots (both the American Airlines pilots and the hijack pilots) had a recording error when recorded on the DFDR, and could not be determined.

For most of the flight, until after the hijackers turned the airplane back towards Washington, both the Captain's and First Officer's Flight Directors were on. During the takeoff, the autopilot was off, and the Flight Director was issuing roll commands based on inputs made in the MCP, and pitch commands based on inputs coming alternatively from the FMC (when in VNAV mode) or from the MCP (when in Altitude Hold or Flight Change modes). Once the flight was cleared to its 35,000 ft. cruising altitude, the autopilot was engaged in LNAV and VNAV modes, which use inputs from the FMC to guide the airplane along the desired horizontal and vertical flight path. During the ascent, and while at the cruise altitude, the right (First Officer's) autopilot was engaged, and heading select mode was used to maneuver the airplane horizontally.

The autothrottle was engaged throughout the initial part of the flight. During the climb the autothrottle mode varied between climb thrust mode, airspeed hold mode, flight level change mode, and Mach mode. Upon reaching the cruise altitudes, first at 33,000 feet, then 35,000 feet, the autothrottle switched to a Mach number hold cruise mode, applying thrust to achieve a Mach number of 0.83.

A few minutes after the hijackers took control of the cockpit (at approximately 08:52), the horizontal mode was changed to a heading select and the airplane began a 180-degree turn back towards Washington. After the new heading was selected, and up until the last nine minutes of the flight, the autopilot operated in modes that receive inputs from the MCP (i.e., target values of altitude, speed, and heading set directly by the operators of the aircraft) rather than from the FMC. The autopilot was off for the last eight minutes of the flight. For the remainder of the flight, the horizontal mode remained in heading select and the vertical mode was operated in altitude hold, altitude, or flight level change mode. Similarly, the autothrottle remained in either airspeed mode or mach mode, except during times of flight level changes.

At about 09:08, after a flight level change was initiated from 25,000 feet, the First Officer's flight director, the autopilot, and the autothrottle all disengaged. This disengagement was concurrent with a right (First Officer's) autopilot warning. The autopilot remained off for approximately two minutes, and then re-engaged on the left side (Captain's side). The autopilot disengaged again, concurrent with an autopilot warning on the left side. After about a half a minute of disengagement, the left autopilot was re-engaged and the autothrottle was re-engaged soon after. Over the next ten minutes, the autothrottle was engaged and disengaged several times, while the aircraft remained at 25,000 feet, until remaining engaged in the flight level change mode during descent from 25,000 feet.

At approximately 9:29, while at an altitude of 7000 feet and approximately 30 nautical miles from Washington Reagan National Airport, the autopilot and autothrottle were disengaged. These remained off during the 360-degree, descending turn to impact with the Pentagon.

UAL 93 Autoflight Activity

Figure 2 shows a time history of the various autopilot and autothrottle modes engaged on Flight 93, from takeoff from Newark to the end of the DFDR data at impact. Also shown in the Figure are the values of speeds, altitudes, headings, and climb/descent rates set in the MCP, along with the values of those parameters that the airplane actually flew.

For most of the flight, until shortly after the hijackers took control of the cockpit (at approximately 09:30), both the Captain's and First Officer's Flight Directors were on. During the takeoff, the autopilot was off, and the Flight Director was issuing roll commands based on inputs made in the MCP, and pitch commands based on inputs coming alternatively from the FMC (when in VNAV mode) or from the MCP (when in Altitude Hold or Flight Change modes). Once the flight was cleared to its 35,000 ft. cruising altitude, the autopilot was engaged in LNAV and VNAV modes, which use inputs from the FMC to guide the airplane along the desired horizontal and vertical flight path.

The autothrottle was engaged throughout the flight. During the climb the autothrottle mode varied between climb thrust mode, airspeed hold mode, and flight level change mode. Upon reaching the 35,000 cruise altitude, the autothrottle switched to a Mach number hold cruise mode, applying thrust to achieve a Mach number of 0.82.

At about 09:33, the autoflight modes started to change. Both the Captain and First Officer's flight directors were turned off, and at about 09:34 the autopilot was turned off briefly. After the autopilot was reengaged (less than a minute later), up until the last three minutes of the flight it operated in modes that receive inputs from the MCP (i.e., target values of altitude, speed, heading, and descent rate set directly by the operators of the aircraft) rather than from the FMC. The autopilot was off for the last three minutes of the flight.

The autothrottle switched from a Mach hold mode to an airspeed hold mode at about 9:33:30, and remained in this mode for the remainder of the flight, except for brief periods where the airspeed was either below or above pre-set limits and the autothrottle adjusted thrust in an attempt to correct the situation (these are the MIN SPD and SPD LIMIT modes).

From 09:33 to the time the autopilot was turned off (about 10:00), the airplane was maneuvered horizontally via the heading select and heading hold modes, with the desired heading set on the MCP. The bottom graph in Figure 2 shows the magnetic heading selected in the MCP was 120 degrees, and also shows the airplane turning towards that heading. From the airplane's position at this point, a magnetic heading of 120 degrees would put the airplane on course for Washington, D.C.. At 09:57, the heading selected in the MCP is changed to 90 degrees. About half a minute later, the autopilot switches from heading hold to heading select modes, and the airplane turns to the 90 degree heading selected in the MCP.

From 09:33 to the time the autopilot was turned off, the airplane was maneuvered vertically using the vertical speed and altitude hold modes. In the vertical speed mode, the desired rate of climb or descent is set in the MCP. In altitude hold mode, the airplane maintains the altitude at which the altitude hold mode button on the MCP is pressed. As shown in Figure 2, initially the vertical speed selected was about +1,500 ft/min, and the airplane climbed accordingly. Interestingly, at the same time, the altitude selected in the MCP was 9,600 feet (lower than the current airplane altitude). At about 09:38 the autopilot entered altitude hold mode at 40,700 feet. A couple of minutes later, the autopilot re-entered vertical speed mode, with a descent rate of -4,200 feet/minute selected in the MCP, and the airplane started to descend. At about 09:47, this descent rate in the MCP was adjusted to about -1,300 feet/minute. At around the same time, the altitude set in the MCP was adjusted to about 5,000 feet. This suggests that the intent of the operators may have been to descend to 5,000 feet.

