Title: Neural Net Safety Monitor Design
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Abstract

The National Aeronautics and Space Administration (NASA) at the Dryden Flight Research Center (DFRC) has been conducting flight-test research using an F-15 aircraft (figure 1). This aircraft has been specially modified to interface a neural net (NN) controller as part of a single-string Airborne Research Test System (ARTS) computer with the existing quad-redundant flight control system (FCC) shown in figure 2. The NN commands are passed to FCC channels 2 and 4 and are cross channel data linked (CCDL) to the other computers as shown. Numerous types of fault-detection monitors exist in the FCC when the NN mode is engaged; these monitors would cause an automatic disengagement of the NN in the event of a triggering fault. Unfortunately, these monitors still may not prevent a possible NN hard-over command from coming through to the control laws. Therefore, an additional and unique safety monitor was designed for a single-string source that allows authority at maximum actuator rates but protects the pilot and structural loads against excessive g-limits in the case of a NN hard-over command input. This additional monitor resides in the FCCs and is executed before the control laws are computed.

This presentation describes a "floating limiter" (FL) concept[1] that was developed and successfully test-flown for this program (figure 3). The FL computes the rate of change of the NN commands that are input to the FCC from the ARTS. A window is created with upper and lower boundaries, which is constantly "floating" and trying to stay centered as the NN command rates are changing. The limiter works by only allowing the window to move at a much slower rate than those of the NN commands. Anywhere within the window, however, full rates are allowed. If a rate persists in one direction, it will eventually "hit" the boundary and be rate-limited to the floating limiter rate. When this happens, a persistent counter begins and after a limit is reached, a NN disengage command is generated. The tunable metrics for the FL are (1) window size, (2) drift rate, and (3) persistence counter. Ultimate range limits are also included in case the NN command should drift slowly to a limit value that would cause the FL to be defeated.

The FL has proven to work as intended. Both high-g transients and excessive structural loads are controlled with NN hard-over commands. This presentation discusses the FL design features and presents test cases. Simulation runs are included to illustrate the dramatic improvement made to the control of NN hard-over effects. A mission control room display from a flight playback is presented to illustrate the neural net fault display representation. The FL is very adaptable to various requirements and is independent of flight condition. It should be considered as a cost-effective safety monitor to control single-string inputs in general.

[1] "Design of Safety Monitor Schemes for a Fault Tolerant Flight Control System," IEEE Transactions on Aerospace and Electronic Systems Vol. 42, No. 2, April 2006.

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Figure 1 – F15 Intelligent Flight Control System Test Bed Aircraft

