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NASA B737 Flight Test Results of the Total Energy Control System

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16. Abstract

The Total Energy Control System (TECS) is an integrated autopilot/autothrottle developed by BCAC that was test flown on NASA Langley's Transport System Research Vehicle (i.e., a highly modified Boeing B737). This system was developed using principles of total energy in which the total kinetic and potential energy of the airplane was controlled by the throttles, and the energy distribution controlled by the elevator.

TECS integrates all the control functions of a conventional pitch autopilot and autothrottle into a single generalized control concept. This integration provides decoupled flightpath and maneuver control, as well as a coordinated throttle response for all maneuvers. A mode hierarchy was established to preclude exceeding airplane safety and performance limits.

The flight test of TECS took place as a series of five flights over a 33-week period during September 1985 at NASA Langley. Most of the original flight test plan was completed within the first three flights with the system not exhibiting any instabilities or design problems that required any gain adjustment during flight.

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1.0 SUMMARY

The Total Energy Control System (TECS) is an integrated autopilot/autothrottle developed by BCAC that was test flown on NASA Langley's Transport System Research Vehicle (i.e., a highly modified Boeing B737). This system was developed using principles of total energy in which the total kinetic and potential energy of the airplane was controlled by the throttles, and the energy distribution controlled by the elevator.

TECS integrates all the control functions of a conventional pitch autopilot and autothrottle into a single generalized control concept. This integration provides decoupled flightpath and maneuver control, as well as a coordinated throttle response for all maneuvers. A mode hierarchy was established to preclude exceeding airplane safety and performance limits.

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2.0 INTRODUCTION

In 1979 NASA funded Boeing to begin the conceptual development of a fully integrated automatic flightpath and speed control system. The work was carried out under NASA contracts NAS1-14880 (1979-1980) and NAS1-16300 (1980-1981). Detailed design and simulator implementation was carried out under Boeing IR&D funding from 1979-1982. The outcome of this work was the Total Energy Control System (TECS).

Following successful detailed simulator development of TECS at Boeing, NASA awarded a contract (NAS1-17509) in 1983 for the flight test of TECS on NASA Langley's Transport Systems Research Vehicle (TSRV), a highly modified Boeing B737-100.

Flight test of TECS took place in September 1985 at NASA Langley in a series of five flights over a 3-week period. Most of the original flight test plan was completed in the first three flights. The final two flights were demonstration flights of TECS.

This document discusses:

- The basic concept of TECS
- The architectural features of the system used for the flight test program
- The detailed flight test results

3.0 SYMBOLS AND ABBREVIATIONS

3.1 SYMBOLS

D	Drag
E	Total energy of system
$\dot{E}_{DE}$	Energy rate distribution error
$\dot{E}_S$	Specific total energy rate
$\dot{E}_{SE}$	Total energy rate error
g	Acceleration due to gravity
h	Altitude
$\dot{h}$	Altitude rate
K_{EI}, K_{EP}, K_{TI}, K_{TP}	Gain constants
K_{GEPS}	Switched gain
s	Laplace operator
T_{REQ}	Thrust required
V	Airspeed
V_{STALL}	Stall speed
$\hat{V}$	Filtered airspeed
$\dot{V}$	Rate of change of airspeed
$\dot{V}_{CMAX}$	Maximum acceleration command
$\dot{V}_{CMIN}$	Minimum acceleration command
$\dot{V}_E$	Rate of change of airspeed error
$\dot{V}_{MAX}$	Maximum acceleration
W	Airplane weight
γ	Flightpath angle
γ_C	Flightpath angle command
γ_E	Flightpath angle error
δ_{EC}	Change in elevator command
δ_{TC}	Change in throttle command
τ_E	Time constant of energy rate loop
τ_D	Time constant of energy rate distribution loop

3.2 ABBREVIATIONS

AFD	Aft flight deck
AFDTH	Aft (flight deck) throttle (deg)
ALPHA	Angle of attack (deg)
ALT HOLD	Altitude hold mode
ALT SEL	Select altitude mode
ALTCOR	Altitude (barometric) (ft)
ALTSUM	Altitude command (ft)
ALW	Angle of attack (wing) (deg)

AOA	Angle of attack
AZ	Vertical acceleration (ft/s^2)
CAS	Calibrated airspeed (kn)
CMP	Control mode panel
DAS	Data acquisition system
DATAC	Digital Autonomous Terminal Access Communication System
DECMD	Elevator command (deg)
DME	Distance measuring equipment
EADI	Electronic attitude display indicator
EPR	Engine pressure ratio
EPRA	Engine pressure ratio (average of engines)
FLAP	Flap handle position (deg)
FMS	Flight management system
FPA	Flightpath angle
FPASUM	Flightpath angle command (degrees)
FPA SEL	Flightpath angle select mode
GA	Go-around mode
GAMEPS	Flightpath error (rad)
GAMMAI	Flightpath angle (rad)
GS	Glideslope capture and tracking mode
HDOT	Height rate (ft/s)
HOR PATH	Horizontal path mode
IASSUM	Calibrated airspeed command (kn)
KGEPS	Switched gain (nominally unity) for flightpath to elevator path
KVEPS	Switched gain (nominally unity) for speed to elevator path
LRU	Line replaceable unit
NCDU	Navigation control and display unit
ND	Navigation display
PFD	Primary flight display
PITCH	Pitch angle (deg)
PMC	Panel mounted controller
Q	Pitch rate (deg)
RFD	Research flight deck
STAB	Stabilizer position (deg)
TECS	Total Energy Control System
TKA SEL	Track angle select mode
TSRV	Transport System Research Vehicle
VEL-CWS	Velocity vector control wheel steering mode
VTER	True airspeed error (ft/s)
WEIGHT	Weight of airplane (lb)

4.0 BASIC CONCEPTS OF TECS

The basic concepts of TECS are discussed in References 1 through 3. However, a review of the design philosophy and theoretical concept is presented in this section.

The work of developing an integrated autopilot/autothrottle was originally initiated to solve the problems identified with conventional uncoupled autopilots and autothrottles:

1. Cross-coupling errors in speed and altitude occur when maneuvering due to the design of autopilots and autothrottles as single input/single output control systems. For example, a speed change can not be accomplished by only a change in throttle setting, but must be accompanied by an elevator retrim if altitude is to be maintained. Conversely, an FPA change cannot be achieved by an elevator deflection, but must be coordinated with a change in throttle setting.
2. Autopilot, autothrottle, and flight management systems (FMS) control laws have developed over a long period of time that has led to duplication of function in the autopilot and FMS computer.

These problems led to a general design philosophy for TECS:

1. Design the system as a multi-input/multi-output system.
2. Design with a generalized inner loop structure and design the outer loop functions to interface with the common inner loop, thus minimizing software duplication.
3. Provide underspeed and overspeed protection for all modes.

This philosophy integrates the conventional pitch and speed control functions into a single control system, which facilitates the replacement of the autopilot and autothrottle found in current airplanes by a single autoflight line replaceable unit (LRU).

The basic concept of TECS is to control the total energy of the airplane. The total energy of the system can be expressed as the sum of the potential and kinetic energy.

$$E = Wh + \frac{1}{2}\frac{W}{g} V^2 \tag{1}$$

Where:

W = airplane weight
h = altitude
g = acceleration due to gravity
V = airspeed

The specific energy rate is given by:

$$\dot{E}_s = \dot{h} + \frac{V\dot{V}}{g} \tag{2}$$

Normalizing by velocity, then:

$$\frac{\dot{E}_s}{V} = \frac{\dot{h}}{V} + \frac{\dot{V}}{g} = \gamma + \frac{\dot{V}}{g} \tag{3}$$

Where γ = flightpath angle (FPA)

From the equations of motion along the flightpath, the thrust required to maneuver is:

$$T_{req} = W\left(\gamma + \frac{\dot{V}}{g}\right) + D \tag{4}$$

Where D = airplane drag

Assuming that drag variation is slow, equations (3) and (4) show that the engine thrust required to maneuver is proportional to the specific energy rate of the system. Alternately, it can be stated that the throttles control the rate at which energy can be added to or deleted from the system.

In response to speed or flightpath changes then, a control law can be developed that uses the throttles to drive the total energy rate error to zero.

$$\delta_{T_C} = \left(K_{TP} + \frac{K_{TI}}{s}\right)\frac{\dot{E}s_E}{V} \tag{5}$$

Where

$$\frac{\dot{E}s_E}{V} = \gamma_E + \frac{\dot{V}_E}{g} \tag{6}$$

This control law uses proportional plus integral control to reduce the total energy error to zero with a first order time constant, $\tau_E = K_{TP} / K_{TI}$. However, achieving a speed maneuver without flightpath perturbation, or vice versa, requires coordinated elevator and thrust inputs. An energy rate distribution error $\dot{E}_{DE}$ can still exist (e.g., too high an FPA and too low an acceleration). Correction of the energy rate distribution error can be accomplished by feeding back the difference of the acceleration error term $\dot{V}_E/g$ and the FPA error γ_E.

Using proportional plus integral control, the elevator control is:

$$\delta_{E_C} = \left(K_{EP} + \frac{K_{EI}}{s}\right)\left(\frac{\dot{V}_E}{g} - \gamma_E\right) \tag{7}$$

Where K_{EP}, K_{EI} = elevator proportional and integral gains respectively.

This control law calls for the use of the elevator to redistribute the energy rate error $\dot{E}_{D_E}$ equally between FPA and acceleration. The response has a first order time constant $\gamma_D = K_{EP}/K_{EI}$. This concept is shown in Figure 1.

To ensure coordinated response to both speed and FPA changes, both the total energy rate error and the energy rate distribution error must go to zero simultaneously. This requires that ideally the dynamic response of equations (5) and (7) should be identical (i.e., $\tau_E = \tau_D$ and $K_{TI} = K_{EI}$).

In addition, the thrust and pitch response are matched by designing engine and pitch inner loops to minimize variations due to the engine or aerodynamics.

The engine loop is designed to produce the net thrust at all flight conditions. This is achieved by converting the net thrust command produced by the control law to a command relating to the engine pressure ratio (EPR), and then closing a feedback loop around the engine using this variable. Software limiting is provided to ensure that neither throttle or EPR limits are exceeded.

The short period pitch dynamics is stabilized in a conventional manner by the feedback of pitch and pitch rate. The gains were selected to match the thrust dynamics. The variable elevator effectiveness is compensated for by gain scheduling the elevator command as a function of dynamic pressure.

An important aspect of the overall TECS design is the utilization of a common inner loop for each mode of the autopilot (Figure 2.). By generating a common flightpath error signal (γ_E) irrespective of which autopilot mode is engaged, software duplication is minimized and system response is consistent. To implement the FPA mode, for example, the γ_E signal is generated by differencing an FPA command (γ_C) from the control mode panel with a γ signal computed from height rate ($\dot{h}$) and filtered velocity ($\hat{V}$).

For control of altitude and glideslope, outer loop control is added to generate the normalized γ_C signals and provide exponential capture of the desired altitude or glideslope. All inputs, except for the velocity vector control wheel steering mode (VEL-CWS) and go-around mode (GA), are rate limited to provided 0.1g maximum normal acceleration during maneuvers.

The CAS and Mach speed modes both use outloop control, similar to the altitude and glideslope modes, to provide exponential capture of the parameter. An acceleration command ($\dot{V}_C$) drives the inner loops.

The control modes are divided into speed or path priority so that, when throttle limiting occurs, either speed or flightpath has priority and control of that parameter is maintained. The other parameter goes open loop and is not controlled. The mode logic of TECS is set up so that FPA, altitude, and GA mode have speed priority, while glideslope and VEL-CWS mode have path priority.

Control of the system, while throttle limiting, is an important aspect of TECS that required significant development on a nonlinear simulator to achieve an implementation with minimum software that provides accurate control and is consistent with the speed/path priority for each mode. This implementation is discussed in more detail in a later section that covers the flight test results.

The result of the TECS design is a fully integrated system that has predictable consistent performance in all modes. Duplication of software has been minimized by maintaining a common inner loop structure.

5.0 ARCHITECTURAL FEATURES OF THE SYSTEM

The TECS flight tests were conducted on NASA Langley's Transport Systems Research Vehicle (TSRV) that is a highly modified Boeing 737-100 aircraft (Figure 3) designed to investigate advanced navigation, guidance, control, and display concepts applicable to the emerging National Airspace System. In this aircraft, the entire experimental flight management system, i.e., all navigation, guidance, and control functions, and primary pilot displays are under software control and can be reprogrammed to suit the requirements of a particular experiment.

The TECS flight tests employed the full-up test configuration wherein the aircraft is flown from a Research Flight Deck (RFD) mounted in the cabin of the aircraft and referred to in this report as the Aft Flight Deck (AFD). The AFD features programmable electronic Primary Flight Displays (PFDs), Navigation Displays (NDs), a Navigation Control and Display Unit (NCDU), a glare-shield mounted Control Mode Panel (CMP), and Panel-Mounted Controllers (PMSs) that take the place of conventional column and wheel controls. The CMP (Figure 4) was modified for these tests by replacing selected baseline switch legends with ones corresponding to the TECS modes.

Figure 5 is a simplified block diagram showing the arrangement of the principal components of the research system. The system is built around two Norden digital flight computers that are militarized versions of the general purpose PDP 11/70 computer. Both computers are interfaced to the AFD and an extensive array of sensors by a global data bus known as the Digital Autonomous Terminal Access Communication (DATAC) system. This installation is the first practical application of DATAC, a high-speed (1-MHz) multitransmitter/receiver data bus that only requires a single twisted wire pair to link all components on the bus. In the TSRV, two DATAC buses are actually used, one for navigation, guidance, and control functions, and the other for the programmable display system. A data acquisition system (DAS) is also coupled to the DATAC bus and is set up to record approximately 540 data channels at 20 samples per second with selected channels at 100 samples per second.

The TECS algorithms are programmed into the Norden Computers via floppy disk and replace the pitch control and throttle control algorithms of the baseline software. The system, as flown on the TSRV airplane, consists of the following longitudinal modes:

1. Velocity vector control wheel steering (VEL-CWS).
2. Glide slope capture and tracking (GS).
3. Flightpath angle select (FPA SEL).
4. Altitude select and hold (ALT S, ALT H).
5. Go Around (GA).

The system longitudinal modes can be flown in either CAS or Mach speed modes.

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The TECS software is integrated with the baseline lateral modes to give default mode pairing. Engagement of a longitudinal mode, for example, would result in the engagement of a corresponding mode in the lateral axis, or vice versa (Figure 6). On "power up" of the TECS system, the system is default in VEL-CWS and CAS modes. Engagement of FPA SEL, ALT H, ALT S, or GA modes gives Track Angle Select (TKA SEL) in the lateral axis.

The lateral VEL-CWS mode incorporates roll rate command/altitude hold for maneuvering flight and track angle hold for nonmaneuvering flight.

In integrating TECS with the baseline, certain selected navigation, guidance, and lateral control functions are retained. These functions include dual DME, aided inertial navigation, and a Horizontal Path (HOR PATH) guidance mode in which the flightpaths can be selected by the pilot from a prestored data base or can be constructed in real-time using the NCDU. The baseline vertical path and time control modes were not enabled during these tests.

6.0 FLIGHT TEST RESULTS

This section discusses in detail the results of the flight test series. A summary of the figures and test conditions is given in Appendix 1. The tasks have been grouped according to mode of operation and do not necessarily follow the order in the test plan (Appendix 2). References 4 and 5 provide a summary of test results and highlight the unique aspect of the system operation.

6.1 FLIGHTPATH ANGLE MODE

Figures 7 through 13 show the performance of the system for FPA dialed in through the CMP while the airplane holds constant speed. Figures 7 through 10 show the performance for a mid-altitude mid-speed condition and Figure 13 shows a low-altitude low-speed condition.

Figure 7 shows the linear response of the system to a change in FPA of ± 2.5 deg. The response shows no transient overshoot. Speed error was generally held within 1.5 kn although peak error during the maneuver was 2.5 kn and the maximum vertical acceleration change was about 3 ft/s^2.

Figures 9 and 10 show the effect of throttle limiting during a large FPA change. As discussed in Section 4, each mode of the autopilot is prioritized to control either speed or path when throttle limiting occurs. In FPA mode the strategy is simple, speed control has priority. Hence, on dialing in a large FPA change, the throttles will limit. The system will now stop controlling FPA, the throttle integrator is limited and the crossfeed between FPA and elevator is cut (i.e., the gain K_{GEPS} (Figure 2) is set to zero). The system controls speed through elevator and with the throttle at the forward limit, any energy not required to maintain speed is available to increase the FPA and, hence, the climb rate.

Figures 10a and 10b provide a good example of the throttle limiting case. In a steady state climb the airplane can maintain about a 6 deg FPA at 200 kn, 10,000 ft, which corresponds to a climb rate of about 40 ft. Maximum speed deviation during this maneuver is about 2 kn. Figure 10b shows the gain K_{GEPS} going to zero during the throttle limiting condition.

Figures 11 and 12 show the performance at high speed high altitude. In this condition the system cannot achieve the +2.5 deg command FPA and can only climb at 0.5 deg and sustain the 300-kn velocity. Throttle limiting occurs at 47 deg. In the -2.5 deg FPA case no limiting occurs and the system holds speeds within 3 kn. Figure 12 shows the result of a large negative FPA change in which the throttle limits at 8 deg. The system holds speed within a maximum error of 3 kn and the maximum FPA descent is at -3 deg. The results of tests 2.1.3 and 2.1.5 were not plotted as they were identical to test 2.1.1, as shown in Figure 11.

Performance of the system at low speed, low altitude is shown in Figure 13. It can be seen that the system limits in a climb of about 2 deg. Speed was held in limiting situations within 3 kn, and normally within 2 kn. Tests 3.1.3 and 3.1.5 are similar to 3.1.1 and are not shown.

6.2 ALTITUDE SELECT AND HOLD MODE

Figures 14 to 20 show the system performance for altitude changes at the three flight conditions discussed in Section 6.1. The linear performance at mid-altitude and mid-speed is shown in Figure 14. The system shows excellent transient response and speed error is less than 2 kn. Throttle limiting does occur during the descent at approximately 92 sec into the run but only for about 2 sec. The performance for large altitude changes is shown in Figures 15 through 17. In Figure 15 an altitude increase of 2,500 ft is selected. In this case speed error is shown to increase up to 5 kn, about 20 sec after throttle limiting occurred. In the TECS design a feedforward was used to minimize speed error during a long climb. In simulation studies the speed loop feedforward gain KVT was set to 1.5, this provided a compromise over the whole flight regime. However, in fight test it was shown that increasing this gain KVT to 3, reduced the maximum speed error to about 3 kn. Simulation studies should be carried out to check the flight test results and optimize the gain value.

The low-altitude low-speed performance is shown in Figure 19. In test 3.2.3 (M) the pilot dialed up 2,500 ft, the airplane reaches a steady-state climb rate of about 600 ft per minute, and the pilot changes command from 2,500 ft to 1,000 ft and the system captures that new altitude.

6.3 CAS/MACH MODE

The performance of the system to speed changes is shown in Figures 20 through 22 for mid-speed mid-altitude condition. For these cases, speed changes of up to 100 kn are performed. Altitude error is less than 20 ft in all cases. The system has a smooth response and no excessive throttle activity is noticed. In Figure 22, which shows a ± 100 kn speed change, throttle limiting occurs at 48 and 9 deg. Speed steps are also carried out at high altitude (Figures 23 through 26) and low altitude (Figure 27). Unfortunately, the airplane had conservative throttle limiting at high altitude. The actual throttle limits are set at lower values than the software limits in the TECS program and, hence, the control did not reconfigure for this limiting situation. It can be seen in Figure 23 that the new speed target is captured successfully with no overshoot, however, a large altitude deviation occurs (in the order of 100 ft). This test is repeated in flight R461 at time 14:23:44. On that occurrence, an altitude error in the region of 65 ft occurs. The details of the physical throttle limiting are not apparent in the baseline documentation and show a difference between the actual airplane and simulation. This test case has previously been successfully demonstrated on the NASA simulator.

Mach changes are shown in Figures 25 and 26. Unfortunately, the same problem with throttle limiting occurs in these cases as occurred earlier in the CAS changes. In Figure 25 the pilot dialed in two incremental changes in Mach number of 0.25 Mach, and followed with a decrease in Mach number of 0.05 Mach. Altitude error increases in the region of throttle limiting that occurs around 1,000 sec into the flight, otherwise altitude error is small throughout these runs. A glitch on the Mach number signal shows this signal going to zero at about 1,030 sec. The true airspeed error signal gives a clearer picture of the error going to zero with time as no glitch appears on that signal. Figure 26 shows the effect of the software limiting for large variations in Mach number. Altitude error increases up to 150 ft during that run. Unfortunately, again a glitch exists on the Mach number and it is shown going to zero at about 1,170 sec. Reference to true airspeed error signal (VTER) shows that the system captures the new velocity exponentially with no overshoot. Performance of the system at low altitude is shown in Figure 27. Examination of test 3.3.3, which starts at 215 sec into the run, shows that the speed dows not reach the commanded airspeed dialed in on the control mode panel and a stand-off of about 20 kn exists. This is caused by the pilot dialing in an airspeed above the flap placard for flaps 40 deg. The system increases speed to approximately 166 kn and holds that speed until the command is dialed down below the flap placard speed as can be seen at approximately 312 sec. Altitude error during that maneuver is shown to be about 50 ft.

Test 2.7.2 (Figure 28) is an example of the automatic Mach to CAS (and vice versa) switching. The airplane is executing a descent maneuver and holding constant Mach number. Just below 20,000 ft the system automatically switches to holding a constant CAS of 330 kn. The maneuver is executed with about 0.1g acceleration.

6.4 VELOCITY VECTOR CONTROL WHEEL STEERING MODE

The Velocity Vector Control Wheel Steering Mode (VEL-CWS) is a manual flying mode with control augmentation that significantly reduces pilot workload when flying a path defined in inertial space. In this mode a column deflection commands a rate of change of FPA. Integration of the column command gives the FPA command (γ_C) to which the system attempts to control. The performance of the VEL-CWS mode is shown in Figures 29 through 36. The response of the system at mid-speed mid-altitude conditions is shown in Figures 29 through 33. The response at high-altitude is shown in Figures 34 through 36.

The response to small column inputs is shown in Figure 29. In this case the pilot has put in a small impulse response on the column to get a gamma command of $\pm 2\frac{1}{2}$ deg. The airplane climbs at 700 ft/min, and airspeed changes by approximately 2 kn. Throttle response is smooth and coordinated with no excessive activity. In test 1.5.3 (Figure 30) the pilot has put in a command of +5 deg FPA and the airplane is just on the verge of limiting the throttles. It is a good example of the airplane climbing out at maximum rate without losing airspeed.

In test 1.5.4 (Figure 31) the pilot has commanded -5 deg gamma, and the throttle has gone to the idle limit. In this situation the limit logic of TECS in the VEL-CWS mode means that path control has priority. Speed control is given up and the gain K_{VEPS}, shown in Figure 2, is set to zero. The crossfeed gain K_{GEPS} is maintained. In this situation the speed error builds up as the path control is maintained. This can be seen as speed increases from the 200 kn that is commanded, up to 215 kn. If the pilot maintains the descent, the speed increases until overspeed protection engages and holds speed at a maximum.

Test 1.5.5 (Figure 32) is an example of a large γ input in which the throttles do not limit and speed is maintained within about 3 kn. Figure 33 shows a large column input that causes throttle limiting. In this case FPA has priority and the command is reached. However, speed bleeds off rapidly and the underspeed protection mode switches in. FPA then decreases despite additional column inputs until minimum speed is reached. This corresponds to about 178 kn for flaps zero. A steady-state gamma of about 11.5 deg is reached. A negative column input decreases gamma and the airplane returns to the initial commanded speed of 200 kn.

Figures 34 through 36 show the VEL-CWS response at high altitude (20,000 ft). In all these cases throttle limiting occurs. The system behaves as predicted in these limiting conditions and shows a smooth gamma response in each case.

6.5 UNDERSPEED PROTECTION

Underspeed is a priority control mode that switches in automatically irrespective of whether the mode engaged has speed or path priority. In the underspeed protection mode, the actual wing angle-of-attack is compared with the reference alpha. The reference alpha value corresponds to $1.3V_{STALL}$ for each flap setting. The error signal is converted to a normalized acceleration command ($\dot{V}_{CMIN}$) that is computed continuously. The mode engages underspeed protection automatically (Figure 2) when:

$$\dot{V}_{CMIN} > \dot{V}_C \tag{8}$$

Examples of the operation of the underspeed protection for angle-of-attack (AOA limiting) are shown in Figures 37 through 39. Figure 37 illustrates the situation of dialing the speed command to a very low value. The airplane slows down and when V_{CMIN} equals V_C the mode switches in a transient-free manner and controls to the reference alpha. At flaps 0 deg this corresponds to about 178 kn. As the flaps were extended to flaps 40 deg, the speed decreases as the system controls to the new reference. Altitude deviation during the maneuver was negligible.

Figure 38 shows the situation of dialing speed to a large value and slowly retracting the flaps from 40 to 0 deg. Figure 39 shows a nonstandard situation in which speed has been dialed down and the flaps rapidly extended to 40 deg. The maneuver was accomplished safely with little deviation although considerable pitchdown was experienced in the airplane.

6.6 ENERGY EXCHANGE MANEUVERS

In Figures 40 and 41 the change in kinetic energy has been set equal to the change in potential energy. This is not a normal maneuver for a pilot, but it does demonstrate clearly the coordination between the throttle and elevator, with the TECS system, for a dual maneuver that changes both speed and altitude. In test 1.7.1 (Figure 40) the airplane loses 600 ft of altitude and gains 20 kn in airspeed. The energy trade is accomplished by using the elevator. Aft flight deck throttle motion is only 0.5 deg through the whole maneuver. Figure 41 shows a modified test 1.7.1. In this case the pilot changes speed by 20 kn and increases and then decreases altitude by 500 ft. The change in potential and kinetic energy is not exactly equal and there is a small throttle movement of about 3 deg.

Test 1.7.3 (Figure 42) is an excellent example of a descent and speed decrease executed as a double maneuver. The airplane is cruising at 15,000 ft, 300 kn, gear and flaps up, the pilot simultaneously dials speed and altitude down. In this situation, prior to the throttles limiting, the autopilot treats the maneuver in a linear fashion and starts descending and decelerating. When the throttle limits out it is impossible to control speed and path, and the system has priority set to control speed and allow path to go open loop. In addition, a strategy is adopted that during descents 100 percent of the available energy is put into deceleration. For descents the energy is negative and it is the drag that can be split into either maintaining path and losing speed or vice versa. Once throttles limit, 100% of the drag is put into decelerating the airplane. The airplane levels out and slows down to 250 kn. Once this desired speed is captured, the airplane pitches over and descends at a rate commensurate with the drag configuration and maintaining airspeed.

During a simultaneous descent and decrease in speed that causes the throttle to limit, 100% of the available energy rate is put into decelerating the airplane. However, during a climbout situation (Figure 43) when the pilot has dialed in a large speed and altitude change, the limit logic computes the total energy available and splits the energy so that 50% is used for climb and 50% is used for acceleration. This is achieved by setting the $\dot{V}_C$ signal path limiter (Figure 2) to 50% of total available energy (i.e., $0.5\ V + \gamma_g$). This ratio is readily adjustable by changing one gain in the software if it is determined by pilot evaluation that an alternative ratio is desirable and that priority should be given to achieving speed or altitude capture first. In the example, the airplane is climbing to 10,000 ft altitude and increasing speed to 270 kn. The energy is split evenly between climbing and accelerating. The acceleration is approximately 2.5 ft/s^2, which in energy terms corresponds to a γ of about 0.08 $_{RAD}$. Once the reference speed of 270 kn is captured, the climb rate doubles from about 35 ft to a maximum of 70 ft. This can be seen to occur 48 sec into the run.

6.7 APPROACH AND GO-AROUND

The full-time underspeed protection, discussed in Section 6.5, can be used during approach to reduce the pilot workload. Figure 44 (tests 3.6.1 and 3.6.2) shows an approach and go-around situation. The airplane approaches the glideslope in altitude hold mode at 3,000 ft, 150 kn, flaps 15 deg, gear down. At glideslope intersection, shown by the glideslope error signal reducing to zero, the flaps are extended rapidly from 15 to 40 deg. The airplane overshot the glideslope by about 30 ft and it is considered that this overshoot was caused by a software problem that caused premature switching to glideslope capture prior to the control law logic switch point. On capture of the glideslope the command speed is dialed from 150 kn to a low value. Speed reduces to the value commensurate to the flap setting. For safety reasons the command speed is dialed up to 120 kn prior to go-around (220 sec into the run).

The TECS system at present does not include a flare control law; therefore this series of tests go-around is initiated at 300 ft. On go-around the control law commands a large FPA. This gives large elevator and throttle commands that cause the airplane to pitch up and climb at the maximum rate attainable while maintaining speed. As discussed earlier, during climbout the energy is split between gaining altitude and increasing speed. By coincidence, in this example the airplane reaches the commanded altitude of 3,000 ft and the new command speed of 225 kn simultaneously.

Elevator activity increases significantly during this run. The TECS system includes a complementary filter in which the time constant varies as a function of altitude. The effect is to improve path-tracking at lower altitudes and improve the system performance to windshear response. However, this has an effect of increasing elevator activity.

Test 3.6.3, 3.6.4 (Figure 45) shows high-speed capture of the glideslope from altitude hold mode. At 105 sec into the run, speed was dialed down to 100 kn, the system decreases speed and holds at approximately 180 kn as the underspeed protection mode switches in. in this run, the same software problem that was previously discussed caused premature switching to glideslope capture. This caused the airplane to pitch up and attempt to capture the glideslope early. Once the glideslope has been captured, the flaps are dropped rapidly to 40 deg and the speed decreases from 180 kn to approximately 120 kn. At 300 ft go-around is initiated, speed is dialed up to 200 kn and the airplane climbs out to 3,000 ft altitude. Figure 46, test 3.6.5, shows the end of the climbout and capture of the commanded altitude of 2,000 ft. This capture is done with negligible overshoot and smooth throttle response.

Figures 47 and 48 show tests 3.6.6 through 3.6.7. This case is very similar to tests 3.6.1 through 3.6.3 except that it shows a low-speed glideslope capture with flaps 40 deg and gear down, prior to glideslope interception.

Test 3.6.9 (Figure 49) shows the ability of the TECS system to capture the glideslope from above. In this case the airplane approached the glideslope flying straight and level, flaps set at 40 deg, gear down. Speed was dialed down to below 1.3 V_{REF} at the start of the run and the airplane was flying in the AOA mode during the whole approach. The airplane flew through the glideslope at about two dots above the glideslope. Approximately 75 sec into the run, the FPA was dialed down to -4.5 deg. The airplane approaches the glideslope from above and at about 157 sec into the run the airplane captures the glideslope. The results show an excellent transition and smooth capture.

Glideslope capture and tracking using the VEL-CWS mode is shown in Figure 50 (tests 3.7.1 and 3.7.2). The airplane is flying straight and level, flaps 15 deg, CAS 150 kn. Speed is stabilized at about 150 kn at 58 sec into the run. At 66 sec the pilot pushes the column forward using the VEL-CWS mode and captures the glideslope. Pathtracking during the run is excellent and the pilot workload required to maintain good glideslope tracking is small. Go-around maneuver is initiated at about 400 ft by the pilot pulling a large column input and simultaneously dialing speed command to 180 kn, and retracting the flaps.

7.0 PILOT REACTION TO FLYING THE TSRV WITH TECS

Pilot reaction to flying the TSRV with TECS was very favorable. Explanation of the TECS concept and philosophy to pilots was very important so that the operation of TECS was predictable and consistent in flight.

A major difference from a conventional system is the full-time autothrottle. Traditionally, autothrottles have been heavily criticized for excessive activity and unpredictable or counterproductive motion in maneuvers. TECS solves that problem and produces an autothrottle that is predictable and minimizes unnecessary throttle activity, both in situations of simultaneous altitude and speed changes and when flying the VEL-CWS mode. The pilot does not need to switch off the autothrottle and fly manual throttles to achieve satisfactory flying qualities.

With TECS, the mode logic is simple and the mode hierarchy is straightforward so the behavior is predictable in throttle limiting conditions. In all events, limiting prevents stall and overspeed irrespective of the mode or combination of modes.

The strategy adopted during simultaneous speed and altitude changes of splitting energy (50%/50% during climb, 100% into deceleration during descent) is flexible and, although considered the preferred system, can readily be changed by adjusting one gain.

The VEL-CWS mode is the preferred method of flying the airplane during climb-out and approach. It allows the pilot, as opposed to the autopilot, to fly the airplane with great precision and yet greatly reduces the workload. Interception and tracking of the glideslope, even in turbulence, is a simple task.

8.0 CONCLUSIONS

- The Total Energy Control System was successfully flight-tested on the NASA Langley TSRV (B757) in a total of five flights. The system did not exhibit any instabilities or design problems that required gain adjustment in flight. No major problems were encountered during the tests.

- The success of the flight tests validates the extensive use that was made of analysis, simulation, and hot bench checkout to thoroughly develop, check out, and verify the system design prior to flight tests. No system tuning was necessary in flight.

- The integrated autopilot/autothrottle received favorable pilot reaction. The full-time autothrottle, inherent in the design, was predictable during maneuvers and did not exhibit unnecessary throttle activity.

- Performance in all modes was comparable to simulation results. Path tracking was excellent, altitude deviation during large speed changes was less than 20 ft. Speed tracking during maneuvers was generally less than 2 kn although a peak error of 5 kn was noted on certain large altitude changes.

- The velocity vector control wheel steering (VEL-CWS) mode received very favorable pilot reaction because of its consistent performance over the flight regime, the predictable and responsive throttle, and the reduction in workload that the mode allows when carrying out precision tracking tasks.

- TECS has provided NASA with a state-of-the-art integrated autopilot/ autothrottle suitable for use with future NASA experiments such as 4D navigation.

9.0 REFERENCES

1. Lambregts, A. A., "Vertical Flightpath and Speed Control Autopilot Design Using Total Energy Principles," AIAA Paper 83-2239CP, August 1983.

2. Lambregts, A. A., "Operational Aspects of the Integrated Vertical Flightpath and Speed Control System," SAE Paper 831420, October 1983.

3. Lambregts, A. A., "Integrated System Design for Flight and Propulsion Control Using Total Energy Principles," AIAA paper 83-2561, October 1983.

4. Bruce, K. R., Kelly, J. R., and Person, L. H. Jr., "NASA B737 Flight Test Results of the Total Energy Control System," AIAA Guidance, Navigation and Control Conference, AIAA 86-2143 CP, August 1986.

5. Kelly, J. R., Person, L. H. Jr., and Bruce, K. R., "Flight Testing TECS - The Total Energy Control System, Aerospace Technology Conference, Long Beach, California," SAE Paper 861803, October 1986.

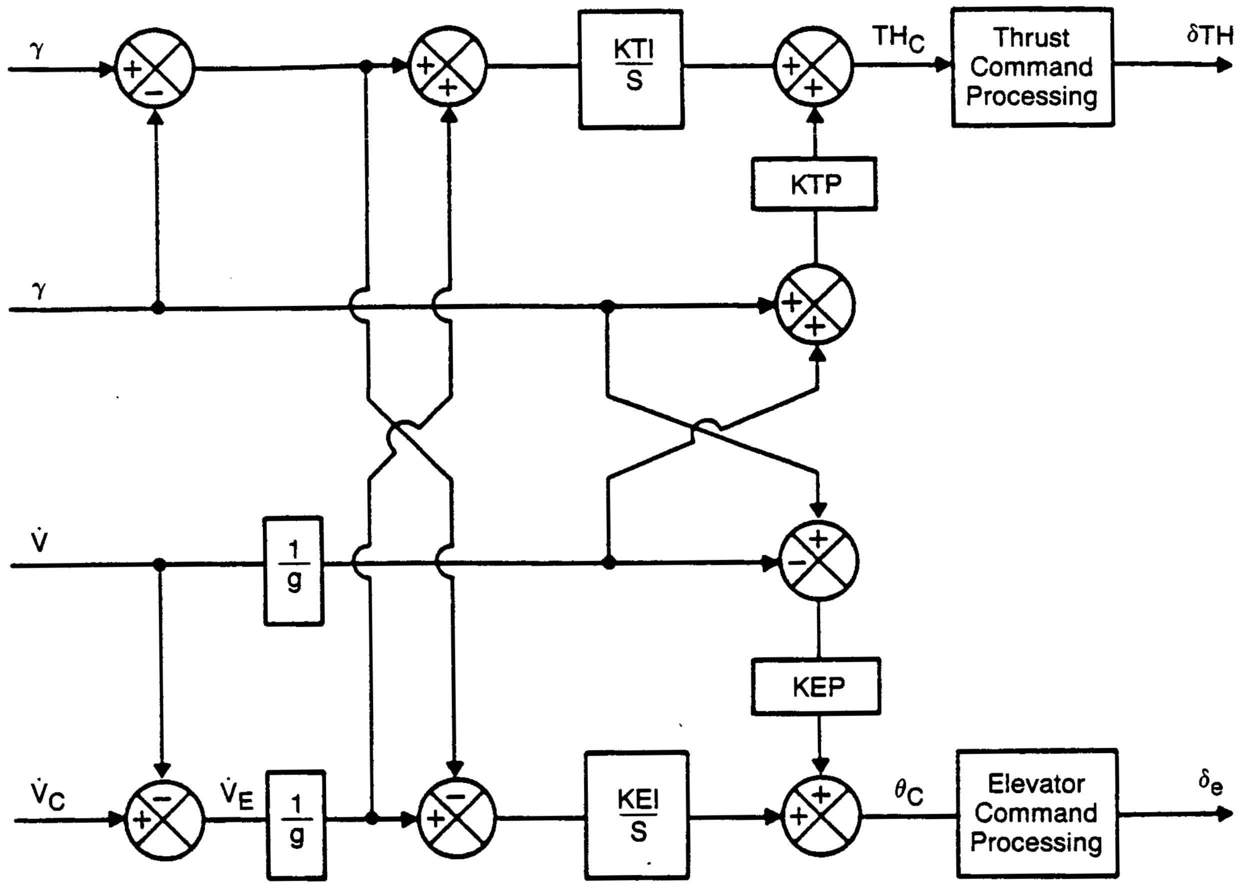

Figure 1. Total Energy Control System Concept

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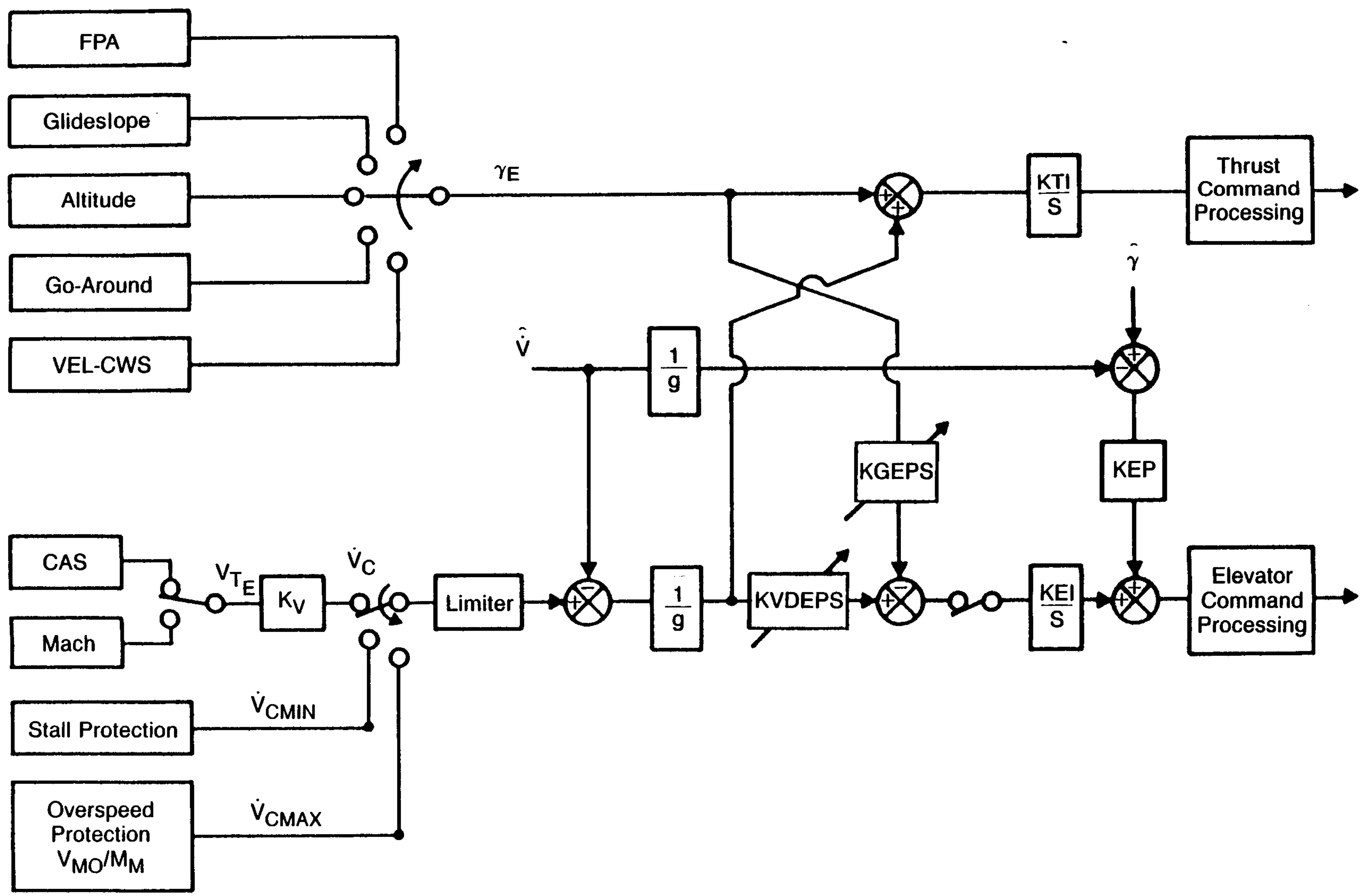


