X-38 Vehicle 131R Free Flights 1 & 2

The X-38 program is using a modern flight control system (FCS) architecture originally developed by Honeywell called MACH. During last year's SAE G&C subcommittee meeting, we outlined the design, implementation and testing of MACH in X-38 Vehicles 132, 131R & 201. During this year's SAE meeting, I'll focus upon the first two free flights of V131R, describing what caused the roll-over in FF1 and how we fixed it for FF2. I only have 30 minutes, so it will be a quick summary including VHS video. A brief "abstract" follows:

X-38 is a NASA JSC/DFRC experimental flight test program developing a series of prototypes for an International Space Station (ISS) Crew Return Vehicle (CRV), often described as an ISS "lifeboat." X-38 Vehicle 132 Free Flight 3 was the first flight test of a modern FCS architecture called Multi-Application ControlH (MACH), developed by the Honeywell Technology Center in Minneapolis and Honeywell's Houston Engineering Center. MACH wraps classical P&I outer attitude loops around modern dynamic inversion attitude rate loops. The presentation at last year's SAE Aerospace Meeting No. 85 focused upon the design and testing of the FCS algorithm and Vehicle 132 Free Flight 3. This presentation will summarize flight control and aerodynamics lessons learned during Free Flights 1 and 2 of Vehicle 131R, a subsonic test vehicle laying the groundwork for the orbital/entry test of Vehicle 201 in 2003.

PRESENTED 3/16/00 AT SAE AEROSPACE
G&C SUBCOMMITTEE MTG. #85

X-38 MACH FCS Overview

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X-38 FCS

Agenda

- *MACH Overview*
  - *What is MACH?*
  - *MACH Applications*
  - *What is Dynamic Inversion?*
  - *MACH Control Law*
  - *MACH vs. Classical Design*
  - *Backup Information*
- *X-38 FCS*
  - *X-38 Flight Test Vehicles*
  - *Why MACH for X-38 FCS?*
  - *V132 MACH Modifications*
  - *V132 Captive Carry Tests*
  - *V132 FF3 Preflight Prediction Plots*
  - *V131R & V201 MACH Status*

What is MACH?

- *"Multi-Application Control - Honeywell", created by Enns and Bugajski at HTC, supported by Wacker at HEC/JSC*
- *Expandable, nonlinear, MIMO FCS architecture*
- *Blended implementation of classical & modern controllers*
  - *Proportional+integral (P+I) outer attitude loops*
  - ***Dynamic inversion** inner rate loops*
- *FCS for X-38 flight test vehicles V132, V131R & V201*

MACH Applications

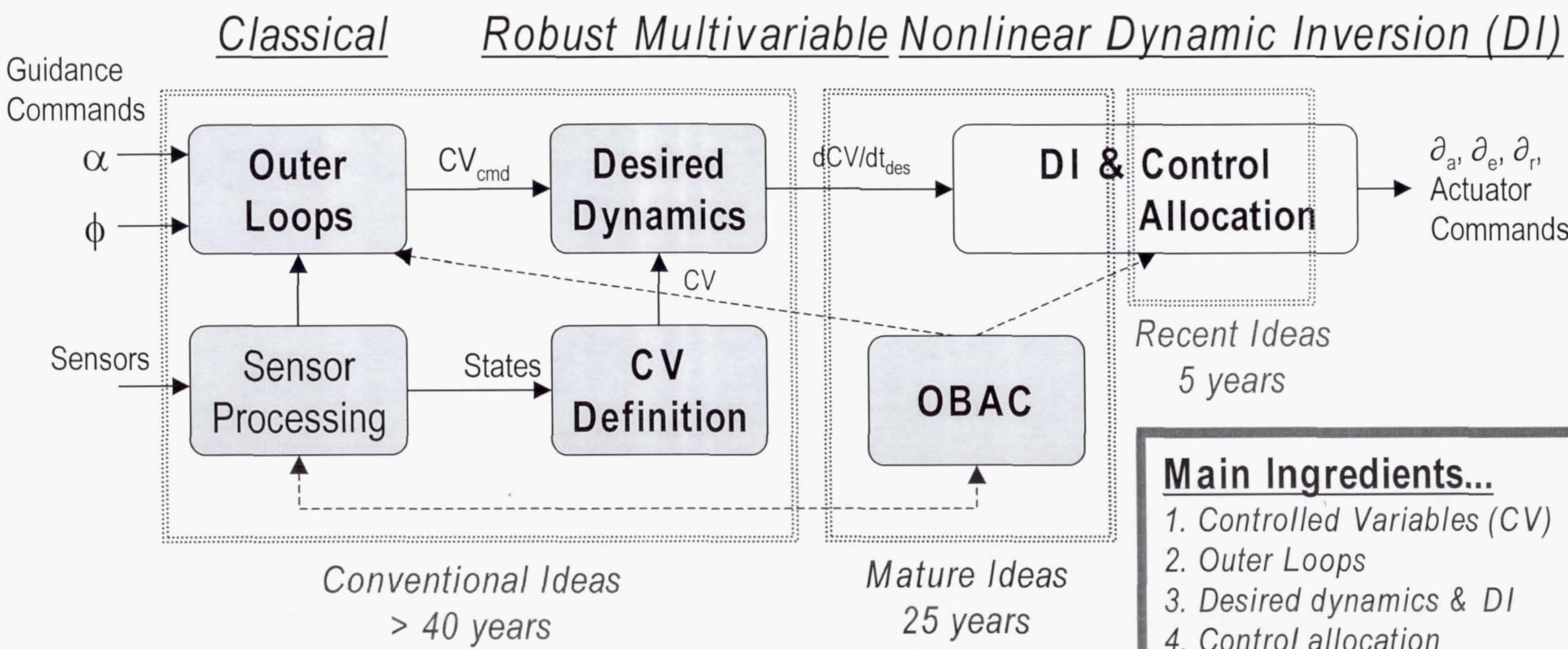
- *MACH is a decade old*

Program/Vehicle	*Years*	*Simulation*
F-18 High Angle-of-attack Research Vehicle (HARV)	*1991-1995*	*HW-in-the-loop*
Joint Defense Attack Munition (JDAM)	*1992*	*Engineering*
DC-X, high AOA atmospheric maneuvering	*1993*	*Engineering*
F117, USAF Multivariable Control Design Guidelines	*1993-1996*	*Engineering*
YF-22, USAF Multivariable Control Design Guidelines	*1993-1996*	*Engineering*
MCT/F-16, USAF Multivariable Control Design Guidelines	*1993-1996*	*Piloted*
Lockheed-Martin Joint Strike Fighter (JSF), Marine STOVL	*1995-1999*	*Piloted*
X-38 V132 (FF3 will be 1st flight test using MACH FCS)	*1996-2000*	*HW-in-the-loop*
X-38 V131R	*1999-2000*	*Engineering*
X-38 V201	*1998-2000*	*Engineering*

What is Dynamic Inversion?