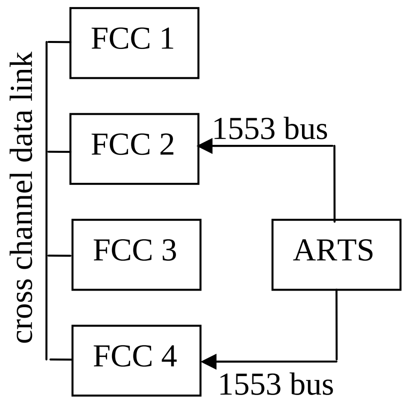

Figure 2 – Neural Net Controller Architecture with Flight Control Computers

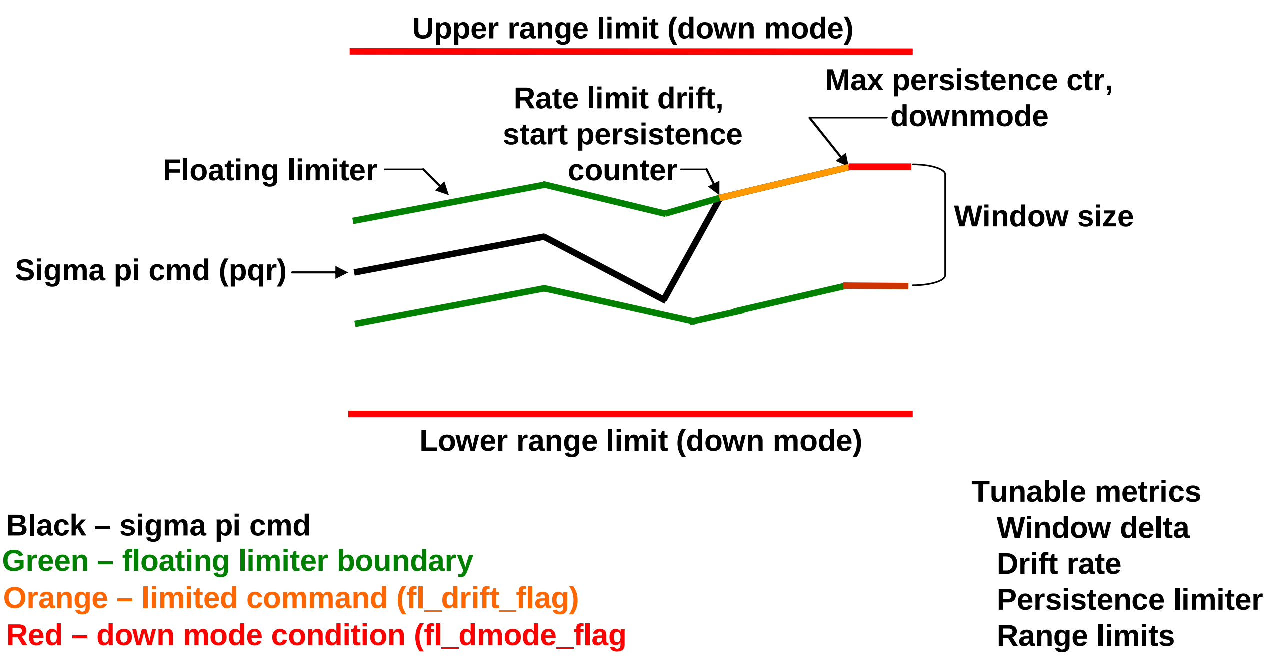

Figure 3 – Floating Limiter Features

Neural Net Safety Monitor Design

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Conference and Exhibit

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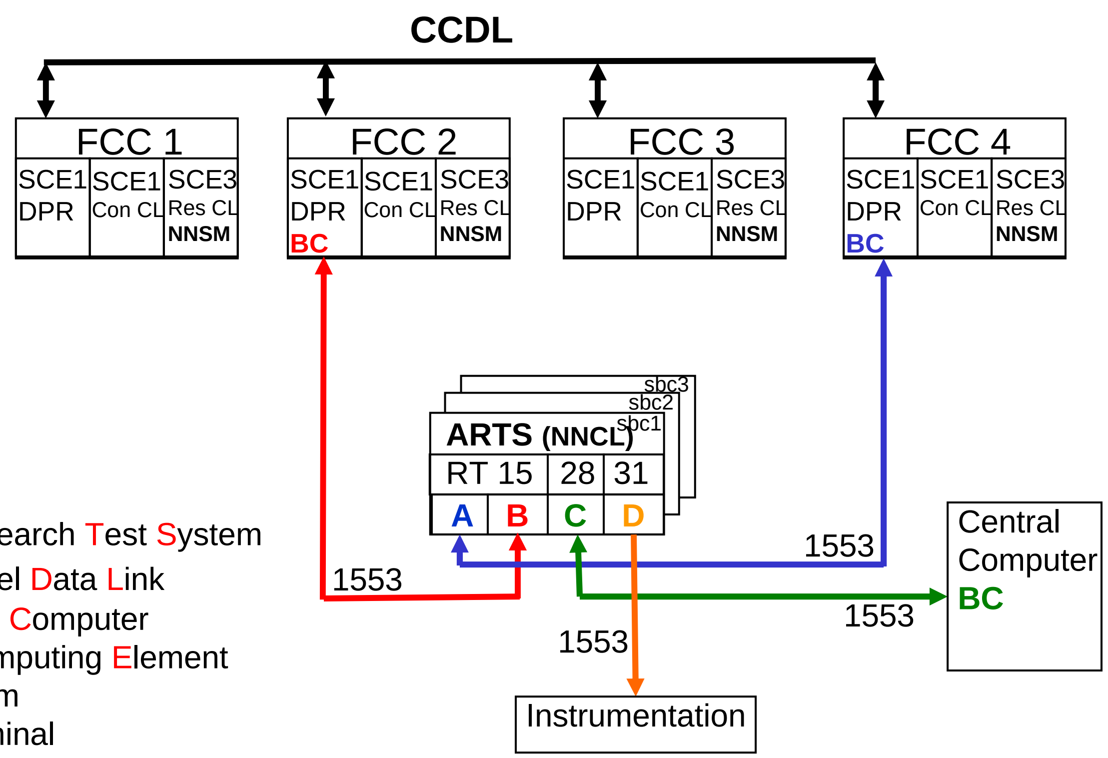
Overview