At about 10:00, the autopilot was turned off, and remained off for the remaining three minutes of the flight.

D. NAVIGATION SYSTEMS DESCRIPTION AND ACTIVITY

The Boeing 757 keeps track of its own position using the Inertial Navigation System (INS), which uses acceleration sensors to calculate the motion of the airplane over the ground. The INS position calculation is periodically updated and corrected using data from ground based radio navigation stations, called “very high frequency omnirange stations” (VORs). By tuning a receiver to the signals broadcast from a VOR, the bearing from the airplane to the VOR can be determined. Tuning in two or more stations and knowing the positions of each, a fix of the airplane position can be obtained.

The 757 has two VOR receivers. The crew can manually tune each of these receivers to a desired station (provided the station is in range), and view the airplane’s bearing relative to the station on a special display mode on the Electronic Horizontal Situation Indicator (EHSI). This mode is most often used when the crew wants to fly either towards or away from the selected VOR station, along a specific bearing or “radial” to or from the station. In other modes, the airplane will automatically tune in VOR stations along the airplane’s route in order to obtain position fixes. The system generally selects stations whose bearings from the airplane differ by about 90 degrees; this configuration results in the most accurate position fixes.

AAL 77 Navigation System Activity

Figure 3 shows the VOR stations tuned to by the two VOR receivers on American Flight 77. The EFIS mode determines the type of display shown on the EHSI. During the initial part of the flight, the EFIS is in “MAP” mode. In this mode, the EHSI displays an airplane symbol pointed towards the top of the display, with the magnetic heading and track shown in a partial compass rose at the top of the display. Various points of interest - VOR stations, fixes, airports, and so on - can be displayed in their correct position relative to the airplane. The planned and projected route of flight can also be displayed in the MAP mode. The range of the MAP mode can be adjusted from 5 miles to 160 nautical miles, depending on the detail or scale of map required. At about 09:08:20, the display switched to VOR mode; in this mode, the EHSI displays the airplane’s angular deviation or position relative to a specified radial from the selected VOR.

The points during the flight at which the VOR receivers were tuned to new frequencies are shown on the map in Figure 2 as yellow diamonds. The points shown occur after the hijackers took control of the cockpit. Lines from the airplane flight path to the stations indicate the VOR stations tuned by the left and right VOR receivers. The point on the flight path from which the lines originate are the points at which the station was first tuned, i.e., the points at which the VOR station frequency selected by each receiver changed.

Note that while the EFIS was initially in MAP mode, the left and right VOR receivers were tuned to stations whose bearings from the airplane differed by about 90 degrees, at the time at which the VOR station pairs were changed. This illustrates the method the system uses for obtaining VOR position fixes to update the INS.

During the turn back to the east, the frequency of the right VOR receiver was set to 111.0 MHz, corresponding to the VOR station located at Washington Reagan National Airport (DCA). At the time the DCA frequency was selected, the station was too far away for its signals to be received by the receiver. The right VOR receiver remained tuned to the DCA VOR for the remainder of the flight, except for a 1-minute period at 9:15. The left VOR receiver was tuned to various frequencies, but was tuned to 113.5 (AML in Herndon, VA near Dulles Airport) at approximately 9:08. At approximately 9:18, the left distance measuring equipment (DME) began receiving information from the AML VOR. After receiving the DME signal, the airplane remained on a constant heading towards the Washington area. At 9:32, both VOR receivers were tuned to the DCA VOR.

UAL 93 Navigation System Activity

Figure 4 shows the VOR stations tuned to by the two VOR receivers on United Flight 93. At the bottom of the Figure, the EFIS mode is shown. For most of the fight, the EFIS is in “MAP” mode.

As in Figure 3, the points during the flight at which the EFIS mode switched to MAP mode and then to VOR mode are shown on the map in Figure 4 as yellow diamonds. The VOR stations tuned by the left and right VOR receivers are indicated by lines from the airplane flight path to the stations. The point on the flight path from which the lines originate are the points at which the station was first tuned.

As with Flight 77, while the EFIS was in MAP mode, the left and right VOR receivers were tuned to stations whose bearings from the airplane differed by about 90 degrees, at the time at which the VOR station pairs were changed. Again, this illustrates the method the system uses for obtaining VOR position fixes to update the INS.

Shortly after the EFIS was switched to VOR mode, the frequency of the left VOR receiver was set to 111.0 MHz, corresponding to the VOR station located at Washington Reagan National Airport (DCA). At the time the DCA frequency was selected, the station was too far away for its signals to be received by the receiver. If DCA VOR had been in range, the display on the EHSI could have been used to show the airplane's position relative to an inbound radial to DCA, and thus help navigate the airplane towards DCA. The selection of the DCA VOR frequency in the airplane's left VOR receiver suggests that the operators of the airplane had an interest in DCA, and may have wanted to use that VOR station to help navigate the airplane towards Washington.

The magnetic heading of 120 degrees selected in the autopilot MCP was the correct heading for flying to Washington. However, even though the EFIS was in the MAP mode at the time, it was in the 80 nautical mile range setting, and so would not have shown DCA on the display; consequently, it is unlikely that the hijackers used the map display on the EHSI to deduce the correct heading for Washington. It follows that the hijackers had some other means of obtaining this heading.

A surprising element in the navigation of flight 93 is the rapid descent from cruise altitudes while still approximately 260 nautical miles from the (presumed) target. If the hijacker's destination was Washington, they started their descent very prematurely. Figure 5 compares the descent profiles of all four airplanes hijacked on September 11. Note that by the time AAL 11, UAL 175, and AAL 77 descended below 5,000 feet, they were all within 10 NM of their targets. UAL 93, on the other hand, descended to 5,000 feet while still 135 NM from Washington.