Figure 2. Simplified TECS Implementation

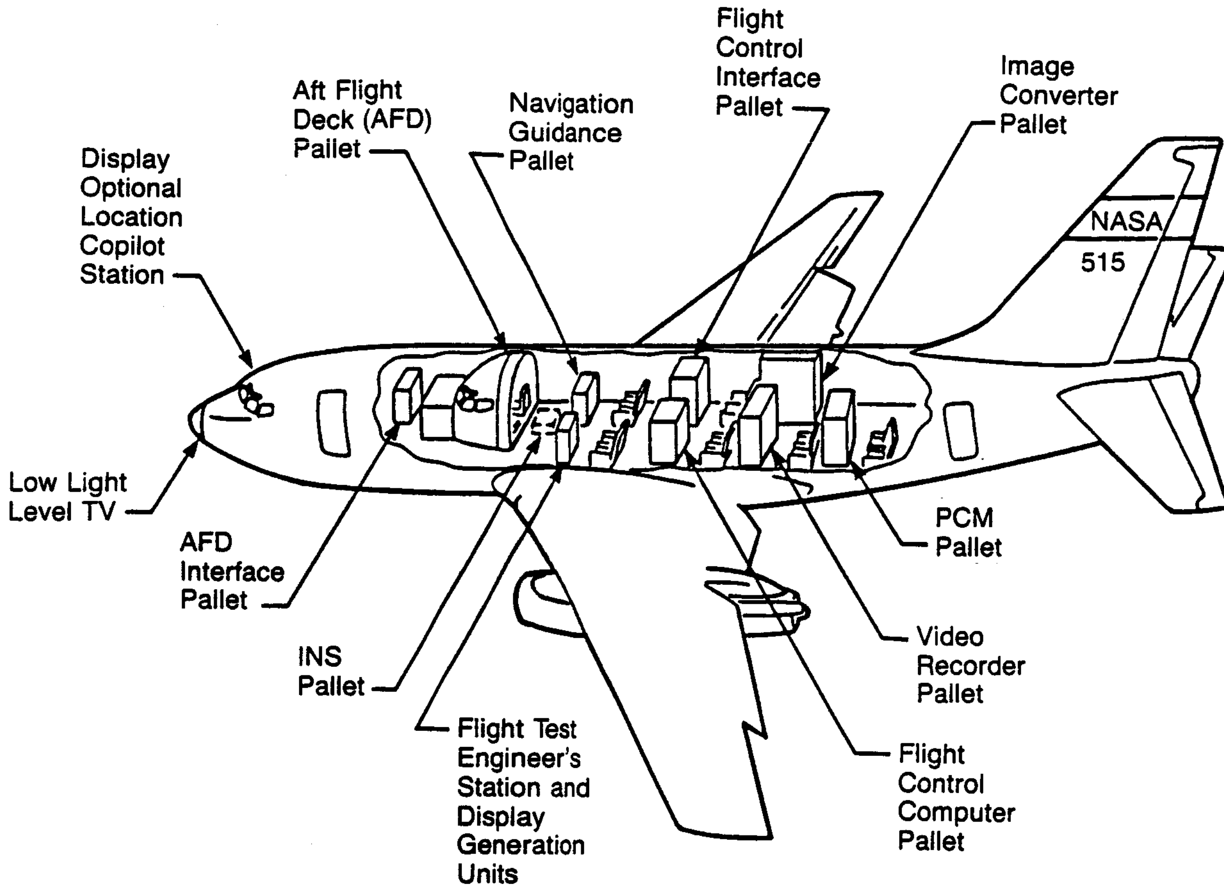


Figure 3. NASA Langley TSRV Showing Internal Arrangements

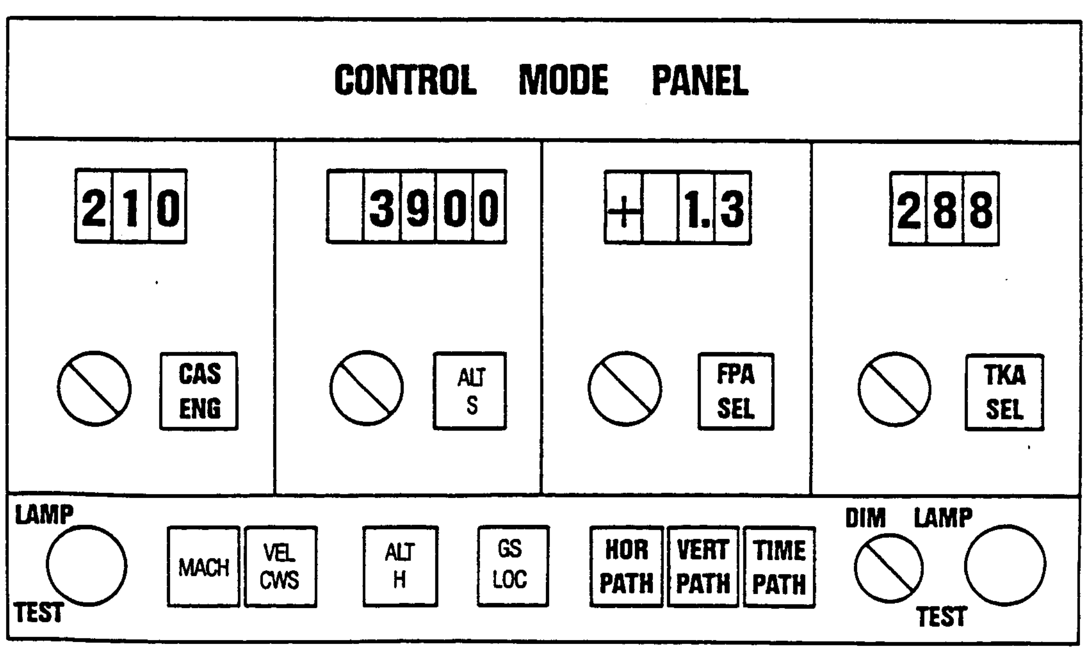


Figure 4. TSRV/TECS Control Mode Panel

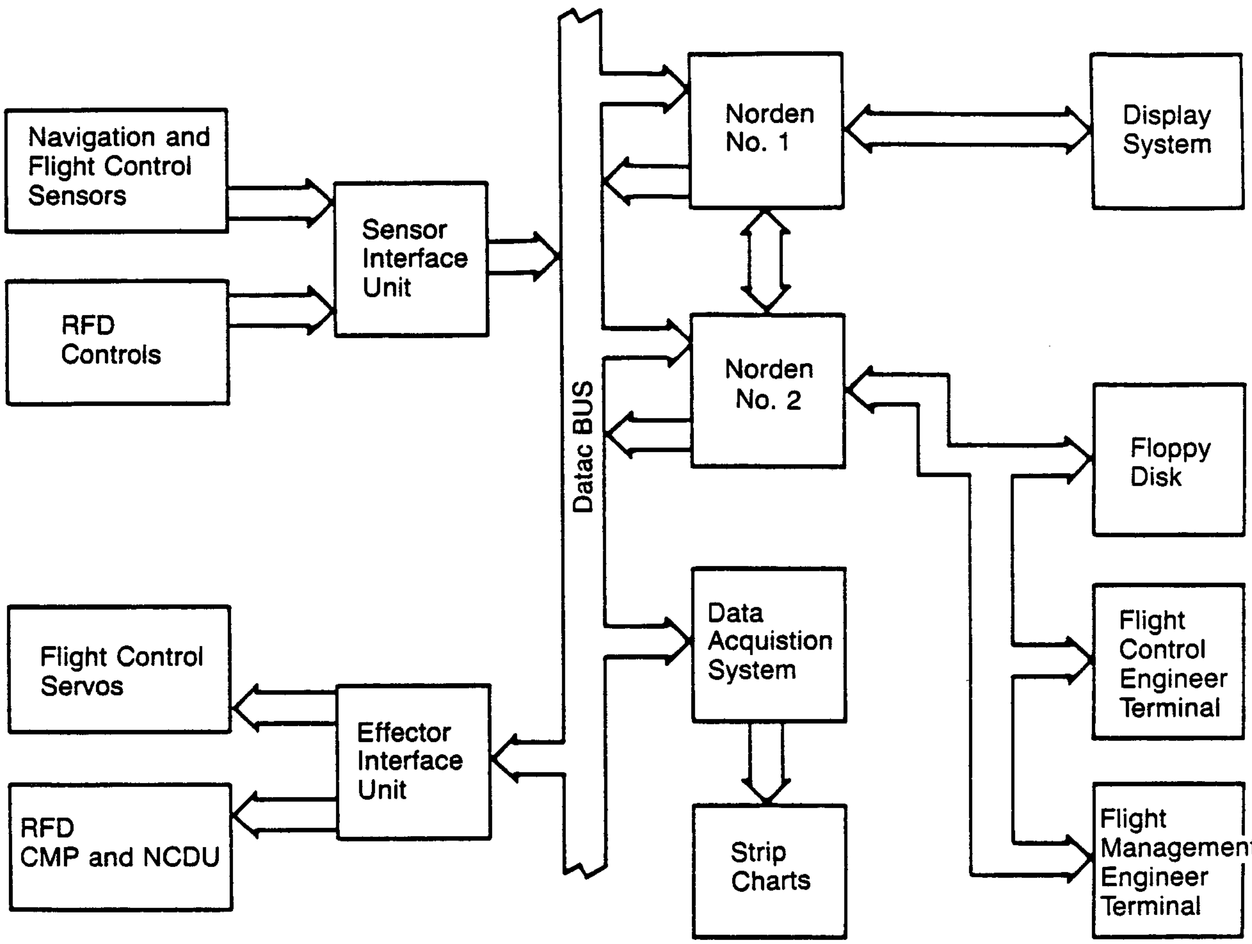


Figure 5. Research System Architecture

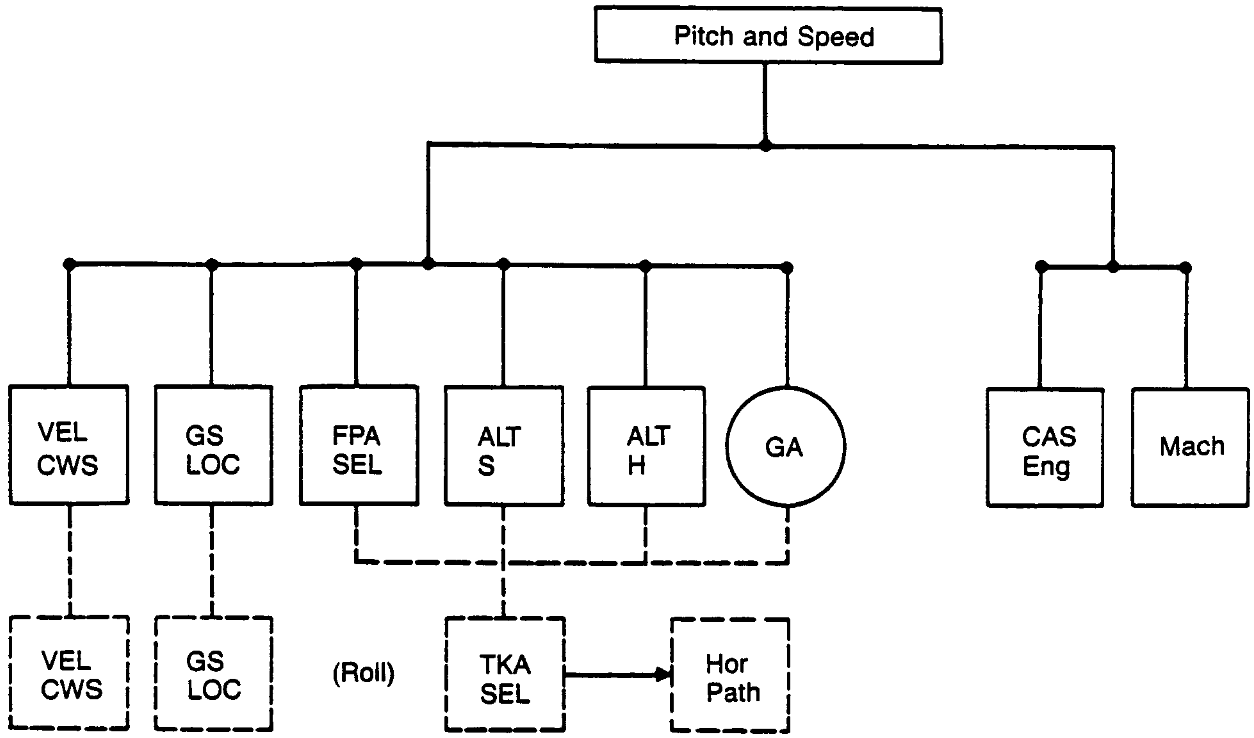


Figure 6. TECS Control Modes

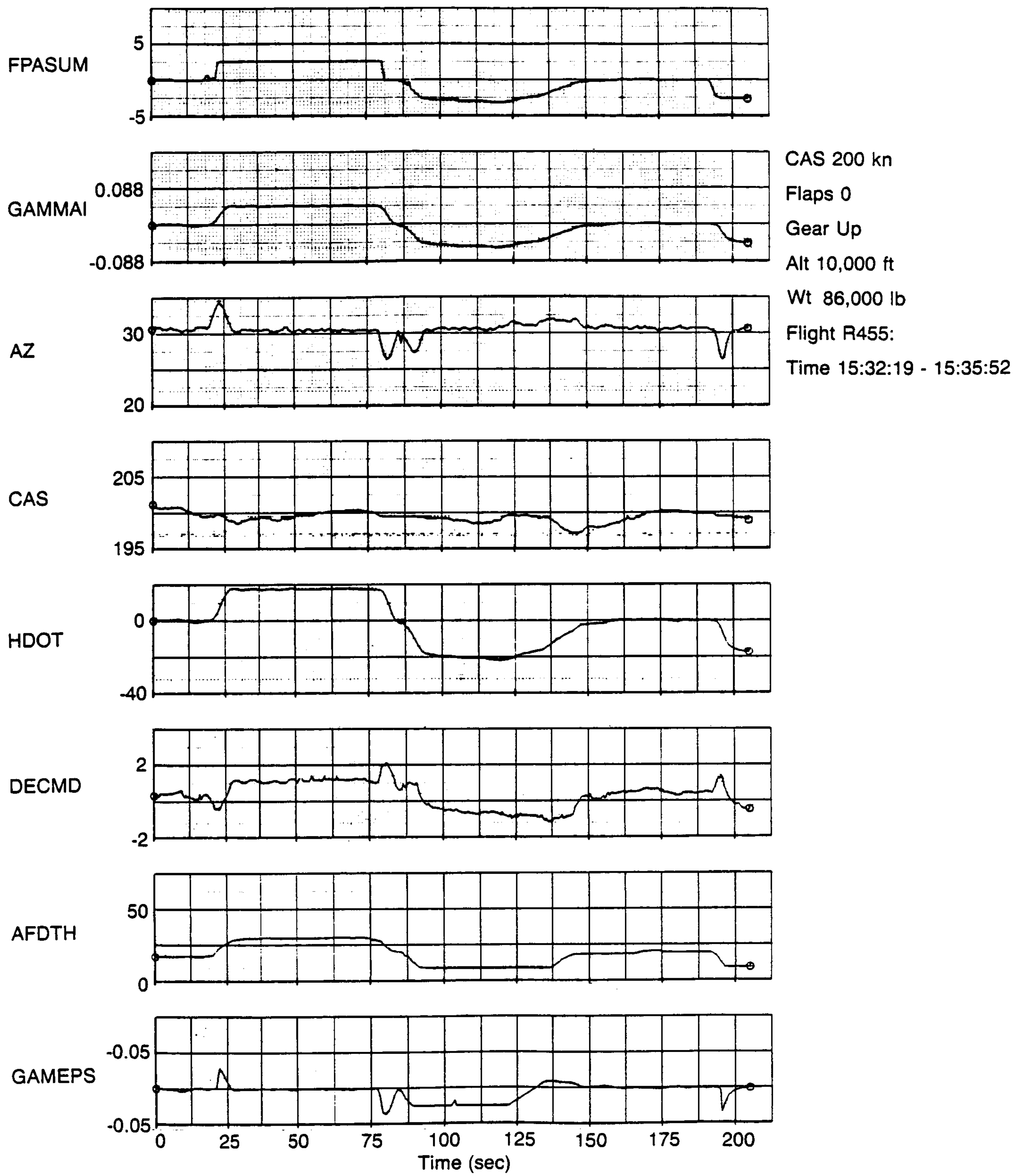


Figure 7. Test 1.1.1-1.1.2; FPA Mode +/-2.5 deg

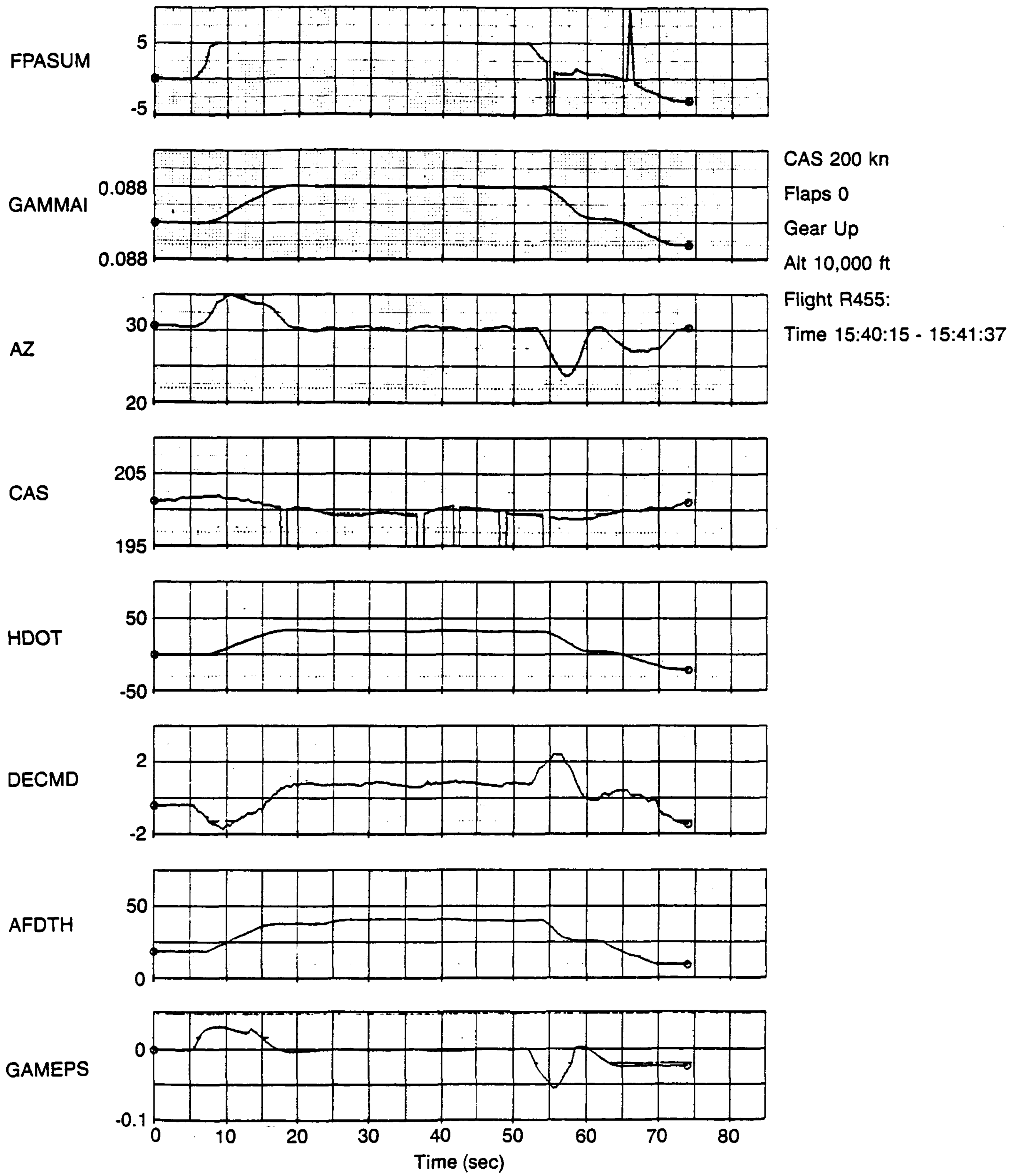
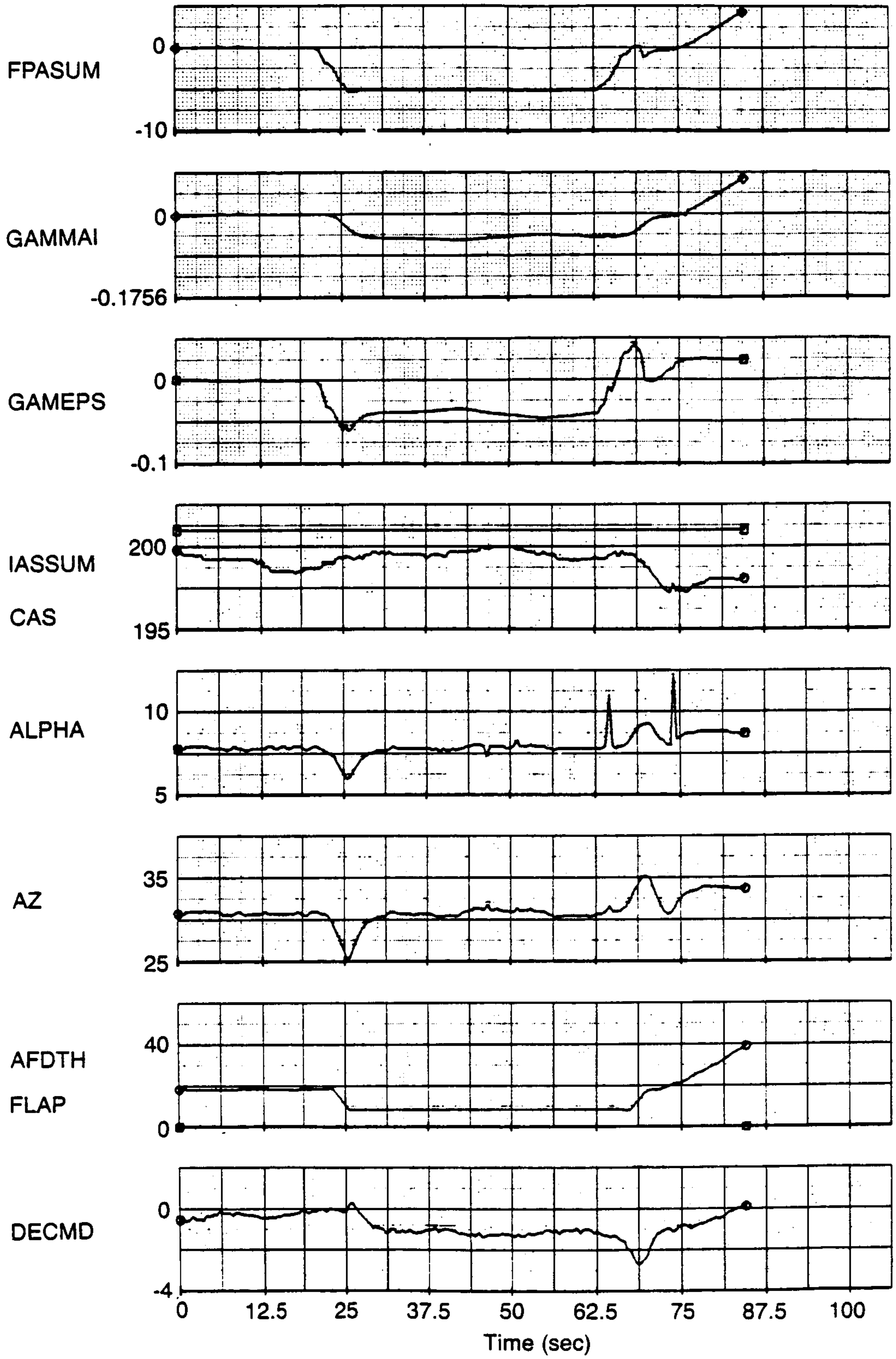


Figure 8. Test 1.1.3; FPA Mode +5 deg



FPA/CAS Mode

Flaps 0

Gear Up

Flight R455:

Time 15:43:05

Figure 9 (a). Test 1.1.4; FPA Mode -5 deg

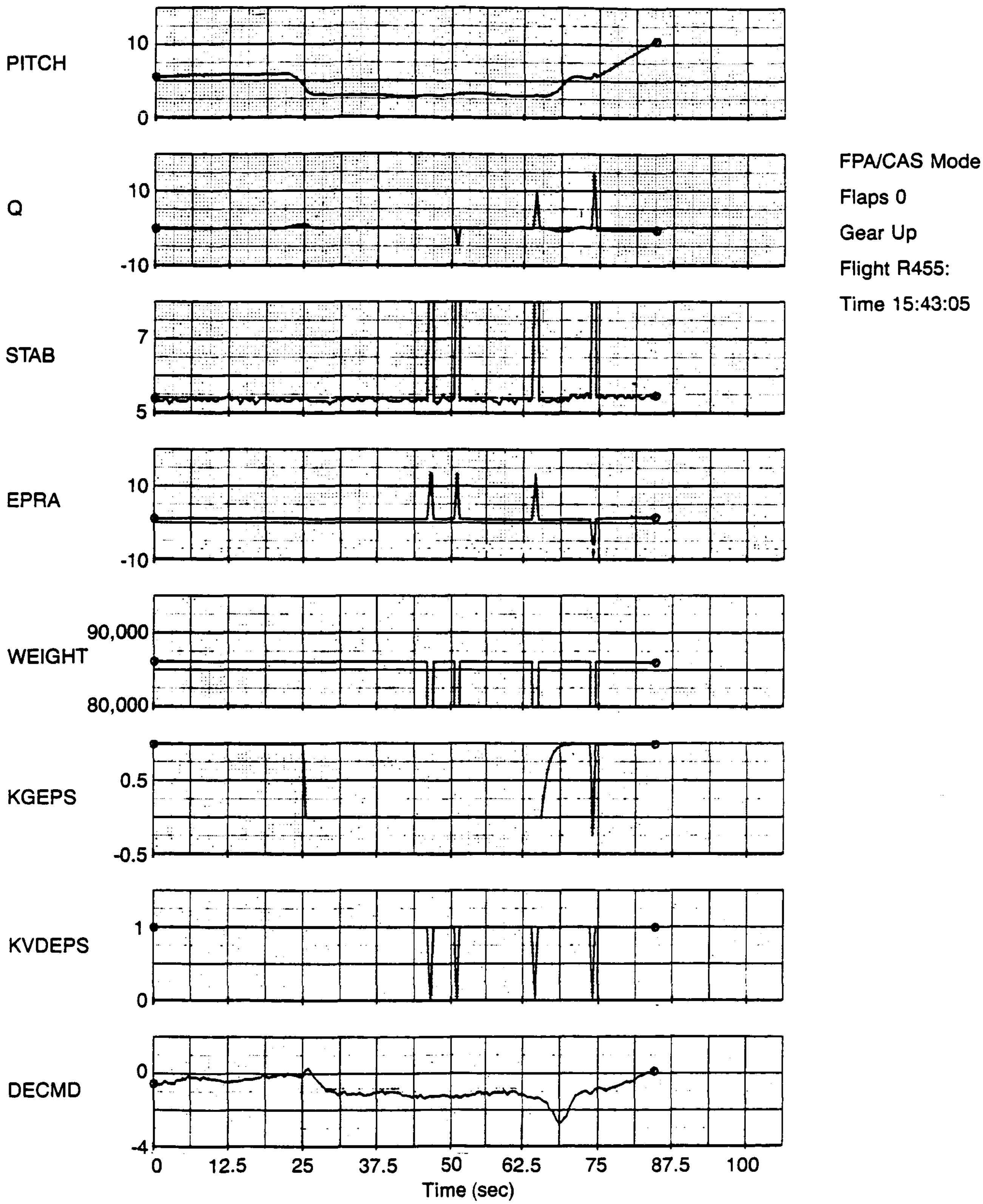


Figure 9 (b). Test 1.1.4; FPA Mode -5 deg

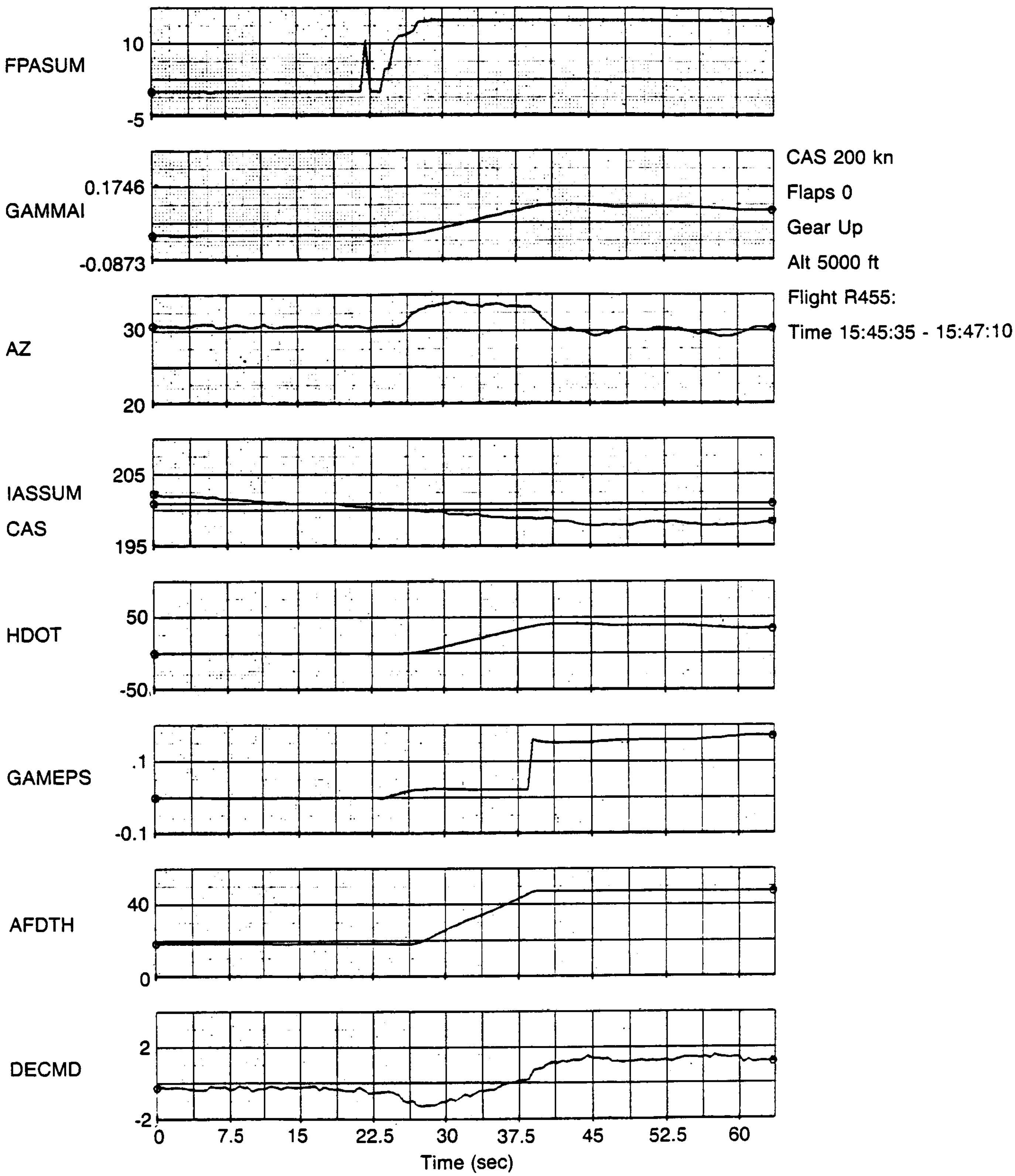


Figure 10 (a). Test 1.1.5; FPA Mode +15 deg

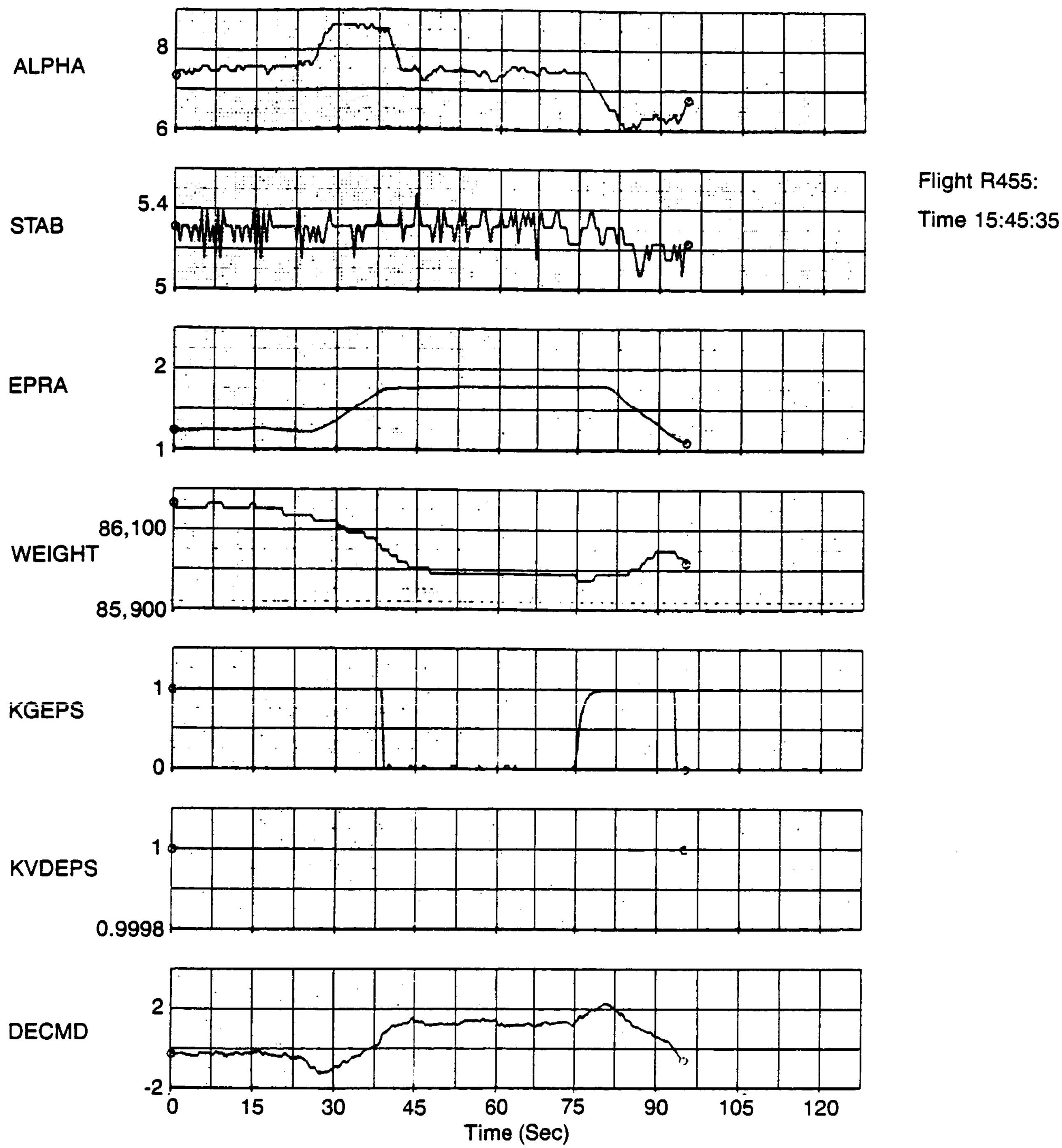


Figure 10 (b). Test 1.1.5; FPA Mode +15 deg

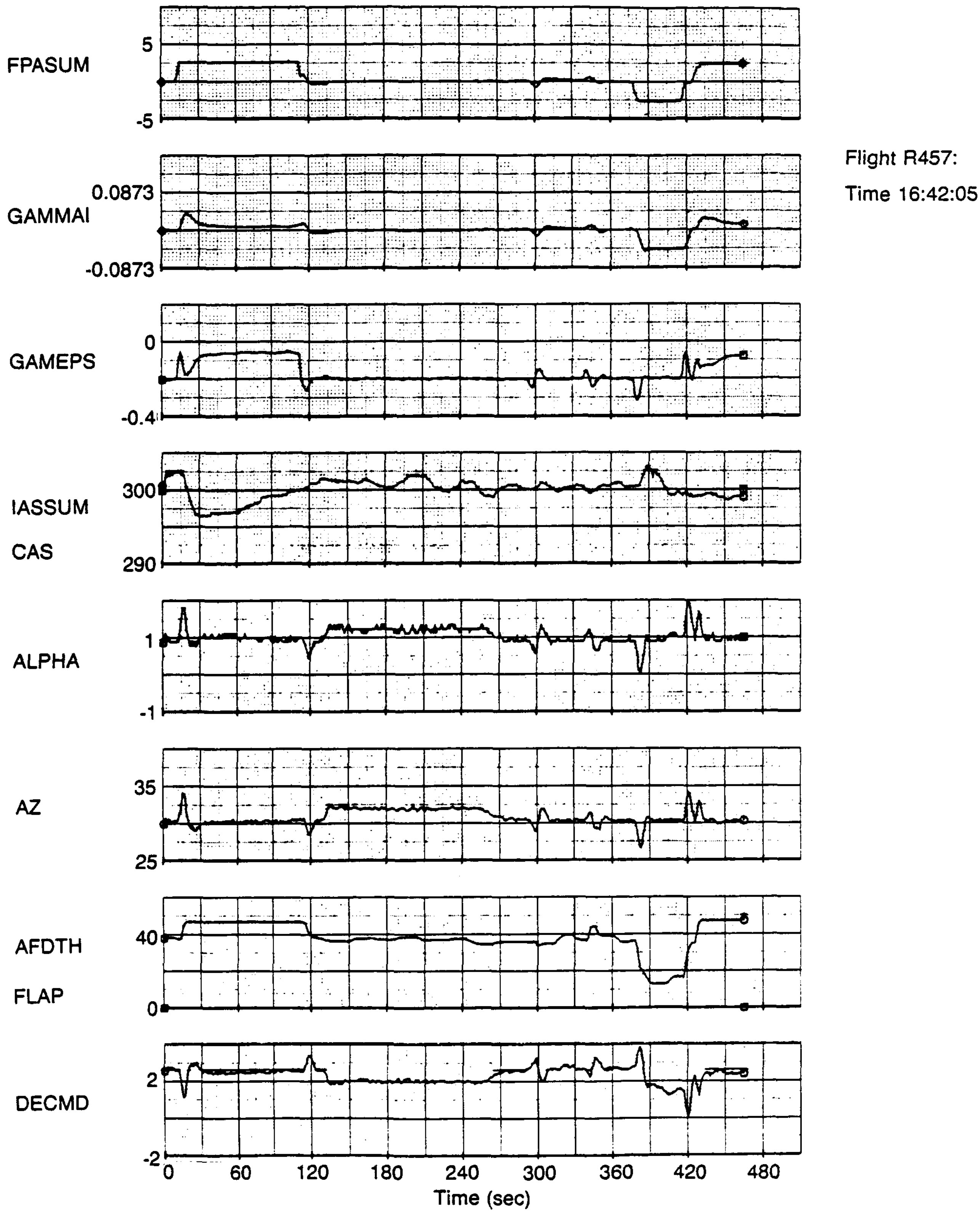


Figure 11 (a). Test 2.1.1, 2.1.2; FPA Mode +/-2.5 deg

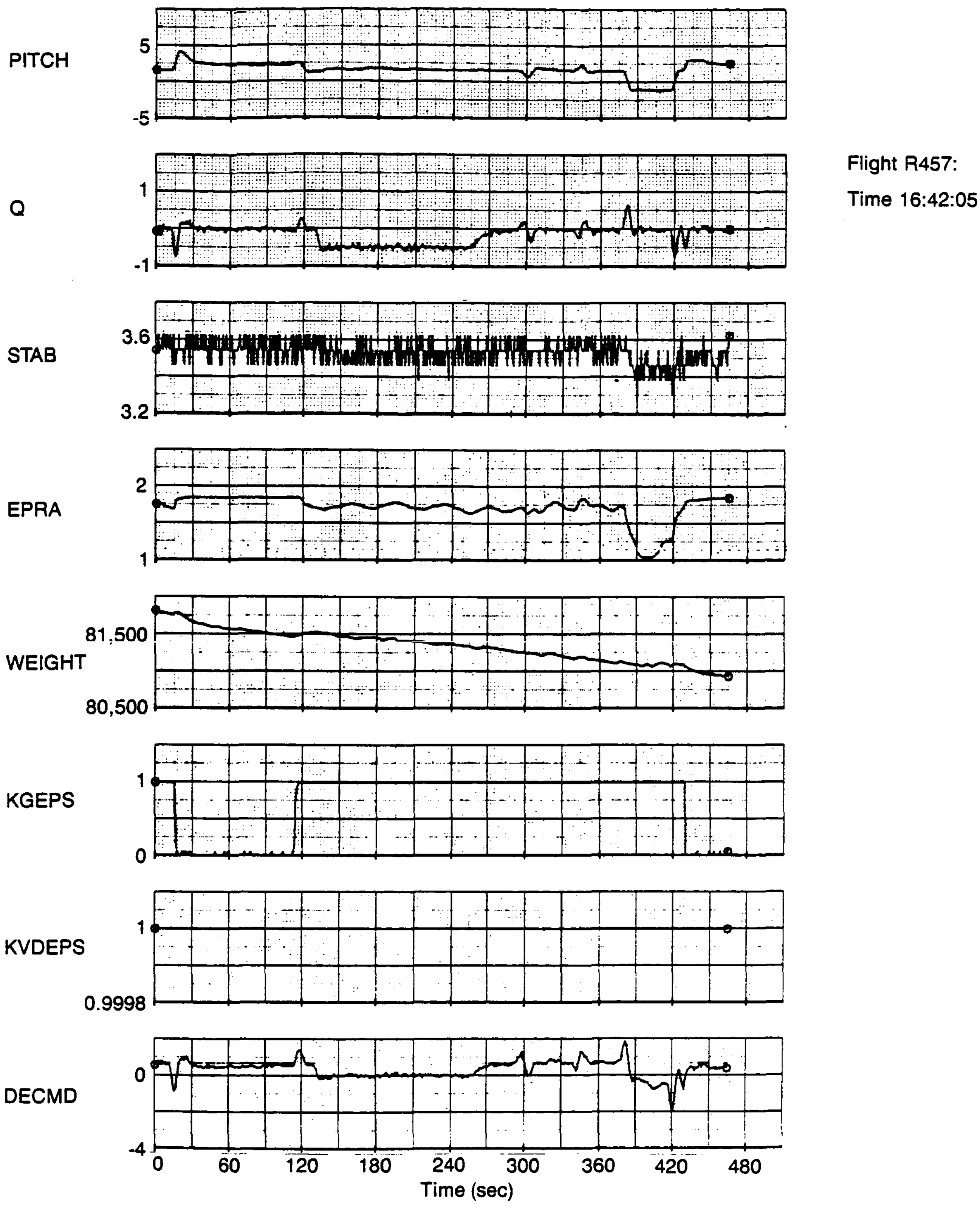


Figure 11 (b). Test 2.1.1, 2.1.2; FPA Mode +/-2.5 deg

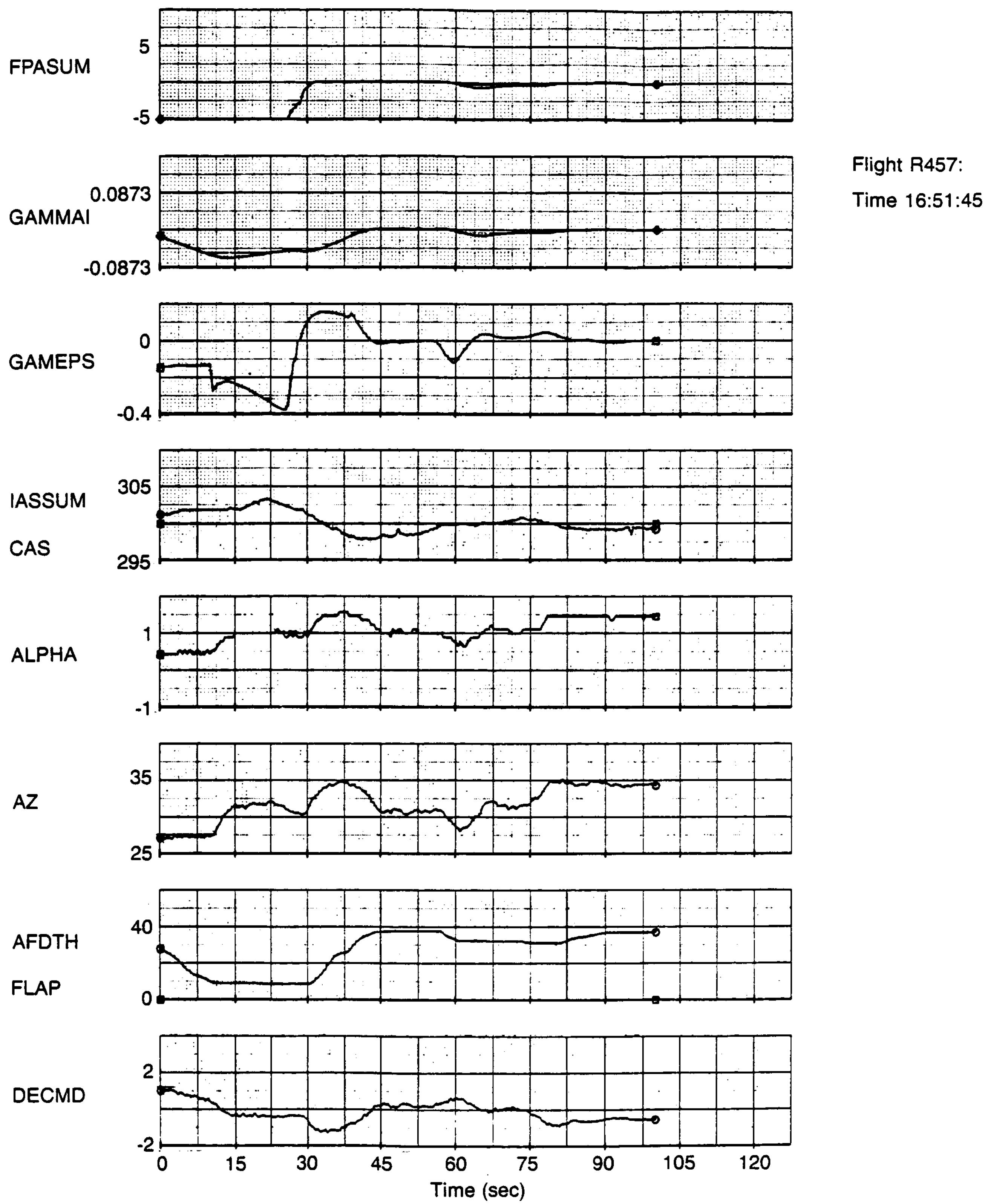


Figure 12 (a). Test 2.1.4; FPA Mode -5 deg

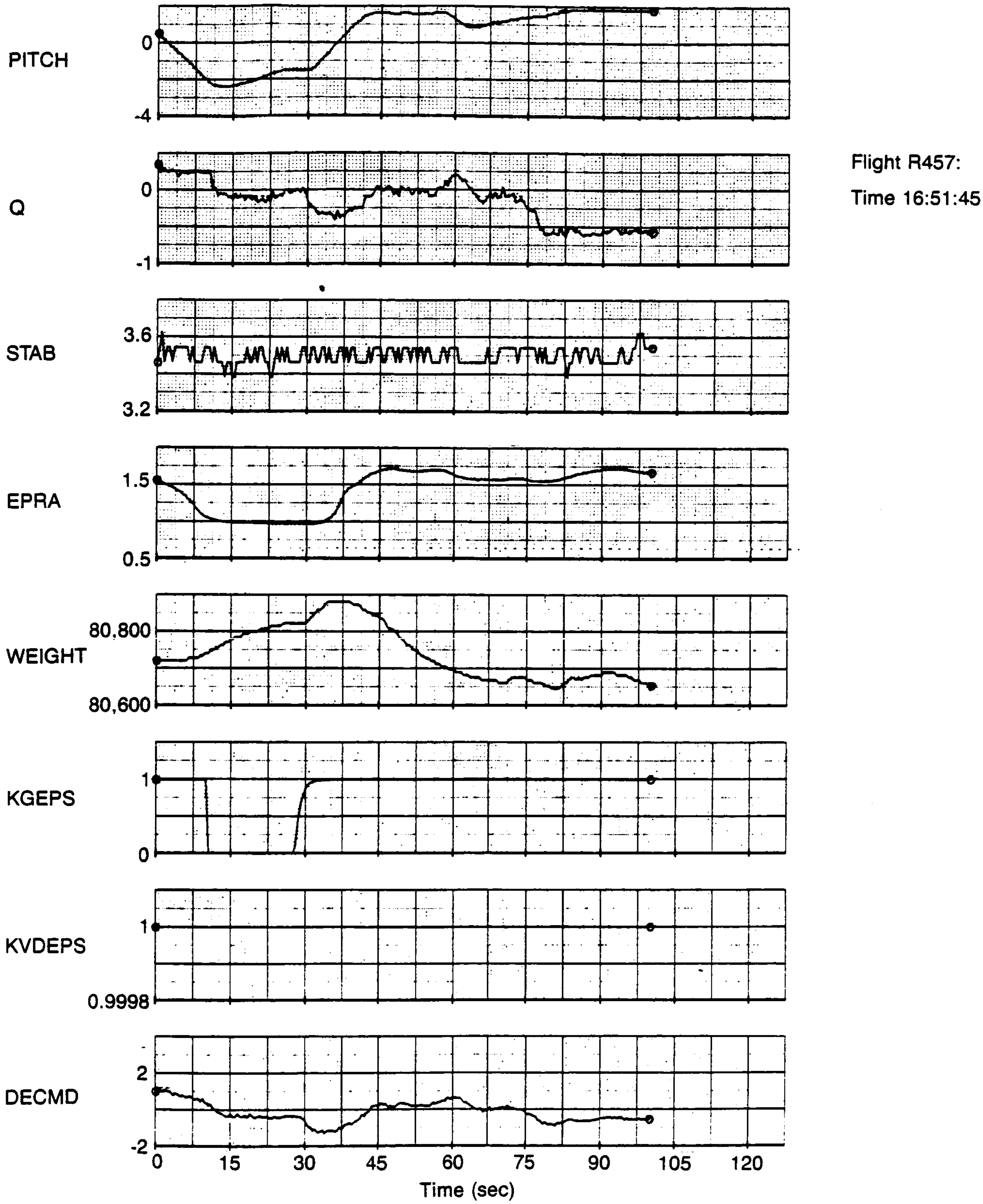


Figure 12 (b). Test 2.1.4; FPA Mode -5 deg

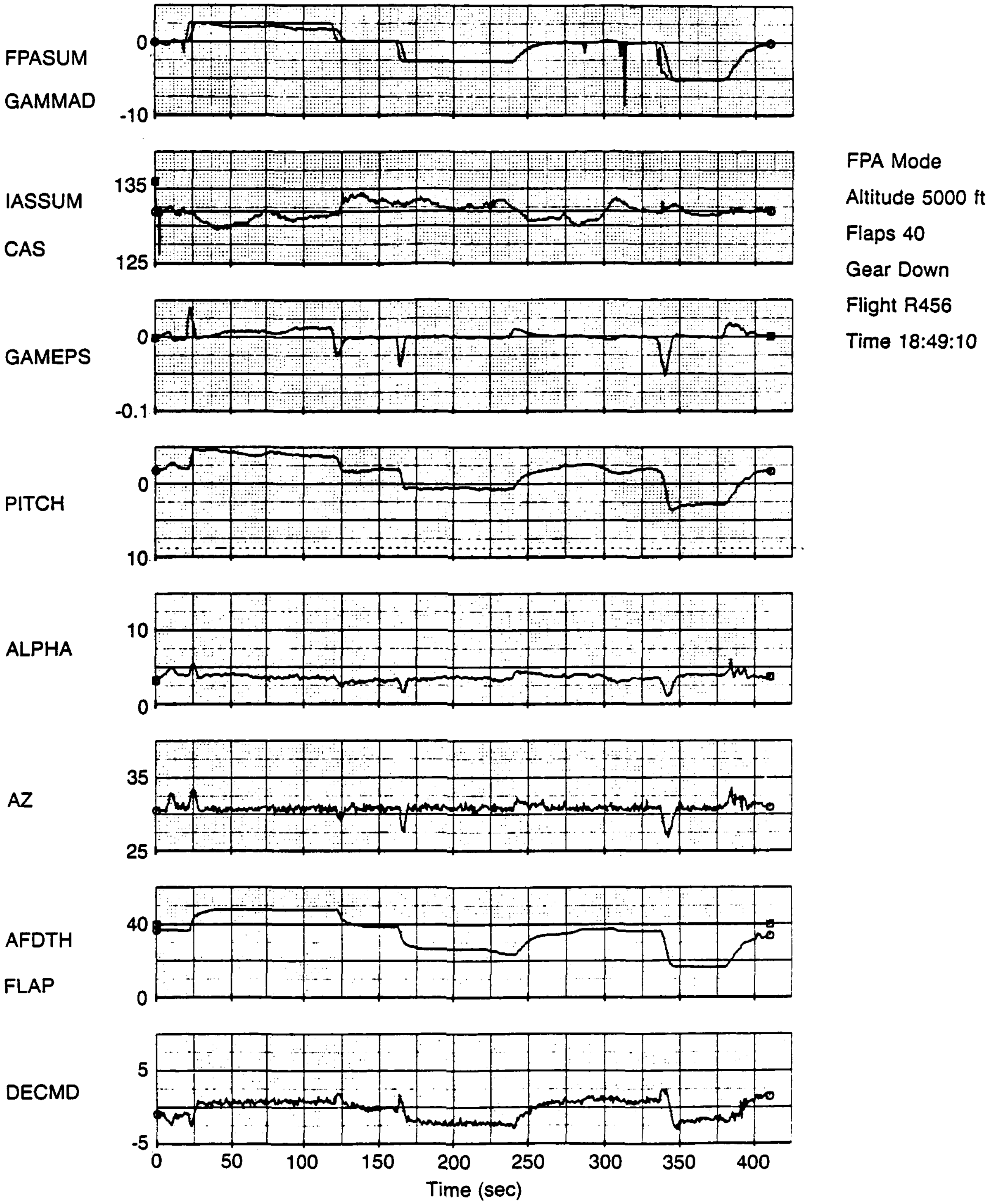


Figure 13 (a). Test 3.1.1, 3.1.2, 3.1.4; FPA Mode +/-2.5 deg, -5.0 deg

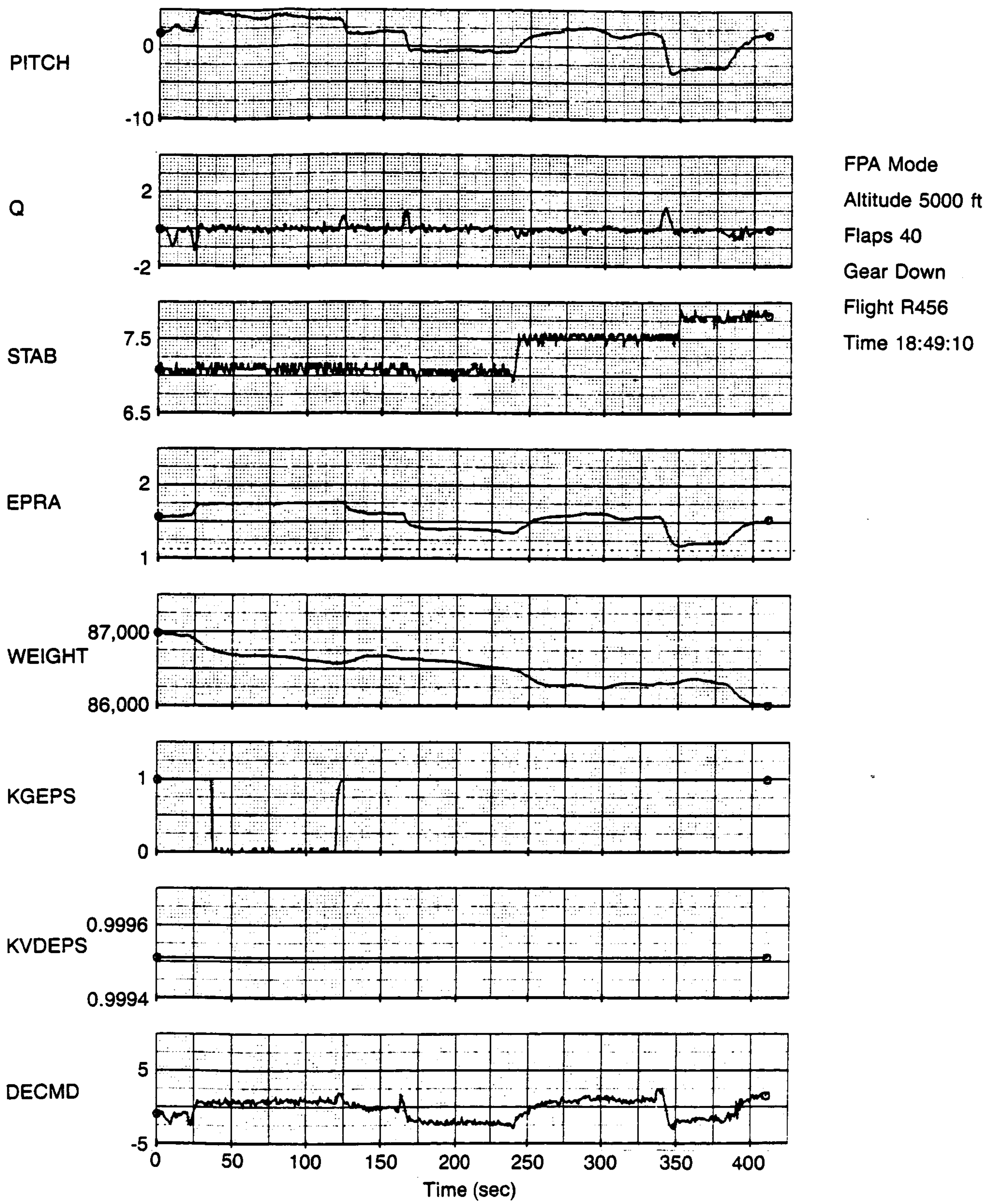


Figure 13 (b). Test 3.1.1, 3.1.2, 3.1.4; FPA Mode +/-2.5 deg, -5.0 deg

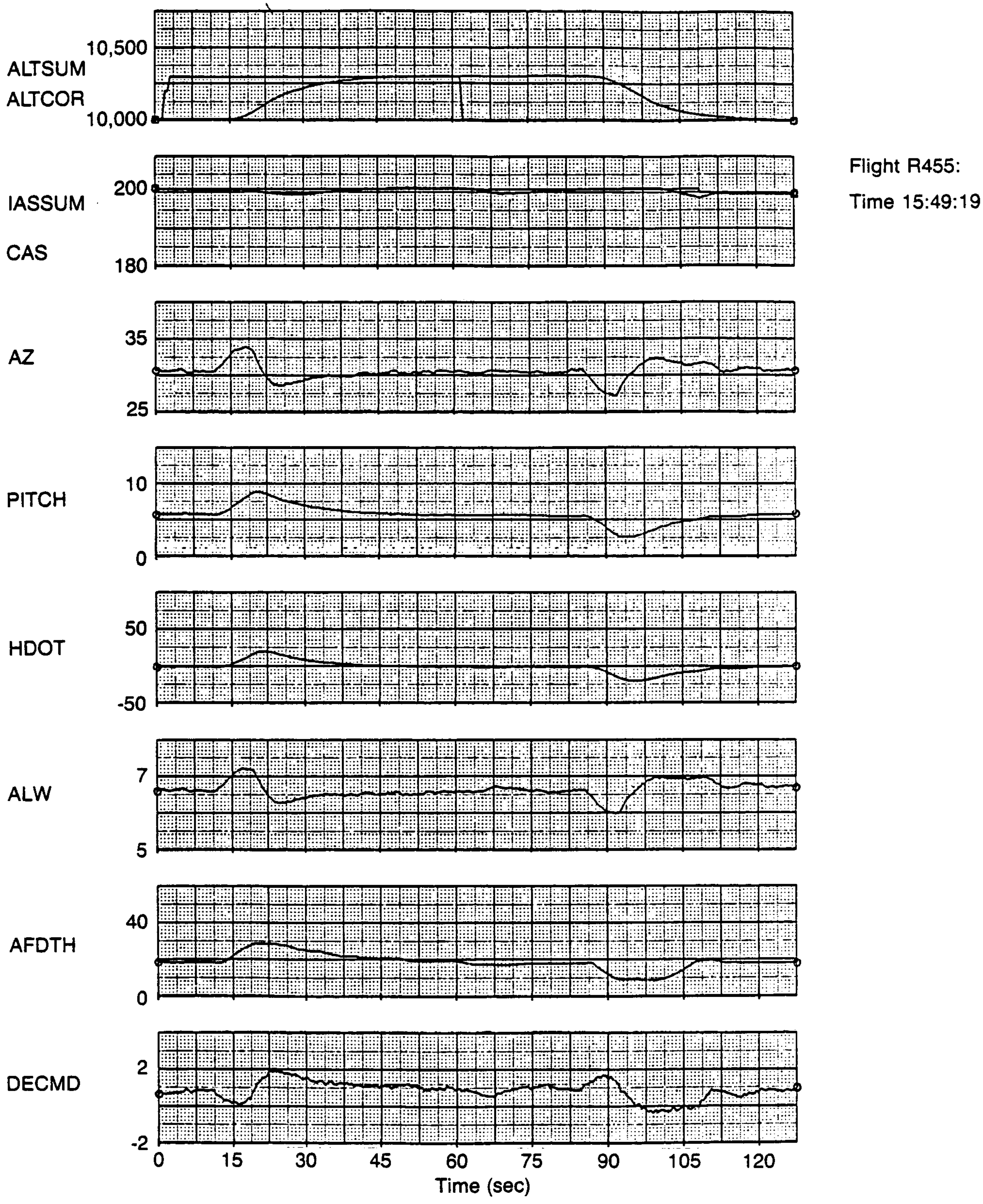


Figure 14 (a). Test 1.2.1 and 1.2.2; Alt +300 ft, -300 ft

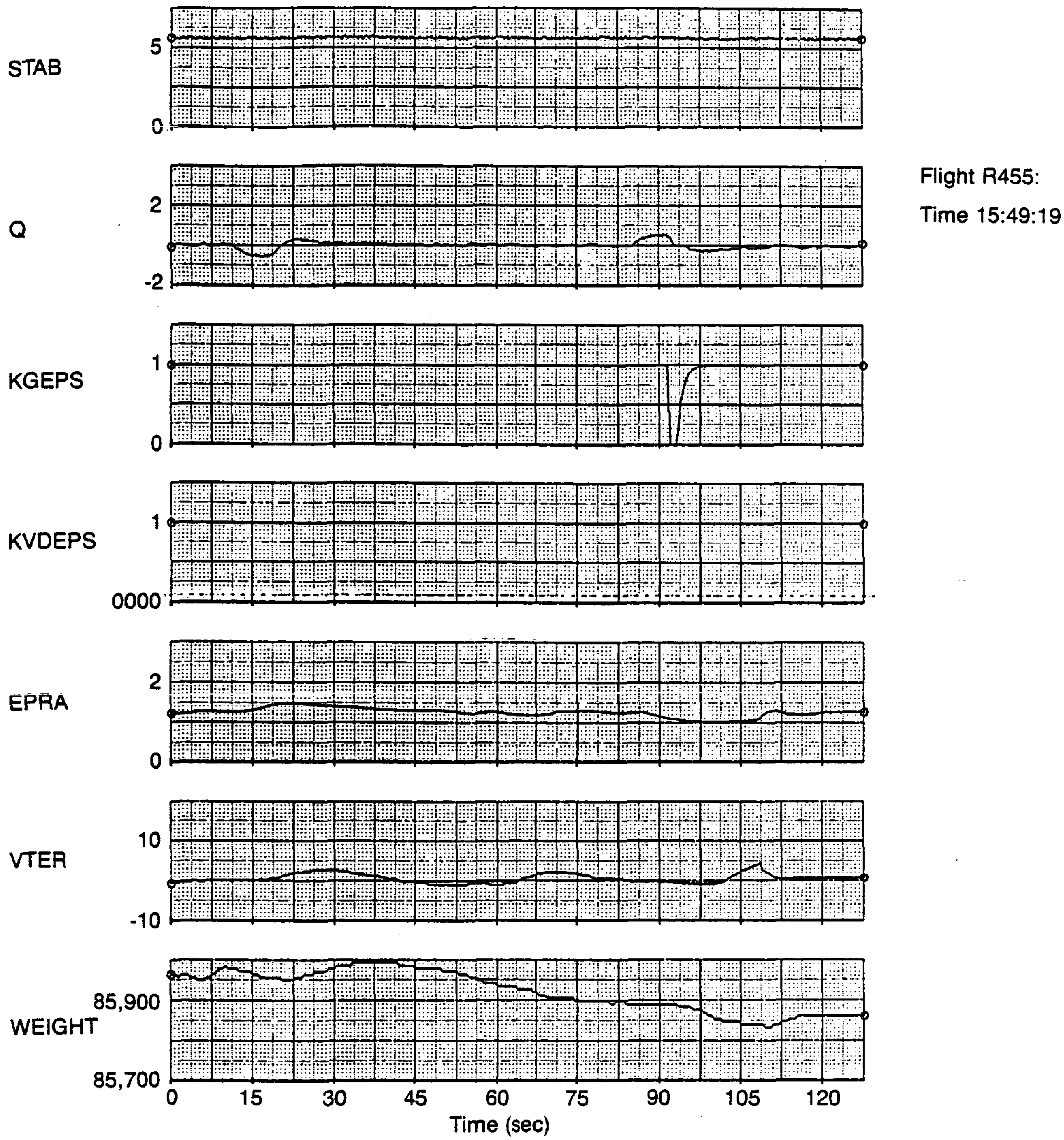
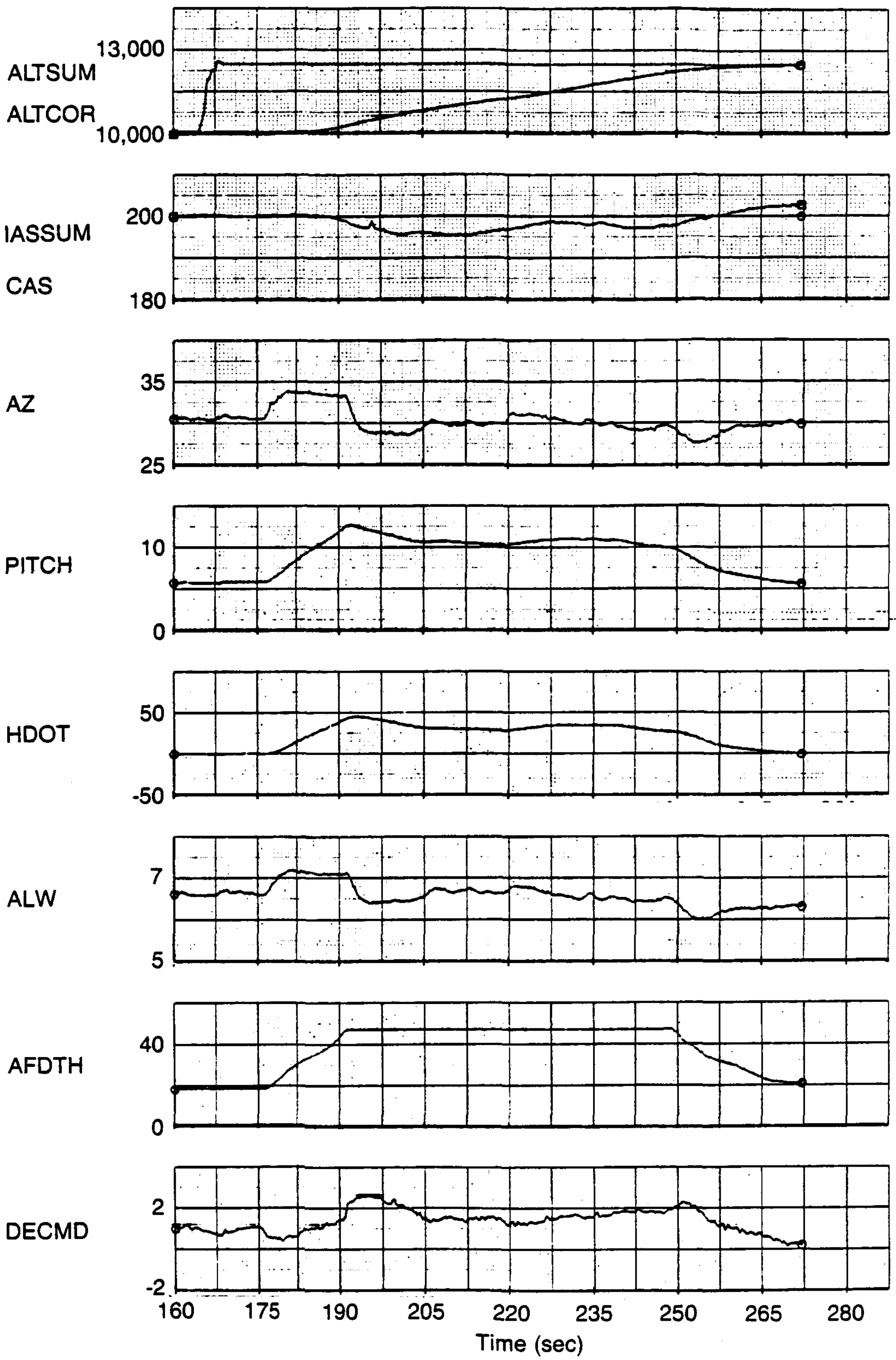


Figure 14 (b). Test 1.2.1 and 1.2.2; Alt +300 ft, -300 ft



Flight R455:
Time 15:54:00

Figure 15 (a). Test 1.2.3; Alt +2,500 ft

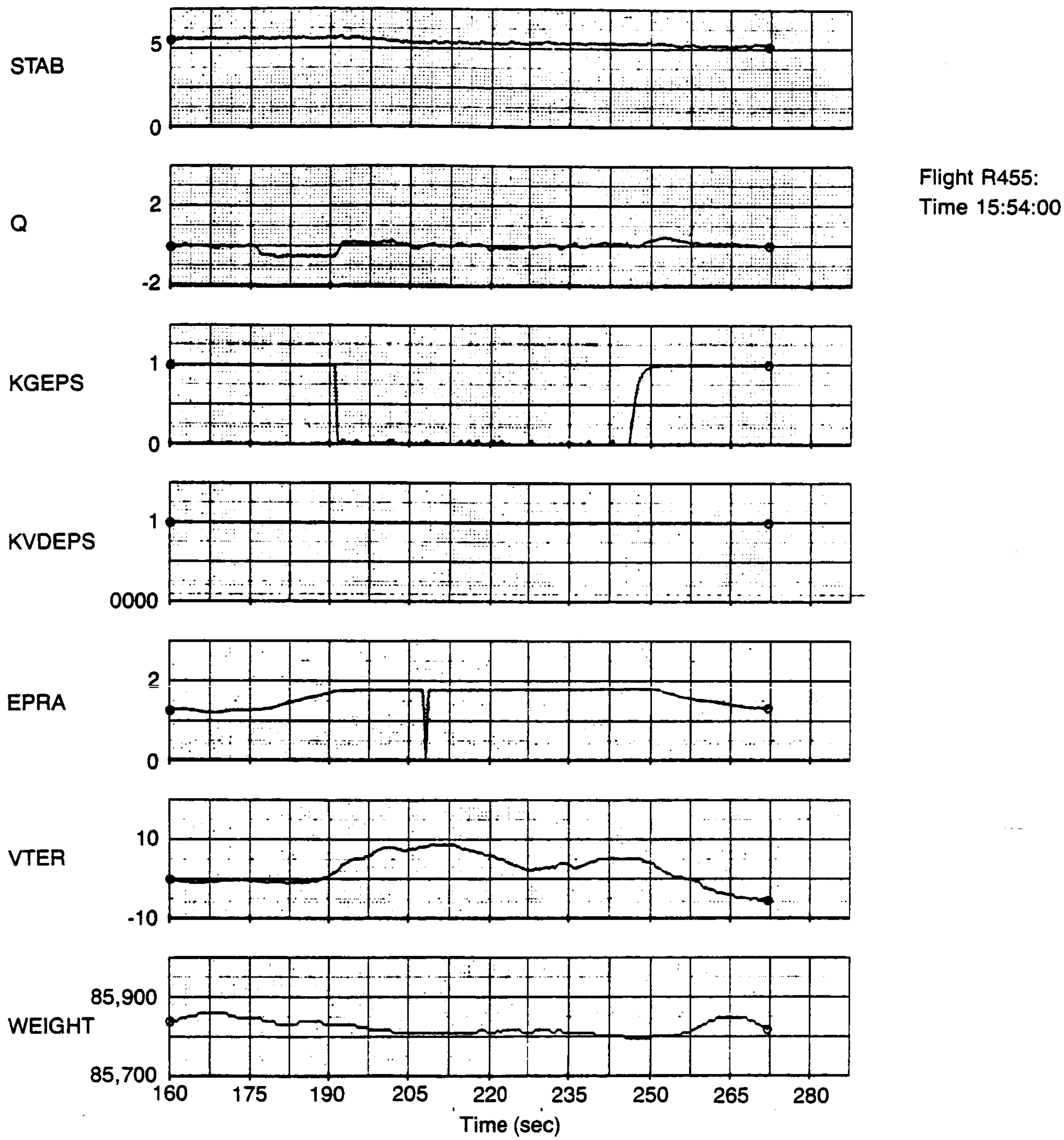


Figure 15 (b). Test 1.2.3; Alt +2,500 ft

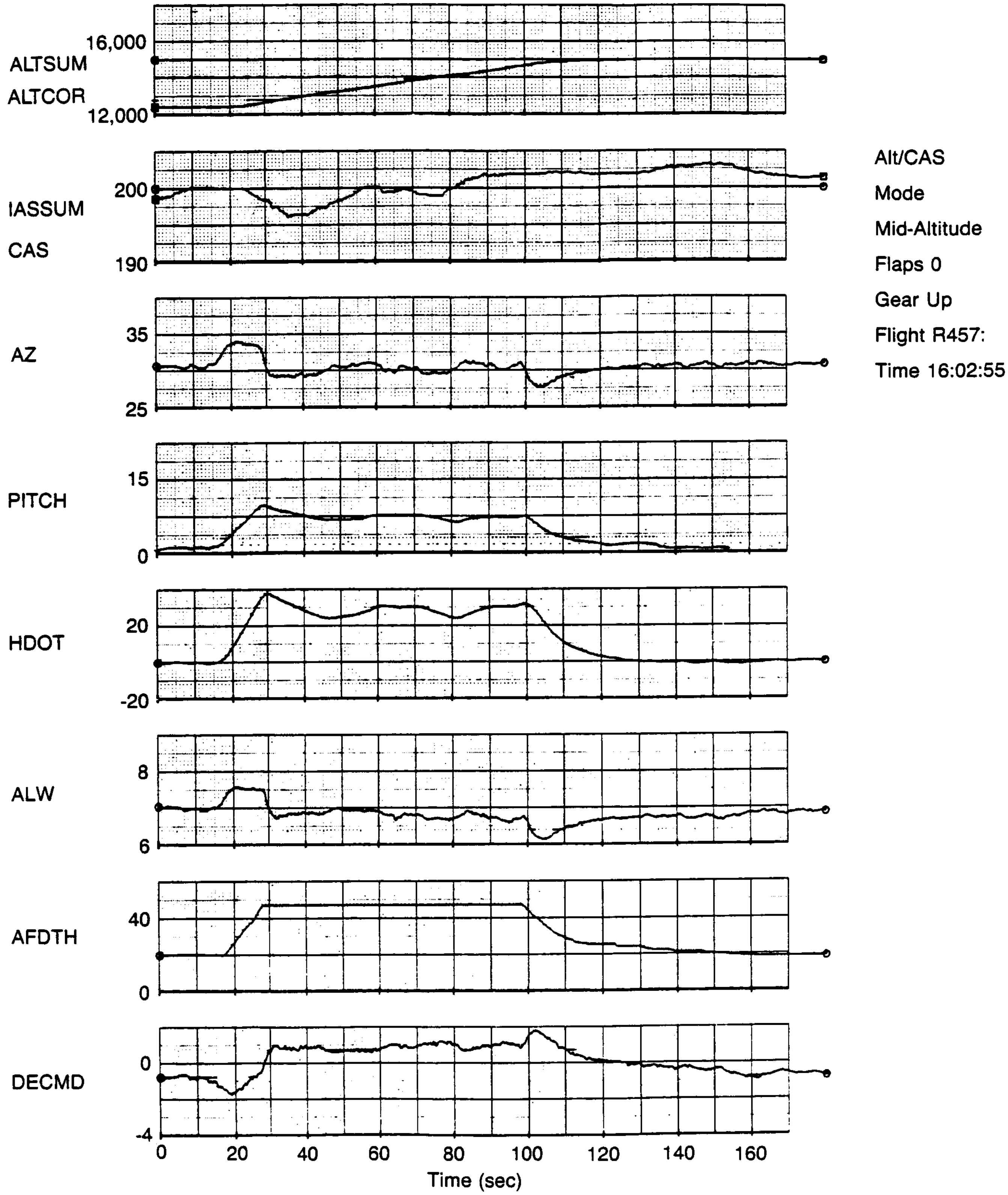


Figure 16 (a). Test 1.2.3M; Altitude Change +4,000 ft

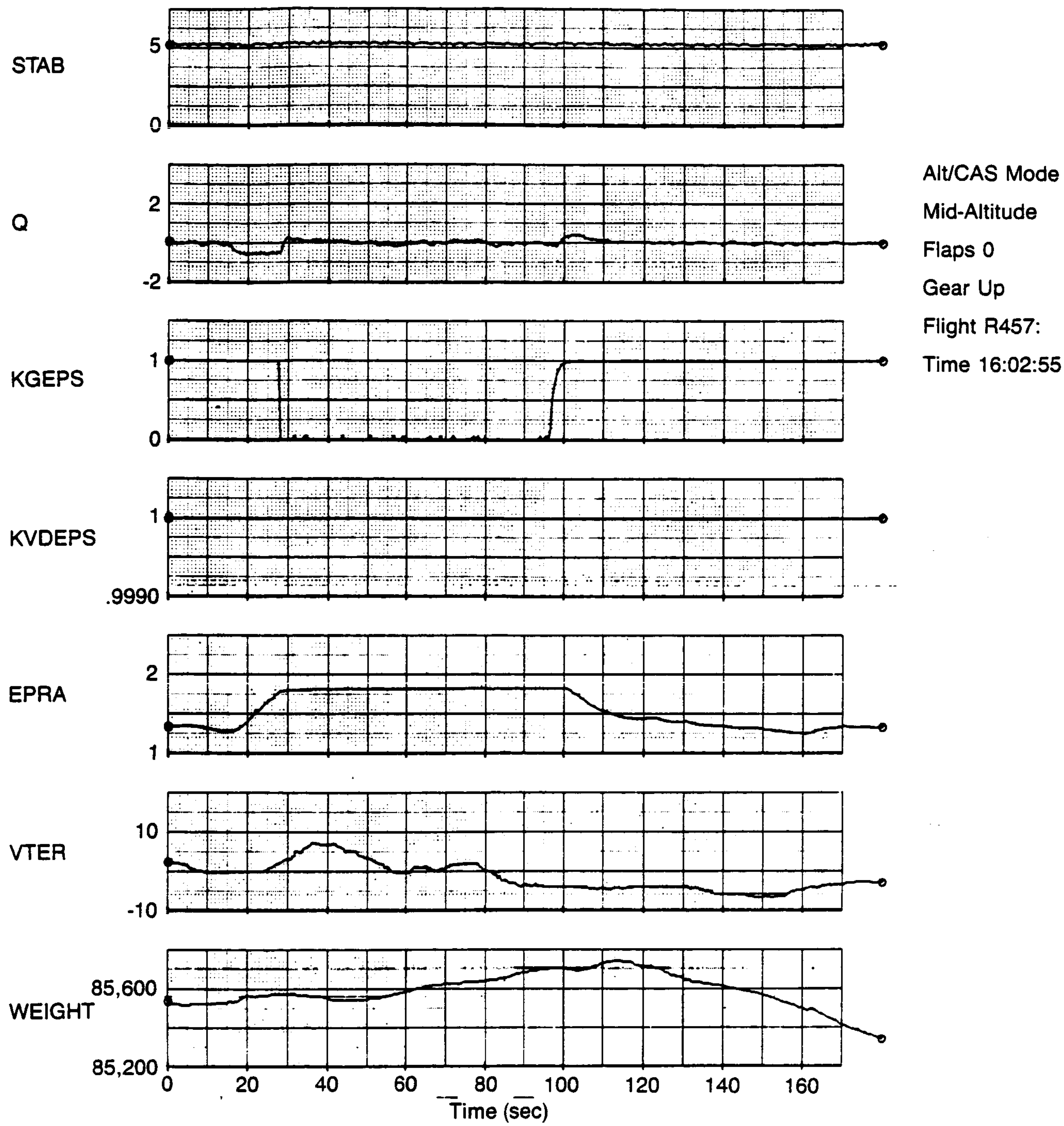
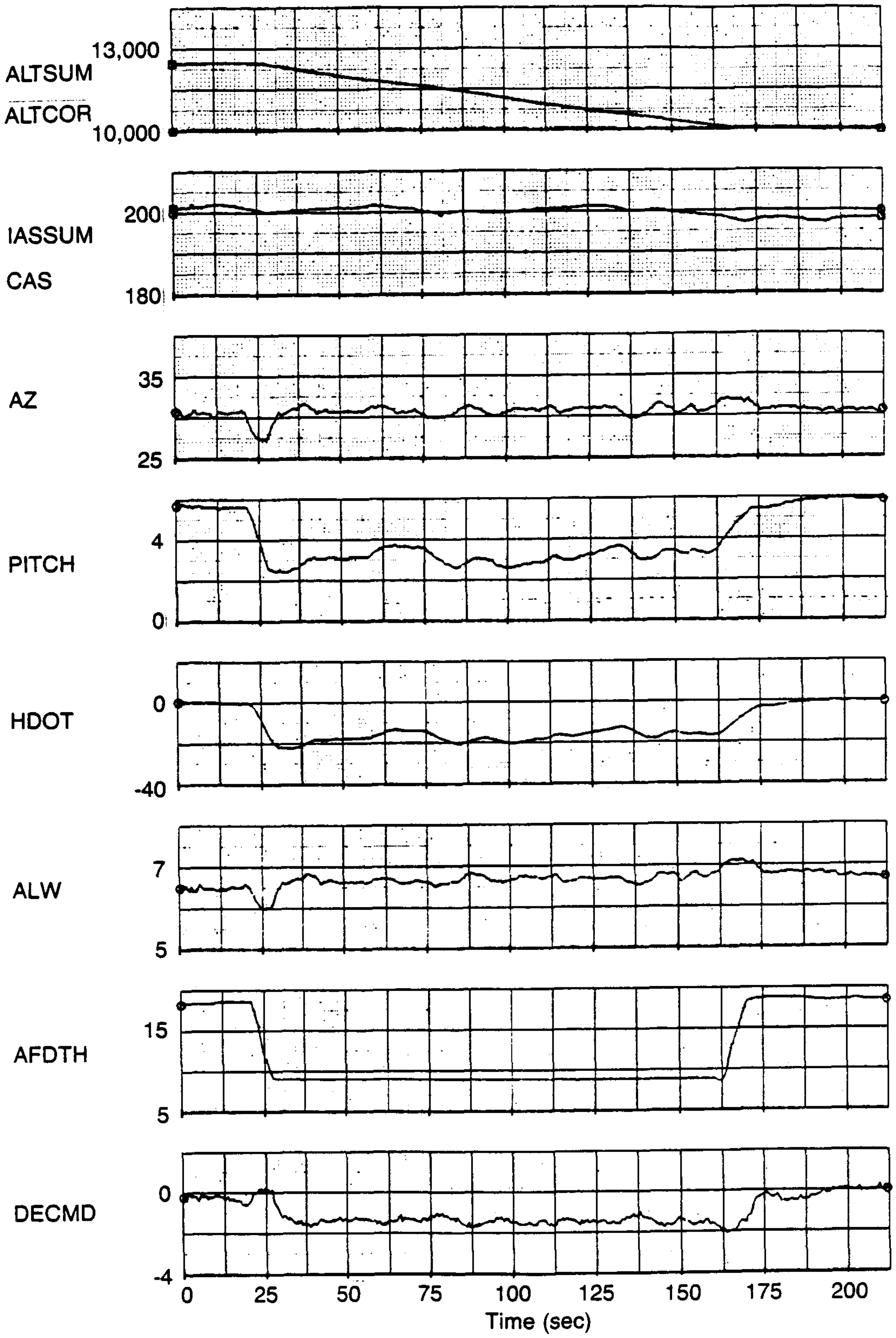