- Requirements
- Neural net interfaces
- Design approach
- Review of existing safety monitors
- New safety monitor developed
- Testing
- A surprise
- Flight data display playback
- Summary

Requirements

- **Interface neural net controller with F15 enhanced control laws for flight test experiment**
  - **Flight conditions: 0.75M/20Kft, and 0.90M/25Kft**
  - **Maximum transients: $\pm$ 2g vertical, $\pm$ 0.5g lateral**
  - **Maneuvers: Straight & level, 3g wind-up-turn (WUT), simulated stabilator/canard failures, loads maneuvers; all maneuvers include pitch/roll/yaw (pqr) doublets**
- **Ground Rules/Constraints**
  - **Protect from exceeding any aircraft structural load limits**
  - **Avoid departure from controlled flight**
  - **Neural net commands shall support full control surface authority at maximum actuator rates**
  - **Minimize nuisance disengagements**

Neural Net Interfaces

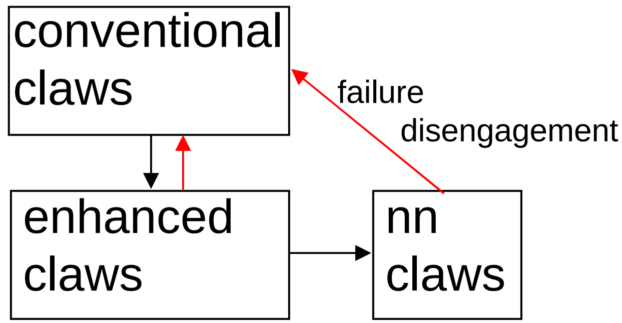


Legend

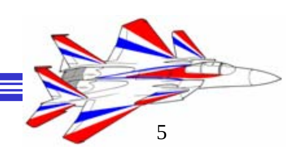
ARTS	Airborne Research Test System
CCDL	Cross Channel Data Link
FCC	Flight Control Computer
SCE	Standard Computing Element
DPR	Dual Port Ram
RT	Remote Terminal
BC	Bus Controller
NNCL	Neural Net Control Laws
NNSM	Neural Net Safety Monitor
SBC	Single Board Computer

Design Approach

- **Specific Aircraft faults which occur while in neural net mode will cause a downmode to conventional mode with a 1 sec fader**



- **Safety monitors are executed in SCE3 at 80hz**
- **Disengagement triggers are instrumented and latched for analysis**
- **All validation testing is done using hardware in the loop closed loop simulation**



Overview of Existing Safety Monitors

- **Flight Computer Faults**
  - Single failure of any dual channel signal
  - Dual failure of any quad channel signal
  - FC Configuration fault (Config fail)
  - Channel fail
  - BLIN (Bit Level Inspect) code
  - PAL (Pick-a-Limit) Violation

FC PAL limits

Parameter	Envelope #1		Envelope #2	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Angle of Attack	-4.0 deg	12.0 deg	-4.0 deg	12.0 deg
Sideslip Angle	-5.0 deg	5.0 deg	-5.0 deg	5.0 deg
Pitch Angle	-180 deg	180 deg	-180 deg	180 deg
Bank Angle	-90 deg	90 deg	-180 deg	180 deg
Pitch Rate	-45 deg/sec	45 deg/sec	-60 deg/sec	60 deg/sec
Roll Rate	-75 deg/sec	75 deg/sec	-300 deg/sec	300 deg/sec
Yaw Rate	-15 deg/sec	15 deg/sec	-60 deg/sec	60 deg/sec
Normal Acceleration	0.0 g	3.0 g	-1.0 g	6.0 g
Lateral Acceleration	-0.5 g	0.5 g	-1.0 g	1.0 g
Mach	0.55	0.95	0.55	0.95
Qbar	253 psf	733 psf	253 psf	733 psf
Altitude	15000 ft	35000 ft	15000 ft	35000 ft
Pitch Stick	-3.1 in	5.46 in	-3.1 in	5.46 in
Roll Stick	-4.0 in	4.0 in	-4.0 in	4.0 in
Yaw Pedal	-3.25 in	3.25 in	-3.25 in	3.25 in
Throttle (PLA)	16.5 deg	130 deg	16.5 deg	130 deg