E. FUEL CONSUMPTION AND FUEL REMAINING CALCULATIONS

<u>AAL 77 Fuel Consumption</u>

Figure 6 shows AAL flight 77's fuel flow to each engine as recorded by the DFDR, and the sum of these, equal to the total fuel flow. By integrating the total fuel flow with time, the amount of fuel consumed throughout the flight can be calculated. Subtracting the fuel consumed from the initial fuel load then gives the amount of fuel remaining, as shown in the bottom plot of Figure 6.

Based on ACARS transmissions to the airplane, the fuel load on the airplane when on the ramp was 48983 lbs. This results in about 36,200 lb. of fuel remaining upon impact with the Pentagon (the end of the DFDR data).

UAL 93 Fuel Consumption

Figure 7 shows fuel flow and fuel remaining for UAL Flight 93, calculated in the same way as just described for AAL Flight 77.

Based on ACARS transmissions to the airplane, the fuel load on takeoff was 48,700 lb. This results in about 37,500 lb. of fuel remaining upon impact (the end of the DFDR data). If instead of descending to about 5,000 feet over Pennsylvania, Flight 93 had continued cruising at 35,000 feet to Washington, it would have arrived over Washington with about 35,500 lb. of fuel on board.

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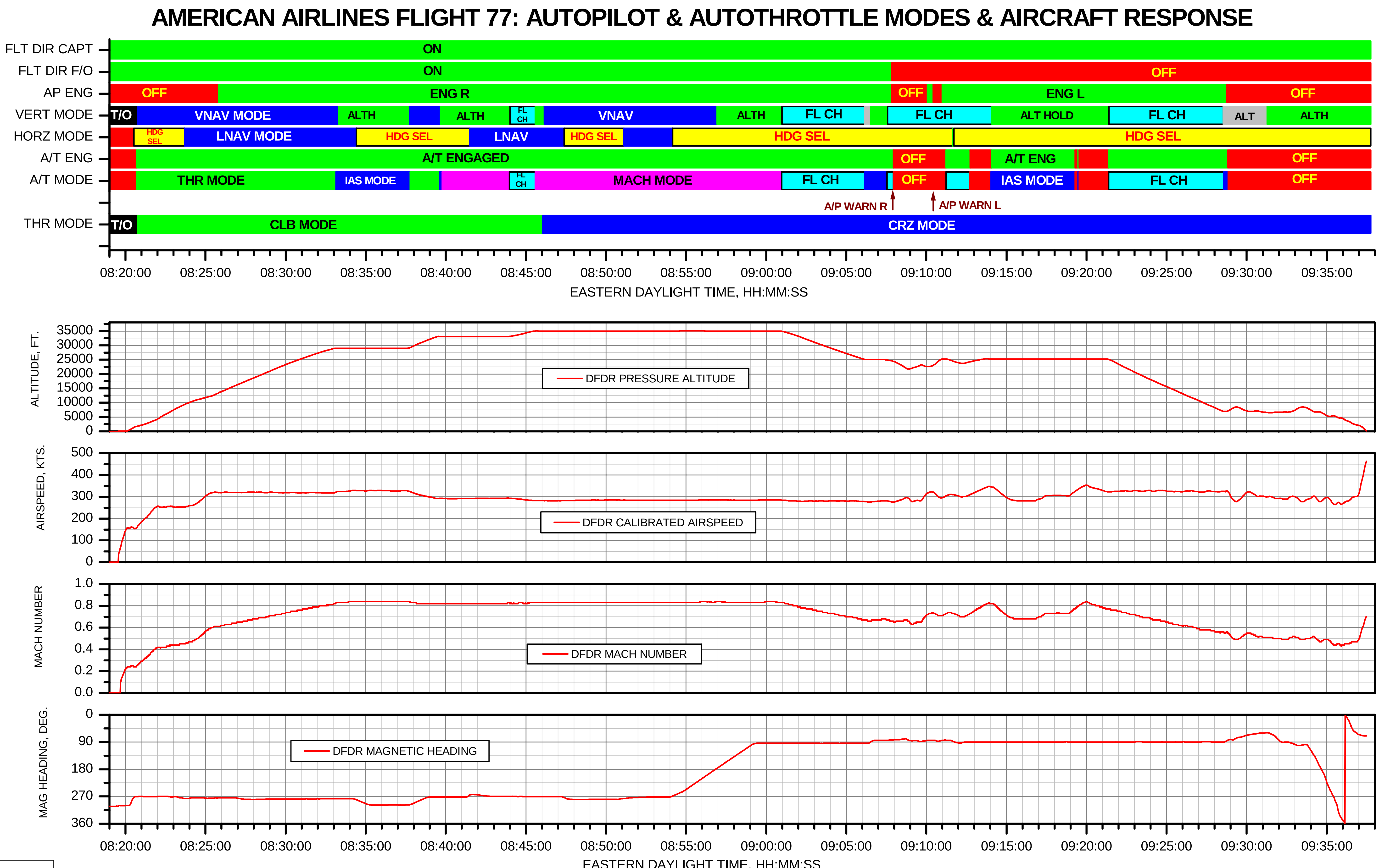

AMERICAN AIRLINES FLIGHT 77: AUTOPILOT & AUTOTHROTTLE MODES & AIRCRAFT RESPONSE
FLT DIR CAPT
FLT DIR F/O
AP ENG
VERT MODE
HORZ MODE
A/T ENG
A/T MODE
THR MODE
ON
OFF
ENG R
ENG L
T/O
VNAV MODE
ALTH
FL CH
VNAV
ALT HOLD
ALT
HDG SEL
LNAV MODE
LNAV
A/T ENGAGED
A/T ENG
THR MODE
IAS MODE
MACH MODE
A/P WARN R
A/P WARN L
CLB MODE
CRZ MODE
EASTERN DAYLIGHT TIME, HH:MM:SS
08:20:00
08:25:00
08:30:00
08:35:00
08:40:00
08:45:00
08:50:00
08:55:00
09:00:00
09:05:00
09:10:00
09:15:00
09:20:00
09:25:00
09:30:00
09:35:00
ALTITUDE, FT.
DFDR PRESSURE ALTITUDE
AIRSPEED, KTS.
DFDR CALIBRATED AIRSPEED
MACH NUMBER
DFDR MACH NUMBER
MAG HEADING, DEG.
DFDR MAGNETIC HEADING