- *Multivariable, nonlinear, model-based controller design technique*
  - *Proposed by Meyer & Cicolani for VSTOL, NASA TN D-7940, 1975*
- *Basics:*
  1. *Compute model of vehicle dynamics during flight*
  2. *Invert nonlinear model to cancel expected dynamics*
  3. *Insert desired vehicle response dynamics, typically linear*
- *Pros:*
  - *+ Automatically handles nonlinear, coupled aerodynamics*
  - *+ Covers flight envelope, reducing/eliminating point-design gain-scheduling*
  - *+ Swap out computational dynamics models for different vehicles*
- *Cons:*
  - *- Computationally intensive => requires modern, fast flight computers*
  - *- Full state feedback => requires full sensor compliment*
  - *- Can be complex to implement (M'A'CH is HTC's implementation)*

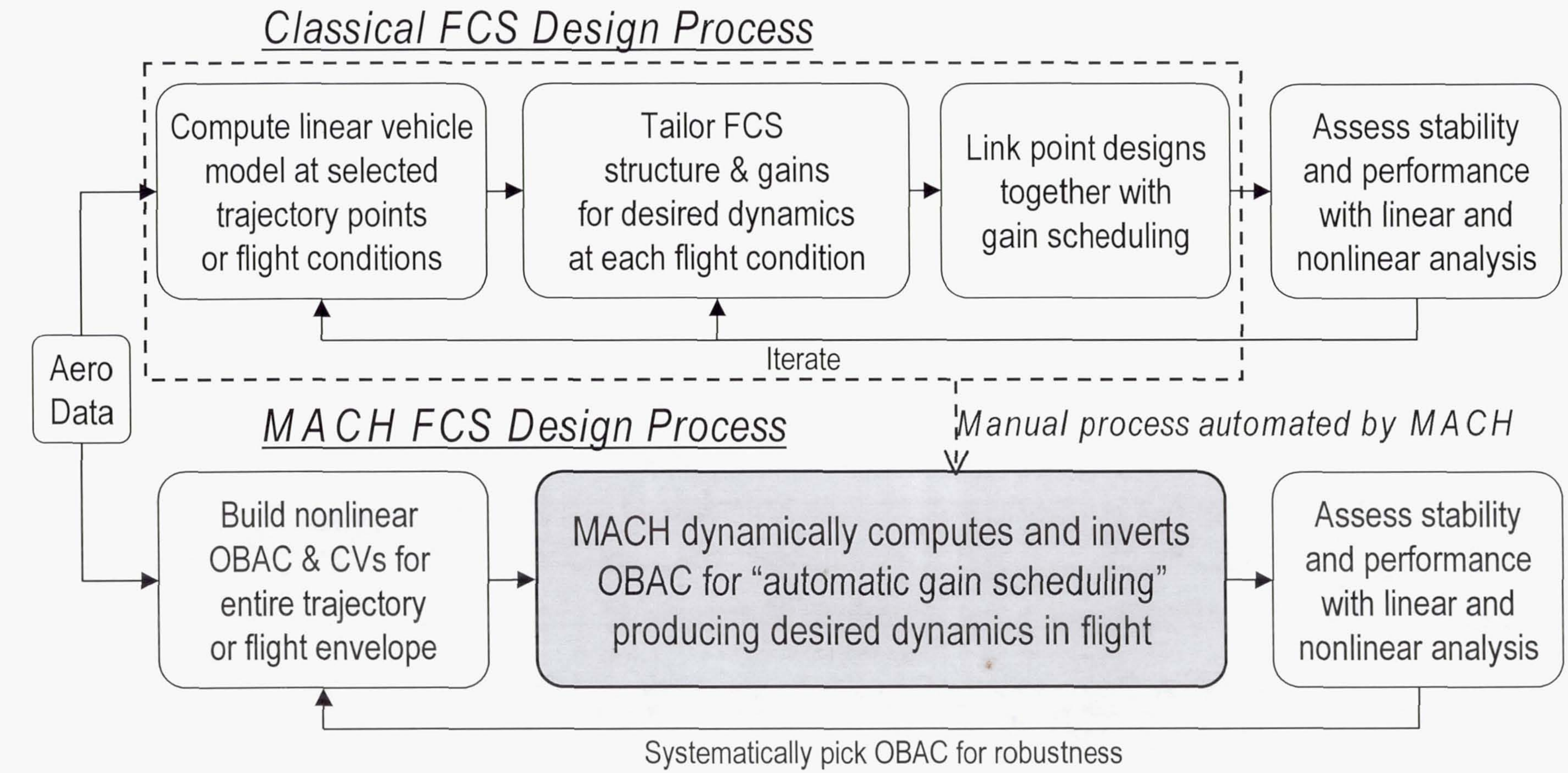
MACH Control Law



Main Ingredients...

1. *Controlled Variables (CV)*
2. *Outer Loops*
3. *Desired dynamics & DI*
4. *Control allocation*
5. *On-Board Aircraft Model (OBAC)*

MACH vs. Classical Design



Backup Information

- *MACH Main Ingredients*
  1. *Controlled Variables*
  2. *Outer Loops*
  3. *Desired Dynamics and Dynamic Inversion*
  4. *Control Allocation*
  5. *On-Board Aircraft Model (OBAC)*
- *MACH Code*

1. Controlled Variables (CV)

- *Select proper CVs for* ***performance*** *and* ***robustness***
  - *Stable zero dynamics*
  - *Good α and ϕ command tracking and disturbance rejection*
  - *Blend rotational and translational control (MCV & NCV)*
  - *Coordinated flight in steady wind*
- *One CV for each rotational axis*

Axis	CV	Definition
Roll	LCV	p_s
Pitch	MCV	$q + \frac{n_{z_{lag}}}{V_c} + \frac{g\cos\gamma\cos\mu}{V\cos\beta} - p_s\tan\beta - K_{\bar{q}}\bar{q} - \left(\frac{g}{V_c} + \frac{g}{V}\right)\cos\gamma$
Yaw	NCV	$r_s + K_\beta \beta_{eq} - \frac{g}{V}\cos\gamma\,\sin\mu$

Turn coordination

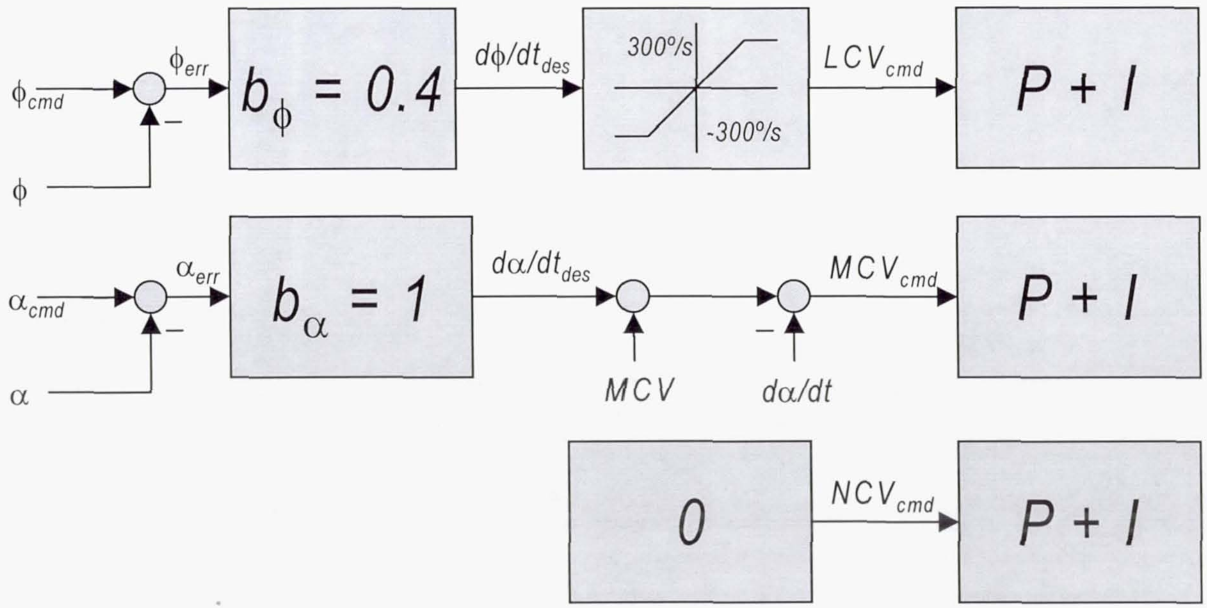
<u>MCV Term Descriptions</u>

- *$d\alpha/dt$*
- *$K_\alpha\,\alpha$*
- *Keep nose up in turn*
- *Phugoid damping*
- *Trim*

Equivalent sideslip angle, β_{eq}:
For robust stability in steady winds, using filtered n_y instead of FADS β, with inertial β assumed zero.