Figure 16 (b). Test 1.2.3M; Altitude Change +4,000 ft



Flight R455:

Time 155:55:28

Figure 17 (a). 1.2.4; Alt -2,500 ft

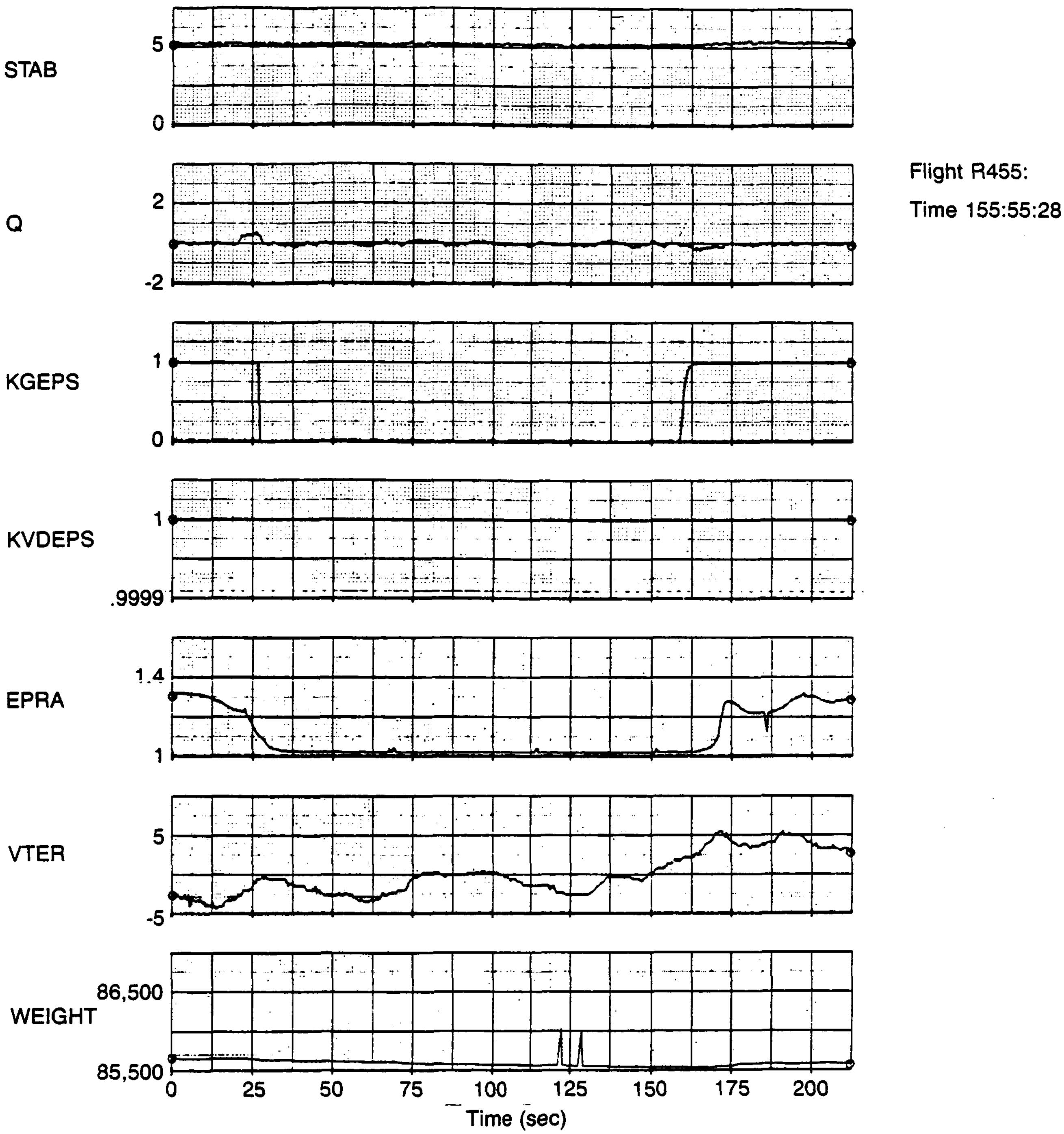
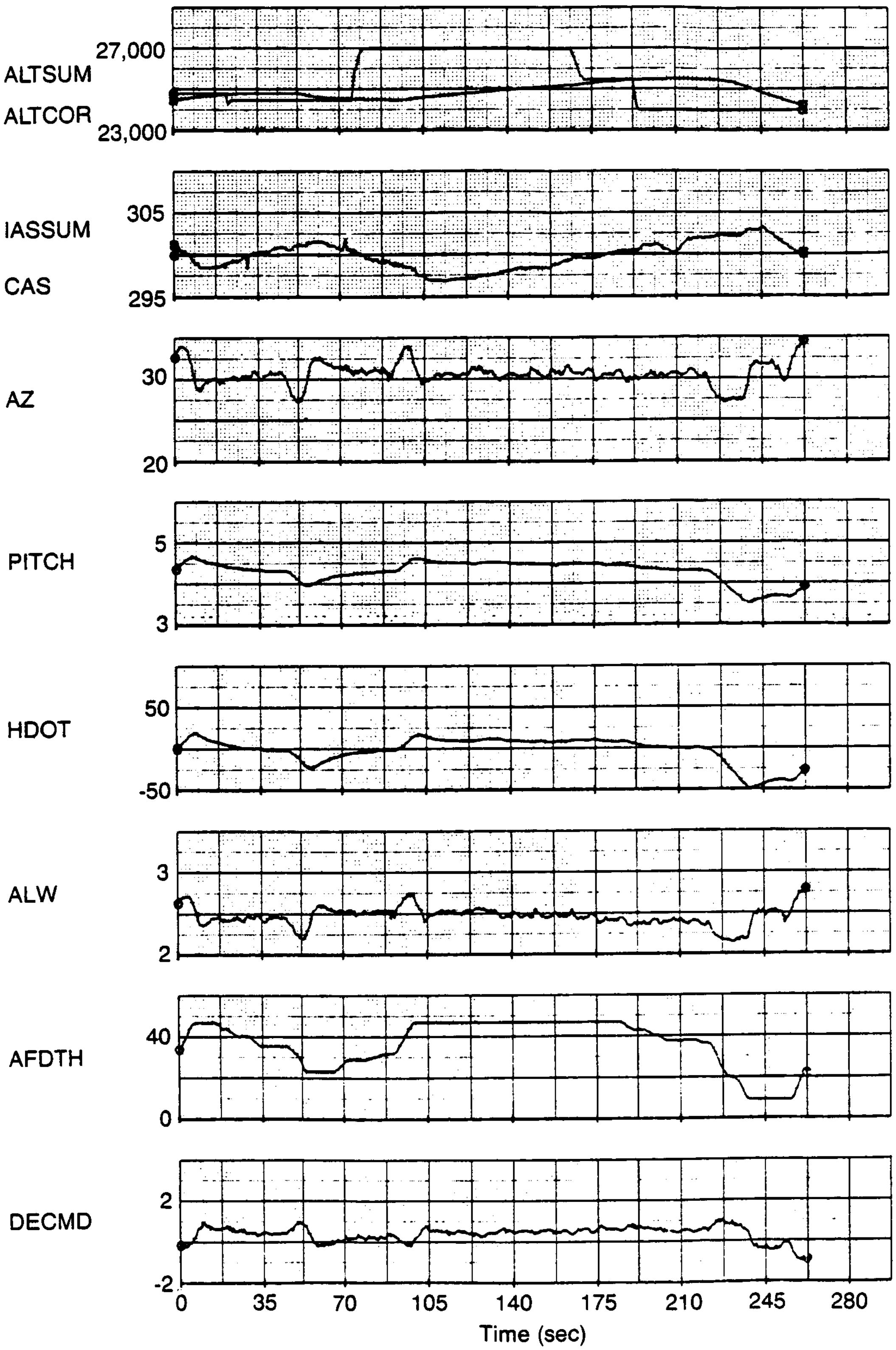


Figure 17 (b). Test 1.2.4; Alt -2,500 ft



Flight R457:

Time 16:56:03

Figure 18 (a). Test 2.2.1-2.2.3; Alt +300, -300, +2,500, -2,500 ft

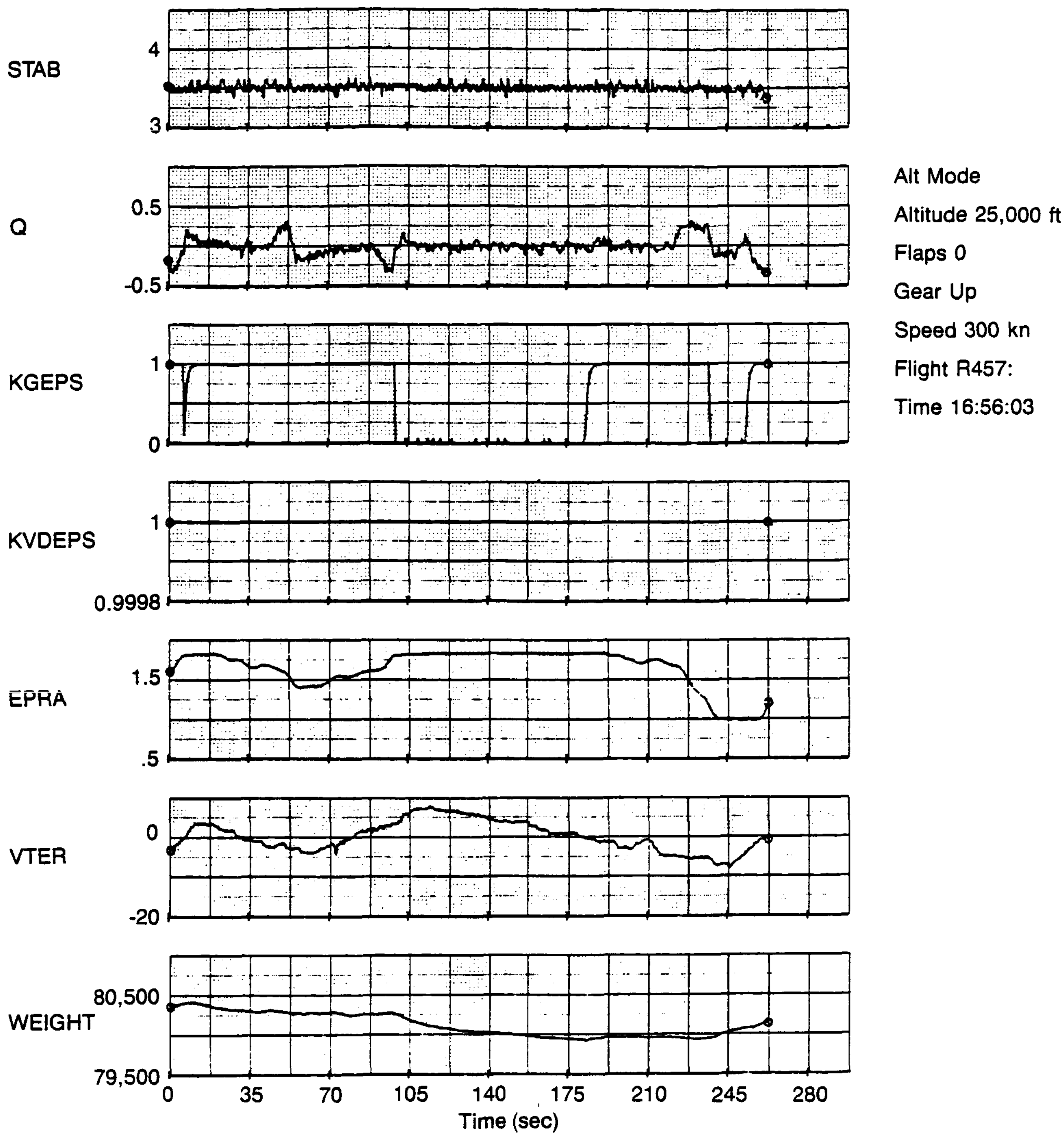


Figure 18 (b). Test 2.2.1-2.2.3; Alt +300, -300, +2,500, -2,500 ft

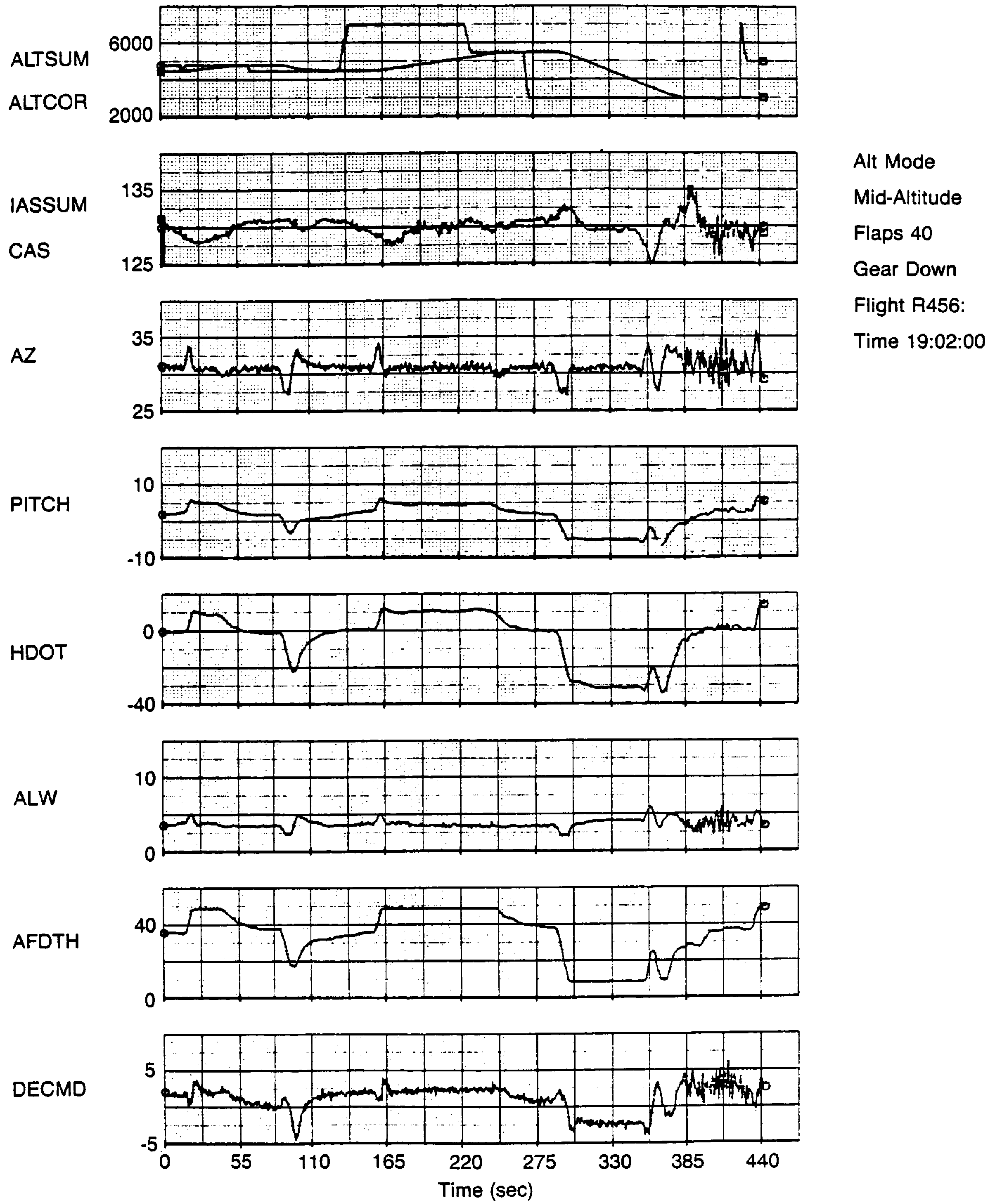


Figure 19 (a). Test 3.2.1-3.2.4; Altitude Changes 300 ft, 2,500 ft

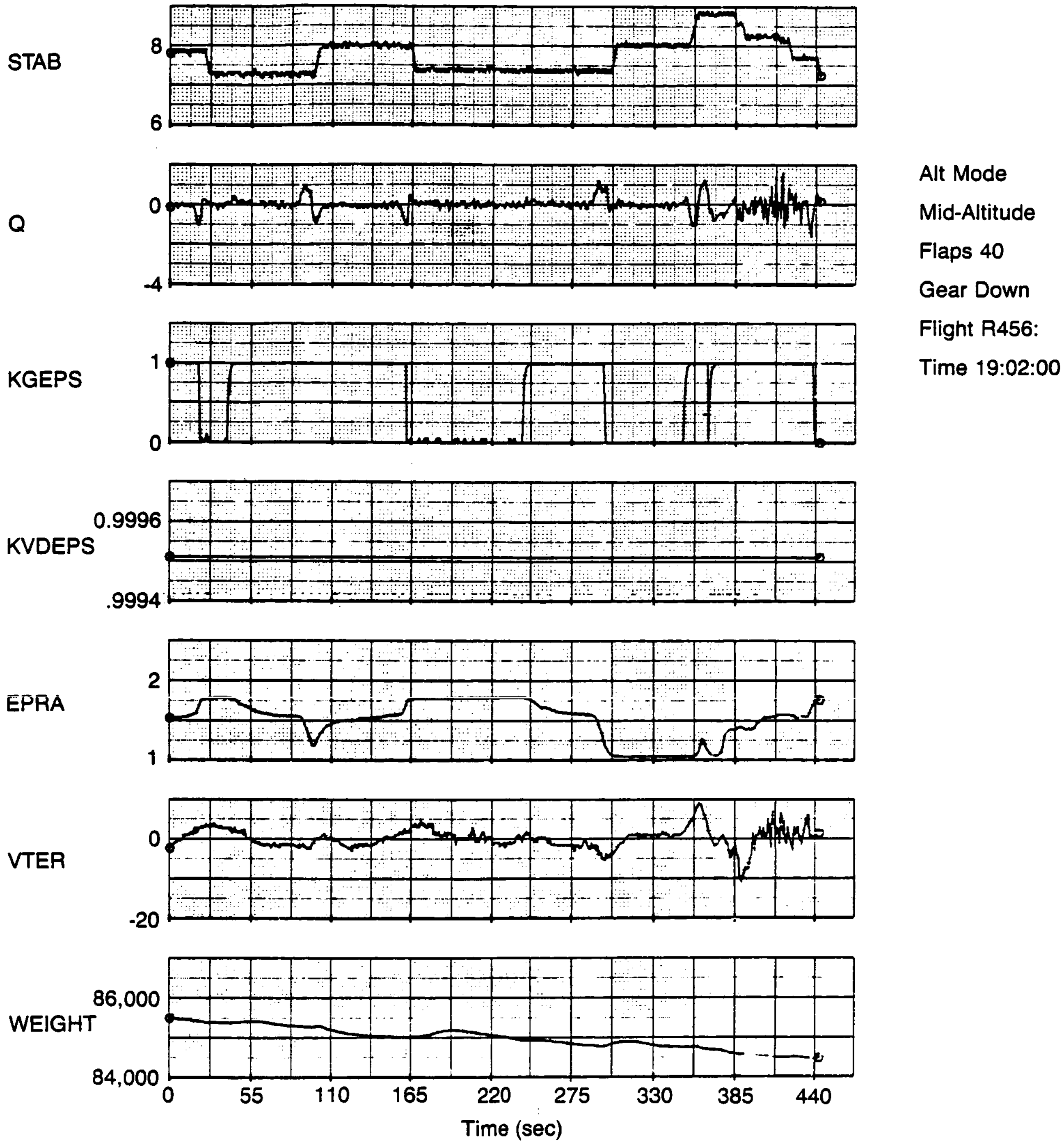


Figure 19 (b). Test 3.2.1-3.2.4; Altitude Changes 300 ft, 2,500 ft

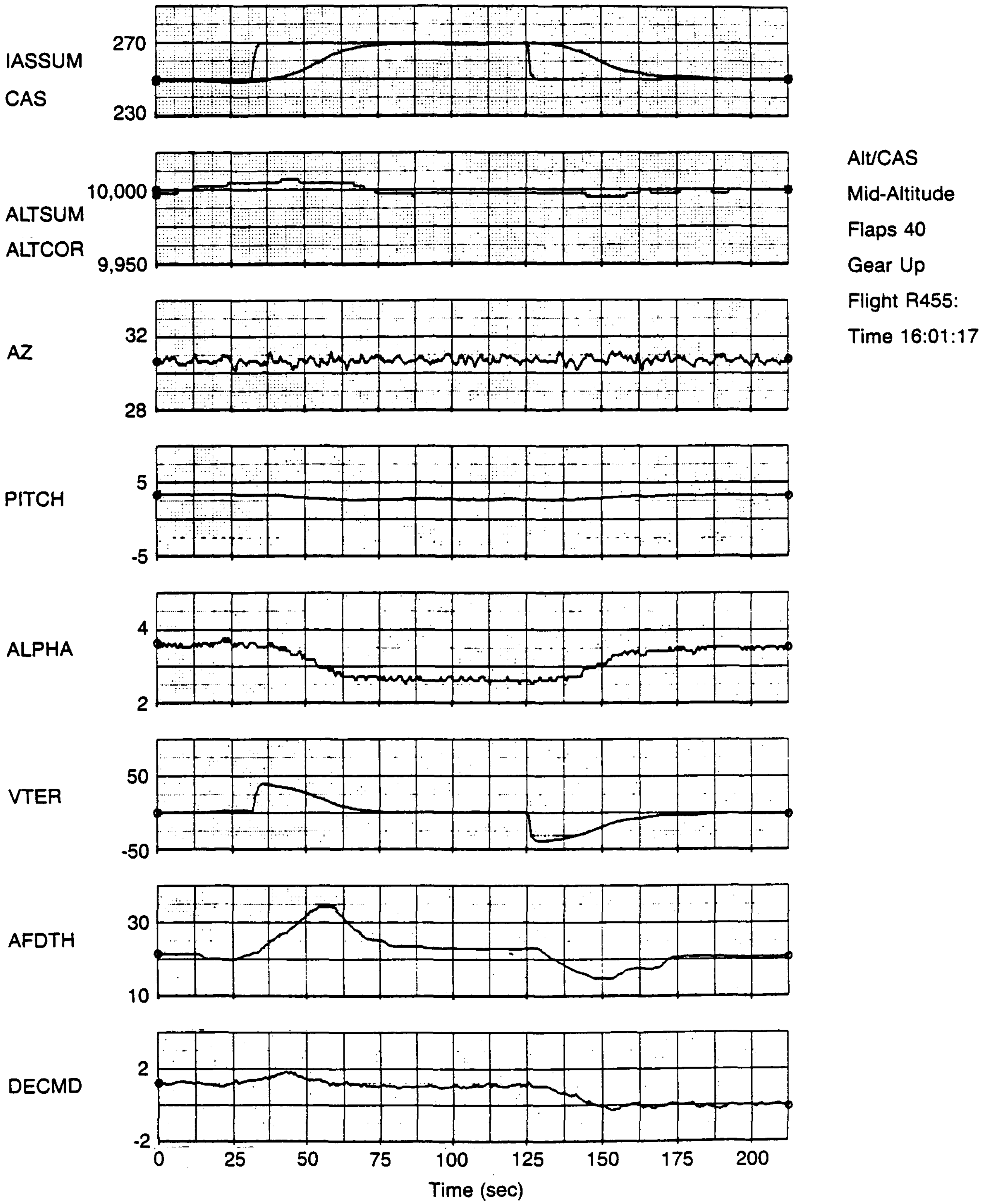


Figure 20 (a). Test 1.3.1 and 1.3.2; CAS +20 -20

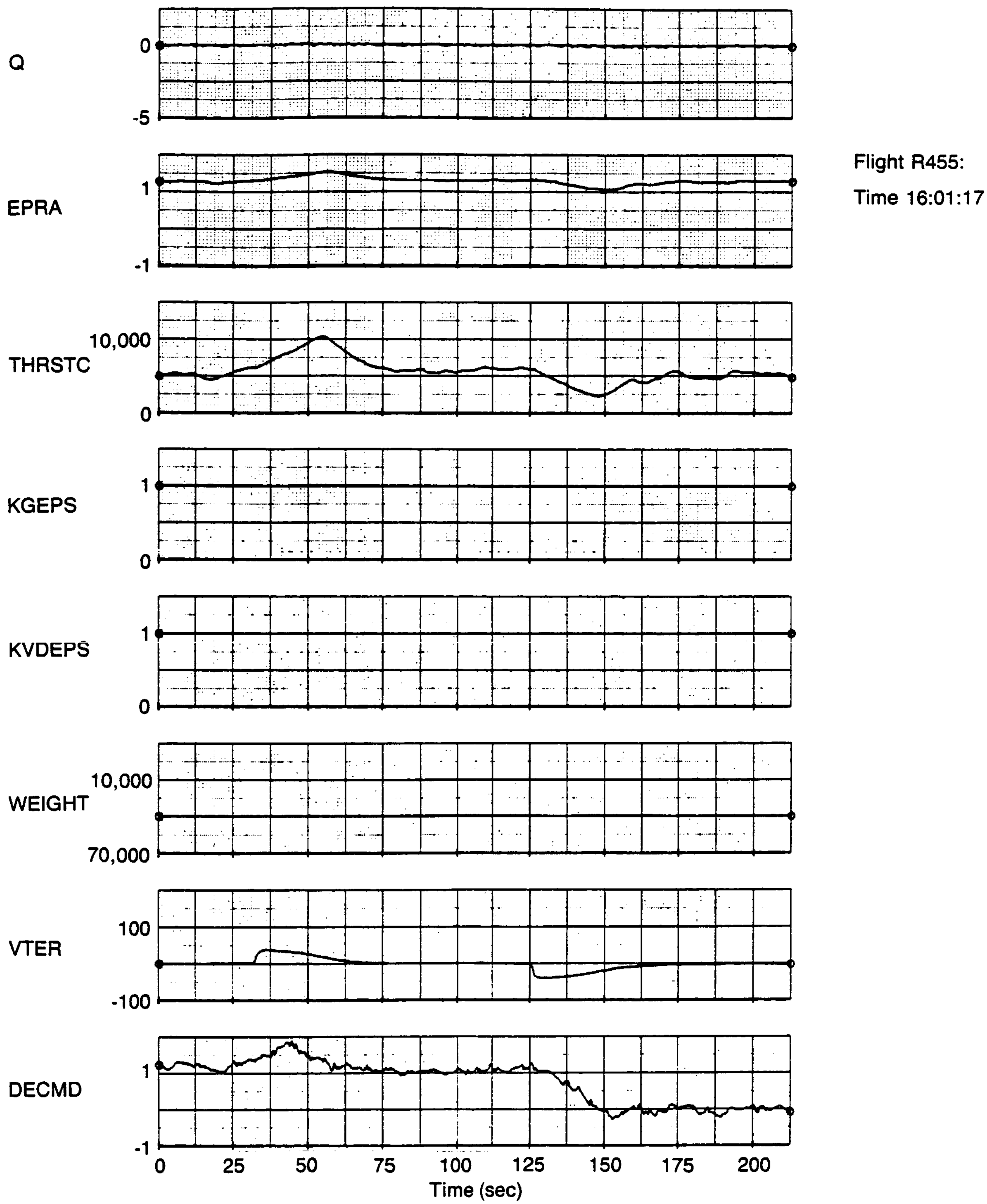


Figure 20 (b). Test 1.3.1 and 1.3.2; CAS +20 -20

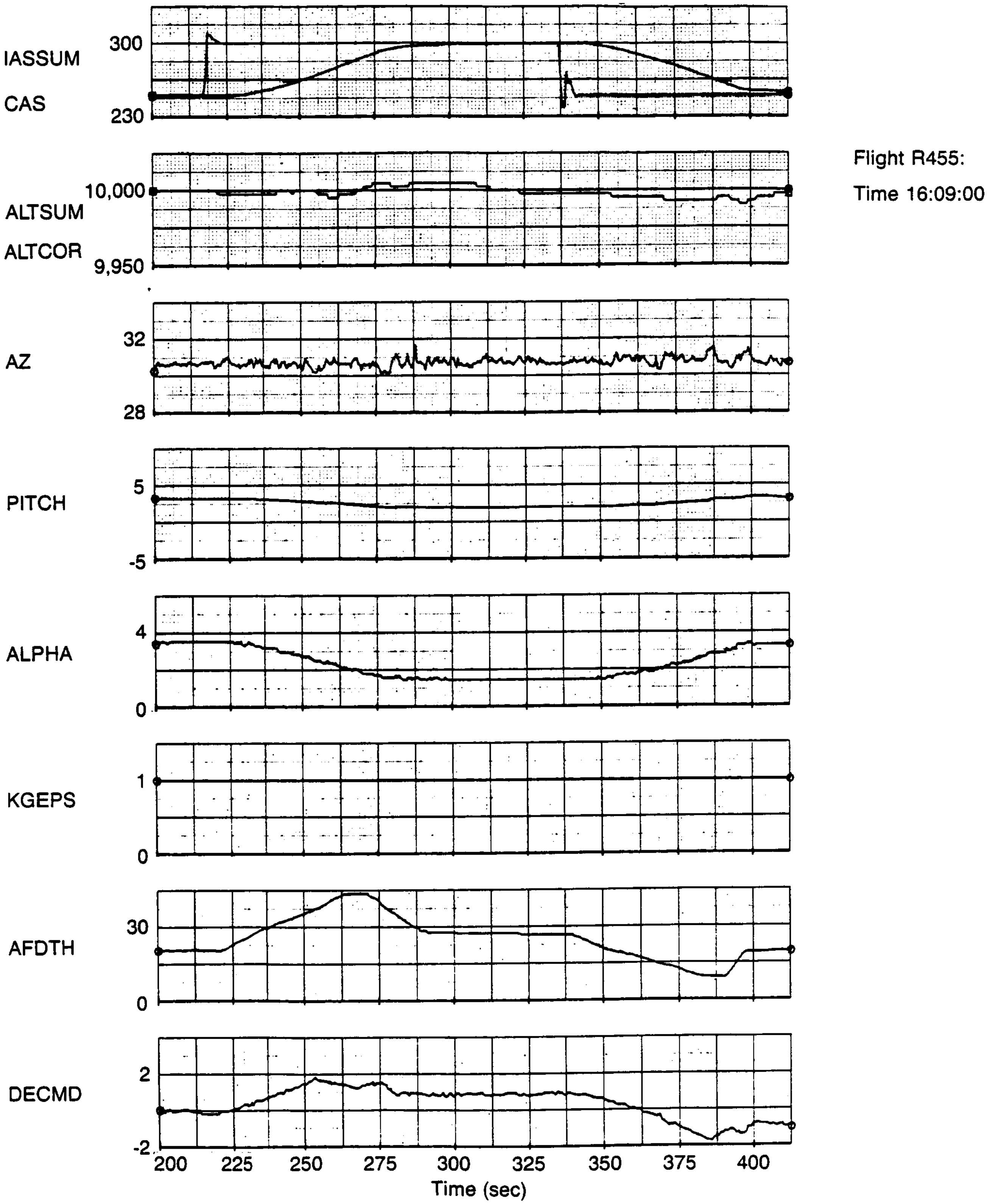
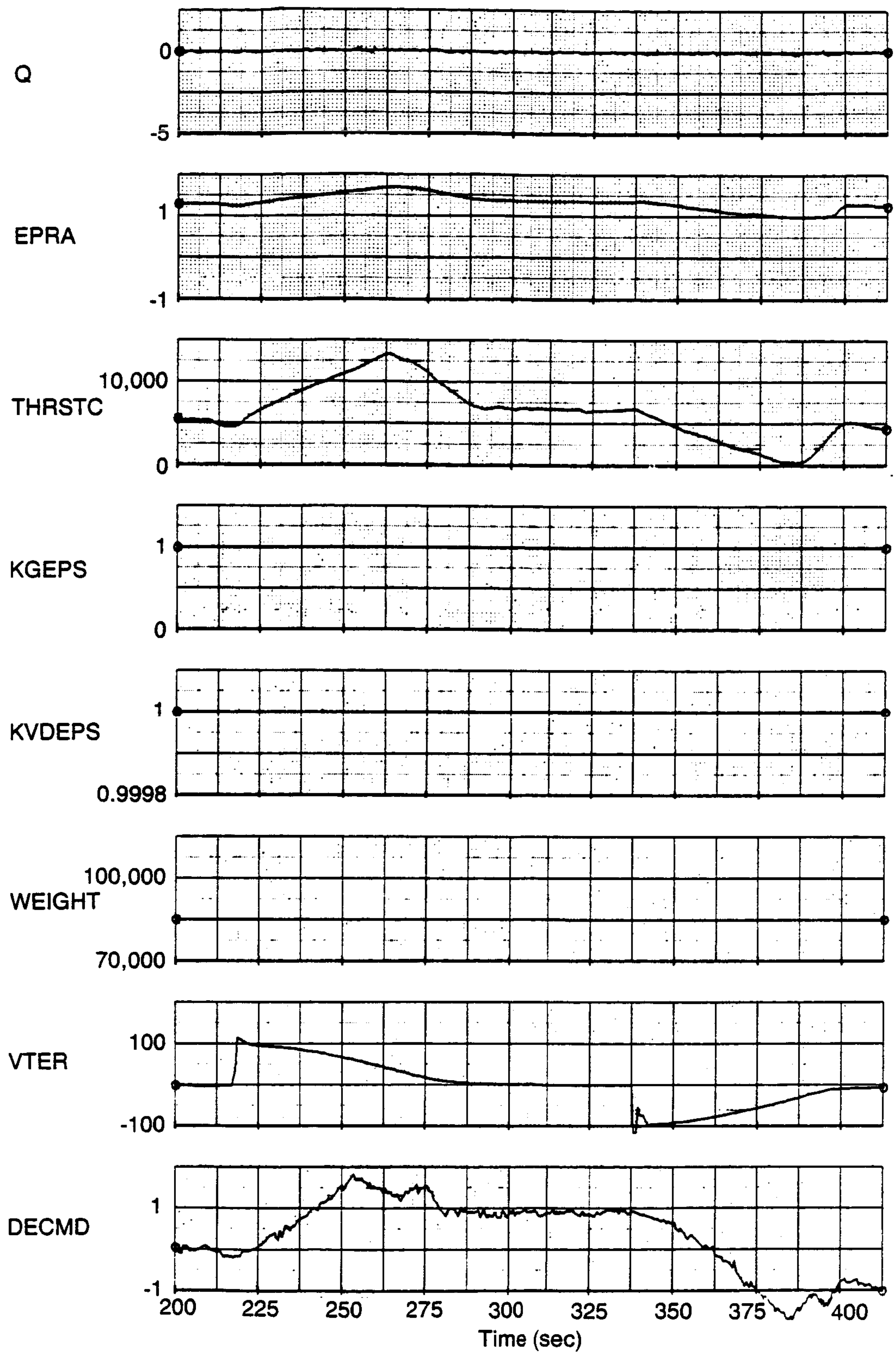


Figure 21 (a). Test 1.3.3 and 1.3.4; CAS +50 -50



Flight R455:

Time 16:09:00

Figure 21 (b). Test 1.3.3 and 1.3.4; CAS +50 -50

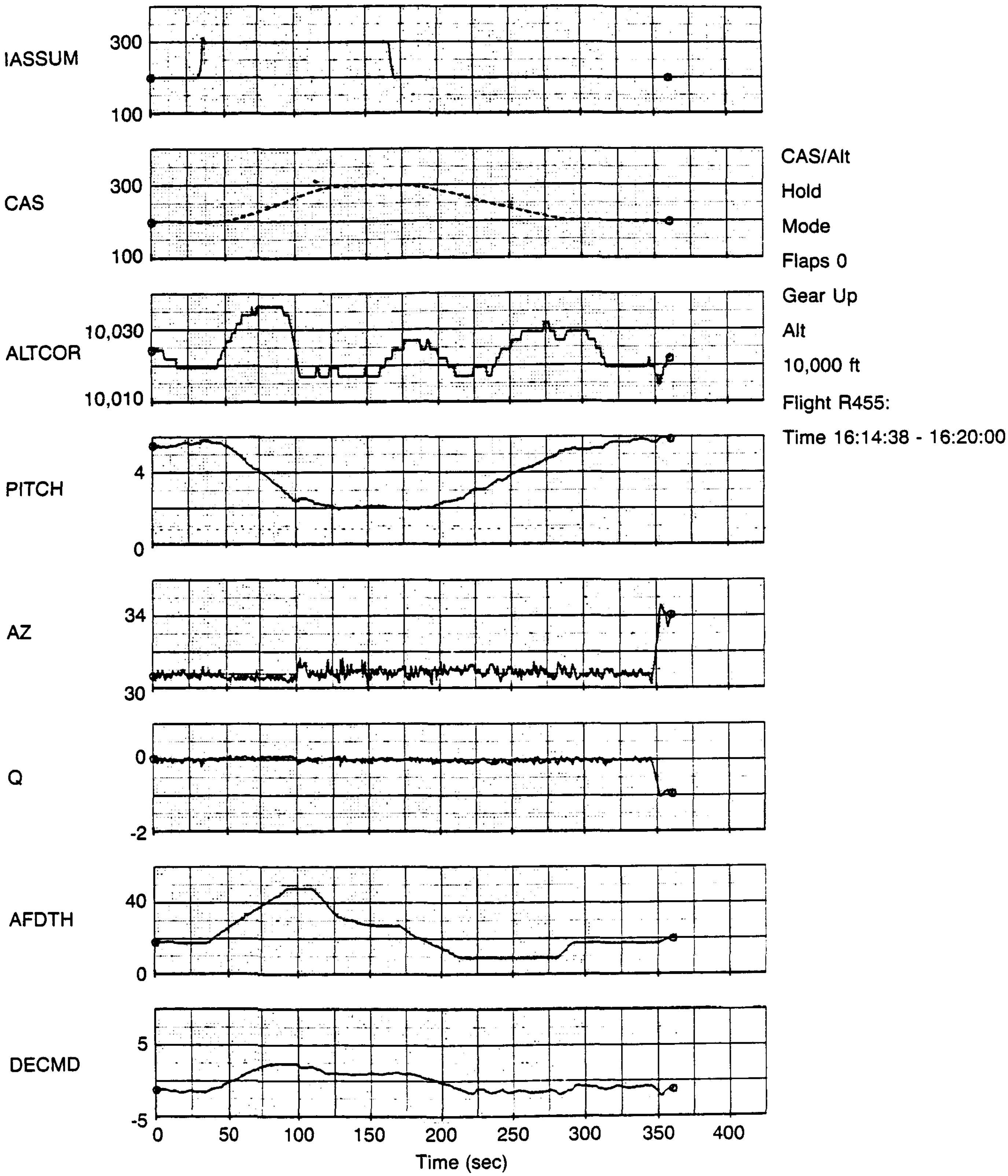


Figure 22. Test 1.3.5, 1.3.6; CAS Change +100 kn, -100 kn

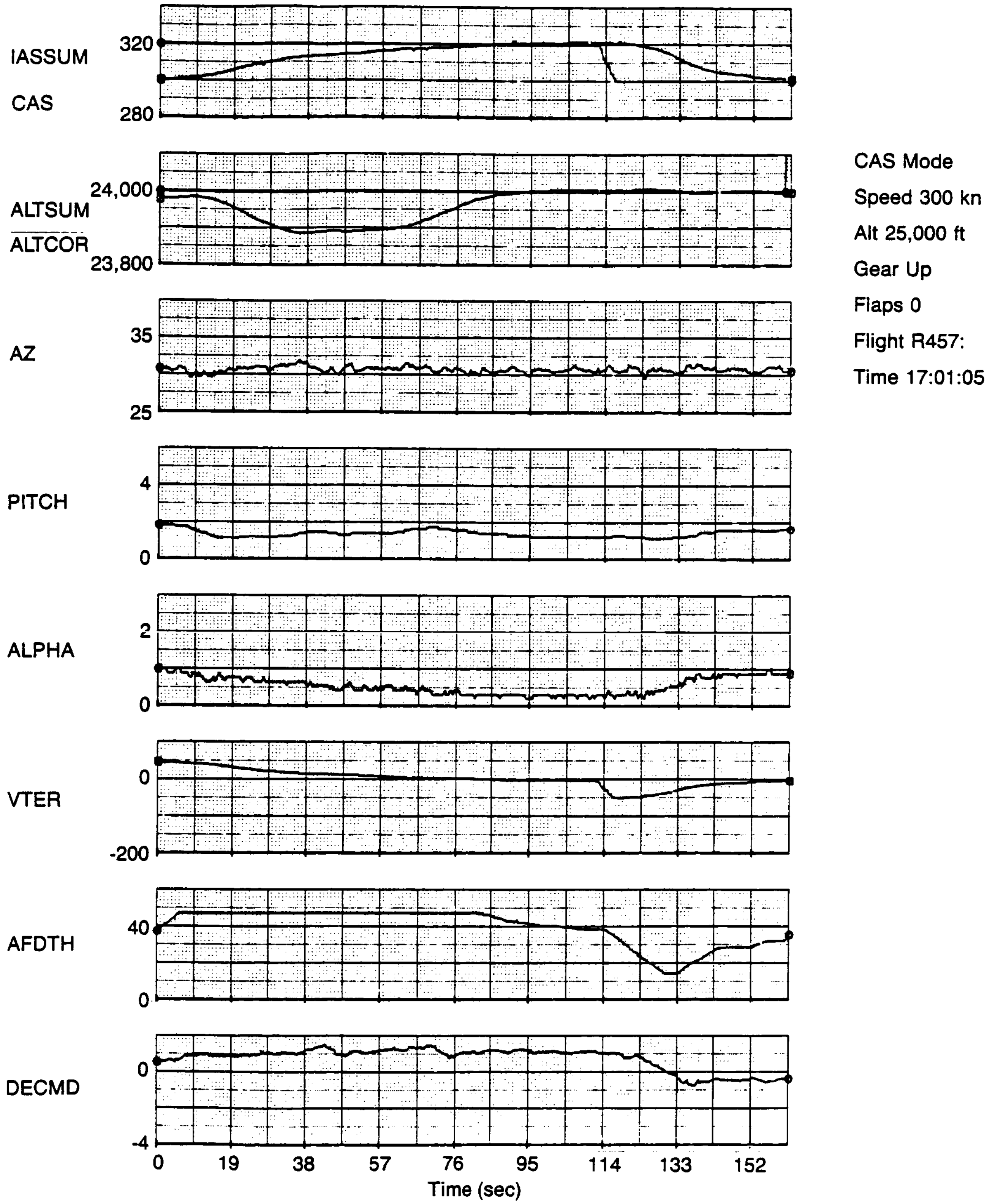


Figure 23 (a). Test 2.3.1 and 2.3.2; CAS +20 -20

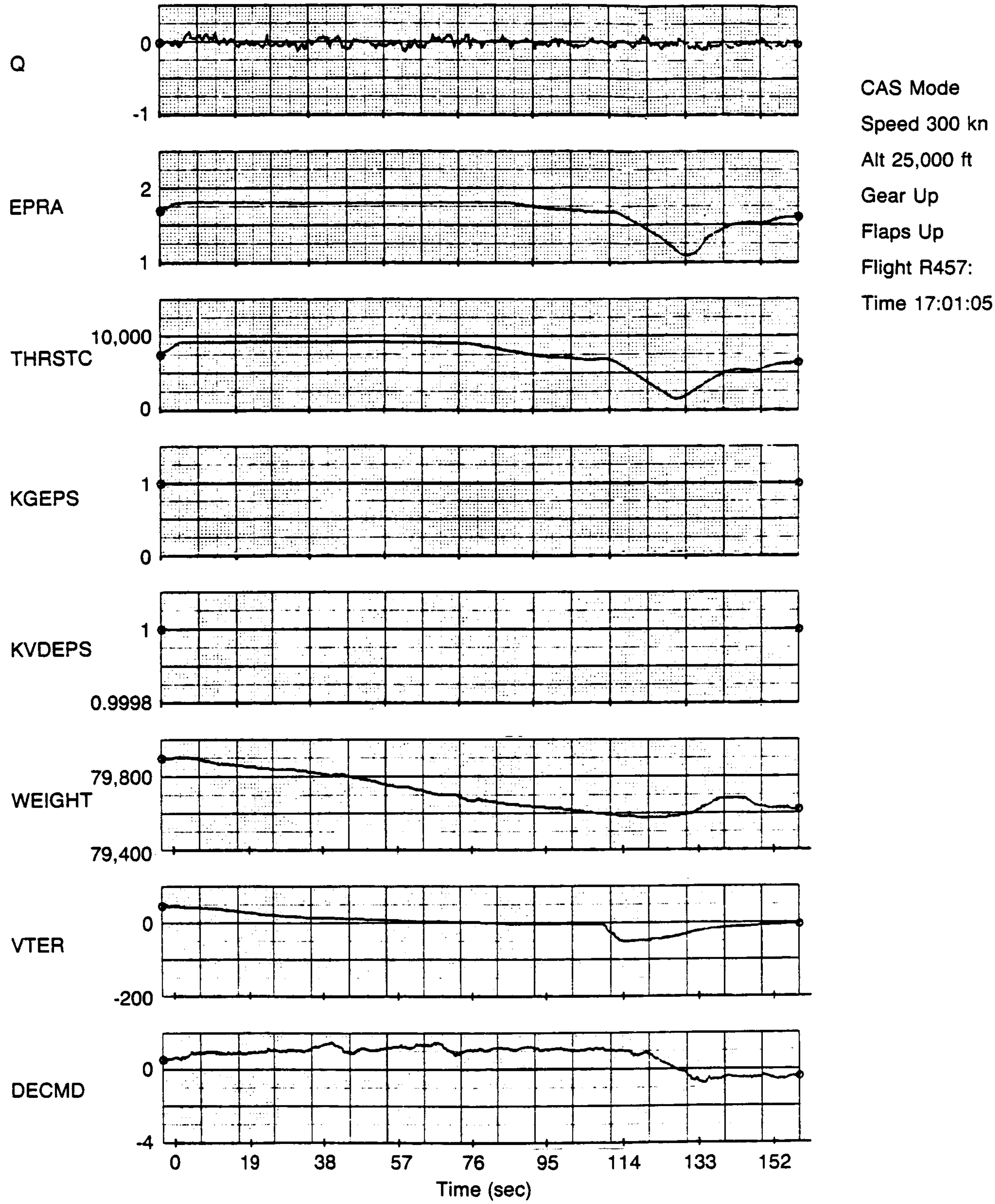


Figure 23 (b). Test 2.3.1 and 2.3.2; CAS +20 -20

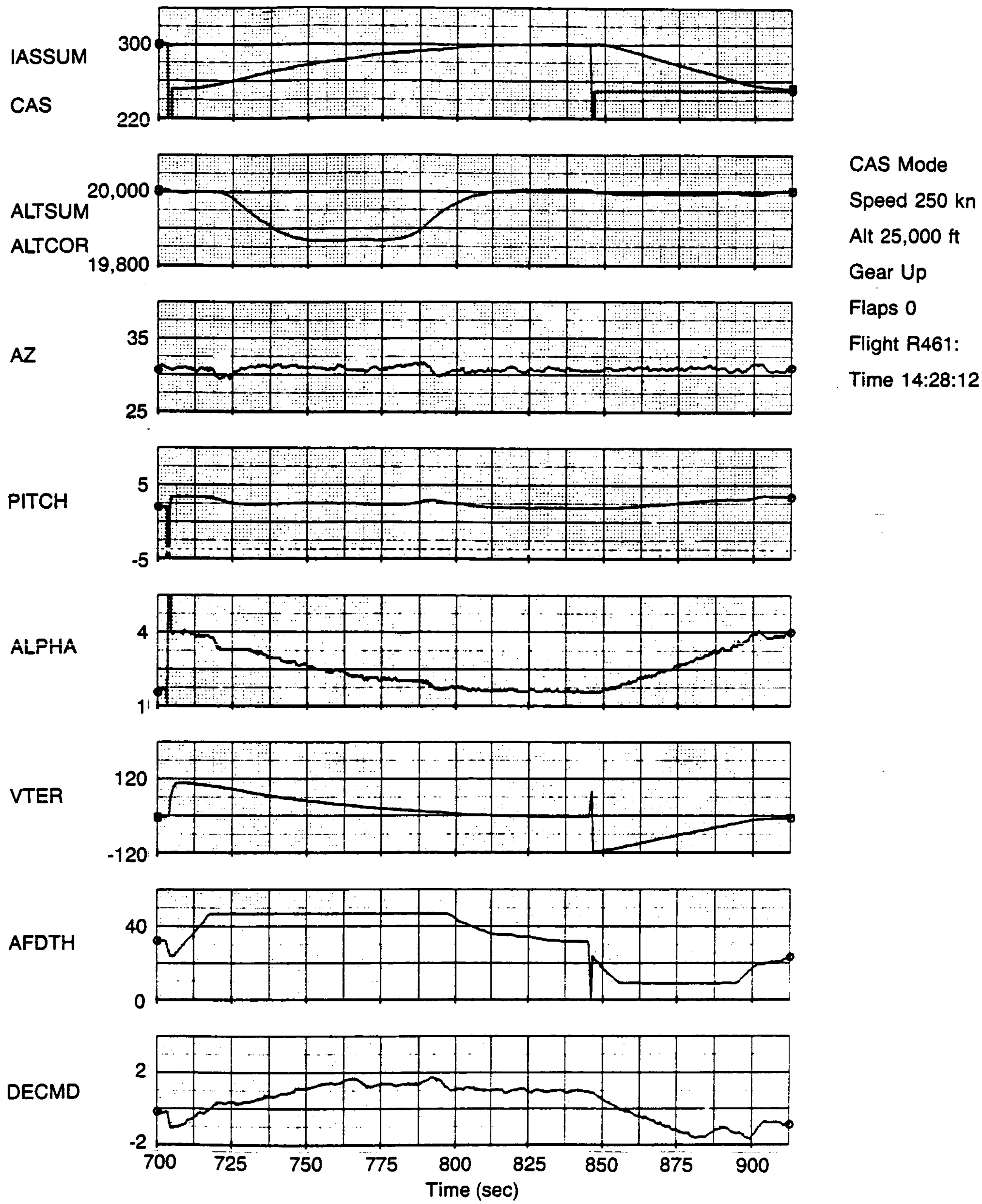
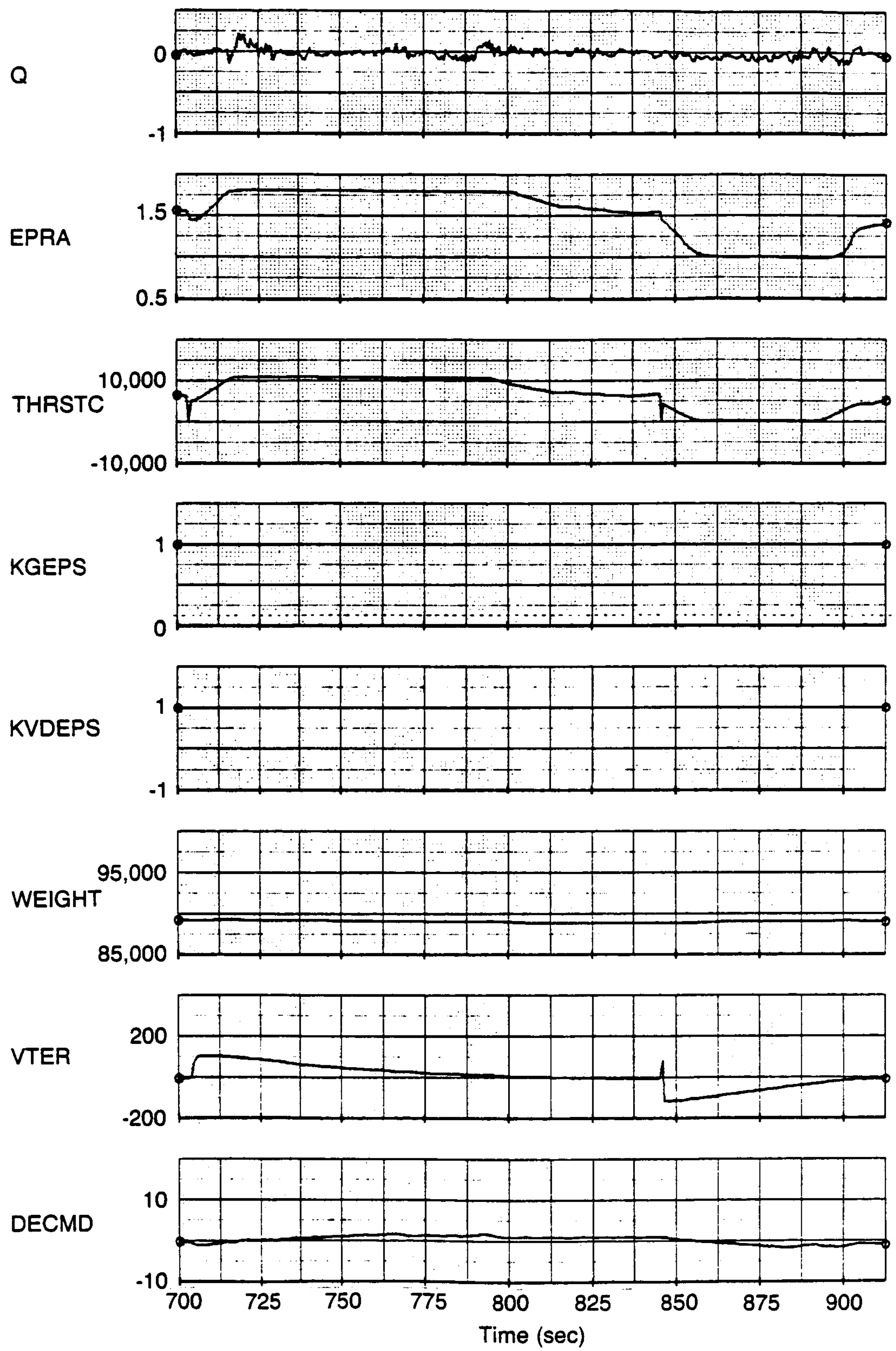
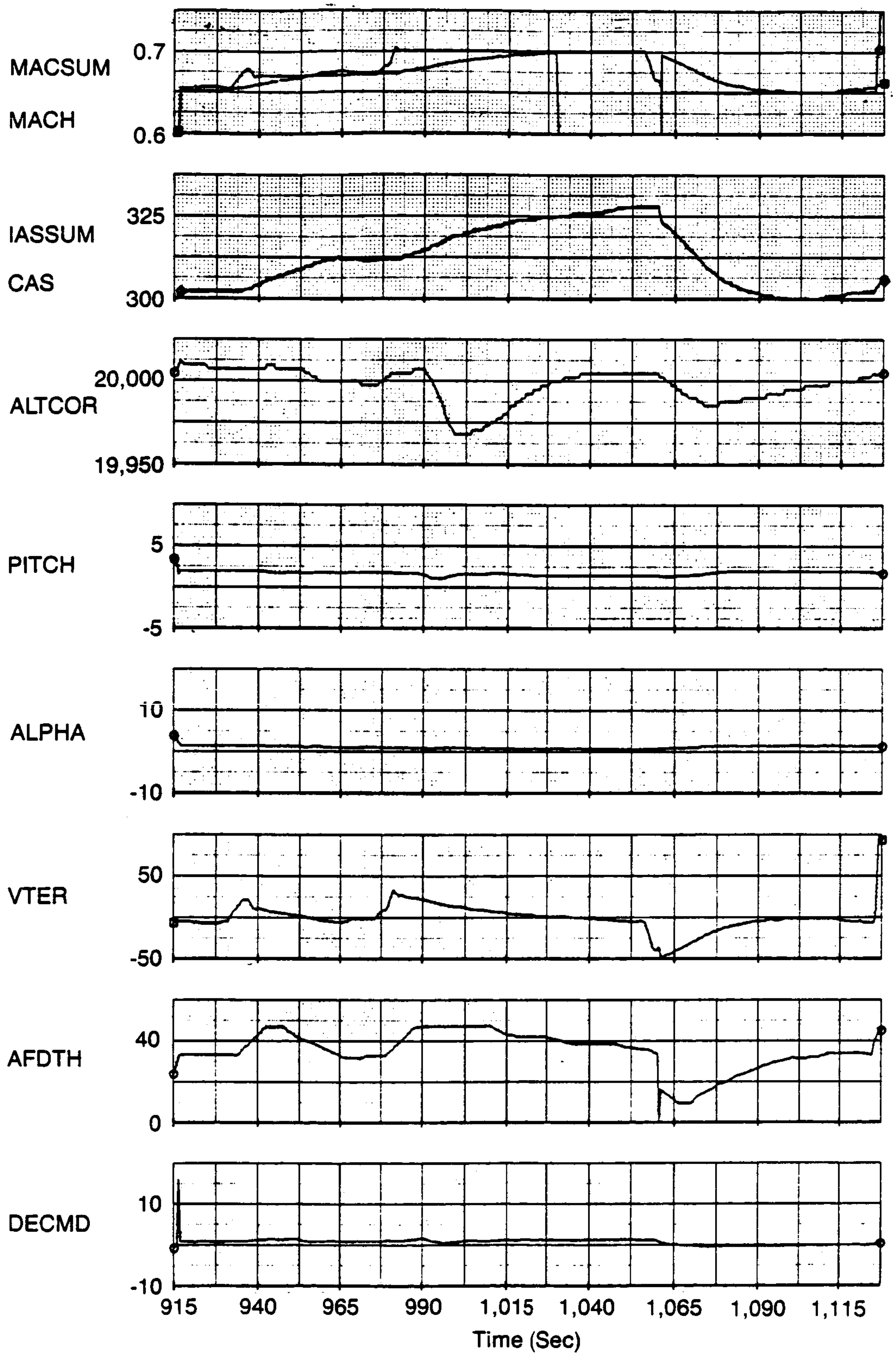


Figure 24 (a). Test 2.3.3-2.3.4; CAS +50 -50



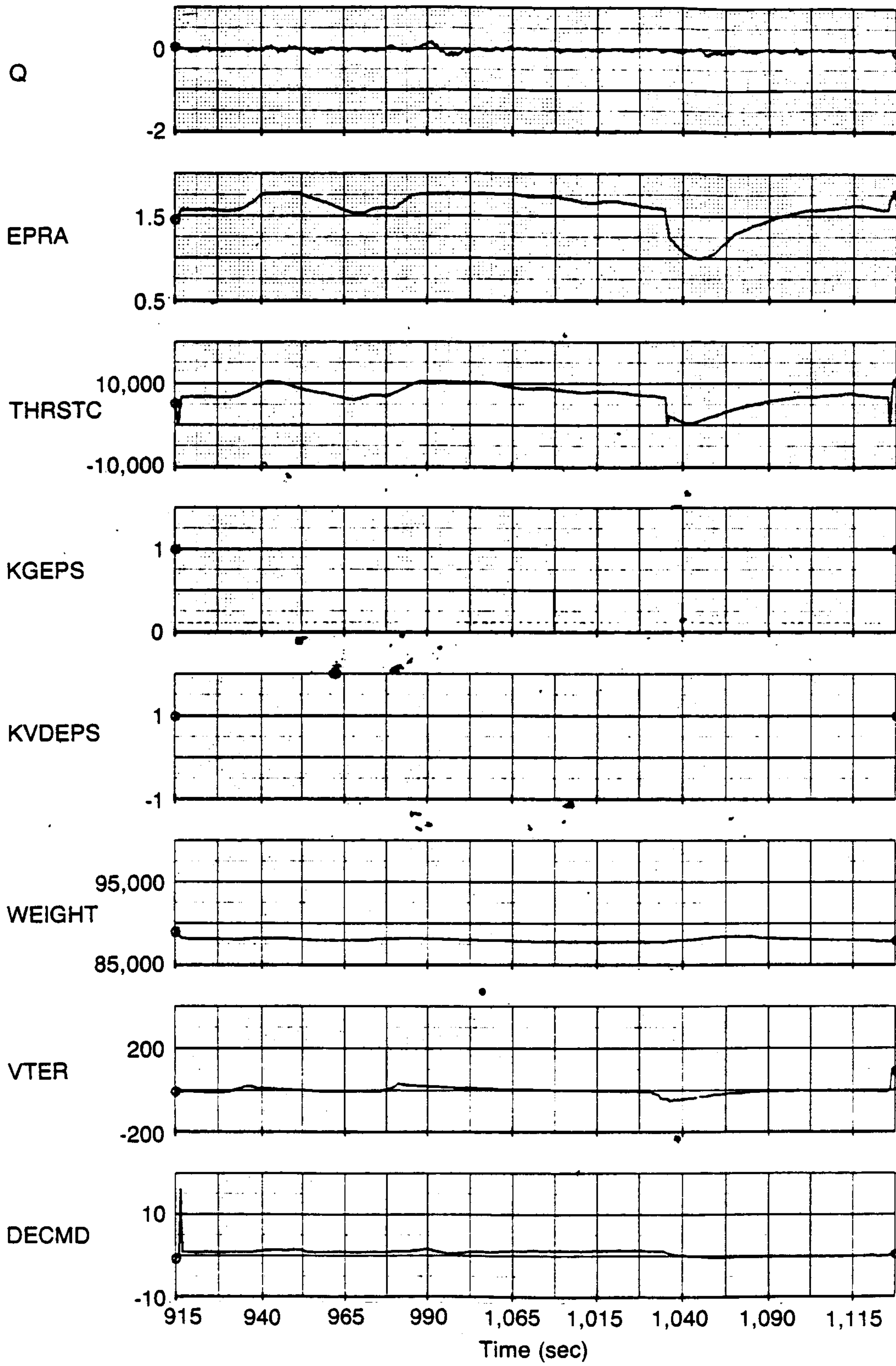
CAS Mode
Speed 250 kn
Alt 25,000 ft
Gear Up
Flaps 0
Flight R461:
Time 14:28:12