Figure 1

UNITED AIRLINES FLIGHT 93: AUTOPILOT & AUTOTHROTTLE MODES & AIRCRAFT RESPONSE

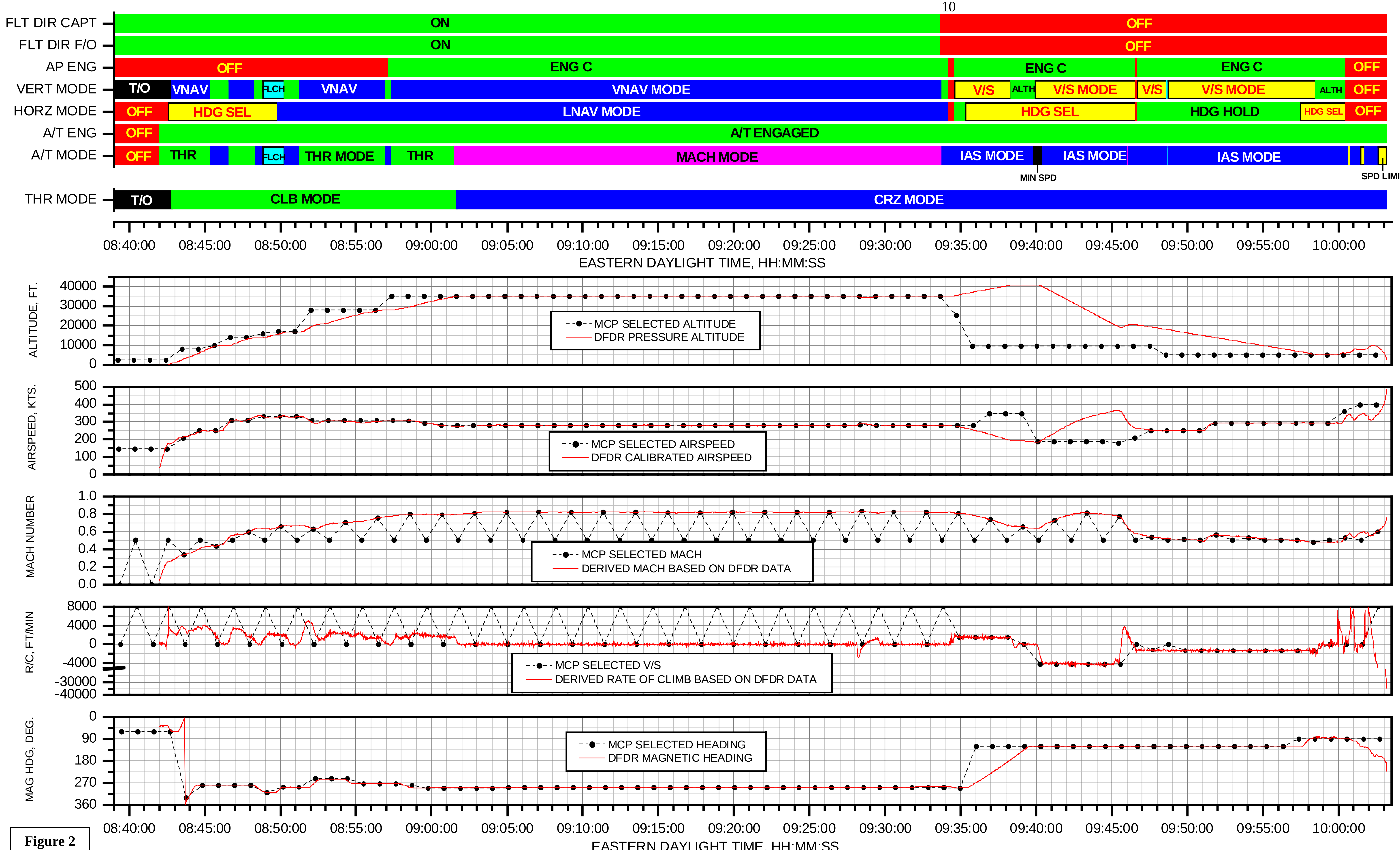