2. Outer Loops

- *Convert guidance commands into CV commands...*



$d\phi/dt \quad p_s = LCV$

$MCV = q + a$
$d\alpha/dt = q + b$
$\Rightarrow d\alpha/dt = MCV - a + b$
$\Rightarrow MCV\_cmd = d\alpha/dt_{des} + a - b$
$\Rightarrow MCV\_cmd = d\alpha/dt_{des} + MCV - d\alpha/dt$

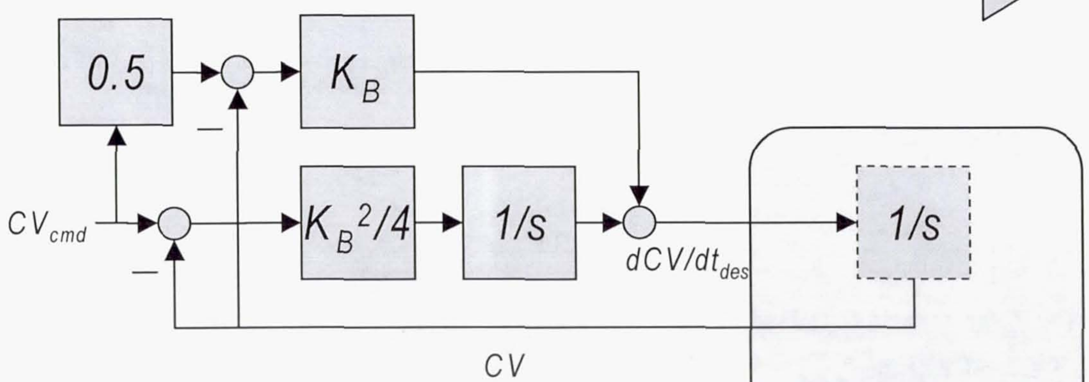
=> no sideslip

3. Desired Dynamics & DI

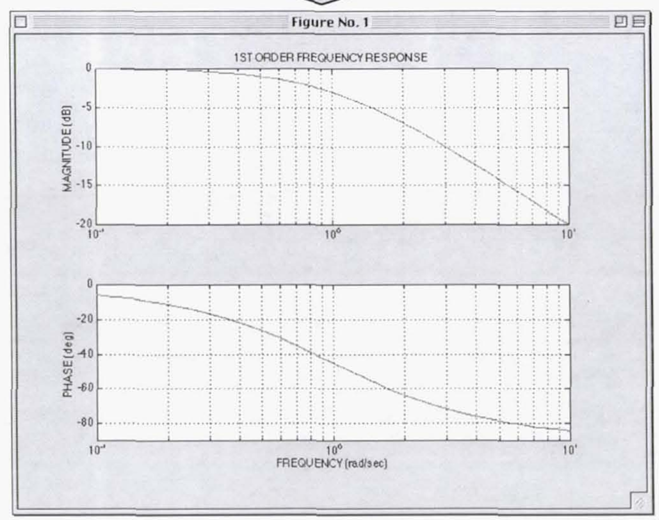
- *P+I and **ideal DI** cancellation leaves 1st order response*

P+I controller for each CV

$$\frac{CV}{CV_{cmd}} = \frac{K_B\cancel{\left(K_B+2s\right)}}{\left(K_B+2s\right)\cancel{\left(K_B+2s\right)}} = \frac{K_B}{K_B+2s} = \frac{\frac{K_B}{2}}{s+\frac{K_B}{2}}$$



- Dynamic inversion
- Control allocation
- OBAC
- Sensor processing
- CV



Design Gains

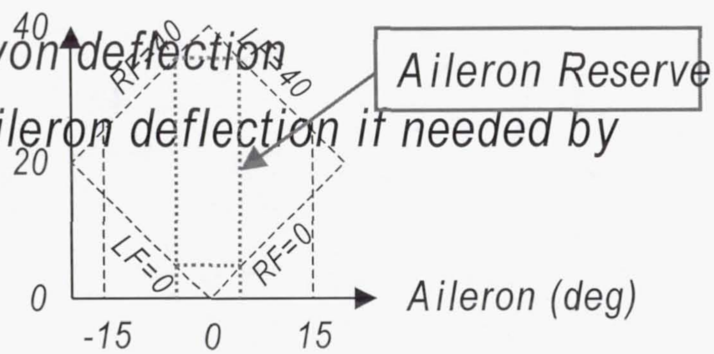
K_B = 2.0 rad/sec for LCV

K_B = 3.4 rad/sec for MCV

K_B = 2.0 rad/sec for NCV

4. Control Allocation

- *Optimally allocates control authority between effectors*
  - *Only when **shared surfaces** are on rate or position limits*
  - *Based upon preset axis priority weighting (NCV/LCV = 5)*
- *V132 shared flaps: elevon priority with aileron reserve*
  - *Pitch axis has first priority, i.e., elevon deflection*
  - *Reserves some flap deflection for aileron deflection if needed by aileron*
  - *Rate reserve is 50%*