FC Configuration Faults

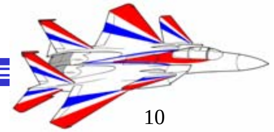
1. Lt Throttle Within PAL Limits
2. Rt Throttle Within PAL Limits
3. Flaps in Correct PAL Mode
4. Landing Gear in Correct PAL Mode
5. Throttle Switch in Correct PAL Mode
6. Spin Switch in Correct PAL Mode
7. Weight-On-Wheels in Correct PAL Mode
8. Qbar Limit Exceeded
9. Aircraft Not At Trim (pitch/bank monitor)

ARTS II Fault Monitors

- **Built in Test Failures**
  - **failure detected through Periodic Bit (PBIT)**
  - **failure detected through Power Up Bit (PUBIT)**
- **Multibit ECC (error code correction) Memory Errors (ARTS-II will log the event and transition to FAILED)**
- **1553 Communications Failure**
  - **1553 Wrap Word Failure**
- **ARTS Neural Net (Sigma Pi) Failures**
  - **failure to initialize data recording**
  - **failure to register experiment with Executive**
  - **failure to receive data from SBC 1 (VXMP failure)**
  - **failure to send data to SBC 1 (VXMP failure)**

ARTS II Fault Monitors
(Continued)

- **Executive Failures:**
  - failure to detect correct checksum
  - failure to receive data from Sigma Pi on SBC 2 (VXMP failure)
  - failure to send data to SBC 2 (VXMP failure)
  - The system monitor (SYSMON) task detects a problem with any other task such as failure to initialize or abnormal termination
  - SBC board boot failure
- **Analog Failures:**
  - analog card fails to load driver
  - analog card fails to calibrate
- **Any disk I/O errors**



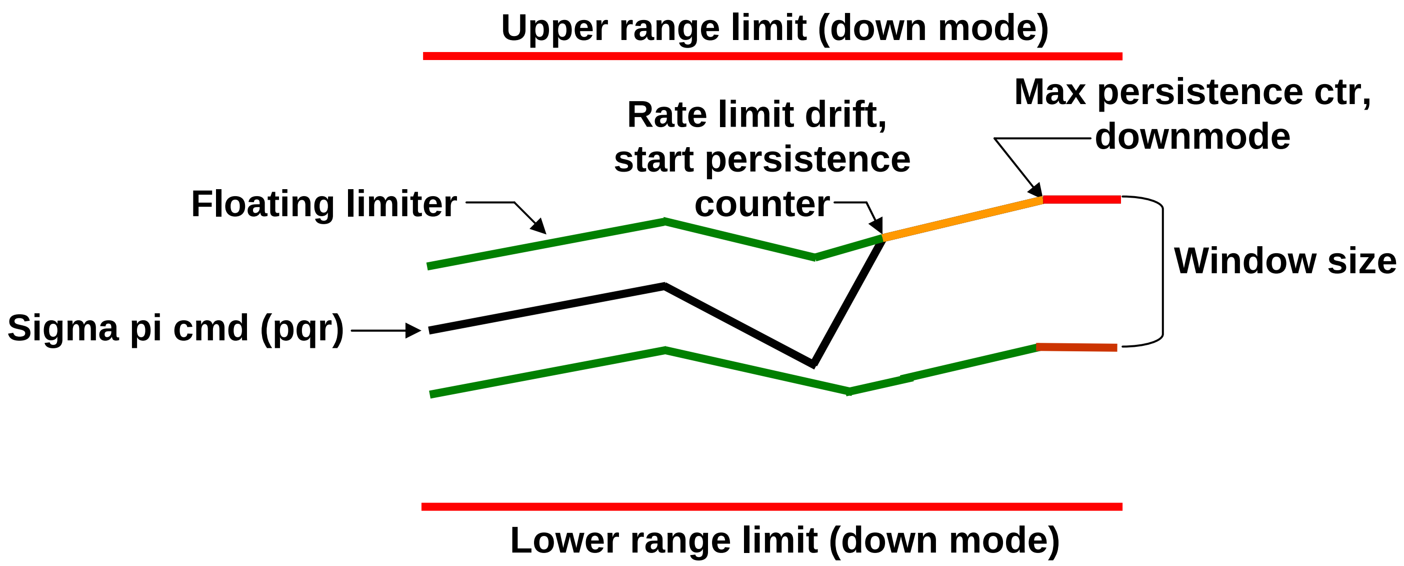
Structural Safety Monitoring

- **Added strain gages to aircraft for loads measurements**
- **Converted existing loads model from FORTRAN to ADA, but memory size too large and execution time too long to fit in 80hz frame cycle in SCE3**
- **Existing loads model was not validated**
- **No confidence that existing fault monitors would prevent a Neural Net hardover from exceeding aircraft G and structural load limits**
- **Conclusion was a new safety monitor was needed**
  - **A Floating Limiter Design was developed**