Figure 2

American Airlines Flight 77 - VOR/DME Activity

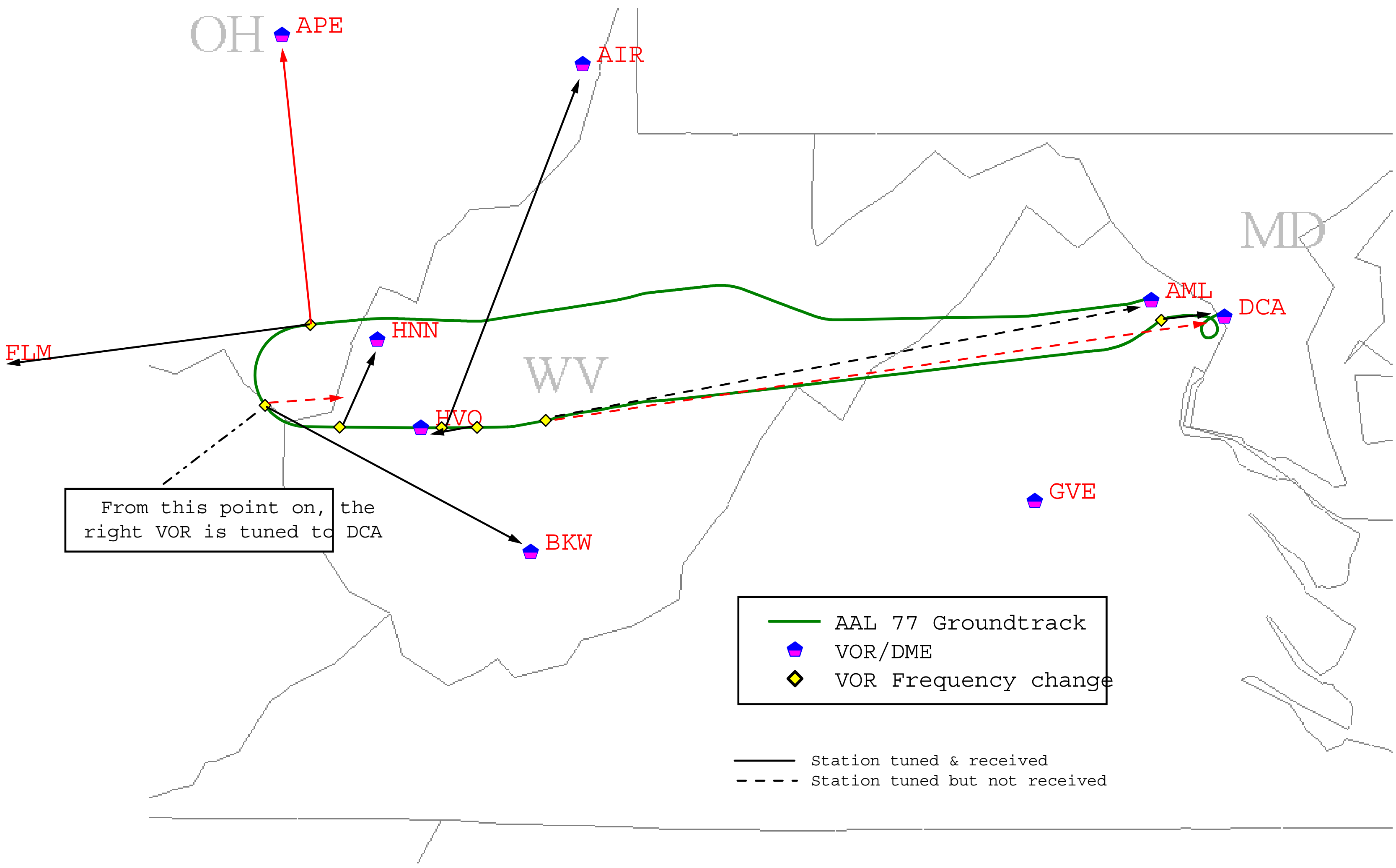