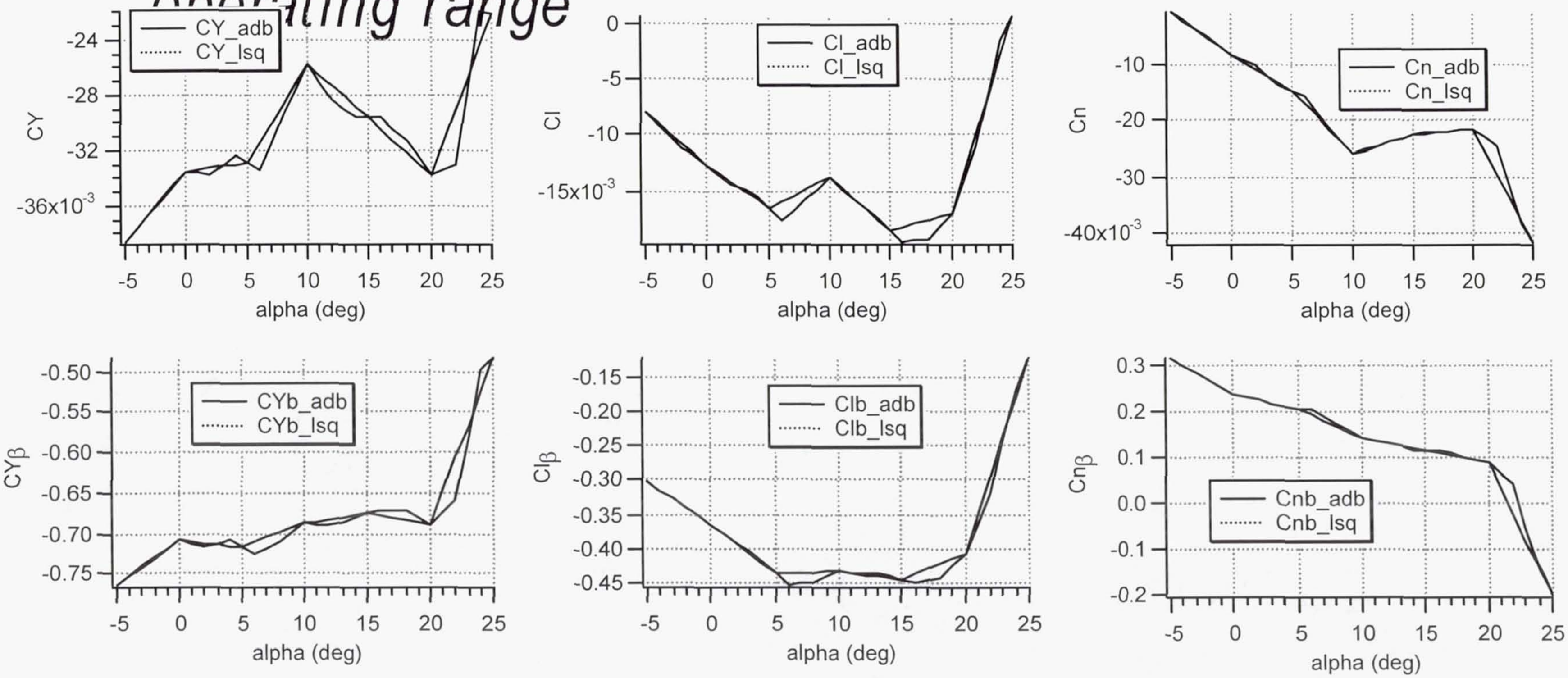


5. On-Board Aircraft Model

- *Full, nonlinear equations of motion on flight computer*
- *Least-squares fit of V132 aerodynamic database*
  - *Compact, fast aero model (175 values for V132)*
  - *Nonlinear in angle of attack (α)*
  - *Linear in angular rates (p, q, r) and aerosurface deflections ($_a$, $_e$, $_r$)*
  - *Constant in mach number (0.6) and trim elevon deflection (30°)*
- *Fit to aero uncertainty set #19, providing robustness to all other worst-on-worst, 5-σ aero uncertainty sets*
  - *Systematic method defined to select best uncertainty set for OBAC*

OBAC vs. Aero Database (ADB)

- *OBAC LSQ fit matches ADB well within operating range*



MACH Code

- *MACH design implemented in **ControlH** source code*
  - *ControlH is an internal Honeywell language*
  - *Will convert MACH from ControlH to MATLAB/MATRIXx*
- *Autocoded into standard C code using ControlH translator*
- *Integrated into GN&C simulation and flight code under strict control of ClearCase configuration management SW*

X-38 Test Vehicles

- *Subsonic test vehicles dropped from B-52*
  - *V131:* • *No FCS, 2 successful drop tests*
  - *V132:* • *FF1 & FF2 used classical, Shuttle-derived FCS*
    - *FF3 & FF4 will use MACH FCS*
    - *25 Hz Motorola 68040 CPU*
  - *V131R:* • *Same size as X-24, same aero as V201*
    - *Beginning integrated GN&C testing at JSC*
- *Orbital re-entry test vehicle "dropped" from Shuttle*
  - *V201:* • *OML is 120% V131R*
    - *Being built at JSC*
    - *Triple redundant avionics*
    - *50 Hz PowerPC CPU*

Why MACH for X-38 FCS?

- *X-38 has what MACH needs*
  - *Required sensors for full-state feedback*
  - *Modern flight computers for computational speed*
  - *Mission includes technology demonstration*
- *MACH has what X-38 needs*
  - *Versatility and speed of MACH design for multiple, similar vehicles*
    - *Similar vehicles*
      - *V132 & V131R have similar missions*
      - *V131R & V201 have same aerodynamic database*
    - *Design for entire V201 entry trajectory in months vs. years (Shuttle)*
  - *Lifting bodies' nonlinear, coupled, MIMO dynamics modeled in OBAC*
  - *Optimal allocation between shared control surfaces during B-52 transient*

V132 MACH Modifications

- *B-52 transient robustness modifications*
  - *Added aileron reserve => limit max elevon deflection when aileron is needed; give it back to elevon when not needed*
  - *NCV integral gain zero from t = 0 - 3 seconds after drop to avoid integrator wind-up while on surface limits*
- *Limits on qbar input to MCV for robustness to FADS failure*
- *Added wind velocity correction into OBAC EOM*
- *Computational speed enhancements...*

V132 MACH Speed Enhancement

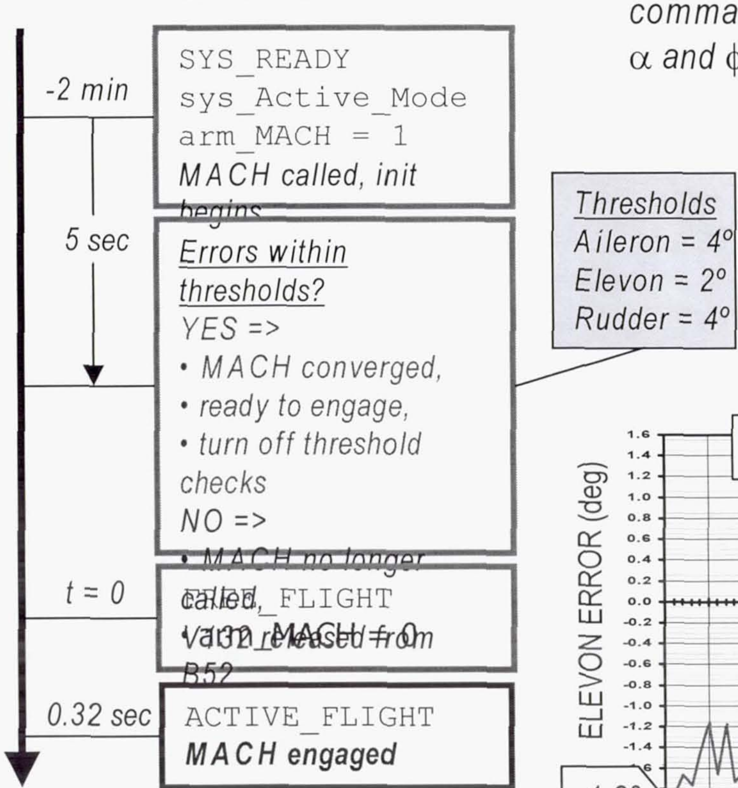
- *Speed enhancements to fit within 2-3 ms budget*
  - *Removed much of generalized, versatile MACH structure and computation*
  - *Shortened arrays, especially in control allocation routines*
  - *More efficient table lookups*
  - *Some trigonometric approximations*
  - *Removed ability to change design parameters at run-time*
  - *Removed ControlH autocode inefficiencies*
  - *Streamlined/customized optimal control allocation routines; limited iterations*
  - *"Inlined" functions in ControlH source code*
- *Reduced computation time from 10.4 to 2.3 ms out of 40 ms frame*
- *Negligible impact upon V132 FCS performance*