Figure 24 (b). Test 2.3.3-2.3.4; CAS +50 -50



Mach Mode
Mach 0.65
Altitude 20,000 ft
Flight R461:
Time 14:37:31

Figure 25 (a). Test 2.4.1-2.4.2; Mach +0.05 -0.05



Mach Mode
Mach 0.65
Altitude 20,000 ft
Flight R461:
Time 14:37:31

Figure 25 (b). Test 2.4.1-2.4.2; Mach +0.05 -0.05

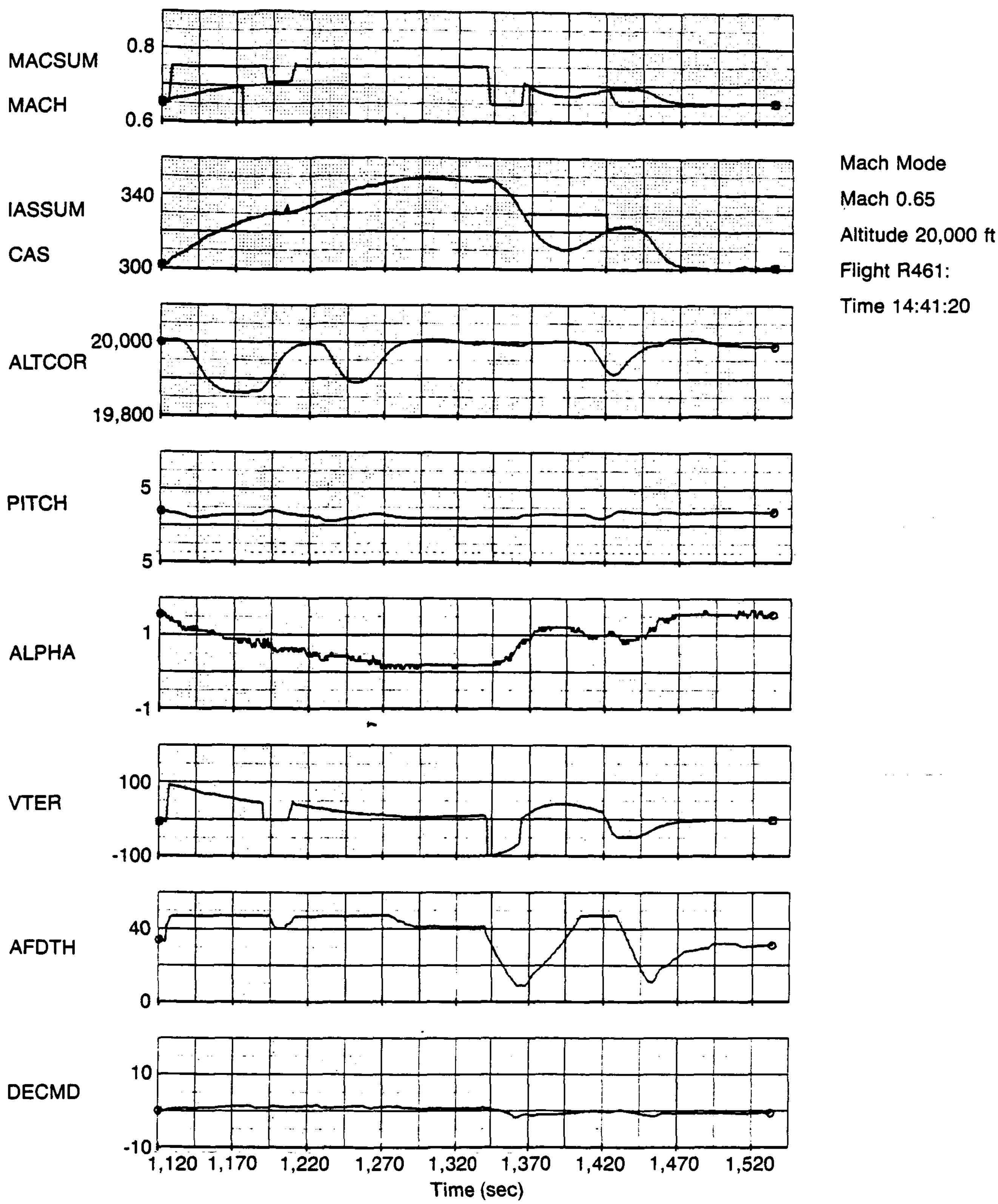


Figure 26 (a). Test 2.4.3-2.4.4; Mach +0.15 -0.15

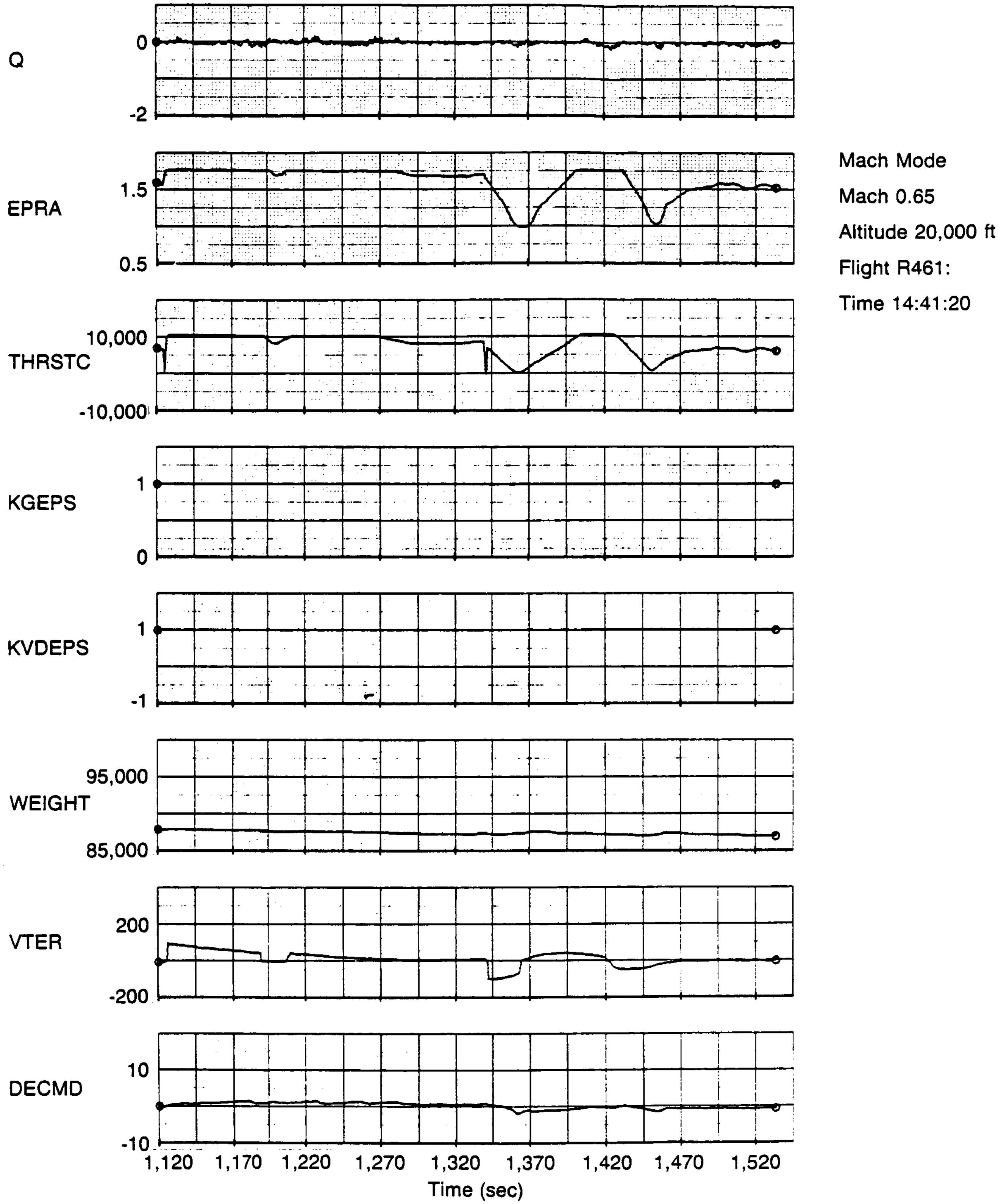


Figure 26 (b). Test 2.4.3-2.4.4; Mach +0.15 -0.15

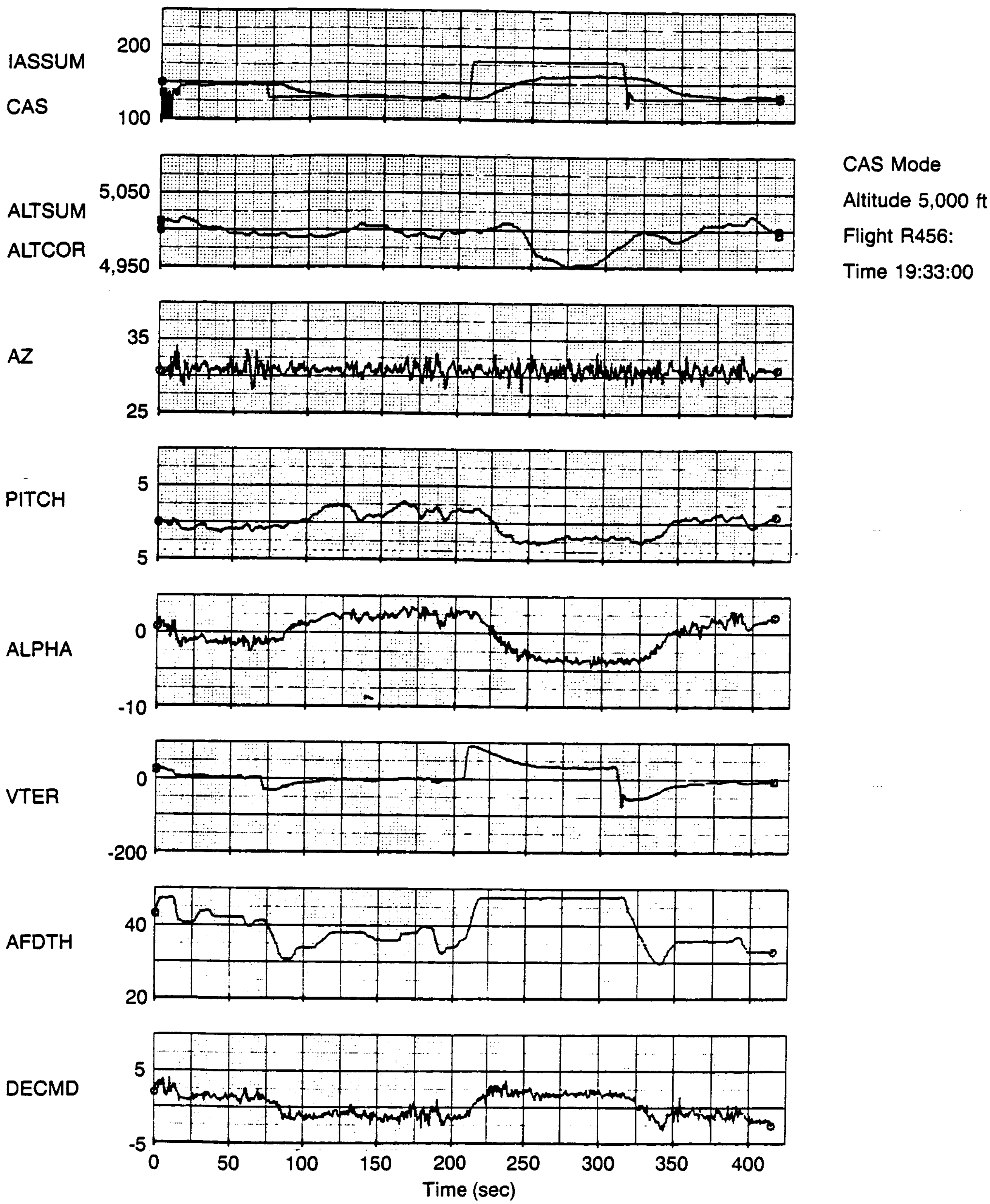


Figure 27. Test 3.3.1-3.3.4; CAS +20, -20, +50, -50 kn

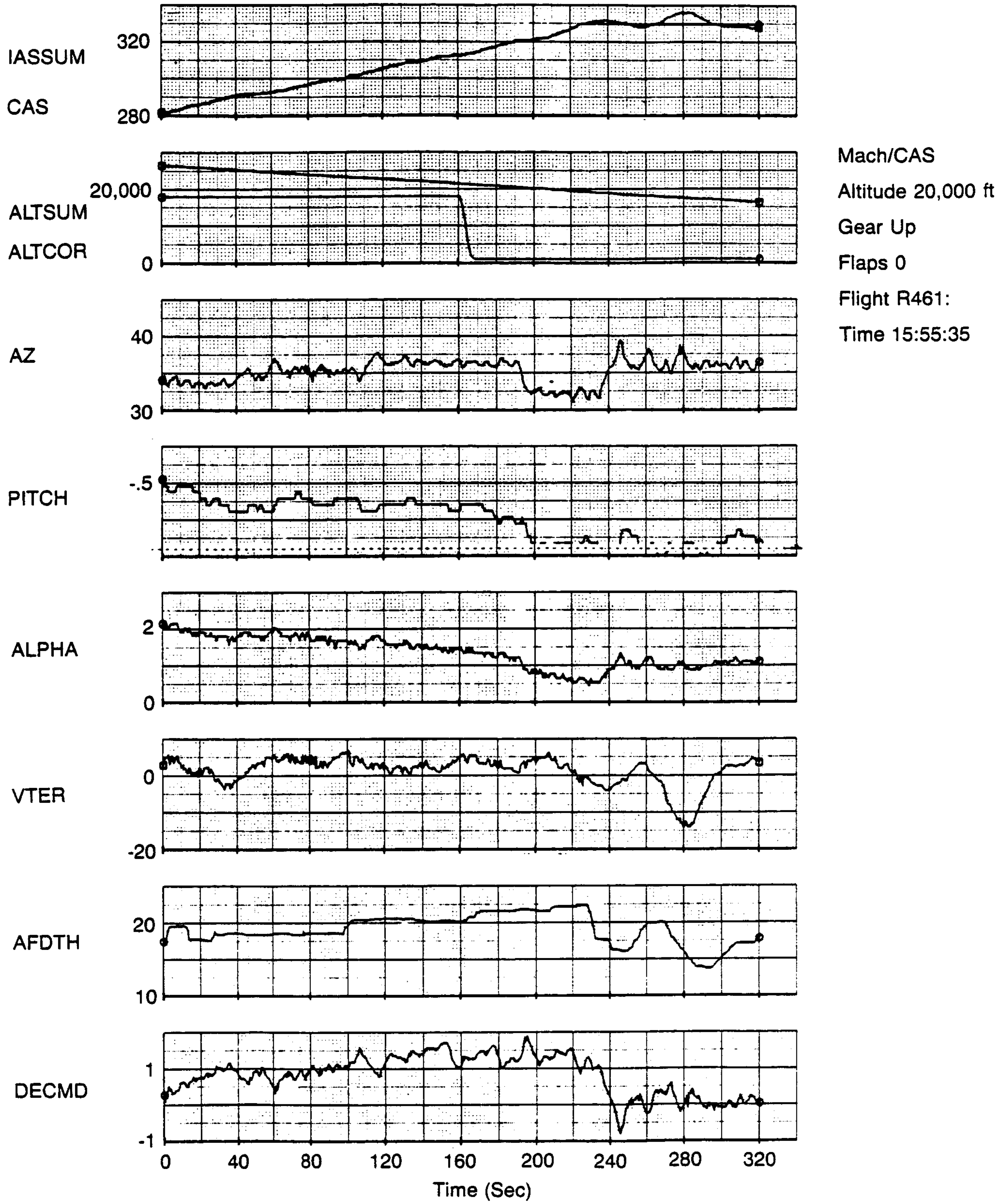


Figure 28. Test 2.7.2; Mach to CAS Switch

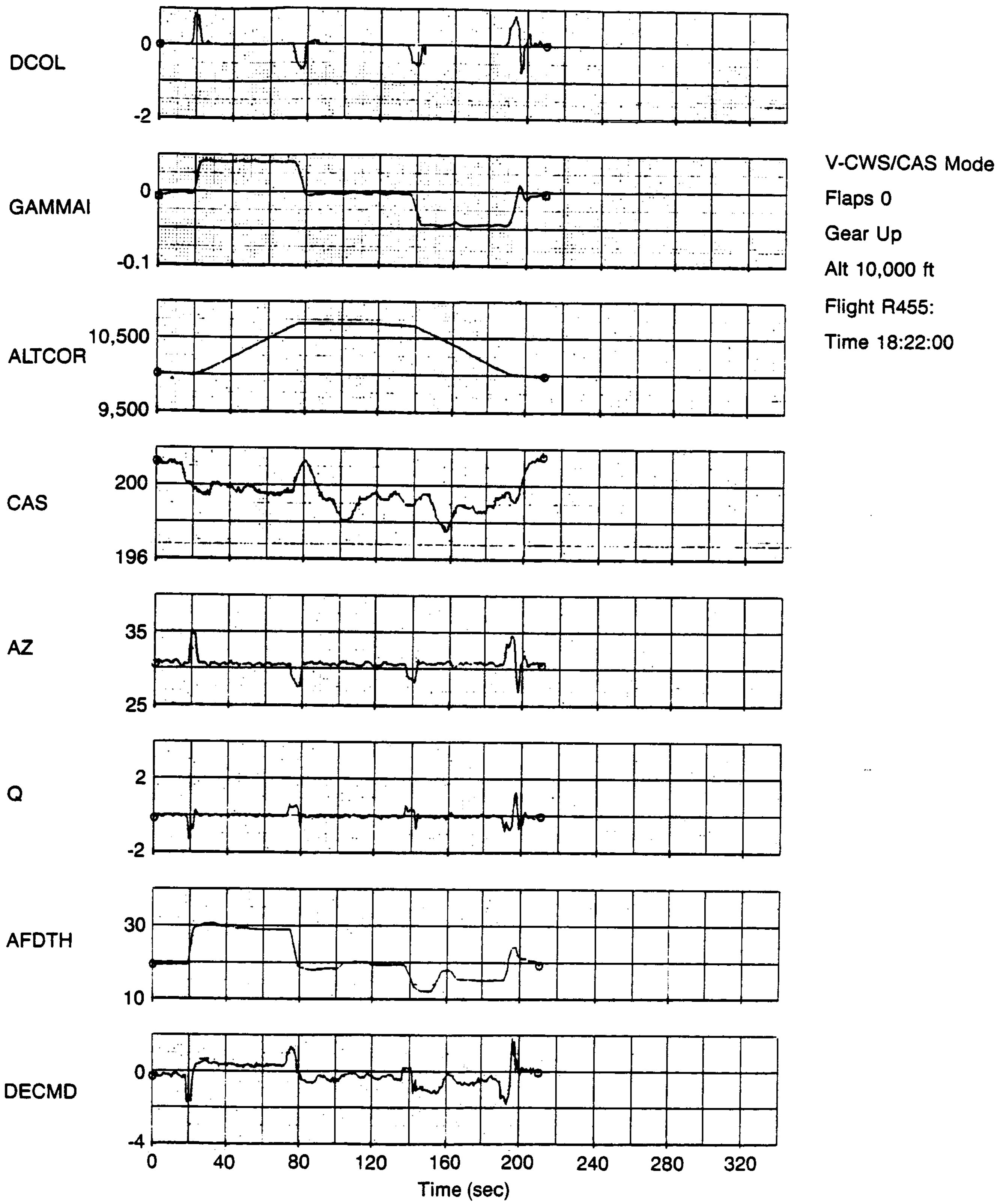


Figure 29. Test 1.5.1, 1.5.2; Velocity Vector-CWS

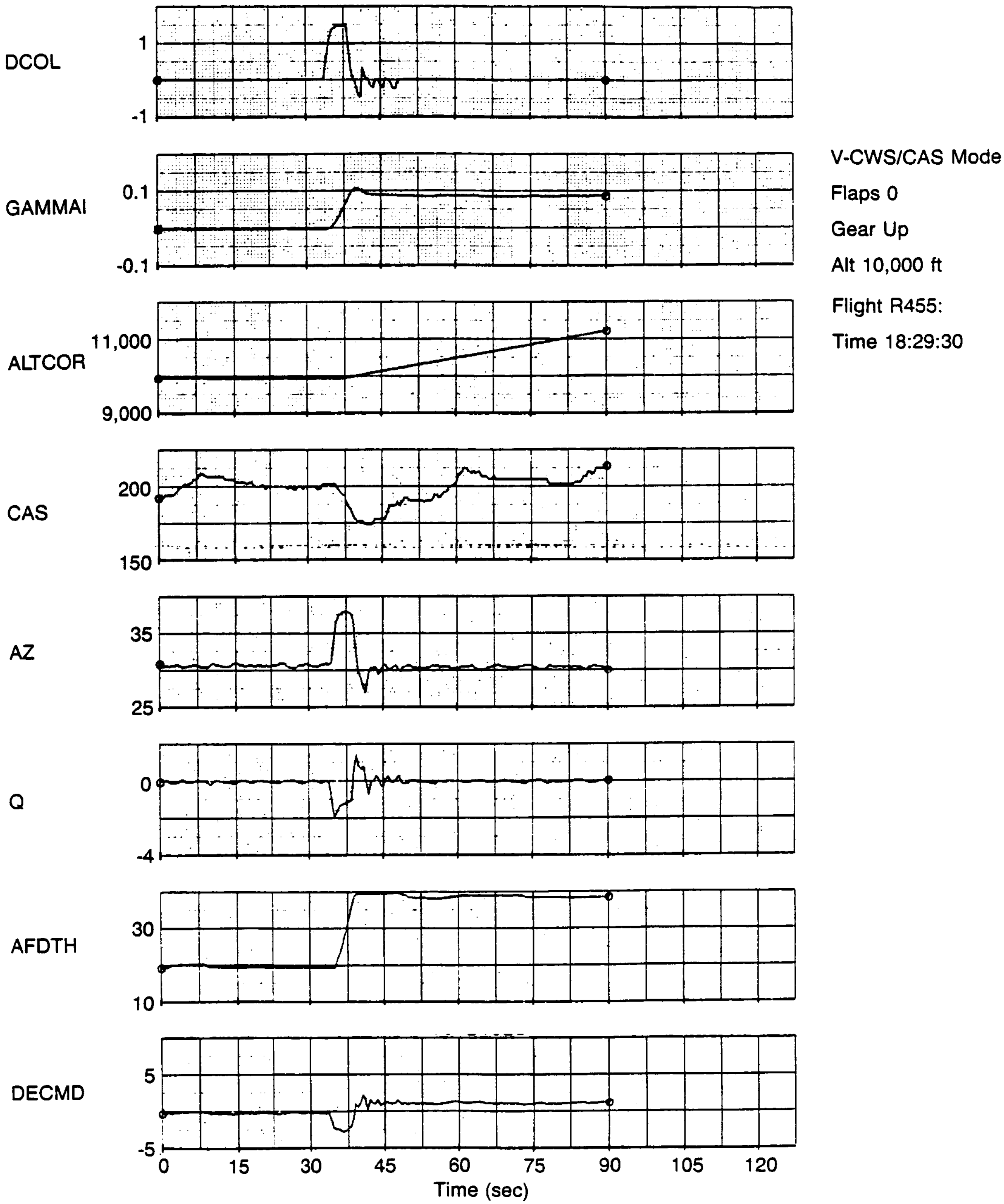


Figure 30. Test 1.5.3; Velocity Vector-CWS

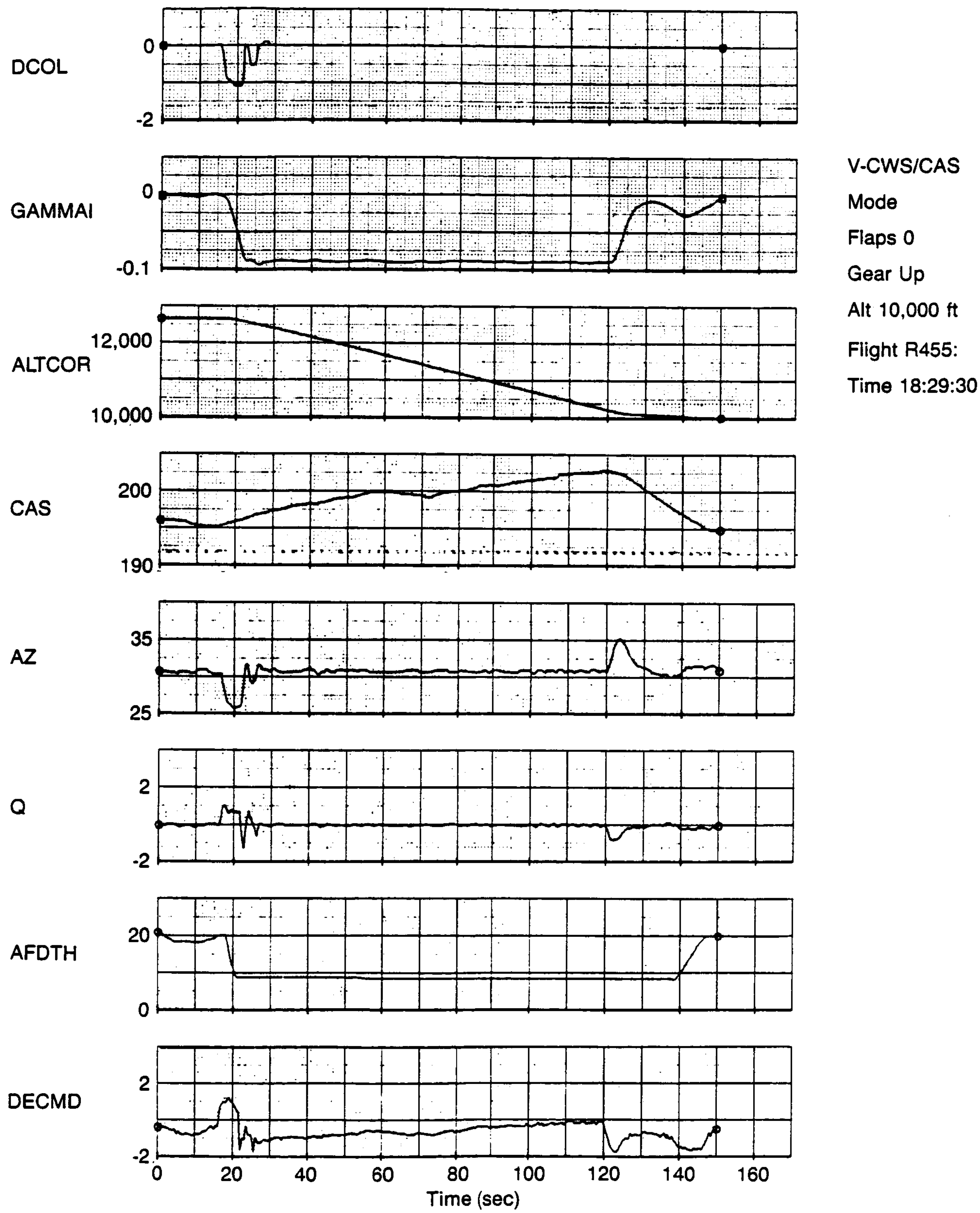


Figure 31. Test 1.5.4; Velocity Vector-CWS

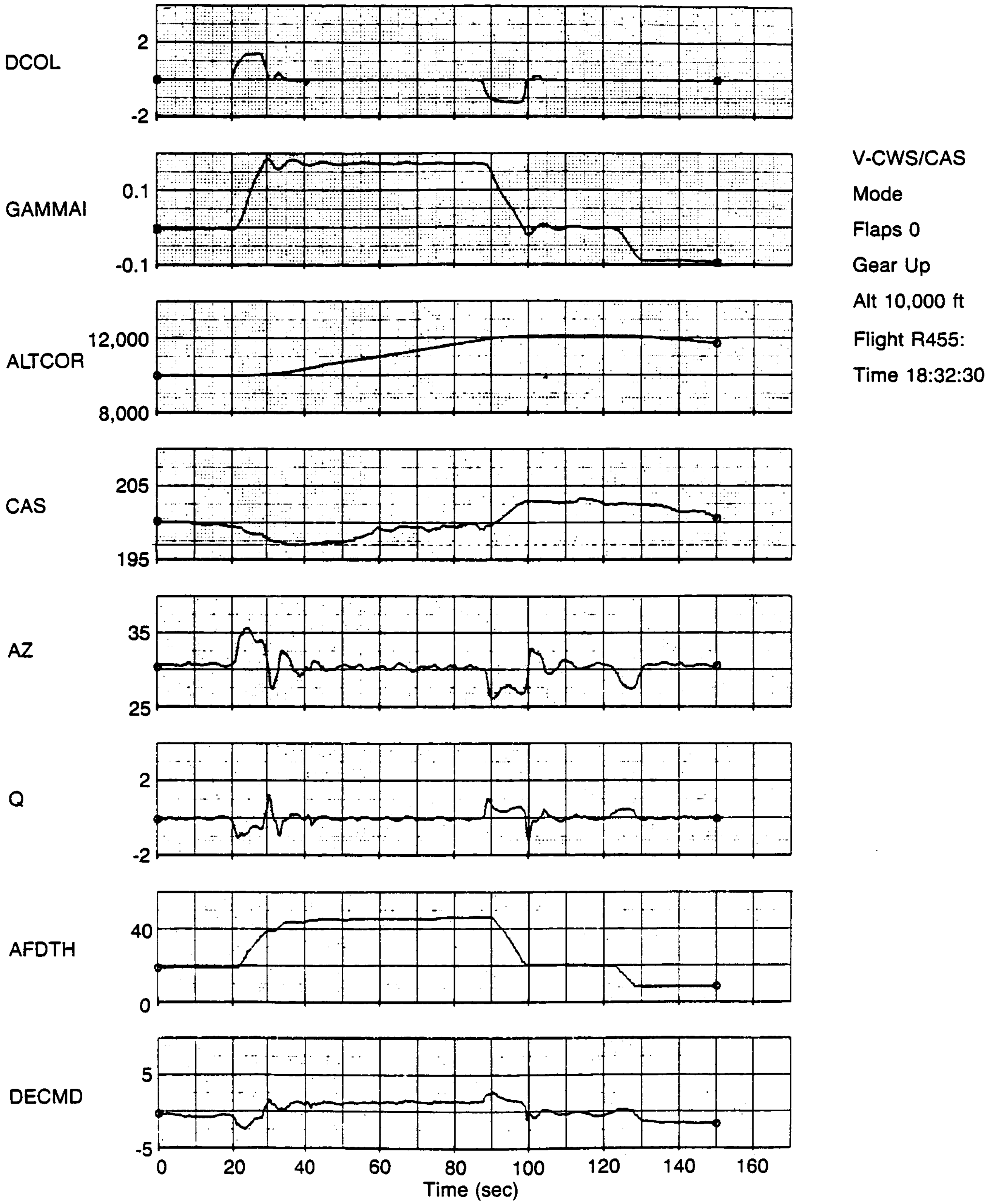


Figure 32. Test 1.5.5; Velocity Vector-CWS

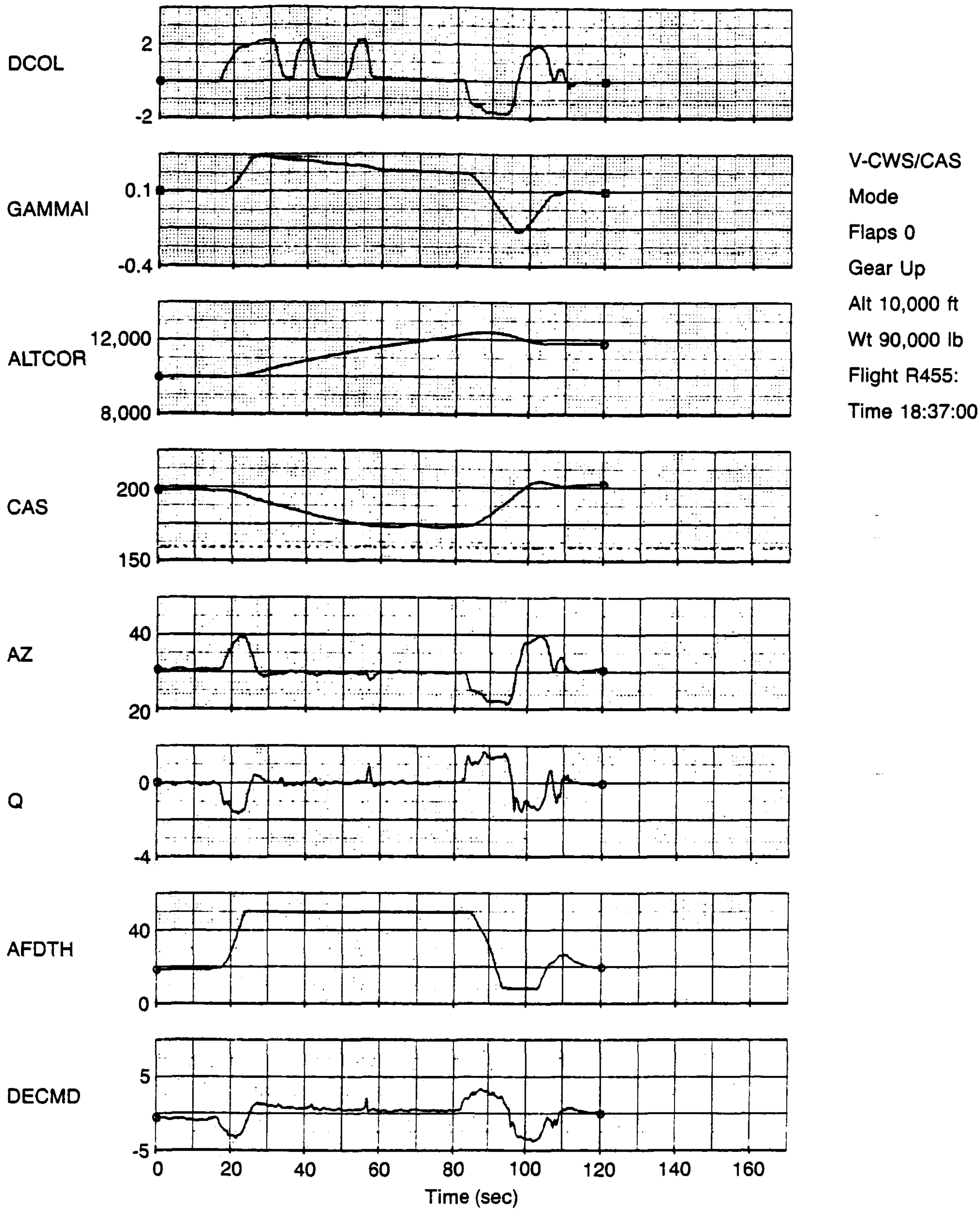


Figure 33. Test 1.5.6; Velocity Vector-CWS

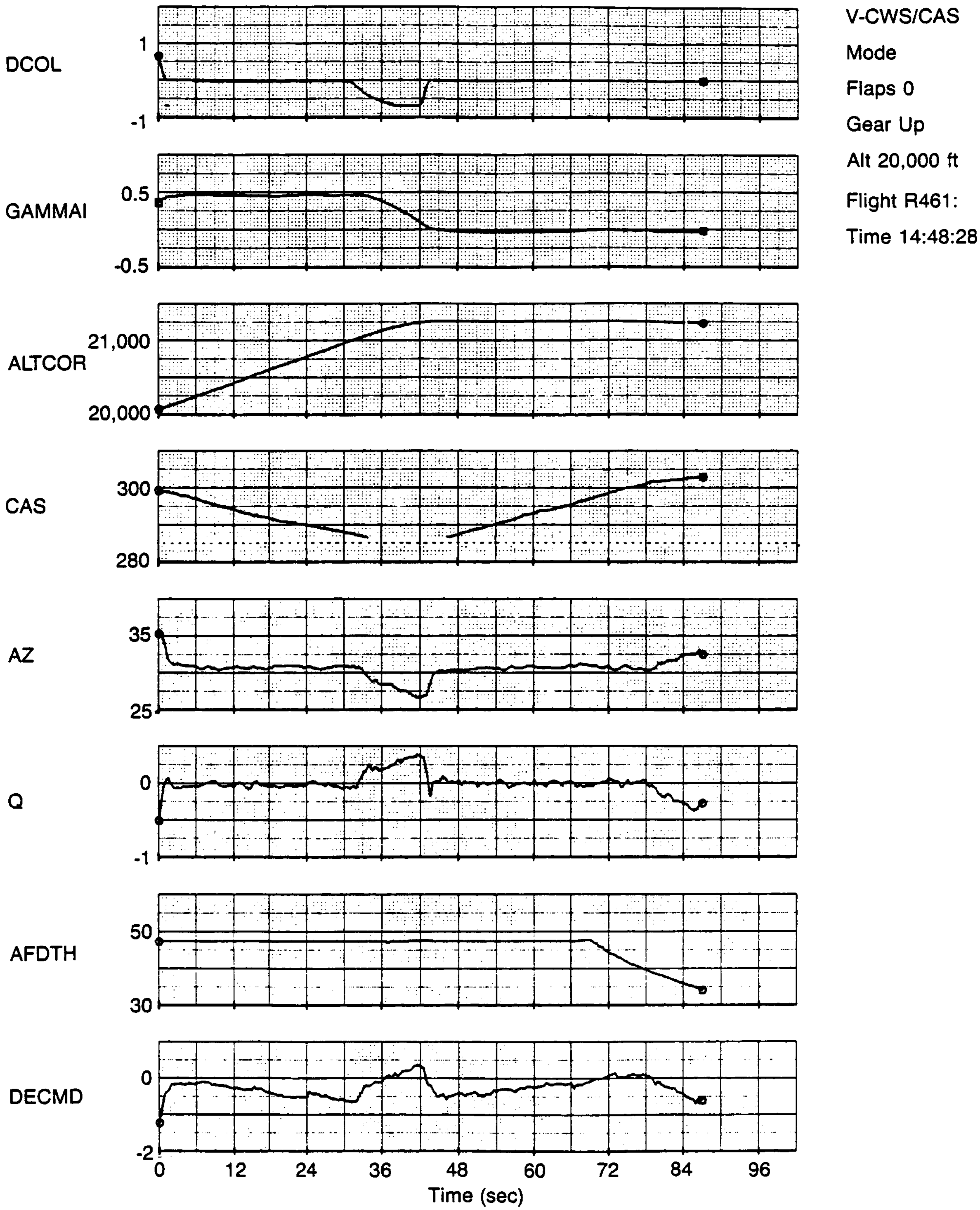