Figure 3

United Airlines Flight 93 - VOR/DME & EFIS Activity

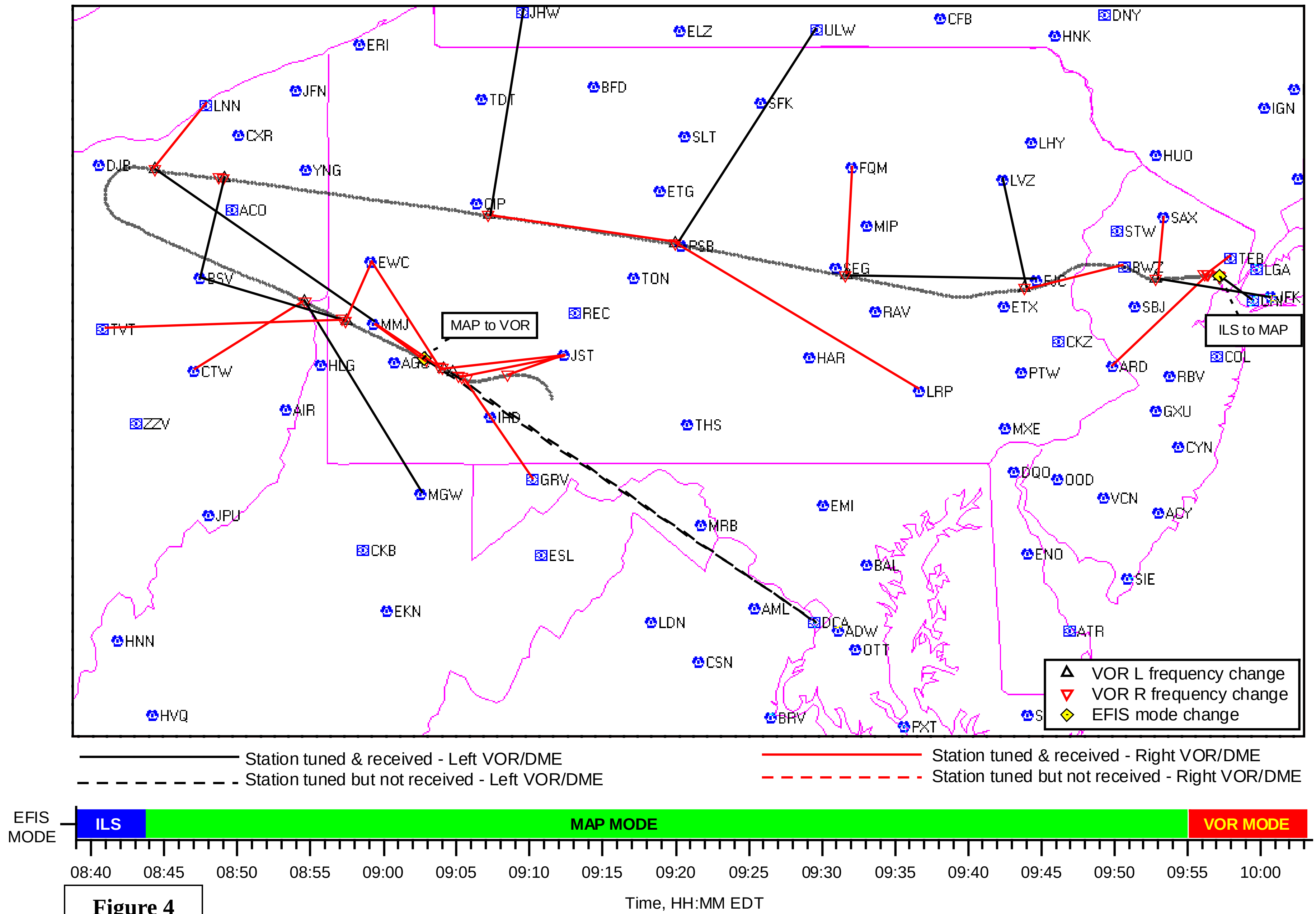