V132 Captive Carry Tests

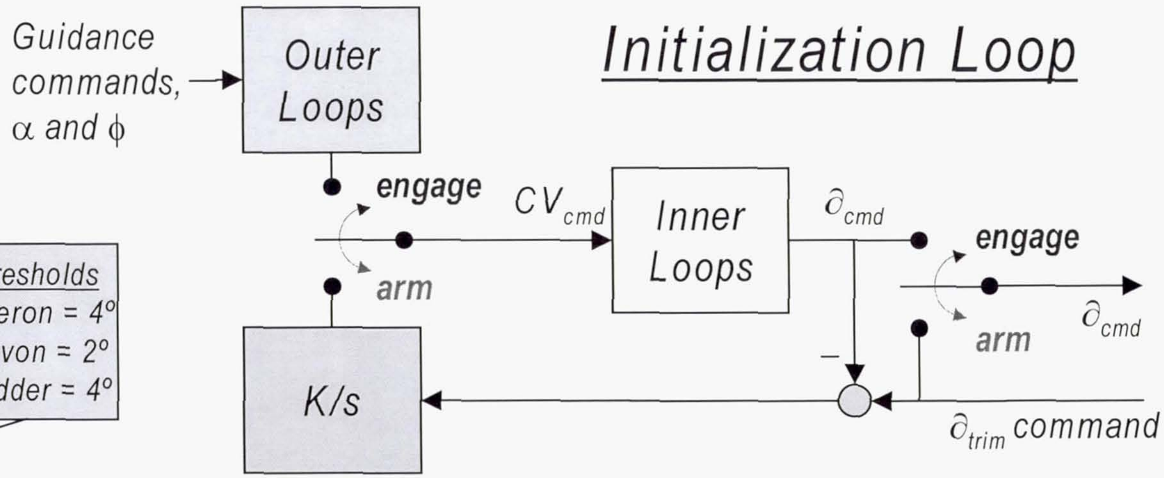
- *V132 carried aloft by B-52 but not released for free flight*
- *MACH tested in CC2, 12-Sep-99, & CC3, 18-Nov-99*
  - *Successful MACH initialization/convergence prior to engagement...*
    - *All commands converged to trim commands in less than 2 seconds*
    - *Remained converged despite B-52 pitch and roll maneuvers*
  - *Generally responded as expected to B-52 dynamics after "breakwire"*
    - *Breakwire => wires broken to signal vehicle it is free-flying*
    - *Aileron & elevon commands quickly saturated due to lack of roll/pitch response*
    - *Rudder command followed yaw rate oscillations*
    - *Uncovered minor flaw in aileron reserve logic*
      - *-2° aileron reserve instead of -4° as intended near zero elevon deflection*
      - *Flaw only near de = 0, not near de = 40° => CC issue => no impact to FF3*