Figure 34. Test 2.5.1; V-CWS +2.5 deg

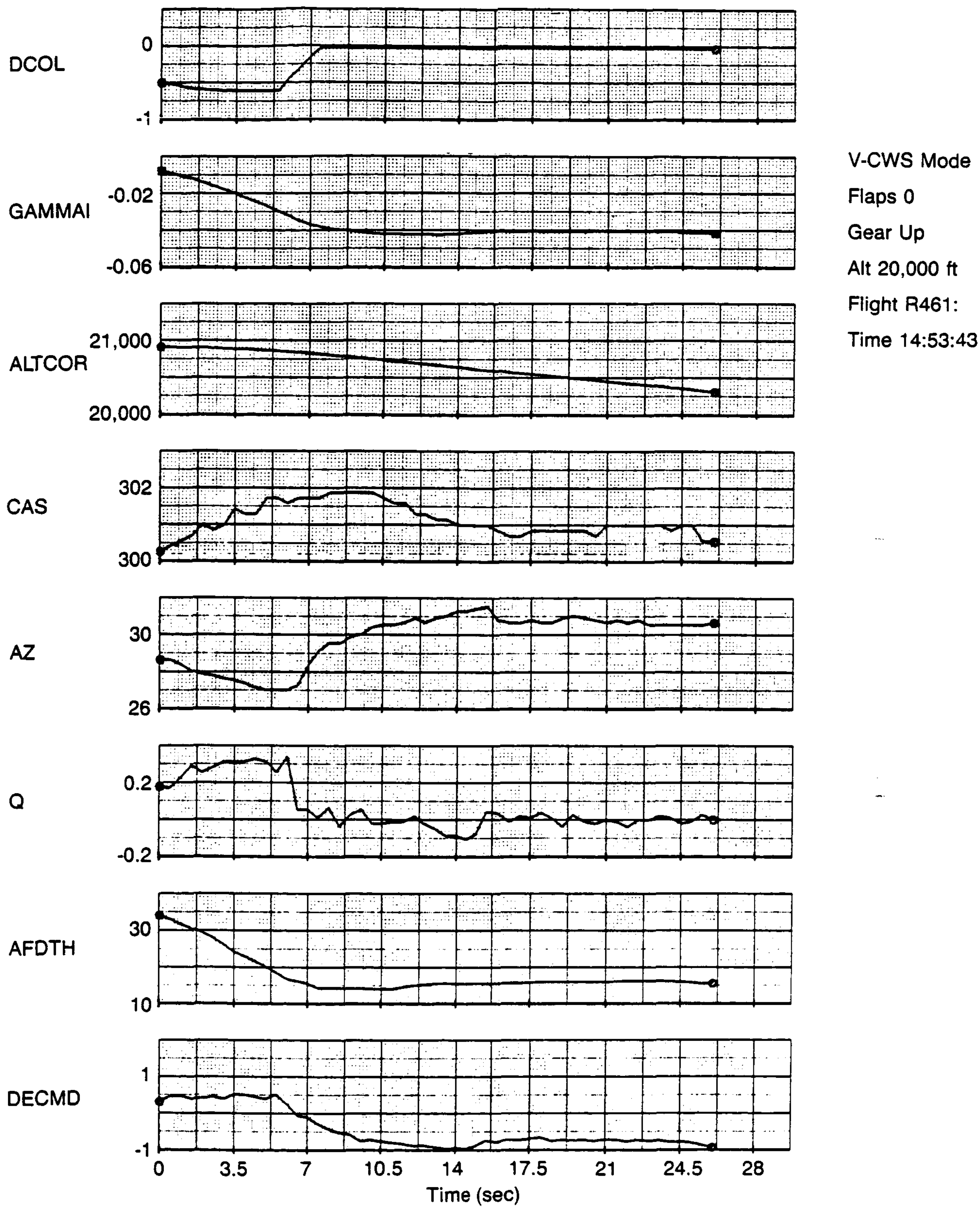


Figure 35. Test 2.5.2; V-CWS -2.5 deg

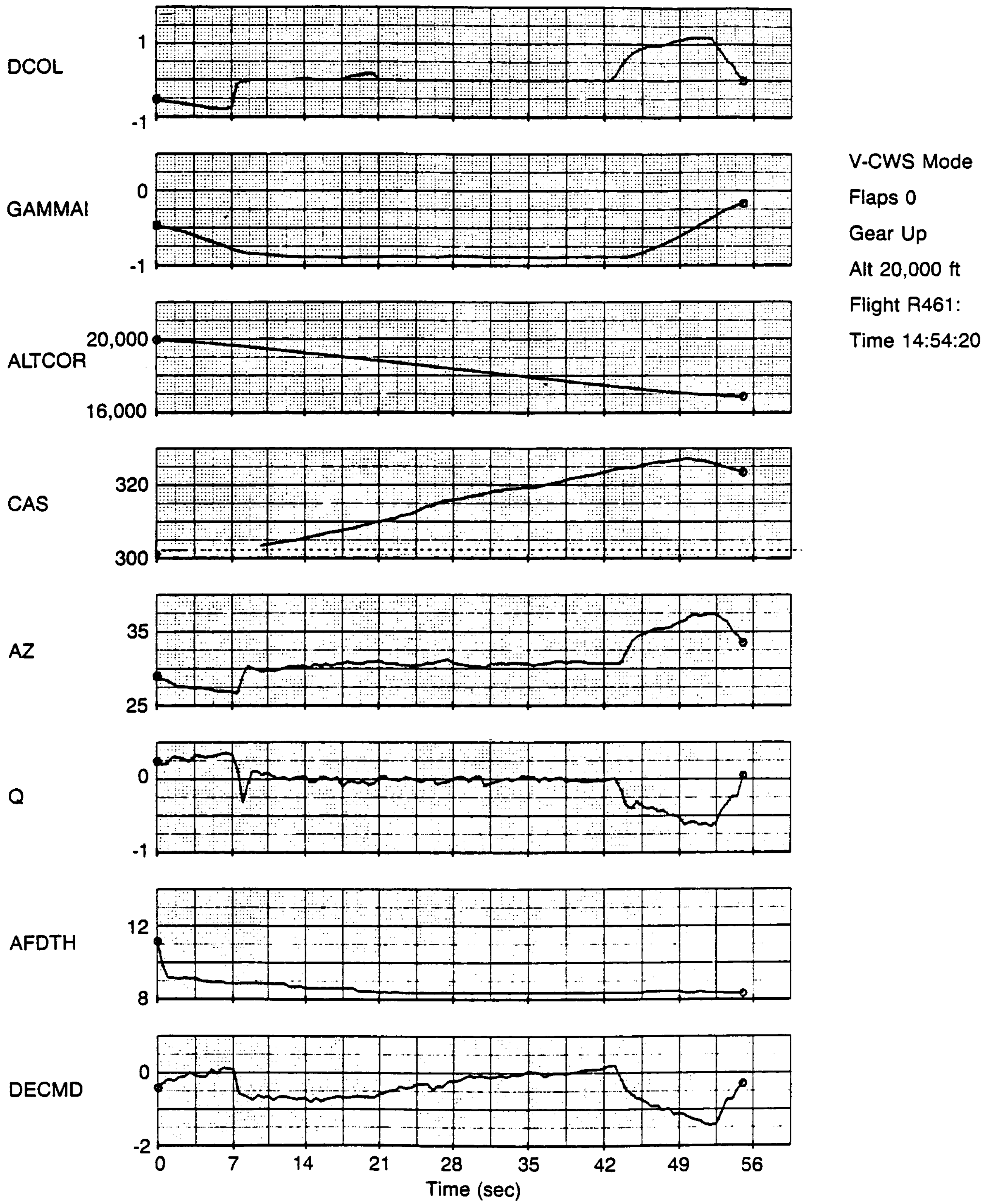


Figure 36. Test 2.5.4; V-CWS -5 deg

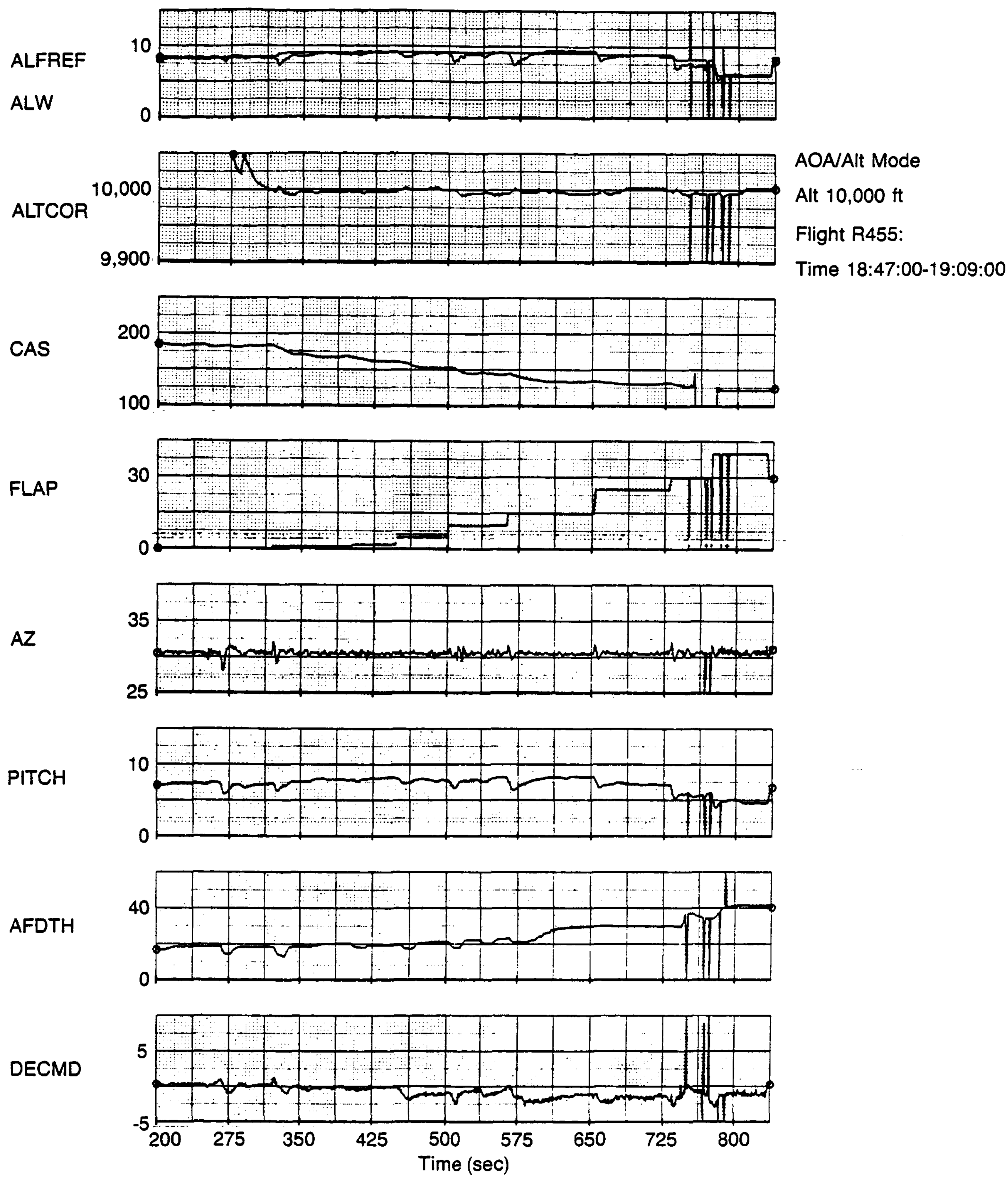


Figure 37 (a). Test 1.6.1-8; AOA Protection

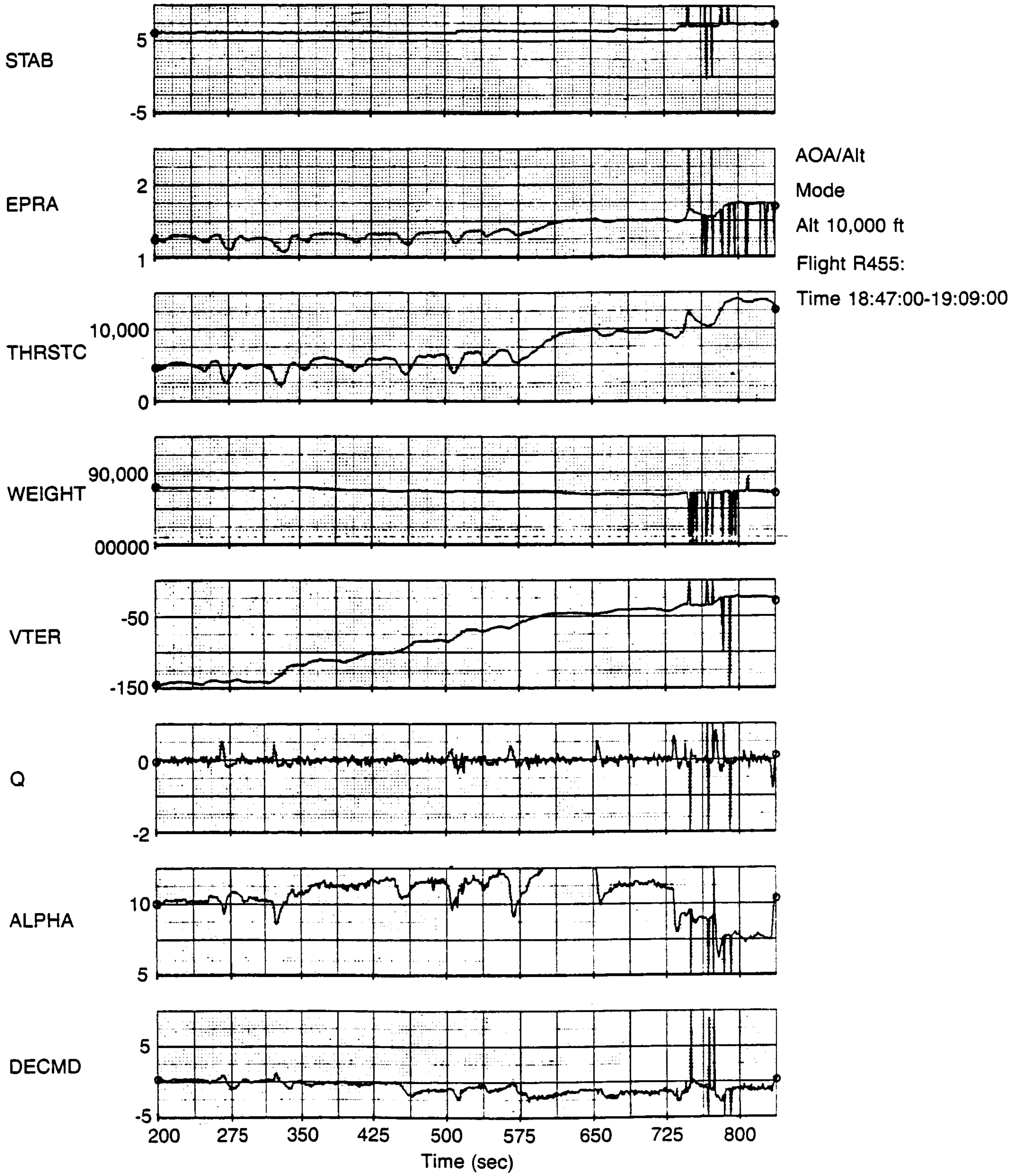


Figure 37 (b). Test 1.6.1-8; AOA Protection

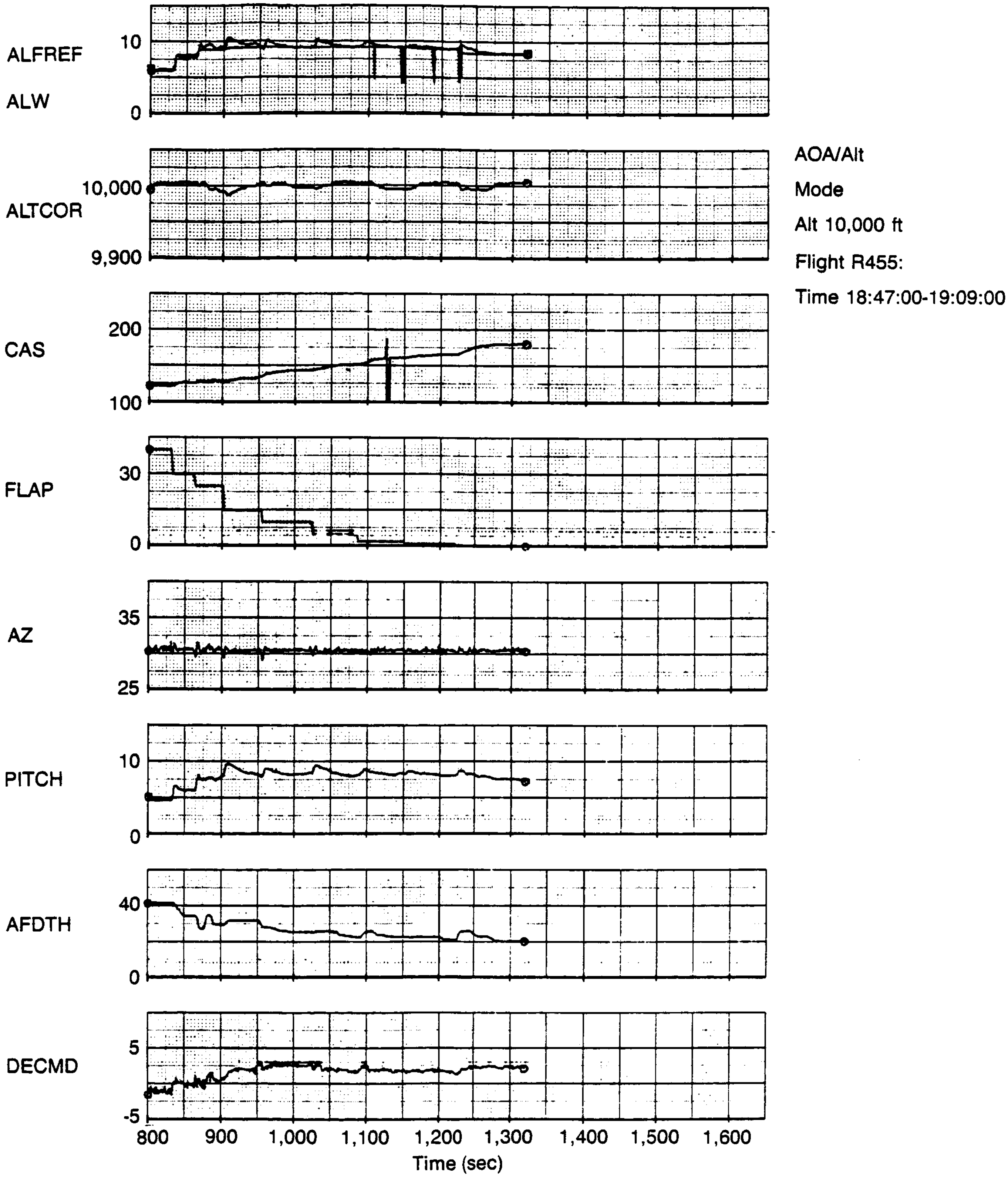


Figure 38 (a). Test 1.6.9-15; AOA Protection

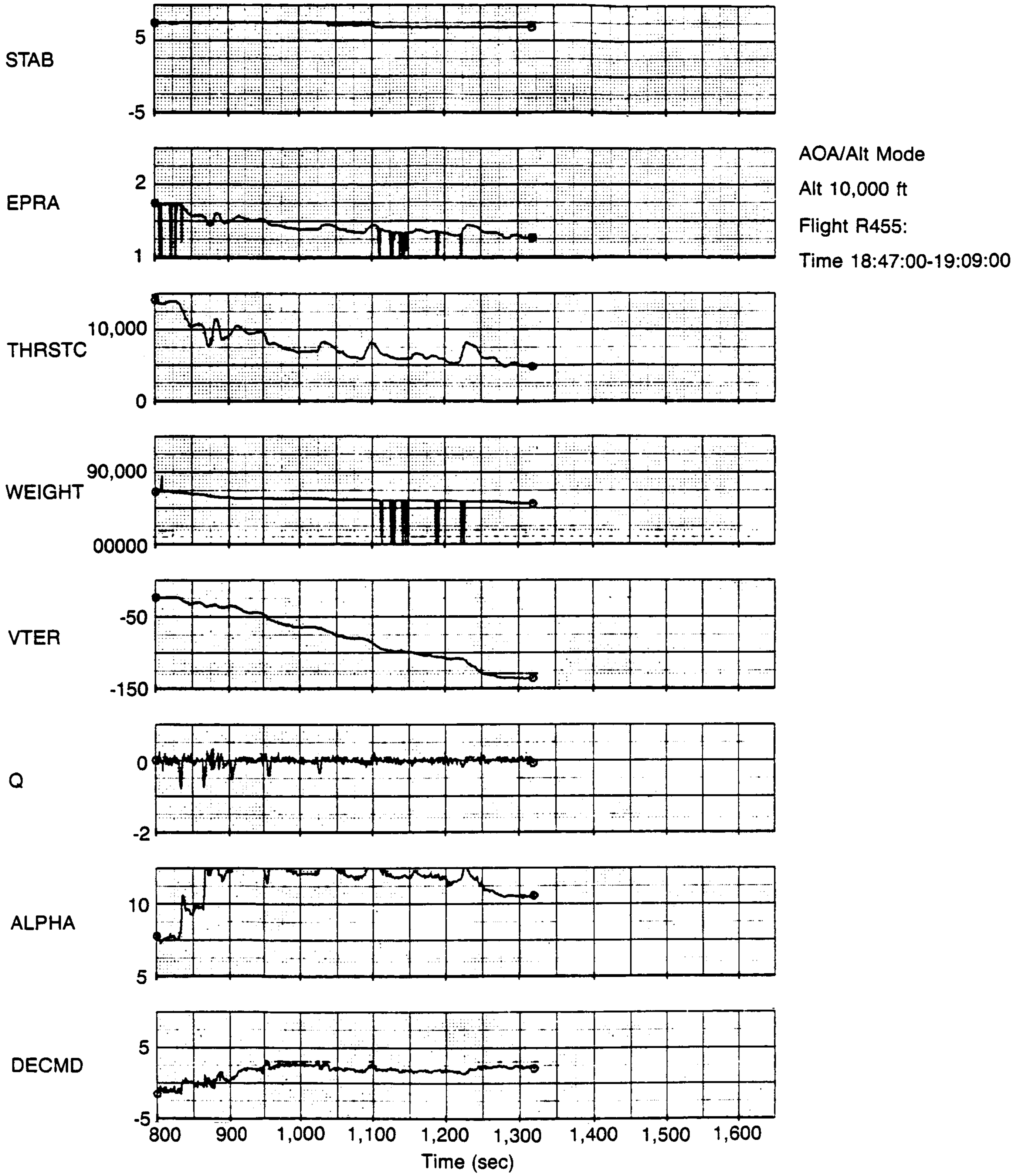


Figure 38 (b). Test 1.6.9-15; AOA Protection

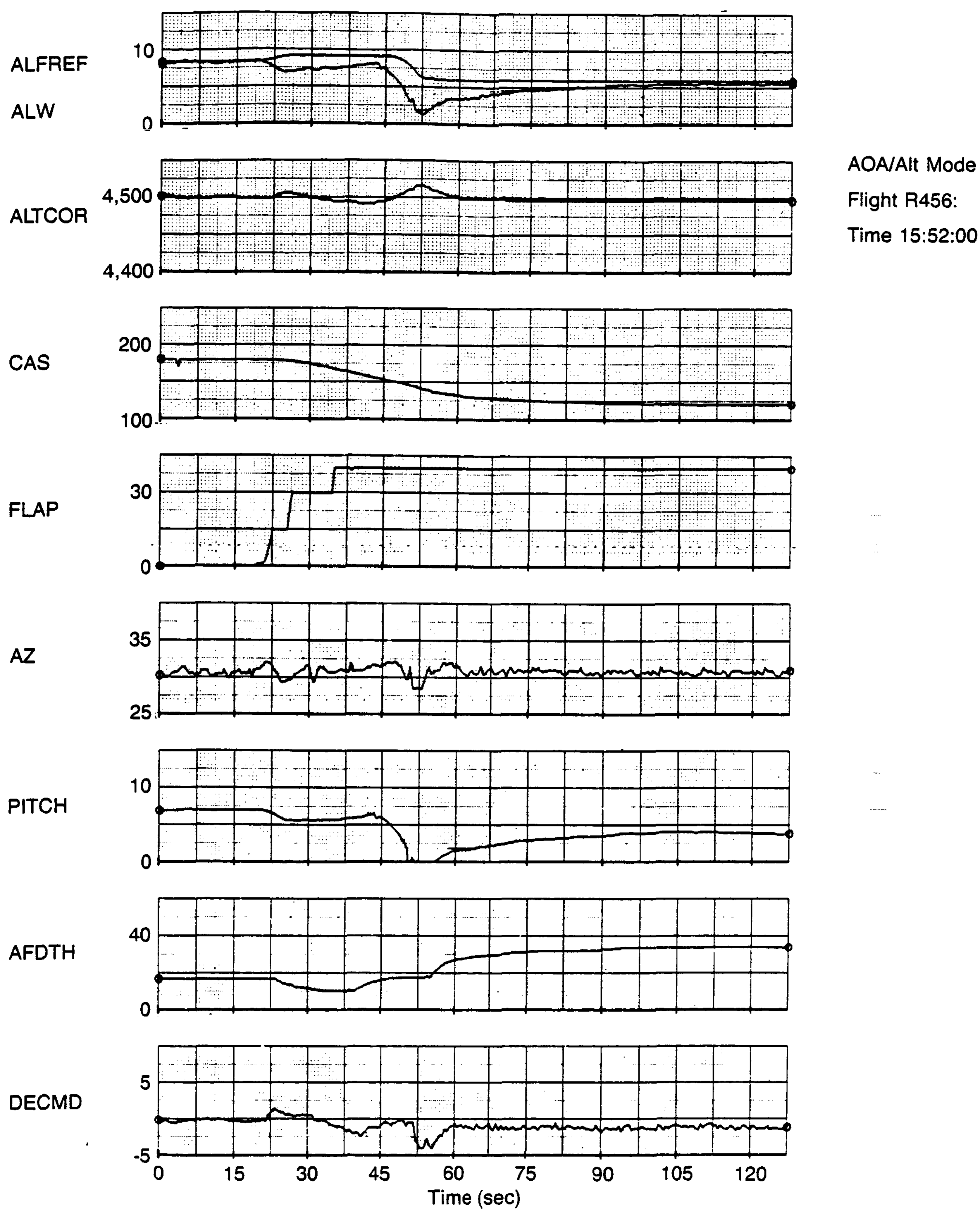


Figure 39. Test 3.5.1; AOA Protection

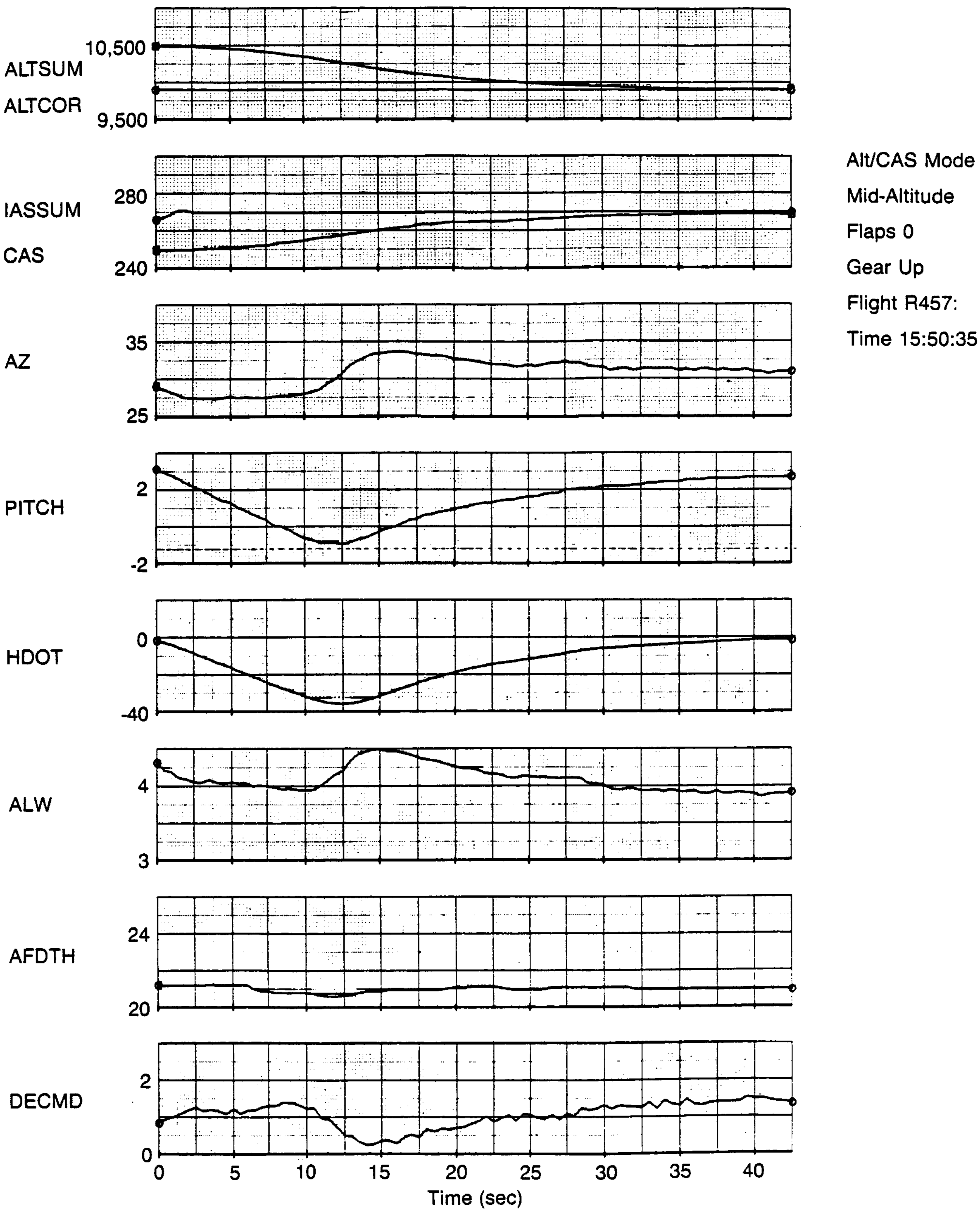


Figure 40. Test 1.7.1; Energy Change (KE=PE)

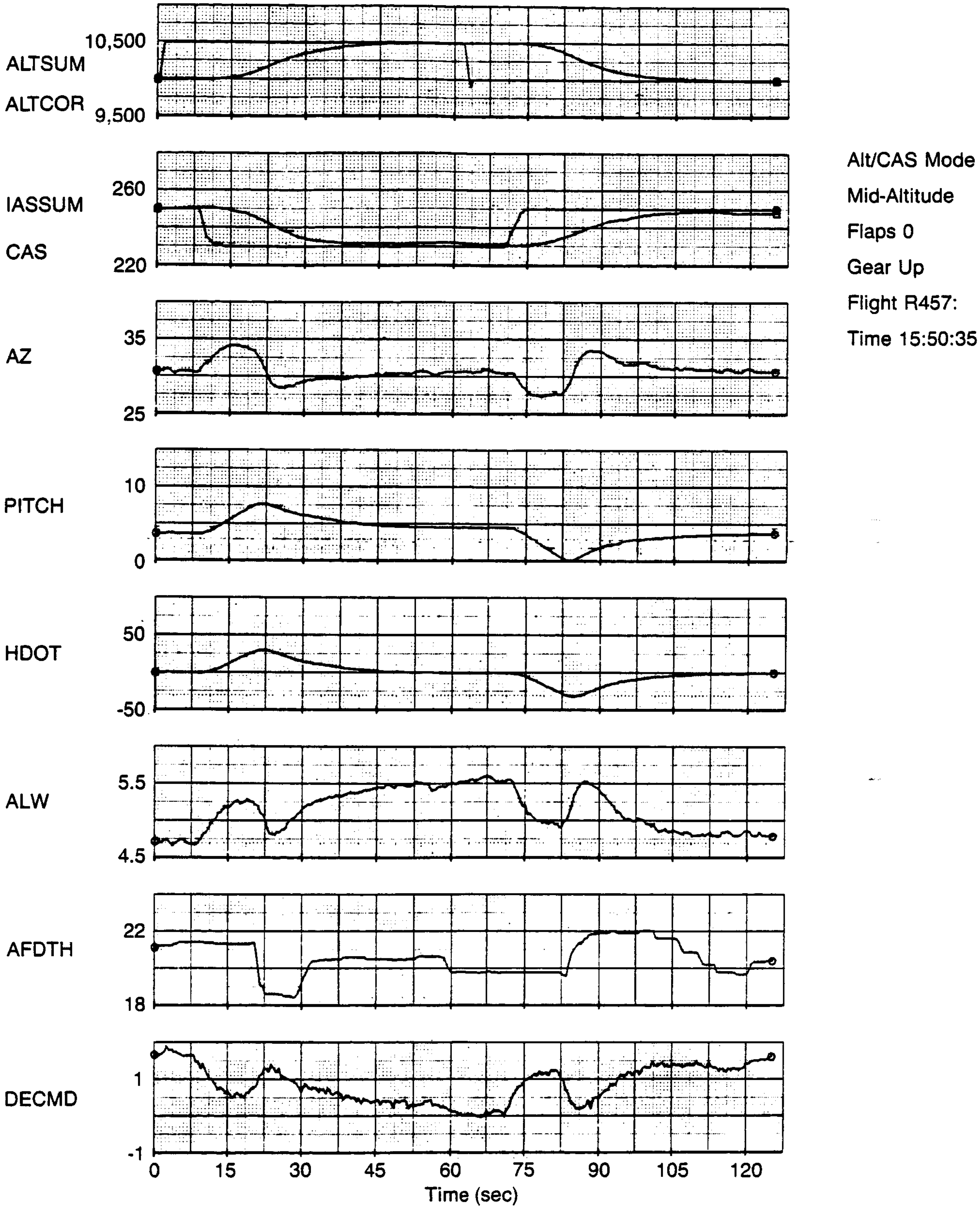


Figure 41. Test 1.7.1; Energy Change (KE=PE)

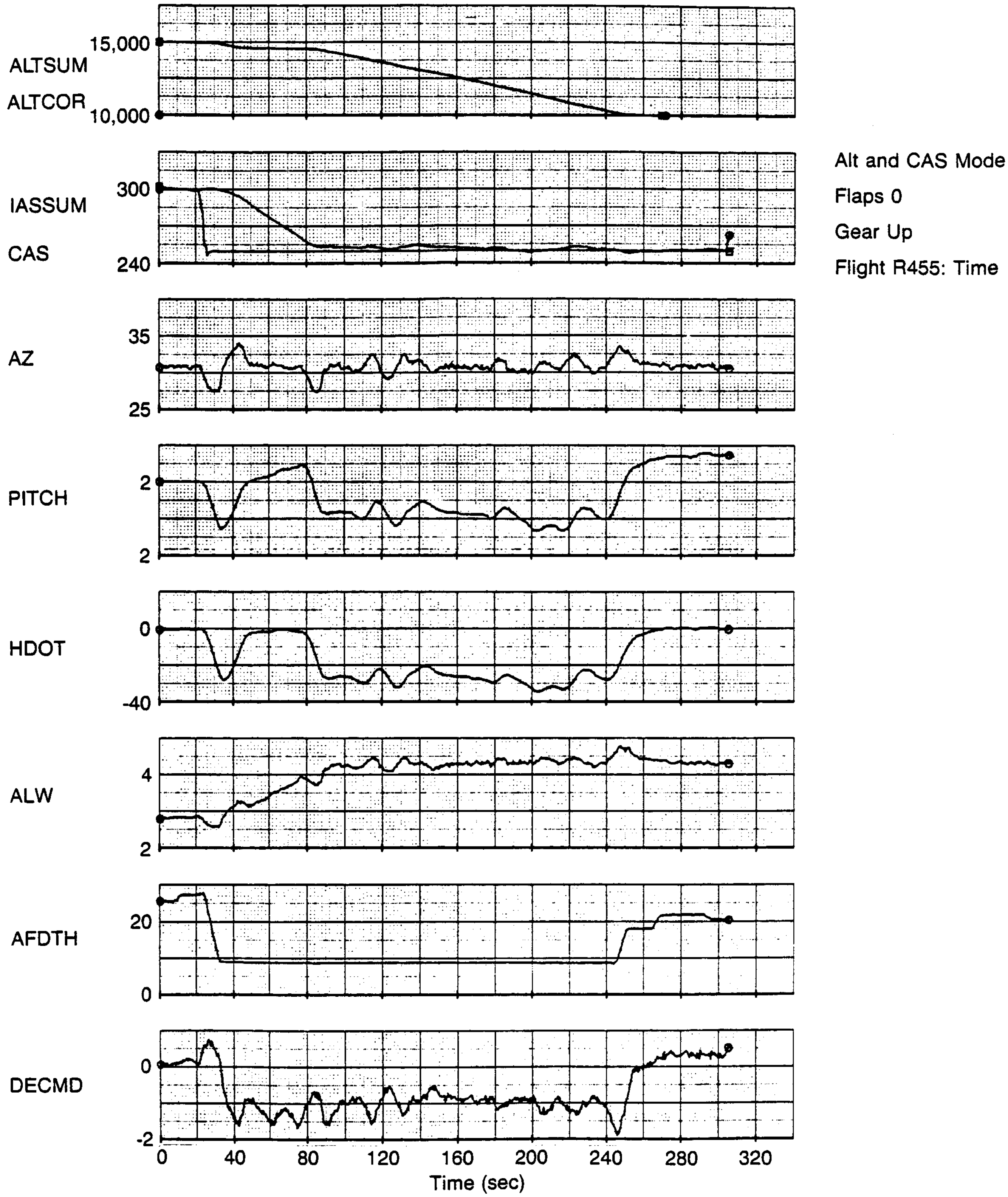


Figure 42 (a). Test 1.7.3; Altitude Change -5,000 ft, Speed Change -50 kn

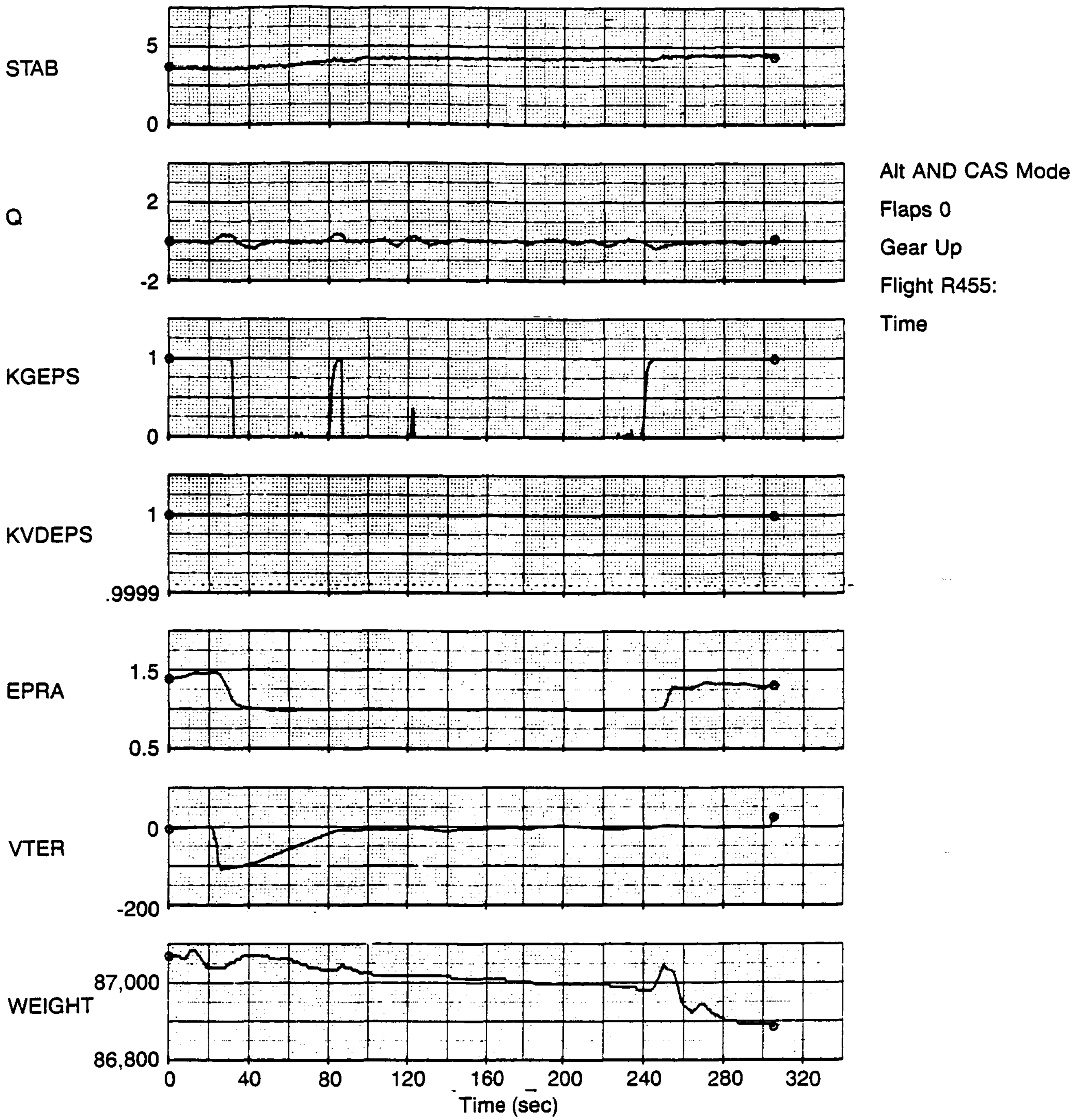
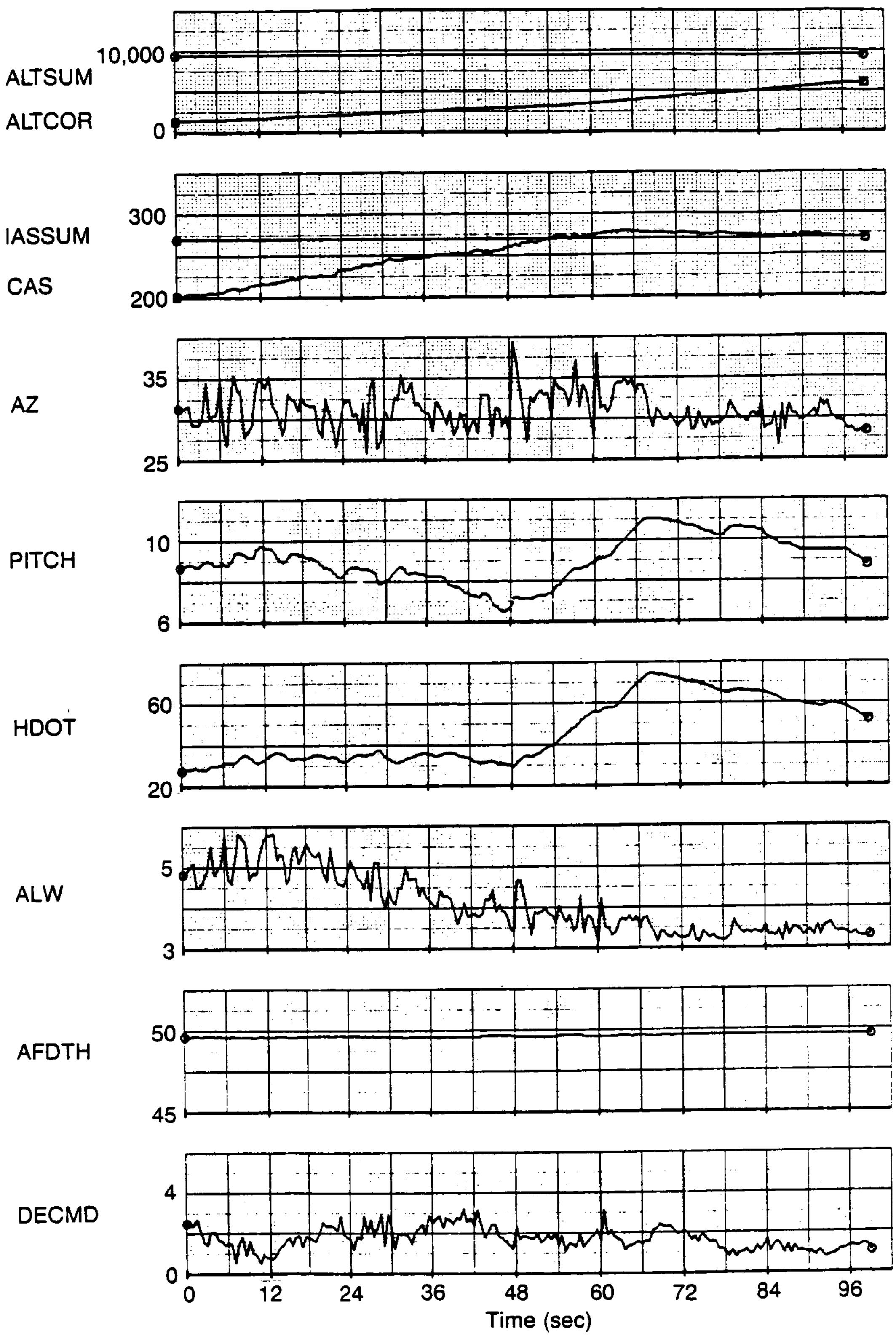


Figure 42 (b). Test 1.7.3; Altitude Change -5,000 ft, Speed Change -50 kn



Alt/CAS Mode

Mid-Altitude

Flaps 0

Gear Up

Flight R459:

Time 19:17:45

Figure 43 (a). Climbout

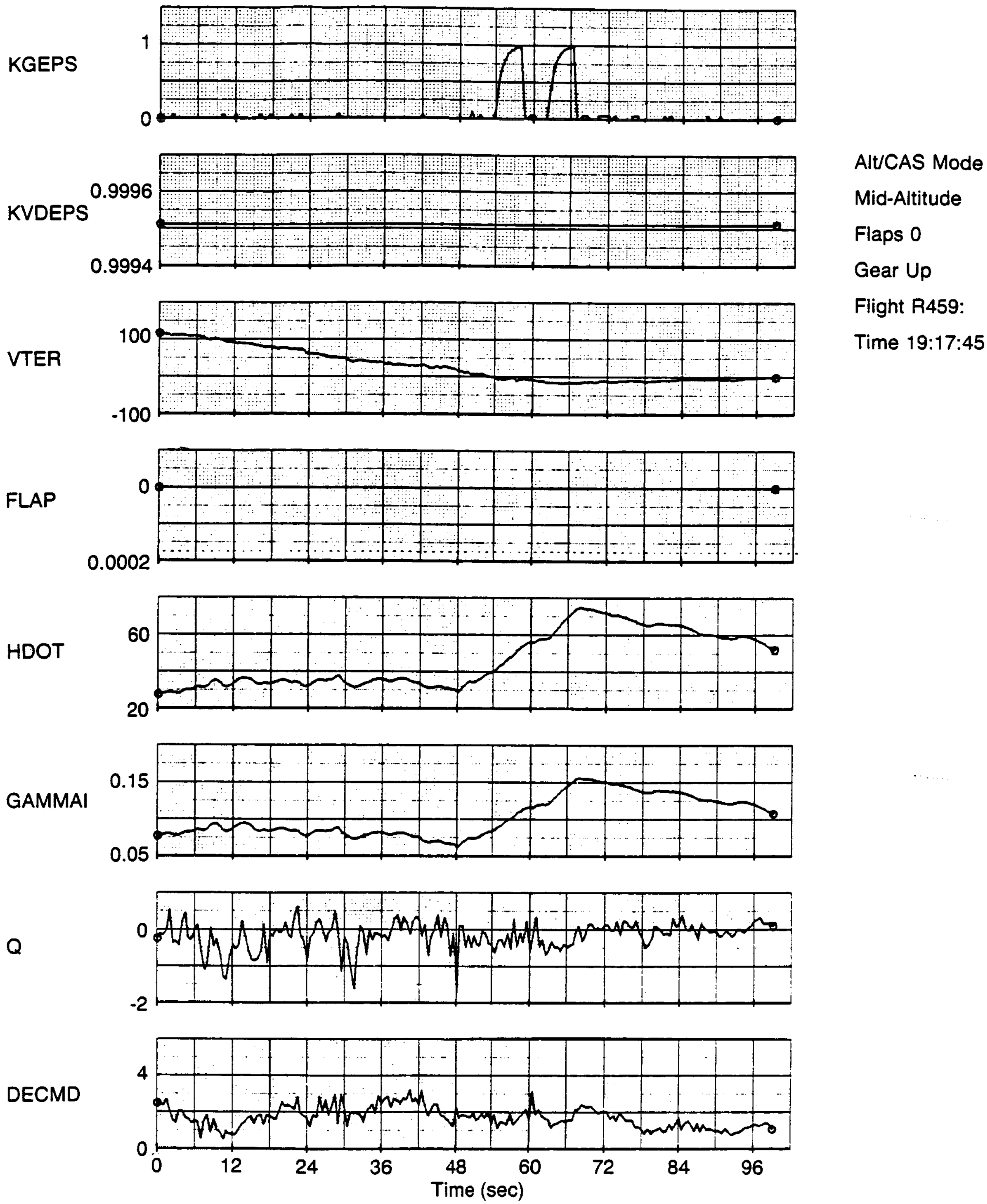


Figure 43 (b). Climbout

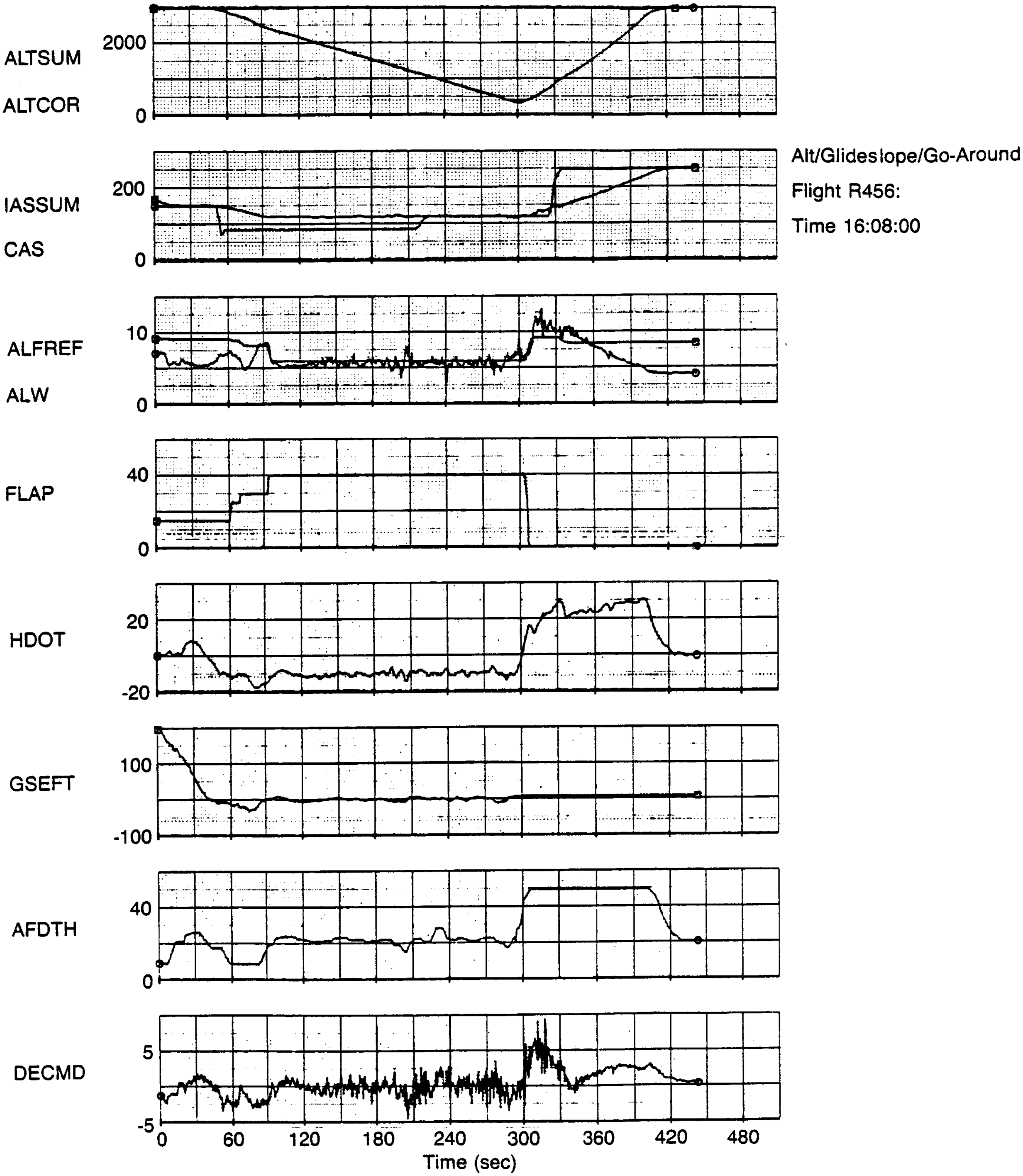


Figure 44. Test 3.6.1, 3.6.2; Approach and Go-Around

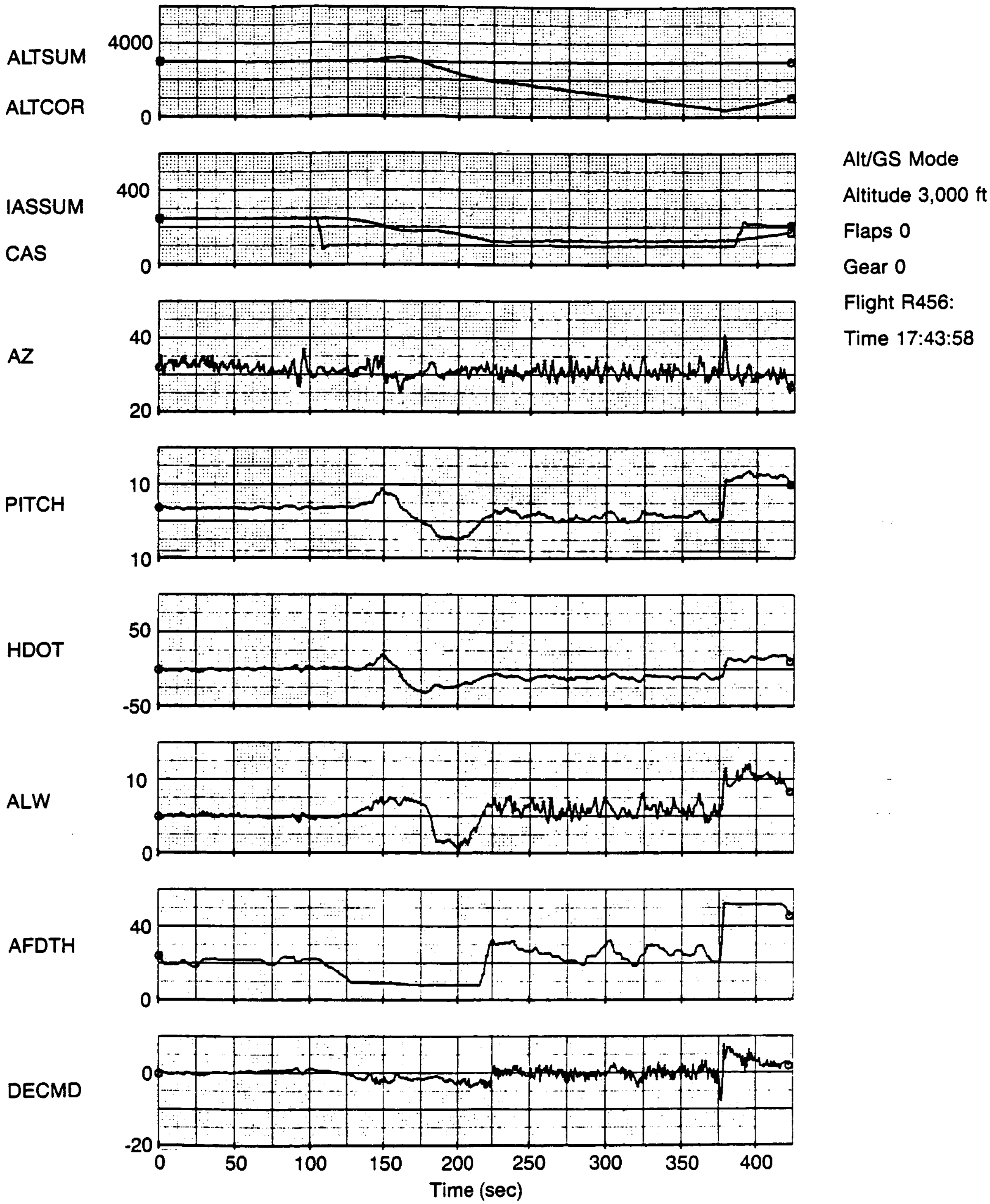


Figure 45 (a). Test 3.6.3R, 3.6.4R; Capture Glideslope

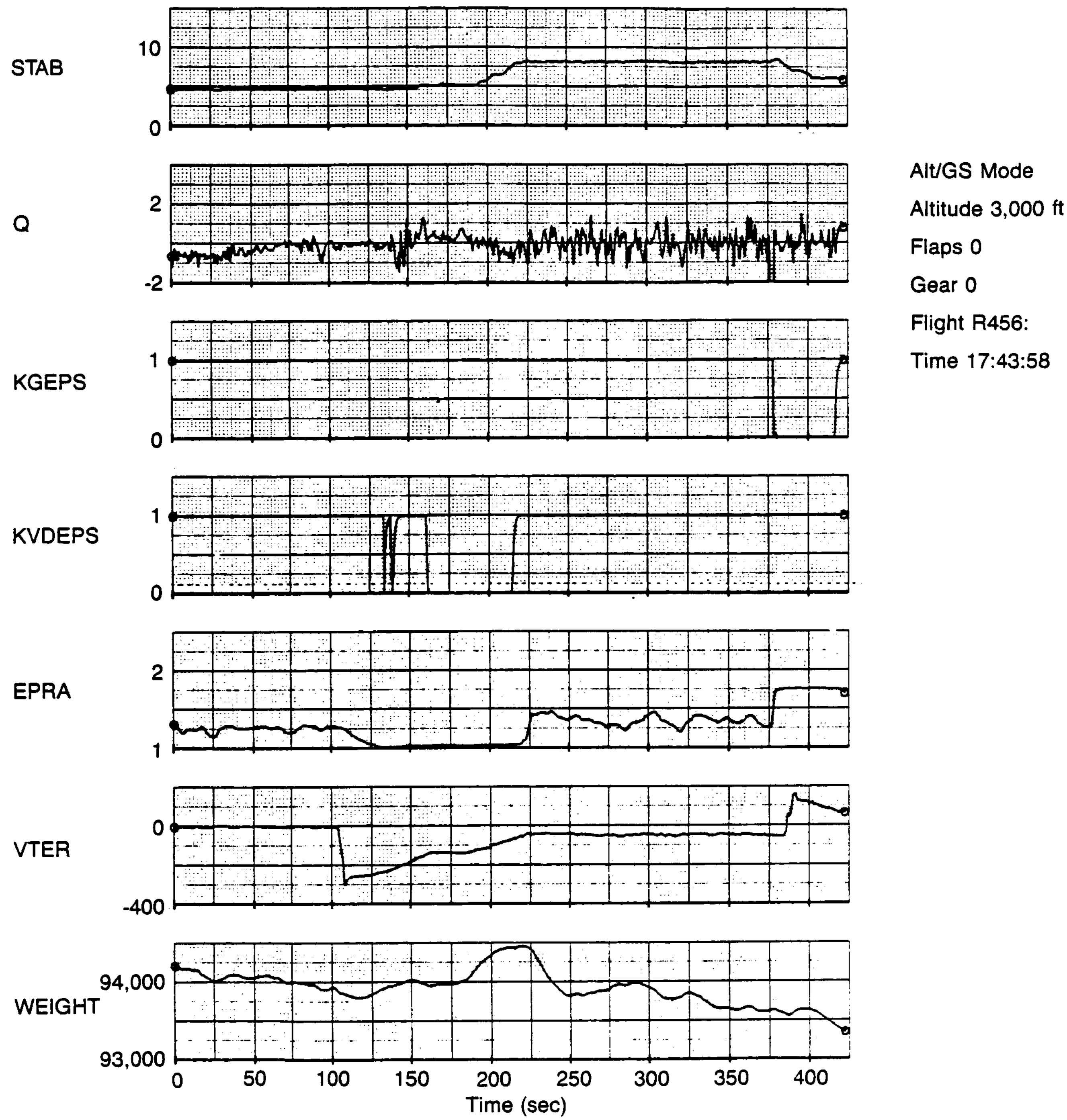


Figure 45 (b). Test 3.6.3R; Capture Glideslope

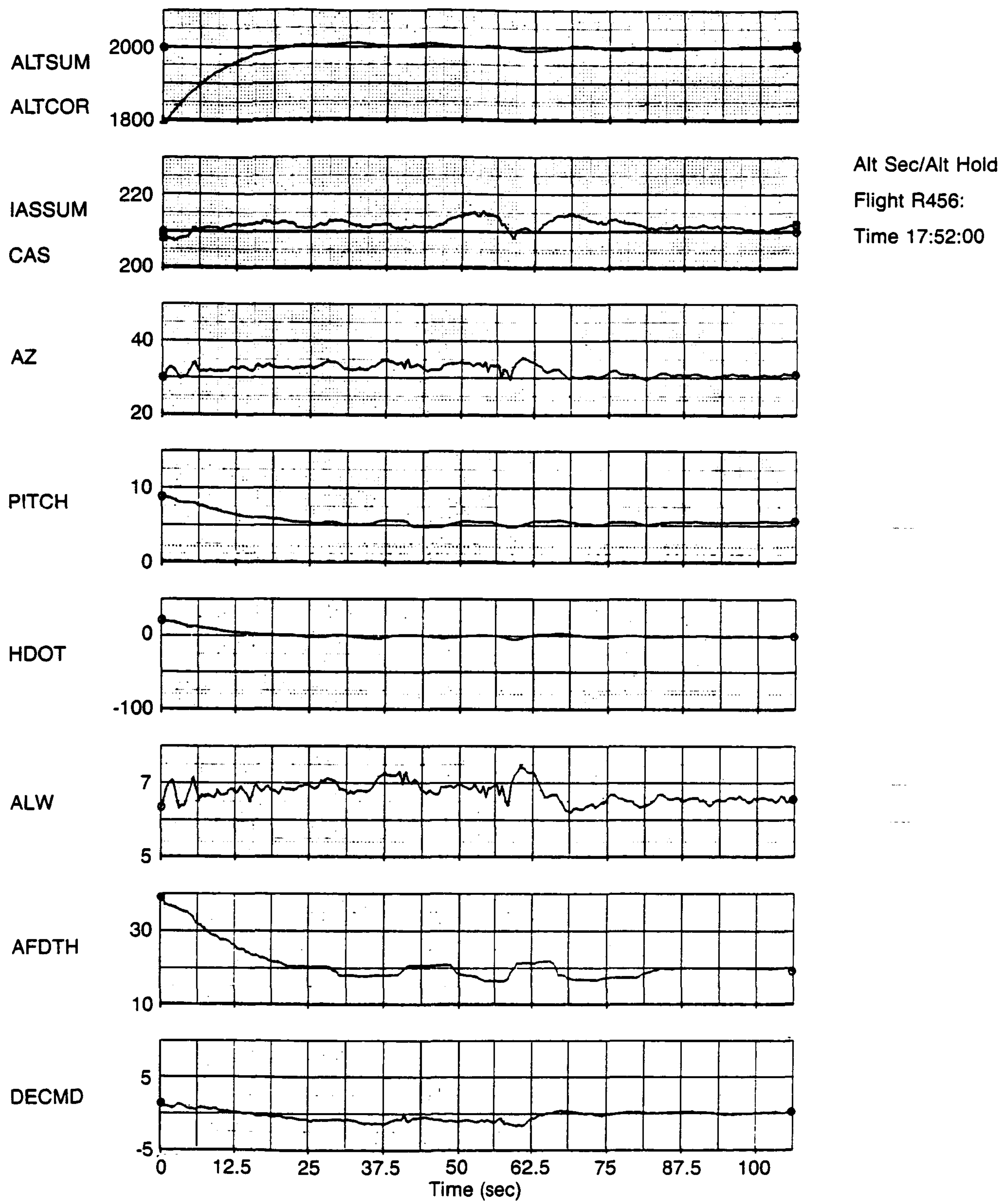


Figure 46. Test 3.6.5; Alt Select to Alt Hold

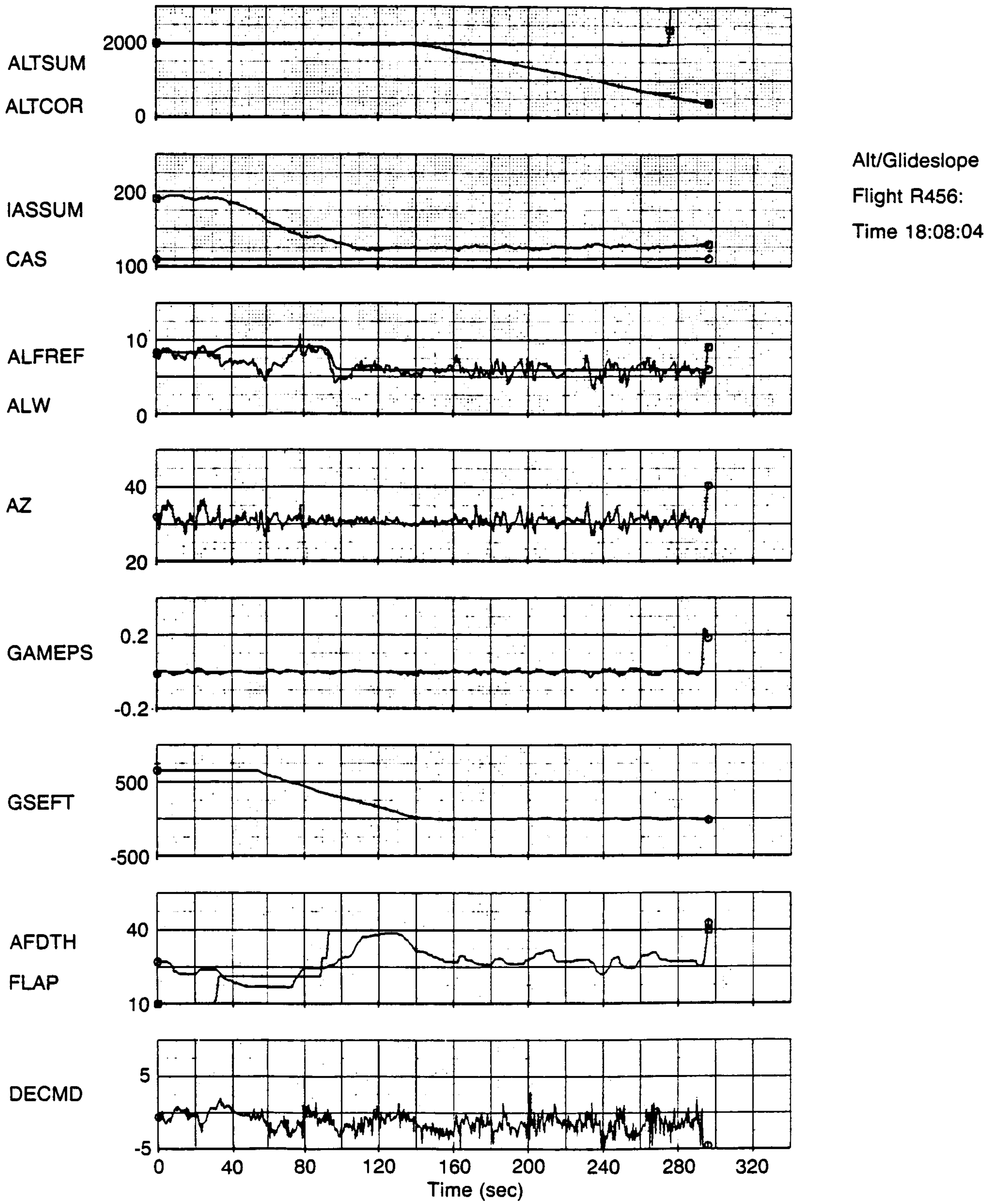


Figure 47 (a). Test 3.6.6 (R); Glideslope Capture

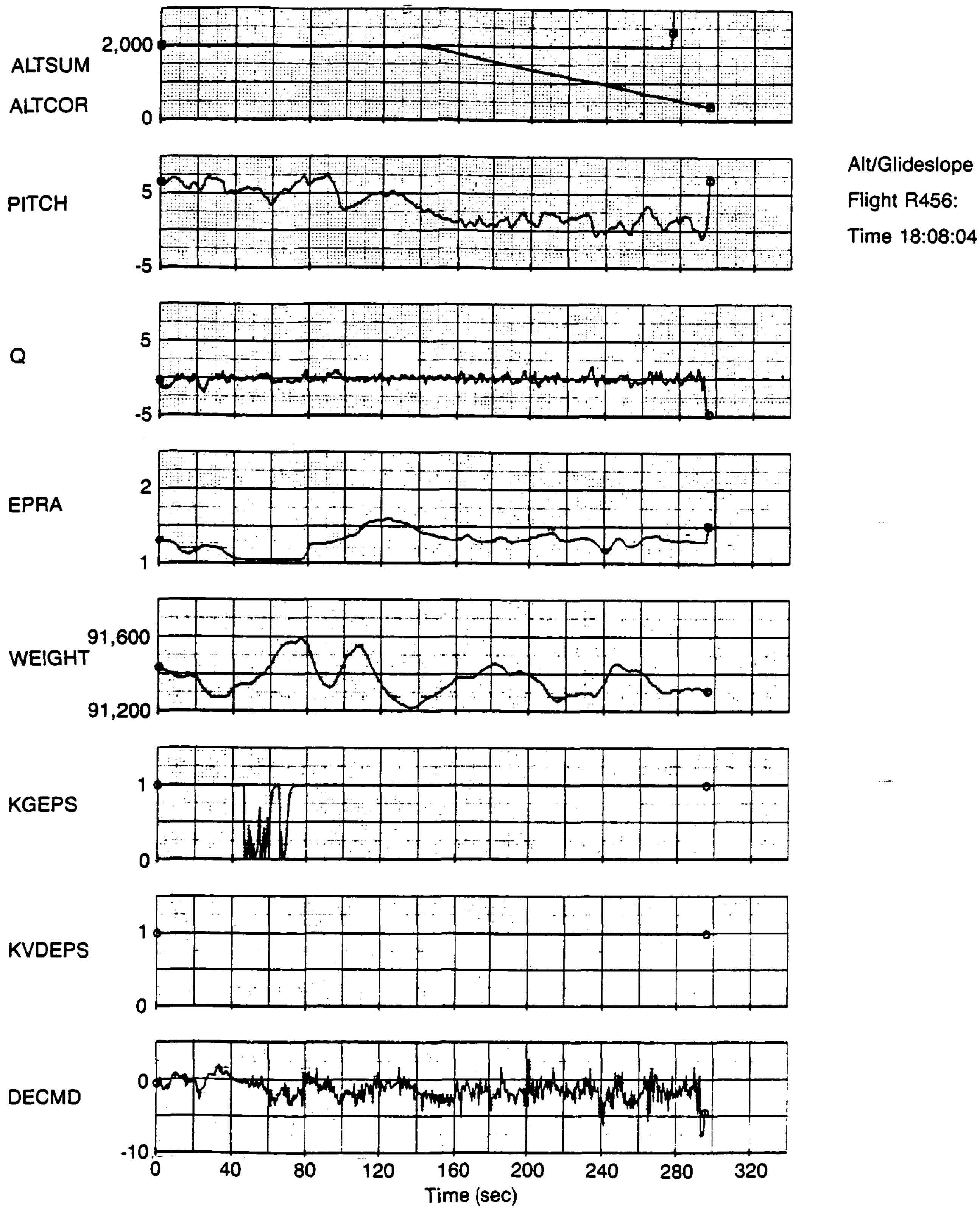


Figure 47 (b). Test 3.6.6 (R); Glideslope Capture

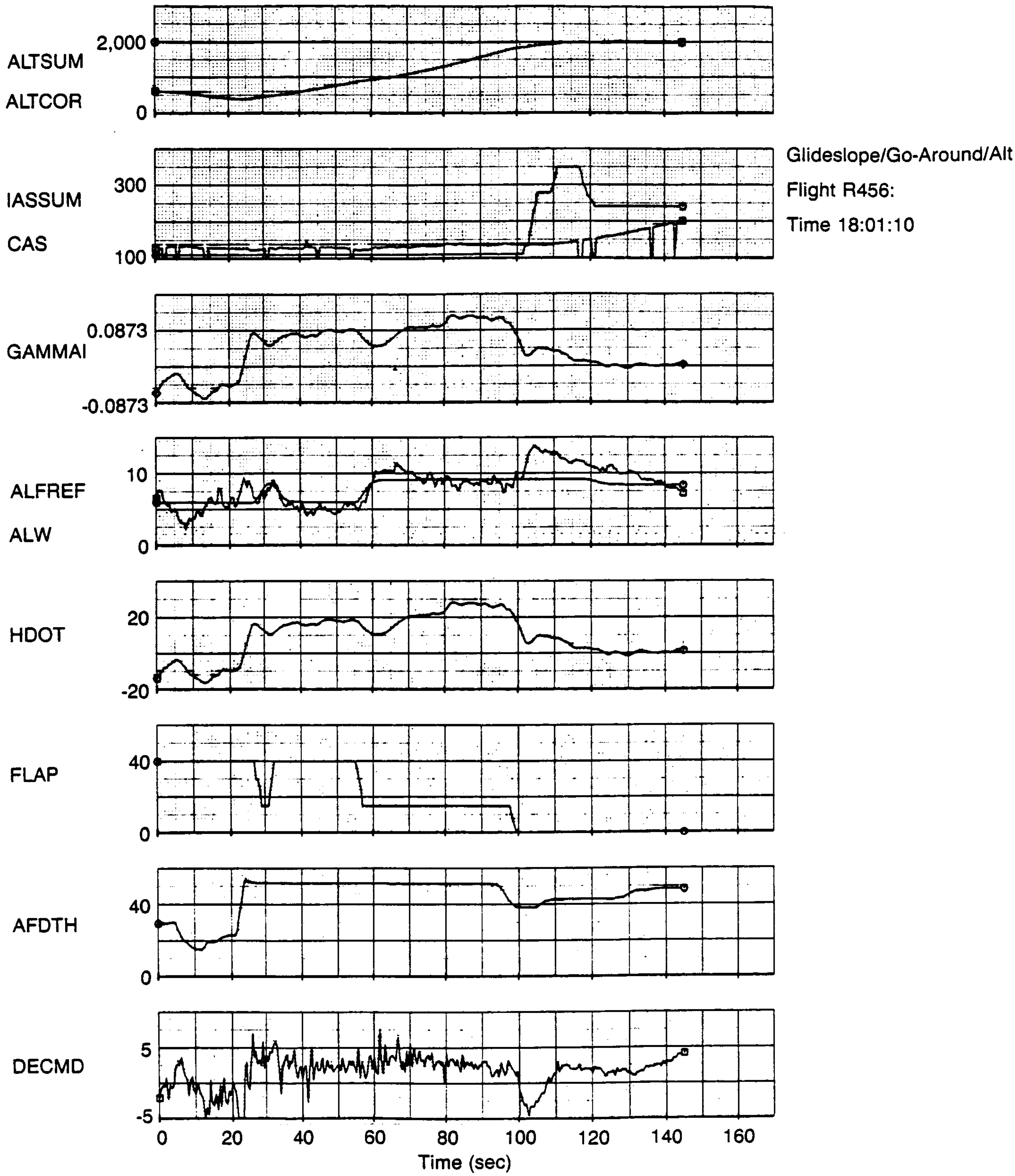


Figure 48. Test 3.6.7; Go-Around and Climbout

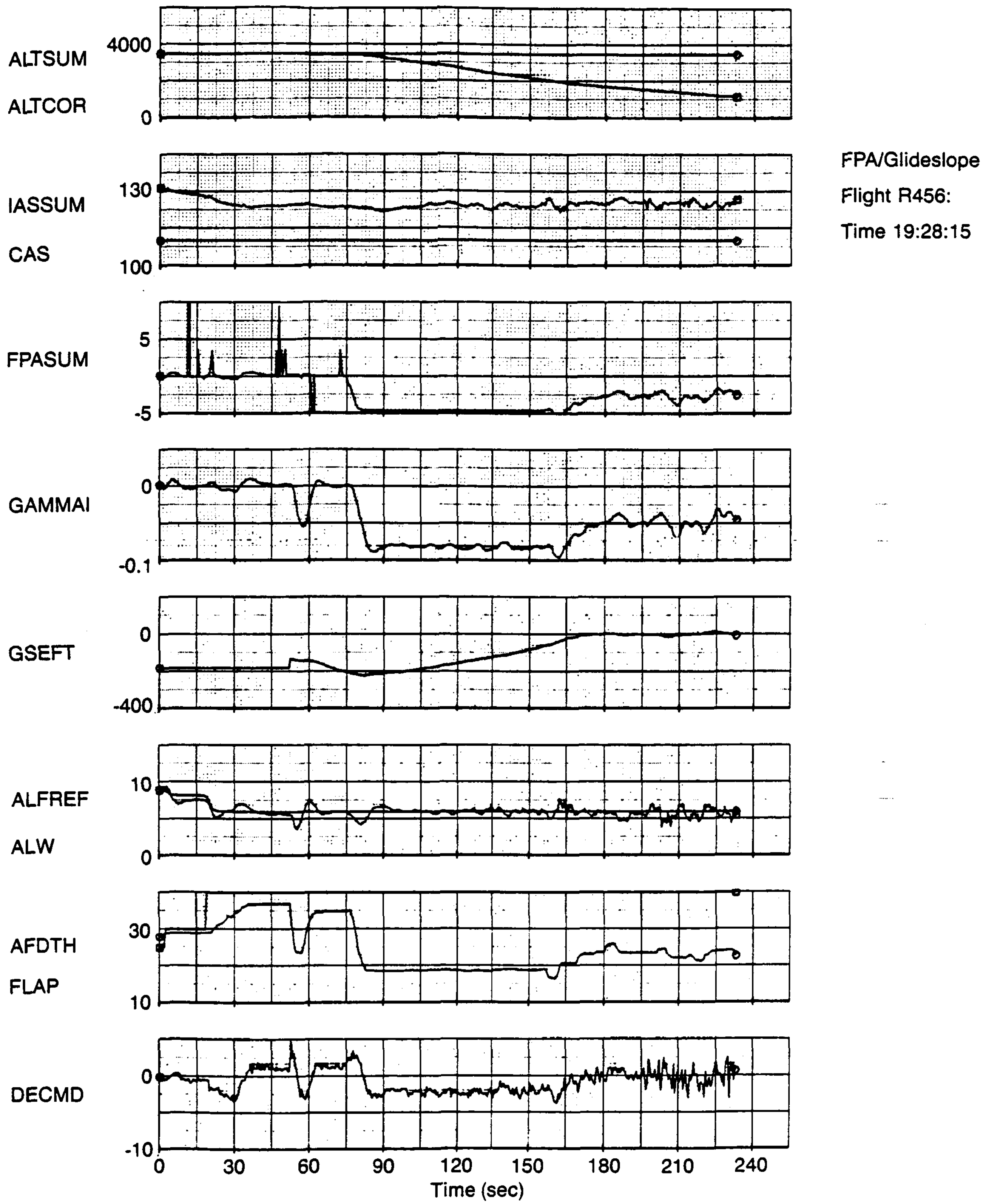


Figure 49 (a). Test 3.6.9 (R); Glideslope Capture From FPA Mode

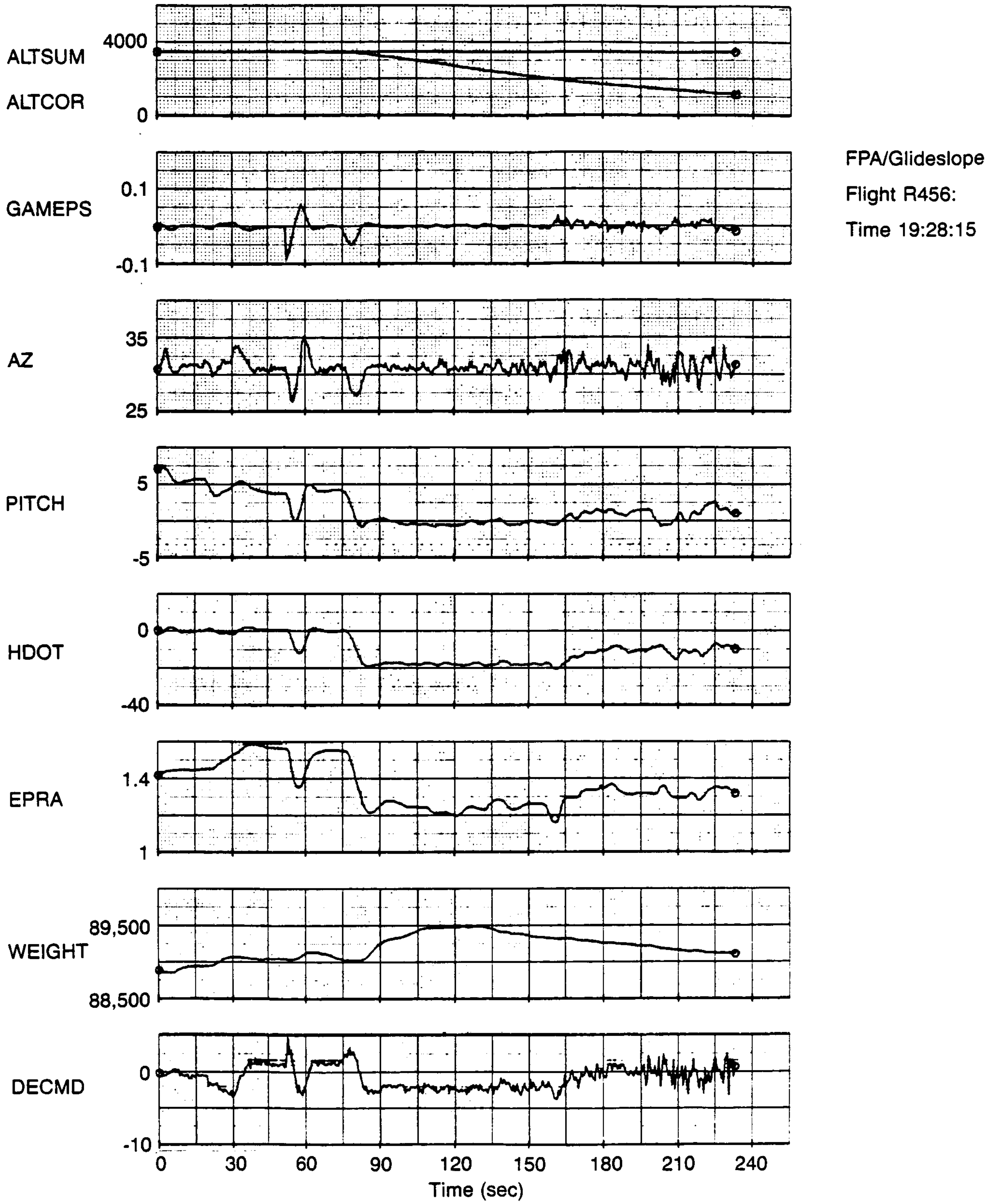


Figure 49 (b). Test 3.6.9 (R); Glideslope Capture From FPA Mode

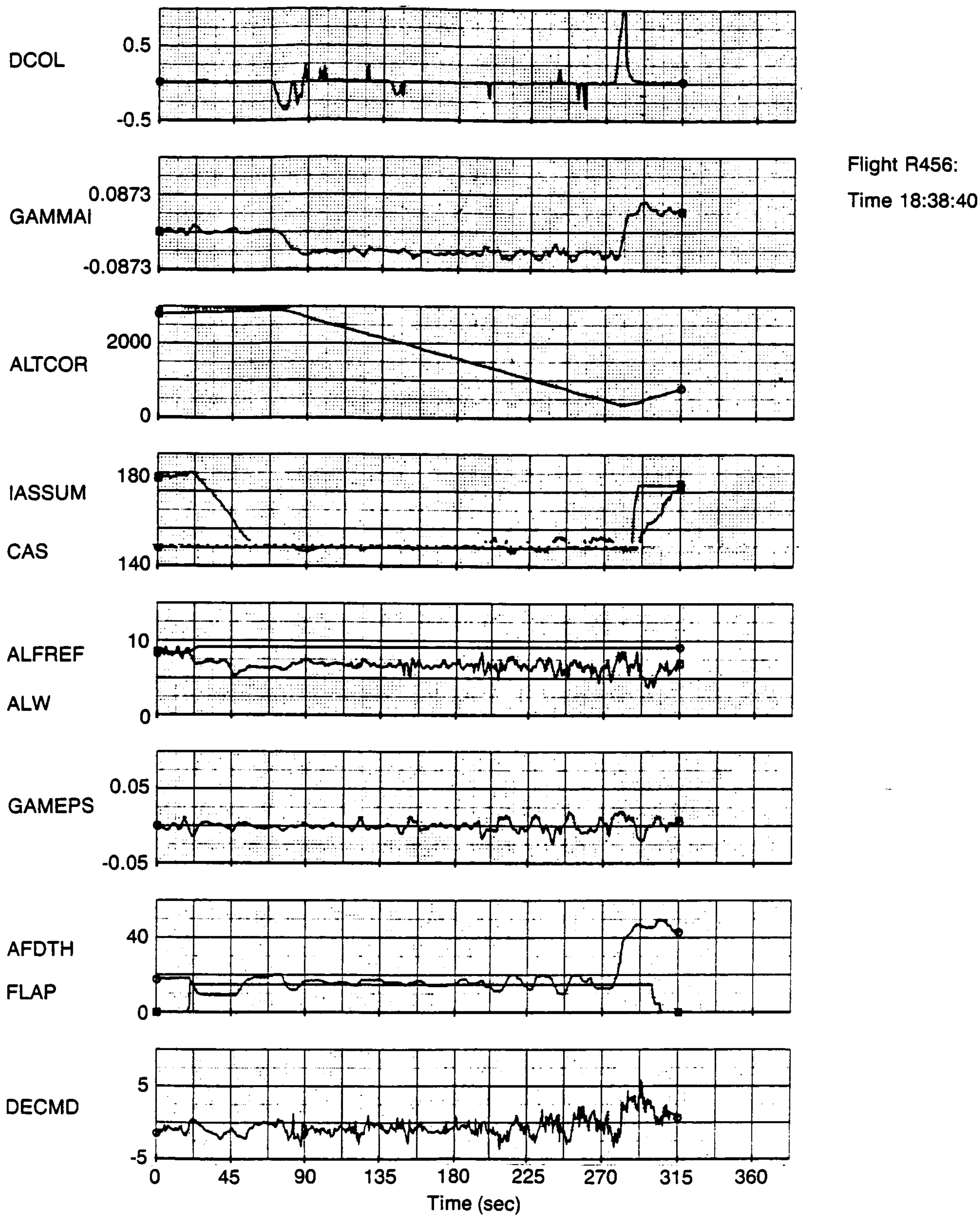


Figure 50 (a). Test 3.7.1, 3.7.2; V-CWS Approach

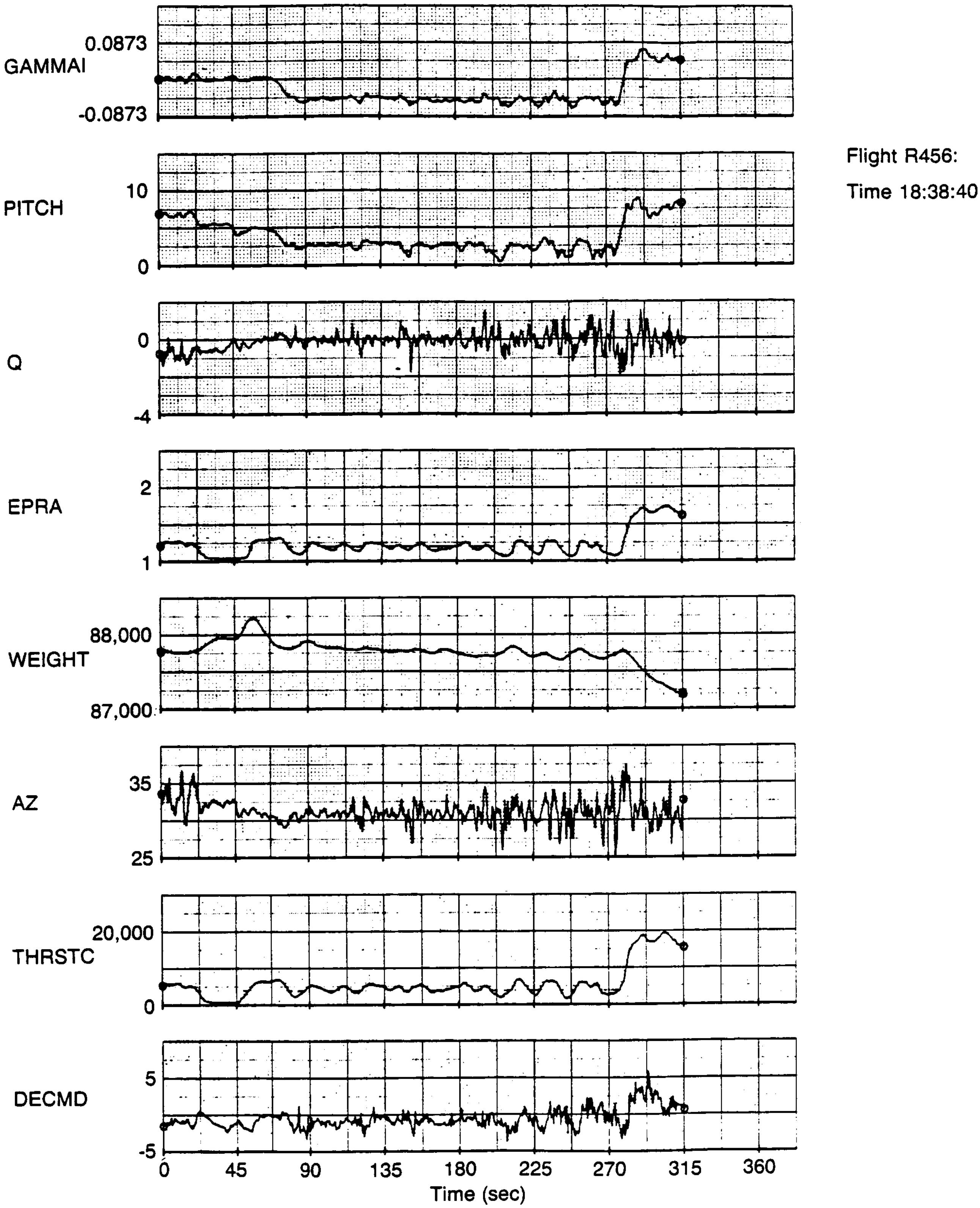


Figure 50 (b). Test 3.7.1, 3.7.2; V-CWS Approach

Appendix 1: Summary of Figures and Test Conditions

Figure	Test	Flight Conditions Alt (ft)	Speed (kn)	Remarks
6.1 FPA MODE				
7(a) (b)	1.1.1-1.1.2	10000	200	$\Delta\ \gamma\ \pm 2\frac{1}{2}^{\circ}$
8	1.1.3	10000	200	$\Delta\ \gamma\ +5^{\circ}$
9(a) (b)	1.1.4	10000	200	$\Delta\ \gamma\ -5^{\circ}$
10(a) (b)	1.1.5	10000	200	$\Delta\ \gamma\ +15^{\circ}$
11(a) (b)	2.1.1-2.1.2	25000	300	$\Delta\ \gamma\ \pm 2\frac{1}{2}^{\circ}$ 2.1.3 and 2.1.5 not plotted response as 2.1.1
12(a) (b)	2.1.4	25000	300	$\Delta\ \gamma\ -5^{\circ}$
13(a) (b)	3.1.1-3.1.2	5000	130	$\Delta\ \gamma\ \pm 2\frac{1}{2}^{\circ}$ 3.1.3 and 3.1.5 not plotted response as 3.1.1
	3.1.4	5000	130	$\Delta\ \gamma\ -5^{\circ}$
6.2 ALT Mode				
14(a) (b)	1.2.1 - 1.2.2	10000	200	$\Delta H\ \pm$ 300ft
15(a) (b)	1.2.3	10000	200	$\Delta H\ +$2500ft
16(a) (b)	1.2.3(M)	10000	200	$\Delta H\ +$4000ft
17(a) (b)	1.2.4	10000	200	ΔH -2500ft
18(a) (b)	2.2.1 - 2.2.4	25000	300	$\Delta H\ \pm$300, $\pm$2500ft
19(a) (b)	3.2.1 - 3.2.4	5000	130	$\Delta H\ \pm$300, $\pm$2500ft
6.3 CAS/MACH MODE				
20(a) (b)	1.3.1 - 1.3.2	10000	250	$\Delta V\ \pm 20$
21(a) (b)	1.3.3 - 1.3.4	10000	250	$\Delta V\ \pm 50$
22	1.3.5 - 1.3.6	10000	250	$\Delta V\ \pm 100$
23(a) (b)	2.3.1 - 2.3.2	24000	300	$\Delta V\ \pm 20$
24(a) (b)	2.3.3 - 2.3.4	24000	300	$\Delta V\ +50$
25(a) (b)	2.4.1 - 2.4.2	24000	300	$\Delta M\ \pm .05$

Figure	Test	Flight Conditions Alt (ft)	Speed (kn)	Remarks
26(a) (b)	2.4.3, 2.4.4	24000	300	$\Delta M \pm .15$
27	3.3.1, 3.3.4	5000	150	$\Delta V \pm 20, \pm 50$
28	2.7.2	20000	330	MACH to CAS Switch
<u>6.4 V-CWS MODE</u>				
29	1.5.1, 1.5.2	10000	200	$\Delta\ \gamma\ \pm 2\frac{1}{2}^\circ$
30	1.5.3	10000	200	$\Delta\ \gamma\ +5^\circ$
31	1.5.4	10000	200	$\Delta\ \gamma\ -5^\circ$
32	1.5.5	10000	200	$\Delta\ \gamma\ +10^\circ$
33	1.5.6	10000	200	$\Delta\ \gamma\ +15^\circ$
34	2.5.1	20000	300	$\Delta\ \gamma\ +2.5^\circ$
35	2.5.2	20000	300	$\Delta\ \gamma\ -.5^\circ$
36	2.5.4	20000	300	$\Delta\ \gamma\ -5^\circ$
<u>6.5 UNDERSPEED PROTECTION MODE</u>				
37(a) (b)	1.6.1, 1.6.8	10000	200	Flaps: 0° - 40° (Slow Transition)
38(a) (b)	1.6.9, 1.6.15	10000	200	Flaps: 40° - 0° (Slow Transition)
39	3.5.1	10000	200	Flaps: Rapid Change
<u>6.6 ENERGY EXCHANGE MANEUVERS</u>				
40	1.7.1	10500	250	- 600ft, + 20kts
41	1.7.1(M)	10000	250	- 500ft, + 20kts
42(a) (b)	1.7.3	15000	300	Simultaneous -5000ft, -50kts
43(a) (b)	DEMO FLIGHT	-------	300	Climb Out + 5000ft + 75kts
<u>6.7 APPROACH AND GO-AROUND</u>				
44	3.6.1, 3.6.2	3000	150	ALT ⇒ GS ⇒ GA
45(a) (b)	3.6.3, 3.6.4	3000	150	High Speed Glideslope Capture
46	3.6.5	3000	150	ALT SEL ⇒ ALT Hold at End of Climb Out
47(a) (b)	3.6.6(R)			Low Speed Glideslope Capture (Flaps 40, Gear Down Prior to Capture)
48	3.6.7			Go Around and Climb Out
49(a) (b)	3.6.9(R)			GS Capture from above
50(a) (b)	3.7.1, 3.7.2			V-CWS Approach

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Appendix 2: Flight Test Conditions

Test No.	Initial Conditions					Parameter	Description of Test Condition
	MODE	SPEED IAS (kts)	ALT (ft)	GEAR	FLAPS		
1.1.1	FPA	200	10000	UP	0	Δγ + 2.5	Response to small and large FPA commands
1.1.2						Δγ - 2.5	
1.1.3						Δγ + 5.0	
1.1.4						Δγ - 5.0	Throttles reach aft limit, TECS gives up controlling FPA but maintains control of speed
1.1.5						Δγ + 15.0	Throttles reach forward limit, TECS gives up controlling FPA but maintains control of speed
1.2.1	ALT	200	10000	UP	0	ΔH + 300 ft	Response to small and large altitude commands
1.2.2						ΔH - 300 ft	
1.2.3						ΔH + 2500 ft	Check speed error, maximum climb rate
1.2.4						ΔH - 2500 ft	
1.3.1	CAS	250	10000			ΔV + 20 kt	Response to small and large velocity (CAS) commands
1.3.2						ΔV - 20 kt	
1.3.3						ΔV + 50 kt	Observe maximum height error during speed changes
1.3.4						ΔV - 50 kt	
1.3.5	CAS	200	10000			ΔV + 100 kt	
1.3.6		300	10000			ΔV - 100 kt	
1.4.1	MACH	0.5/277	10000			ΔM + 0.05	Response to small and large Mach commands
1.4.2						ΔM - 0.05	
1.4.3						ΔM + 0.15	
1.4.4						ΔM - 0.15	
1.5.1	V-CWS	200	10000	UP	0	Δγ + 2.5	Examine V-CWS performance with small and large column inputs. Examine general V-CWS performance in smooth air and turbulence (if available)
1.5.2						Δγ -2.5	
1.5.3						Δγ + 5.0	

C-2

Test No.	Initial Conditions					Parameter	Description of Test Condition
	MODE	SPEED IAS (kts)	ALT (ft)	GEAR	FLAPS		
1.5.4						$\Delta\gamma$ - 5.0	
1.5.5						$\Delta\gamma$ + 10	For small FPA changes, system controls FPA and speed
1.5.6						$\Delta\gamma$ + 15	For larger positive commands, the throttles will limit; the system will continue to control to FPA and speed will decrease. AOA protection will prevent stall. Maintain command for sufficient time to demonstrate AOA protection.
1.6.1	AOA	200	10000	UP	0		Dial down speed. Examine AOA protection at flap settings. 0 → 40°. Extend gear at Flaps 15°.
1.6.2				"	1		
1.6.3				"	2		
1.6.4				"	5		
1.6.5				DOWN	15		
1.6.6				DOWN	25		
1.6.7				"	30		
1.6.8				"	40		
1.6.9				"	30		
1.6.10				"	25		
1.6.11				"	15		
1.6.12				UP	5		
1.6.13				"	2		
1.6.14				"	1		
1.6.15				"	0		
1.7.1	ALT and CAS	250	10000	UP	0	ΔH = -600 ΔV = +20 kt	Zero net energy exchange (rate of KE change equals the rate of PE change)
1.7.2	ALT and CAS	250	10000	UP	0	ΔH = 5000 ft ΔV = 50kt	Execute as double maneuver
1.7.3	ALT and CAS	300	15000	UP	0	ΔH = -5000 ft ΔV = -50 kt	Execute as double maneuver
1.7.4	ALT and CAS	250	10000	UP	0	ΔV = +50 kt ΔH = +5000 ft	Execute as double maneuver

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Test No.	Initial Conditions					Parameter	Description of Test Condition
	MODE	SPEED IAS (kts)	ALT (ft)	GEAR	FLAPS		
2.1.1	FPA	325	25000	UP	0	$\Delta\gamma$ + 2.5°	Response to small and large FPA commands
2.1.2						$\Delta\gamma$ - 2.5°	
2.1.3						$\Delta\gamma$ + 5.0°	Throttles reach forward limit, TECS gives up controlling FPA but maintains control of speed
2.1.4						$\Delta\gamma$ - 5.0°	Throttles reach aft limit, TECS gives up controlling FPA but maintains control of speed
2.2.1	ALT	325	25000	UP	0	ΔH + 300 ft	Response to small and large altitude command
2.2.2						ΔH - 300 ft	
2.2.3						ΔH + 2500	Check speed error, maximum climb rate
2.2.4						ΔH - 2500	
2.3.1	CAS	300	25000	UP	0	ΔV + 20	Observe maximum height error during speed changes
2.3.2						ΔV - 20	
2.3.3		250	10000			ΔV + 50	
2.3.4						ΔV - 50	
2.4.1	MACH	M 0.65	25000			ΔM = .05	
2.4.2						ΔM = -.05	
2.4.3						ΔM = .15	
2.4.4						ΔM = -.15	
2.5.1	V-CWS	300	20000	UP	0	$\Delta\gamma$ + 2.5	Examine V-CWS performance with small and large column inputs. Examine general V-CWS performance in smooth air and turbulence if conditions permit.
2.5.2						$\Delta\gamma$ - 2.5	
2.5.3						$\Delta\gamma$ + 5.0	
2.5.4						$\Delta\gamma$ - 5.0	For large, negative commands, the throttles will limit; the system will continue to control to FPA and speed will increase. V_{max} protection will prevent overspeed.
2.6.1	V_{MAX}	CAS = 300		UP	0	+ΔV = 100 kts	Descend from 25000 ft and check operation of V_{MAX} mode.

Test No.	Initial Conditions					Parameter	Description of Test Condition
	MODE	SPEED IAS (kts)	ALT (ft)	GEAR	FLAPS		
2.7.1	Automatic CAS → MACH Switching	330 kts	18000	UP	0		1. Fly CAS, ALT HOLD mode at 18000 ft. 2. Dial in 20000 ft and select ALT SEL. 3. Climb to 20000 ft. 4. CAS → MACH Automatic switching occurs at 330 kts, 0.7M and approx. 19000 ft.
2.7.2	Automatic MACH → CAS Switching	M 0.7	20000	UP	0		1. Fly MACH, ALT HOLD mode at 20000 ft. 2. Dial in 18000 ft and select ALT SEL. 3. Descend to 18000 ft. 4. Observe MACH → CAS automatic switching.
3.1.1	FPA	V_{ref} + 10 kts	5000	DOWN	40	$\Delta\gamma$ + 2.5	Response to small and large FPA commands
3.1.2						$\Delta\gamma$ - 2.5	
3.1.3						$\Delta\gamma$ + 5.0	
3.1.4						$\Delta\gamma$ - 5.0	Throttles reach aft limit, TECS gives up controlling FPA but maintains control of speed
3.1.5						$\Delta\gamma$ + 15	Throttles reach forward limit, TECS gives up controlling FPA but maintains control of speed
3.2.1	ALT	V_{ref} + 10 kts	5000	DOWN	40	ΔH + 300 ft	Response to small and large ALT commands.
3.2.2						ΔH - 300 ft	
3.2.3						ΔH + 2500 ft	Check speed error, maximum climb rate
3.2.4						ΔH - 2500 ft	
3.3.1	CAS	V_{ref} + 10 kts	5000			ΔV + 20 kt	Response to small and large CAS commands.
3.3.2						ΔV - 20 kt	
3.3.3						ΔV + 50 kt	Observe maximum height error during speed changes.
3.3.4						ΔV - 50 kt	
3.3.5						ΔV + 100 kt	
3.3.6						ΔV - 100 kt	

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Test No.	Initial Conditions					Parameter	Description of Test Condition
	MODE	SPEED IAS (kts)	ALT (ft)	GEAR	FLAPS		
3.4.1	MACH	0.5/277	10000			ΔM + 0.05	
3.4.2						ΔM - 0.05	
3.4.3						ΔM + 0.15	
3.4.4						ΔM - 0.15	
3.5.1	AOA	175	5000	UP	0		Dial down speed. Examine AOA protection during rapid flap extension (0 → 40°). Extend gear at flaps 15°.
3.5.2	AOA	125	5000	DOWN	40		Leave speed command at 125 kts. Examine AOA protection during rapid flap retraction (40°→0°). Retract gear at flaps 15°.
3.6.1	ALT → GS HOLD	150	3000	1	15		Intercept glideslope from ATL HOLD mode at 150 kt, 3000 ft. Continue descent on glideslope and extend flaps to 40°. Decrease speed to 1.3 V_{ref}.
3.6.2	G.A.	1.3 V_{ref}	500	1	40		Engage G.A. at 500 ft and climb out to 3000 ft. Automatically engage ALT HOLD at 3000 ft. Increase speed to 250 kts during climb out.
3.6.3	ALT → GS	250	3000	0	0		Capture glideslope. Dial down speed to 100 kts. Extend flaps while flying down glideslope.
3.6.4	G.A.	1.3 V_{ref}	500	1	40		Engage go around at 500 ft.
3.6.5	ALT SEL → ALT HOLD	1.3 V_{ref}	~1000	DOWN	40	SELECT ALTITUDE 2000 ft	Engage ALT SELECT and fly airplane to approach position.
3.6.6	ALT HOLD → GS	1.3 V_{ref}	2000	1	40		Capture glideslope at 1.3 V_{ref} and fly down to 500 ft altitude.
3.6.7	G.A.	1.3 V_{ref}	500	1	40		At 500 ft altitude engage go-around mode, climb out to 1000 ft.
3.6.8	FPA	1.3 V_{ref}	1000	1	40	FPA +5°	Engage FPA climb out to 3500 ft and fly airplane to approach position approximately 10 nm from runway threshold.

Test No.	Initial Conditions					Parameter	Description of Test Condition
	MODE	SPEED IAS (kts)	ALT (ft)	GEAR	FLAPS		
3.6.9	FPA → GS	1.3 V_{ref}	3500 (~10nm range from thresh-old)	1	40	FPA -4°	Approach and capture glideslope from above at -4° FPA.
3.7.1	V-CWS	150	3000	1	15		Approach and fly down glideslope using V-CWS mode.
3.7.2	V-CWS	150	500	1	15		Go-around at 500 ft altitude using V-CWS mode.