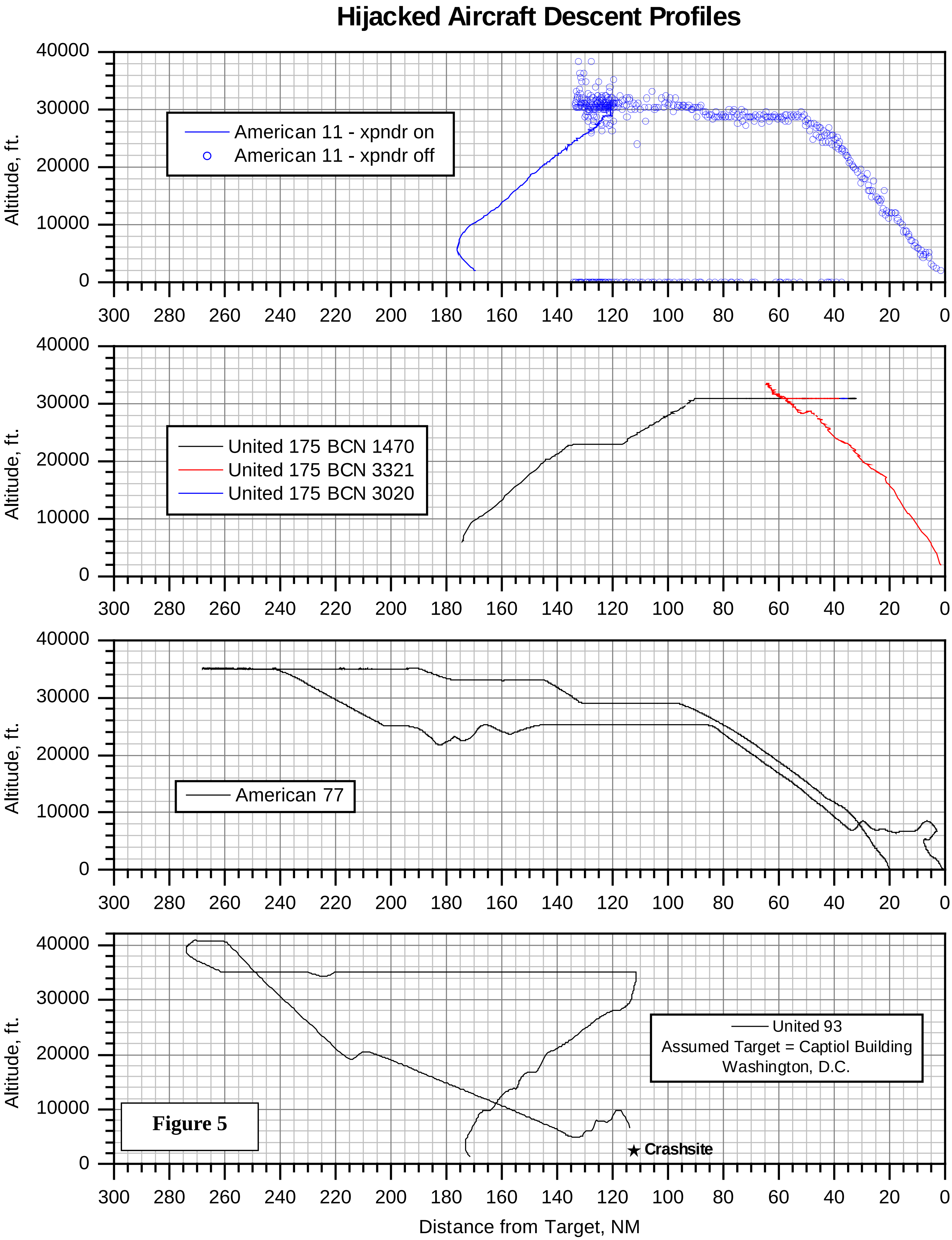
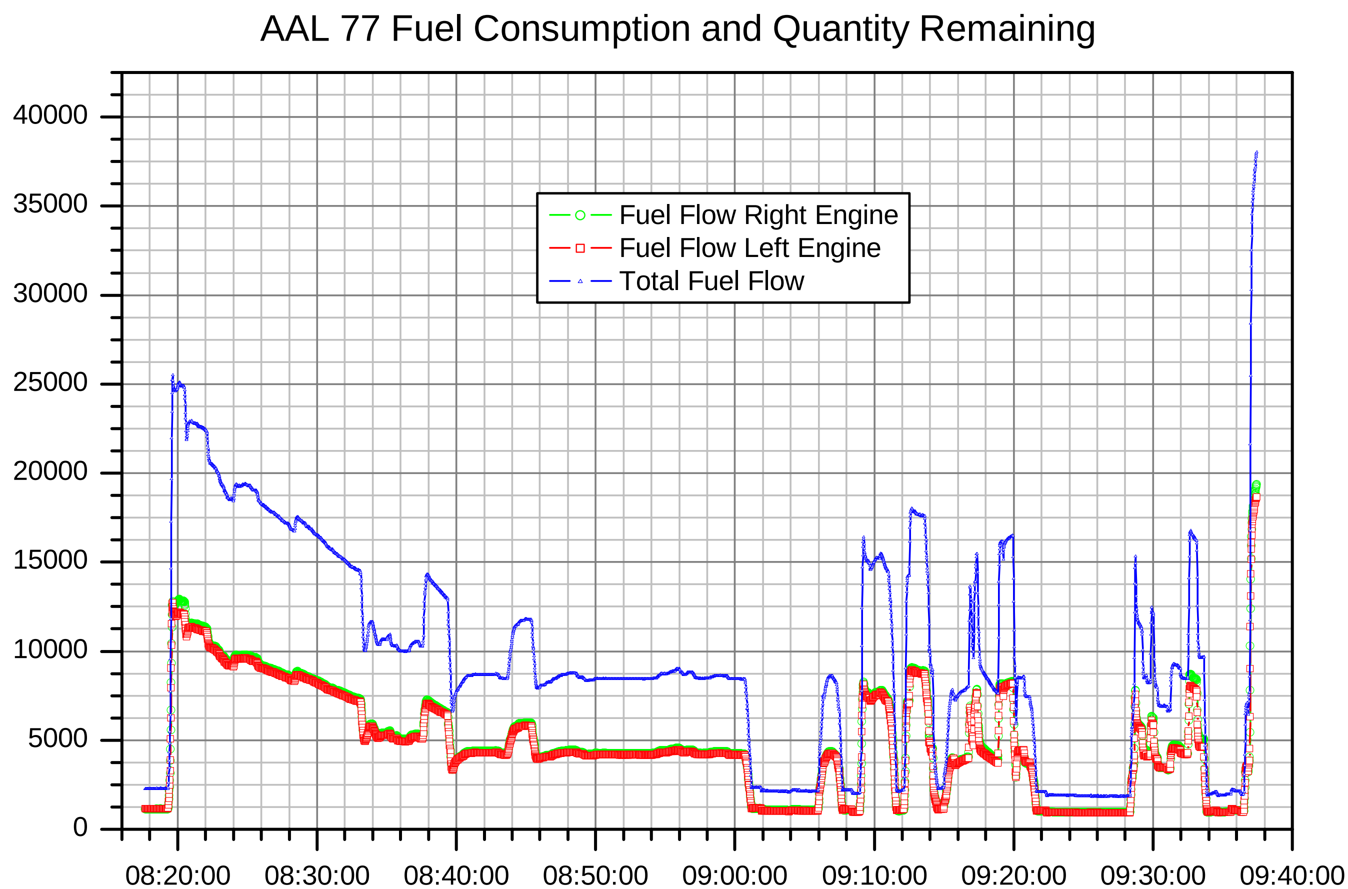
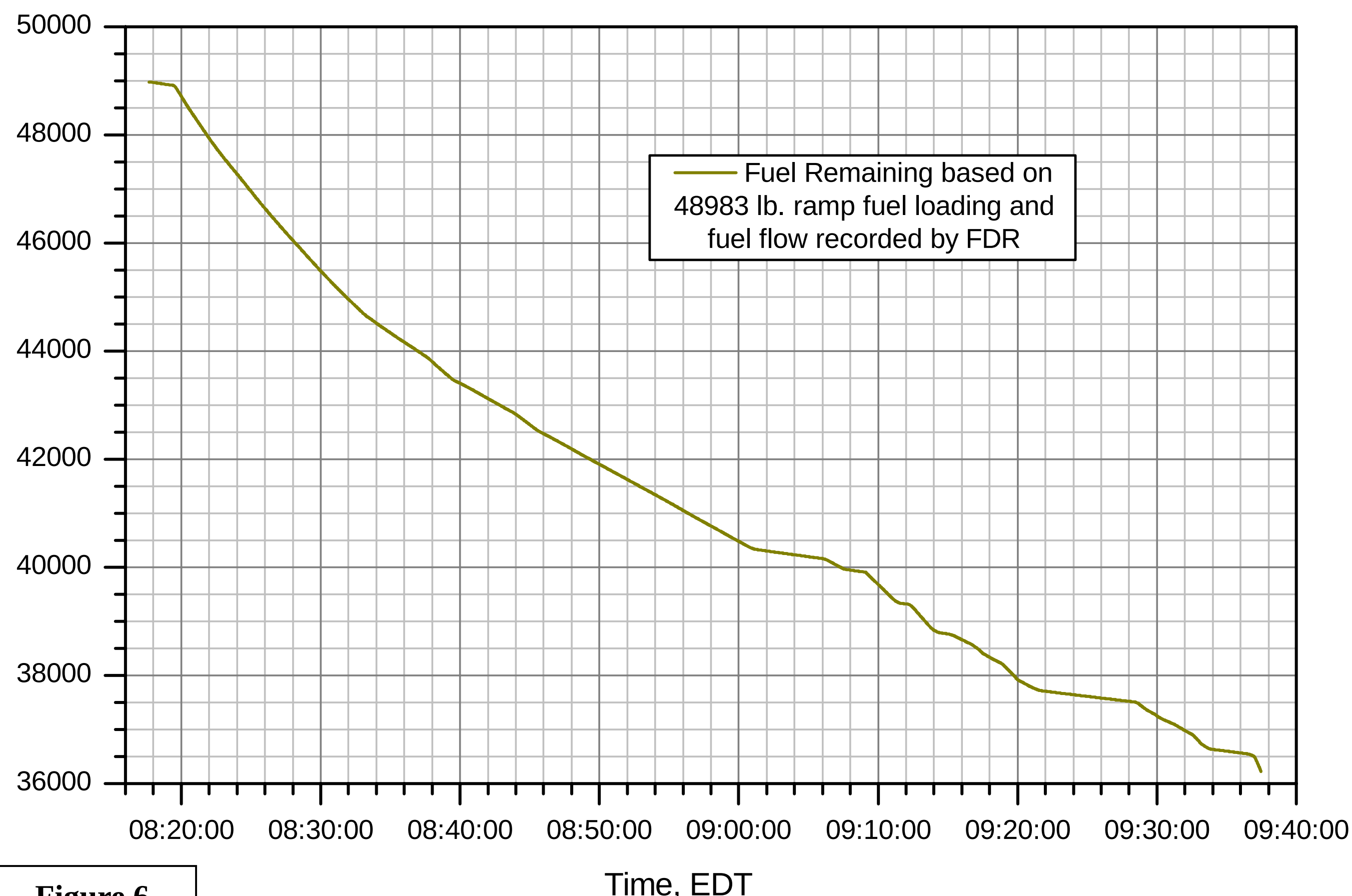