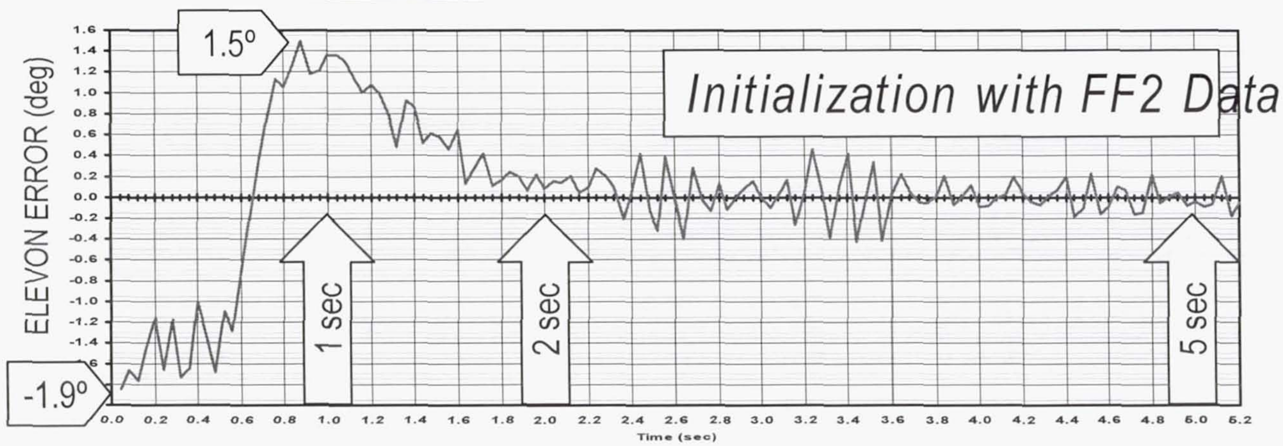
V132 MACH Initialization

Timeline

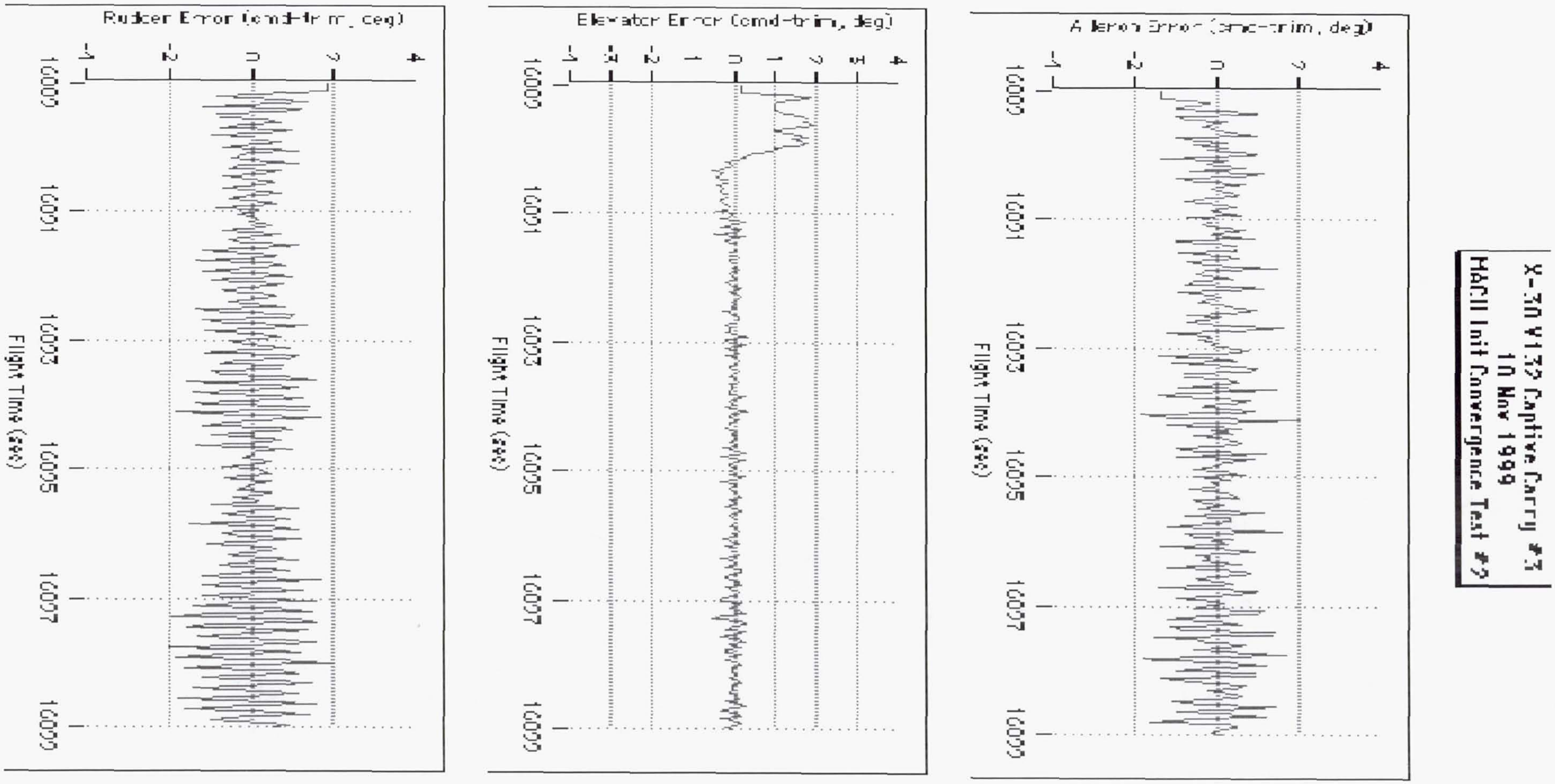


Initialization Loop

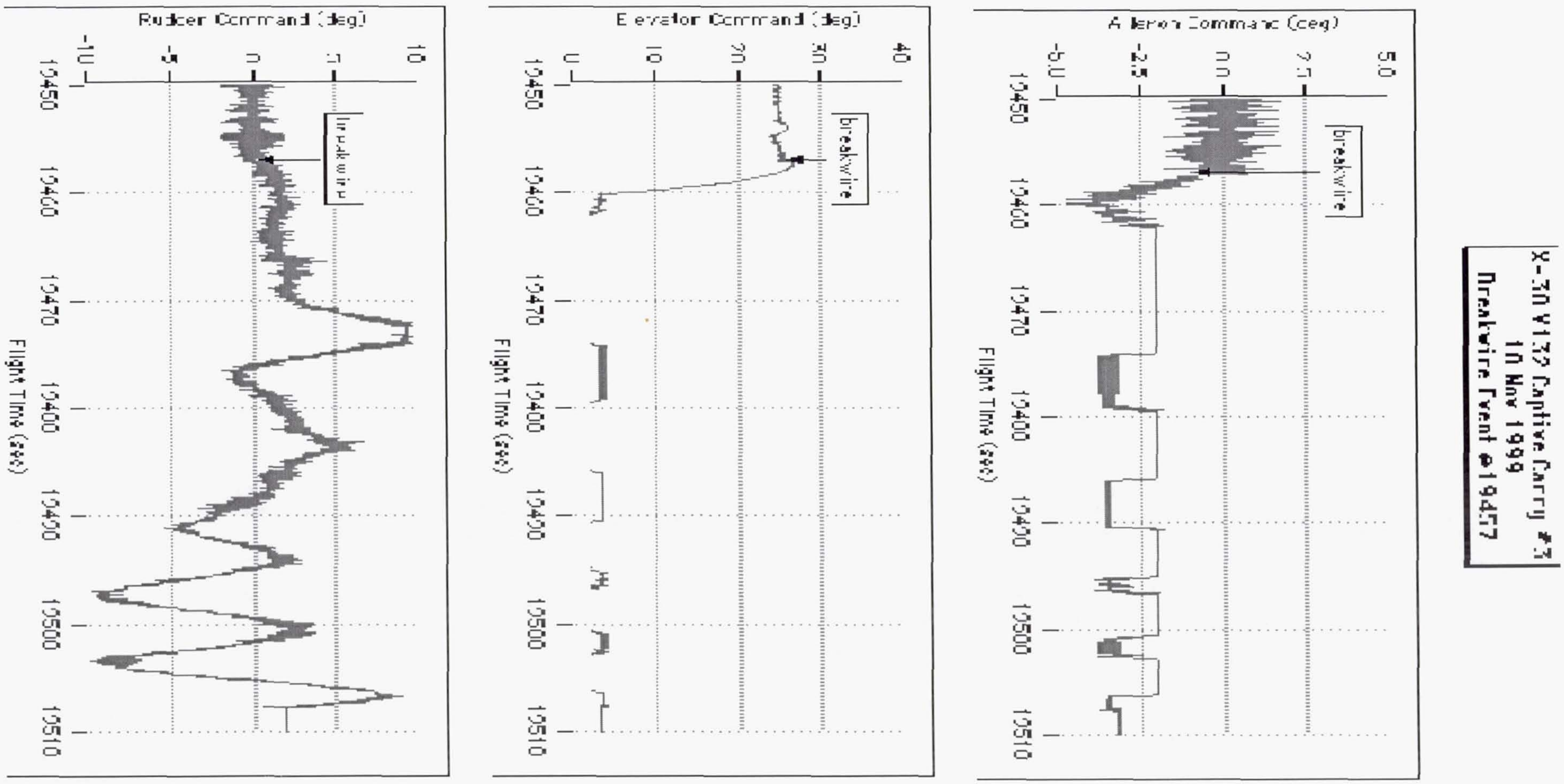




V132 CC3 MACH Initialization

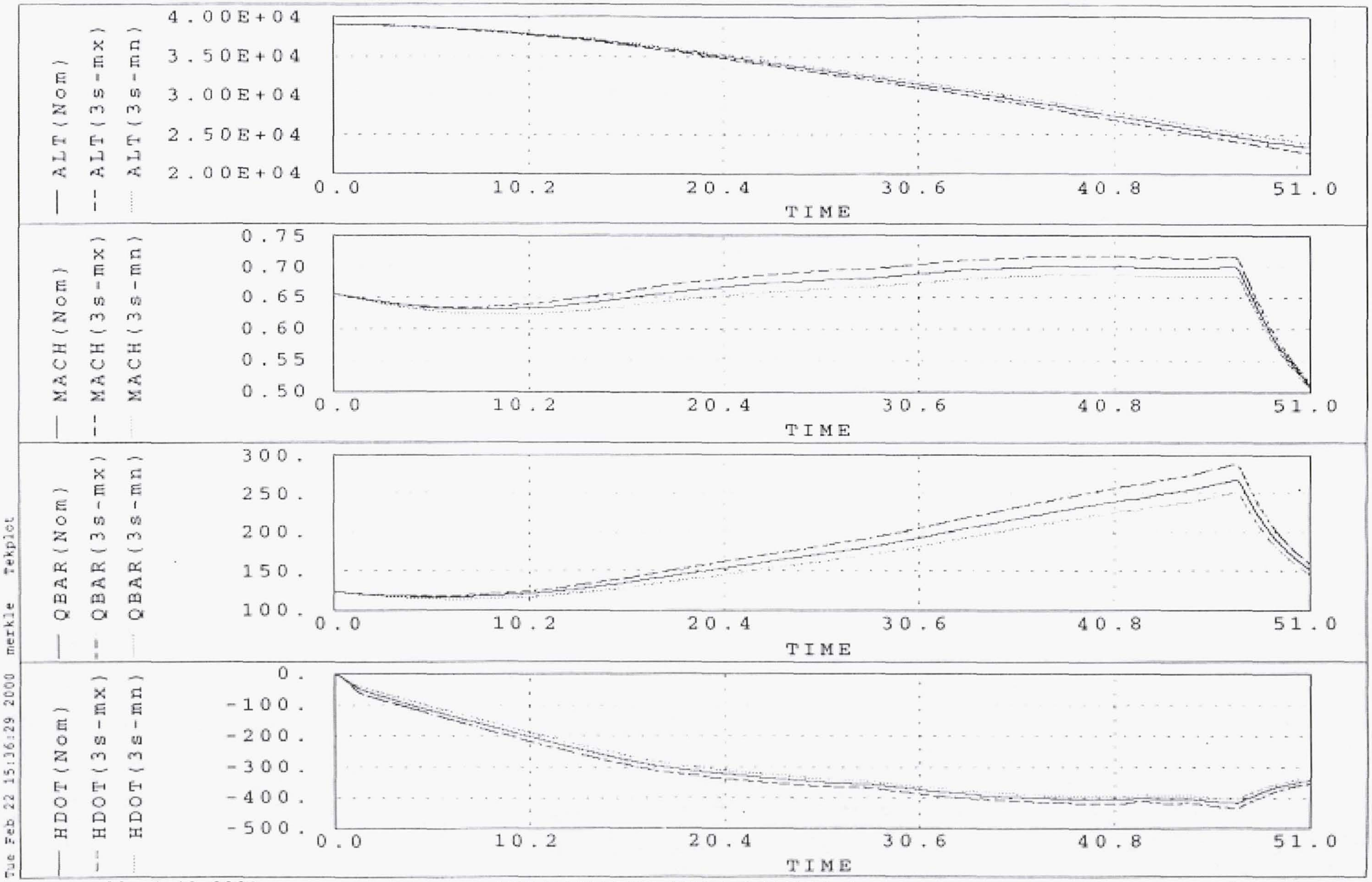


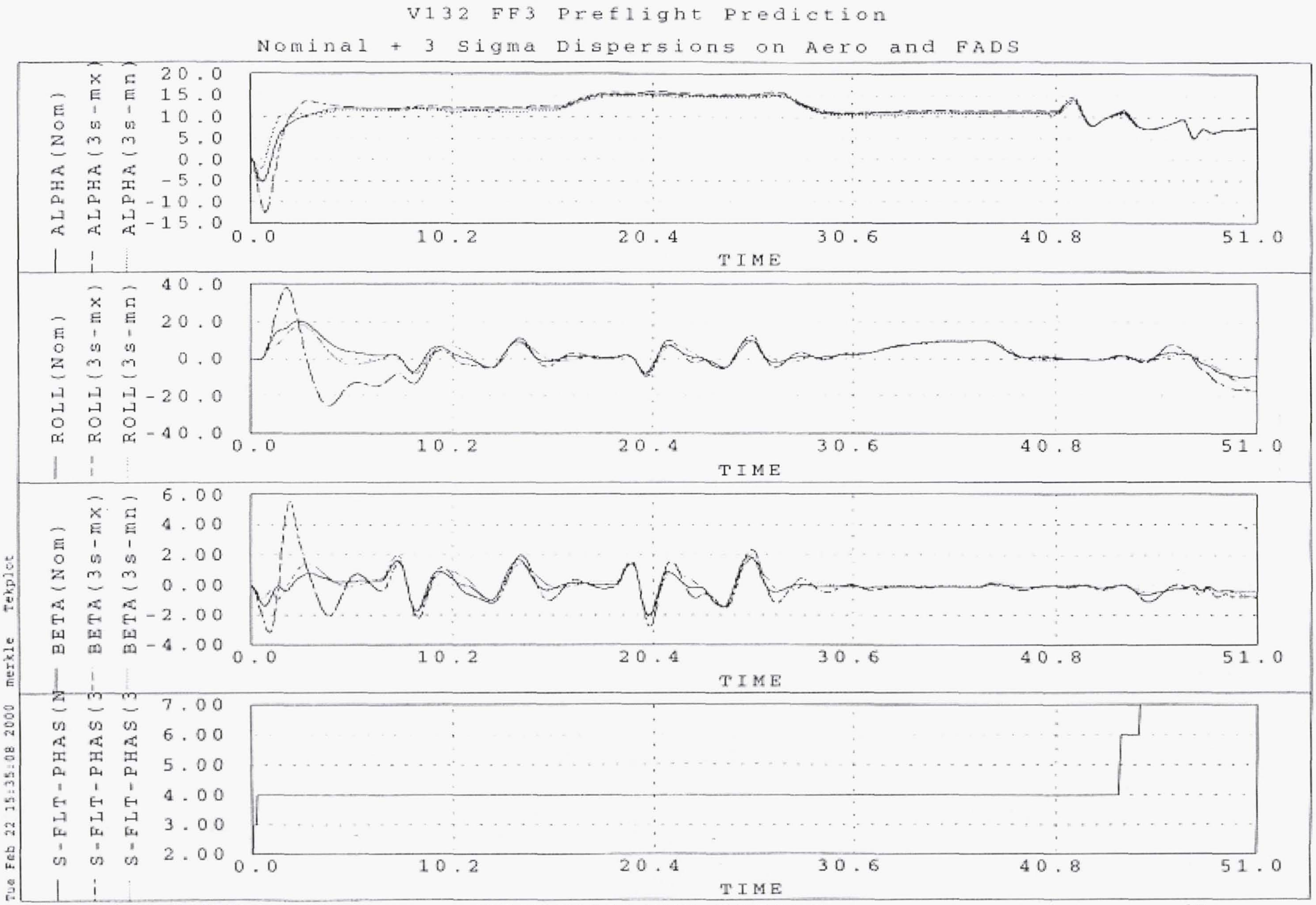
V132 CC3 Breakwire Event

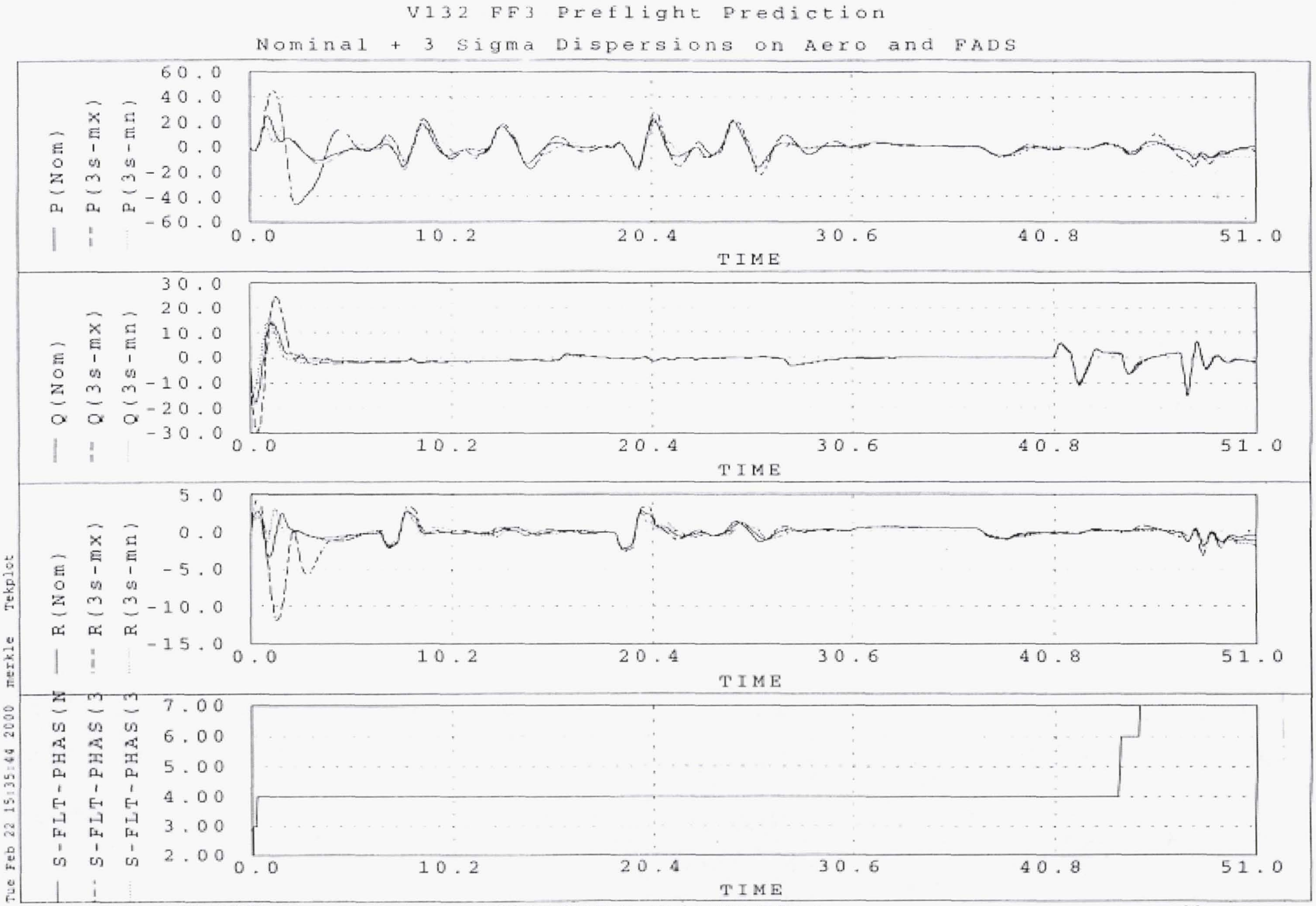


V132 FF3 Preflight Prediction

Nominal + 3 Sigma Dispersions on Aero and FADS




V132 FF3 Preflight Prediction
Nominal + 3 Sigma Dispersions on Aero and FADS
ALPHA(Nom)
ALPHA(3s-mx)
ALPHA(3s-mn)
ROLL(Nom)
ROLL(3s-mx)
ROLL(3s-mn)
BETA(Nom)
BETA(3s-mx)
BETA(3s-mn)
S-FLT-PHAS(N
S-FLT-PHAS(3
S-FLT-PHAS(3
TIME
Tue Feb 22 15:35:08 2000 merkle Tekplot