Figure 4


Hijacked Aircraft Descent Profiles
Altitude, ft.
American 11 - xpndr on
American 11 - xpndr off
United 175 BCN 1470
United 175 BCN 3321
United 175 BCN 3020
American 77
United 93
Assumed Target = Captiol Building
Washington, D.C.
Figure 5
★ Crashsite
Distance from Target, NM
0
10000
20000
30000
40000
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0

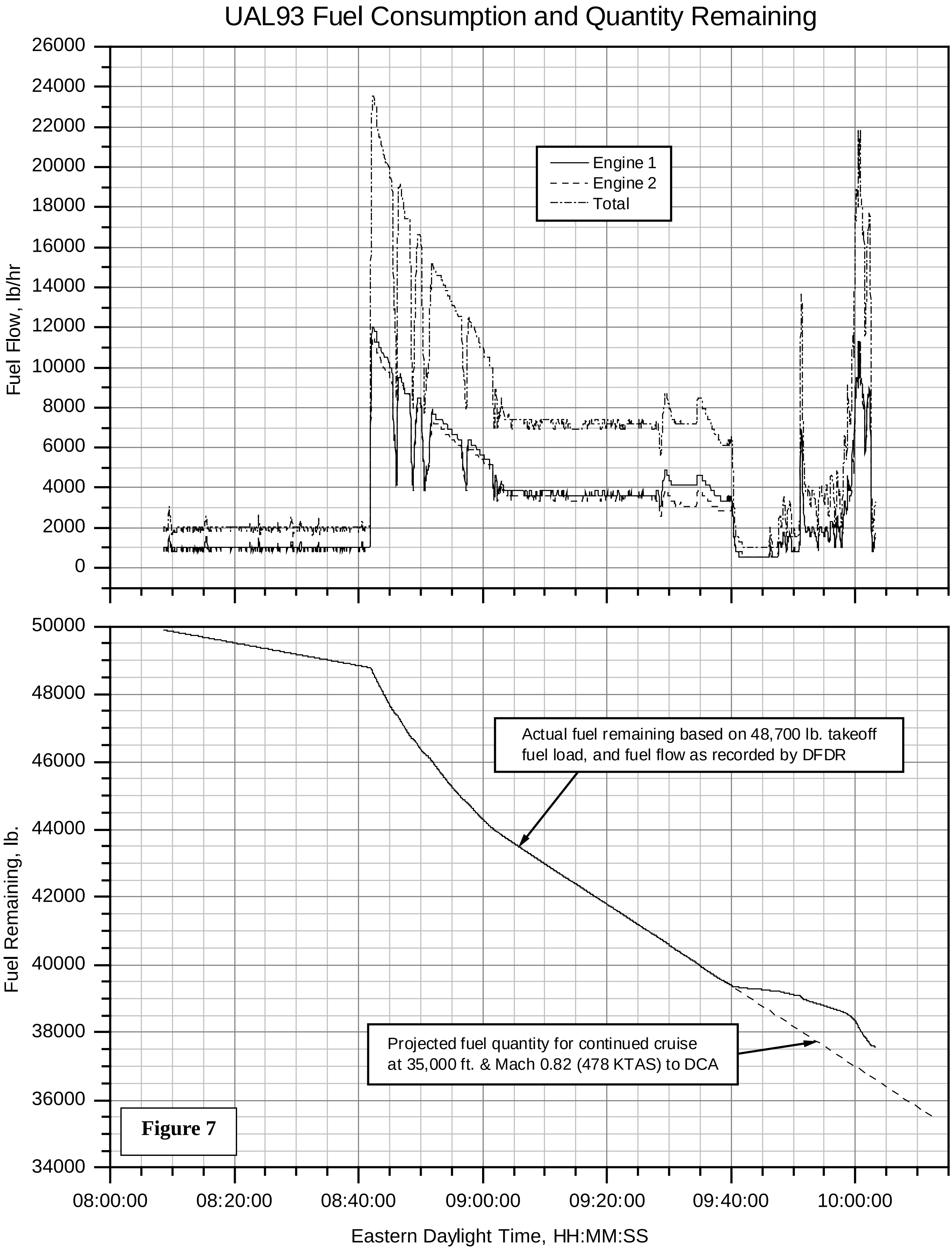


AAL 77 Fuel Consumption and Quantity Remaining
Fuel Flow Right Engine
Fuel Flow Left Engine
Total Fuel Flow
40000
35000
30000
25000
20000
15000
10000
5000
0
08:20:00
08:30:00
08:40:00
08:50:00
09:00:00
09:10:00
09:20:00
09:30:00
09:40:00



Fuel Remaining based on 48983 lb. ramp fuel loading and fuel flow recorded by FDR
50000
48000
46000
44000
42000
40000
38000
36000
08:20:00
08:30:00
08:40:00
08:50:00
09:00:00
09:10:00
09:20:00
09:30:00
09:40:00
Time, EDT

Figure 6



UAL93 Fuel Consumption and Quantity Remaining
Engine 1
Engine 2
Total
Fuel Flow, lb/hr
26000
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Fuel Remaining, lb.
50000
48000
46000
44000
42000
40000
38000
36000
34000
Actual fuel remaining based on 48,700 lb. takeoff fuel load, and fuel flow as recorded by DFDR
Projected fuel quantity for continued cruise at 35,000 ft. & Mach 0.82 (478 KTAS) to DCA
08:00:00
08:20:00
08:40:00
09:00:00
09:20:00
09:40:00
10:00:00
Eastern Daylight Time, HH:MM:SS

Figure 7