V132 FF3 Preflight Prediction
Nominal + 3 Sigma Dispersions on Aero and FADS
P(Nom)
P(3s-mx)
P(3s-mn)
Q(Nom)
Q(3s-mx)
Q(3s-mn)
R(Nom)
R(3s-mx)
R(3s-mn)
S-FLT-PHAS(N
S-FLT-PHAS(3
S-FLT-PHAS(3
TIME
0.0
10.2
20.4
30.6
40.8
51.0
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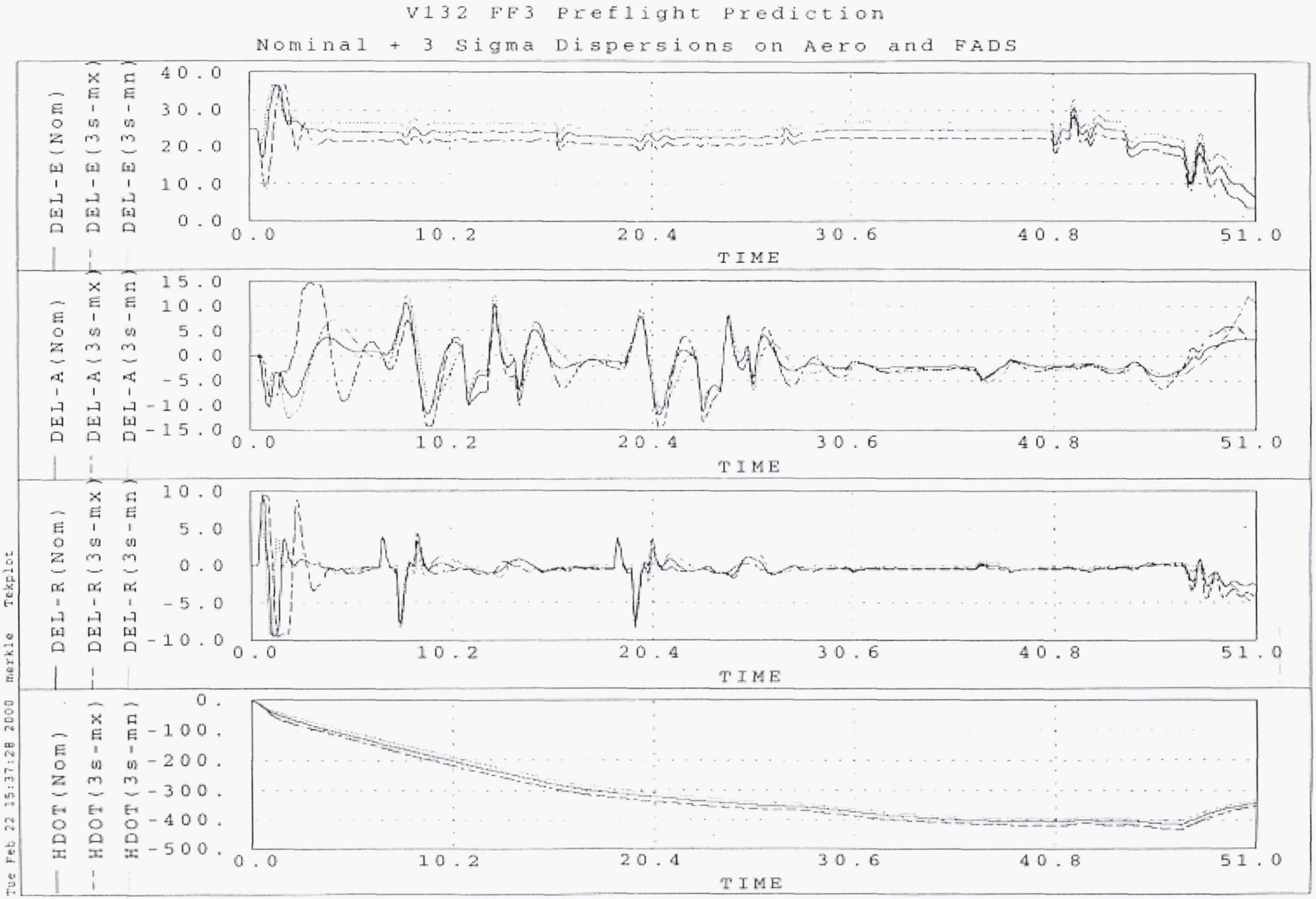

V132 FF3 Preflight Prediction
Nominal + 3 Sigma Dispersions on Aero and FADS
DEL-E(Nom)
DEL-E(3s-mx)
DEL-E(3s-mn)
DEL-A(Nom)
DEL-A(3s-mx)
DEL-A(3s-mn)
DEL-R(Nom)
DEL-R(3s-mx)
DEL-R(3s-mn)
HDOT(Nom)
HDOT(3s-mx)
HDOT(3s-mn)
TIME
0.0
10.2
20.4
30.6
40.8
51.0
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V131R & V201 MACH Status

- *V131R MACH flying in simulation*
  - *V132 MACH with V131R OBAC model*
  - *Follows active guidance instead of open-loop alpha profile*
- *V201 MACH flying in simulation, full re-entry down to drogue deployment*
  - *Based upon "off the shelf", generalized MACH, not customized V132 MACH*
  - *Added ACS jet torques to OBAC model*
  - *Different modes & CVs along re-entry trajectory*
    - *ACS jets only at qbar < 2 psf*
    - *Blended jets and flaps for 2 < qbar < 30 psf*
    - *Flaps only at qbar > 30 psf and M > 6 => LCV & NCV combined into one CV => 2 CV's & 2 controls*
    - *Flaps and rudders at M < 6 => back to 3 CV's & 3 controls*
    - *Rudder only during aileron reversal (exact onset unknown) at mach numbers near transonic*
  - *Not yet known if speed enhancements will be required on Motorola*