Floating Limiter Design

- **Apply floating limiter windows for the sigma pi (neural net) commands (P,Q,R)**
- **Maximum rate of change is allowed within the window**
- **Limit the rate of change while on the floating limiter boundary**
- **Allow full authority up to the range limiter**
- **Provide flags to sigma pi to stop learning**

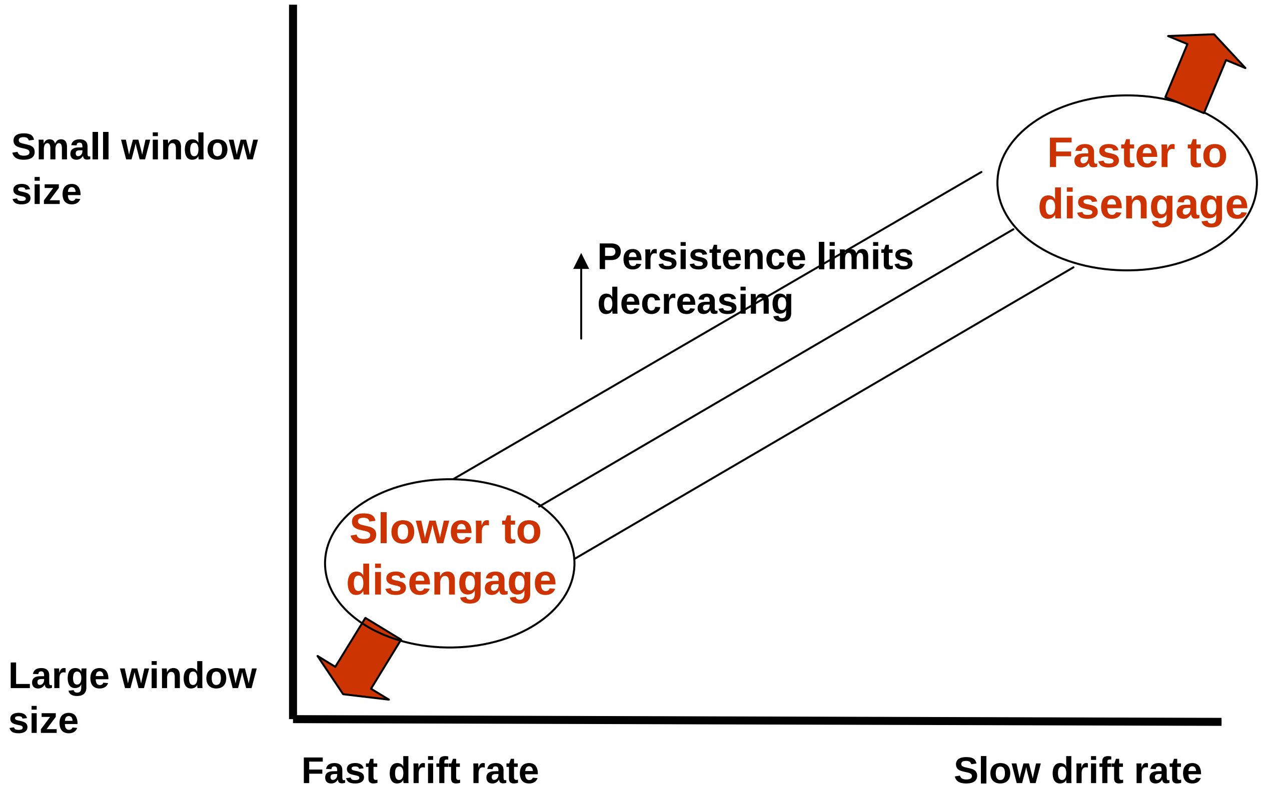
NN Floating Limiter



Black – sigma pi cmd
Green – floating limiter boundary
Orange – limited command (fl_drift_flag)
Red – down mode condition (fl_dmode_flag

Tunable metrics
- **Window delta**
- **Drift rate**
- **Persistence limiter**
- **Range limits**

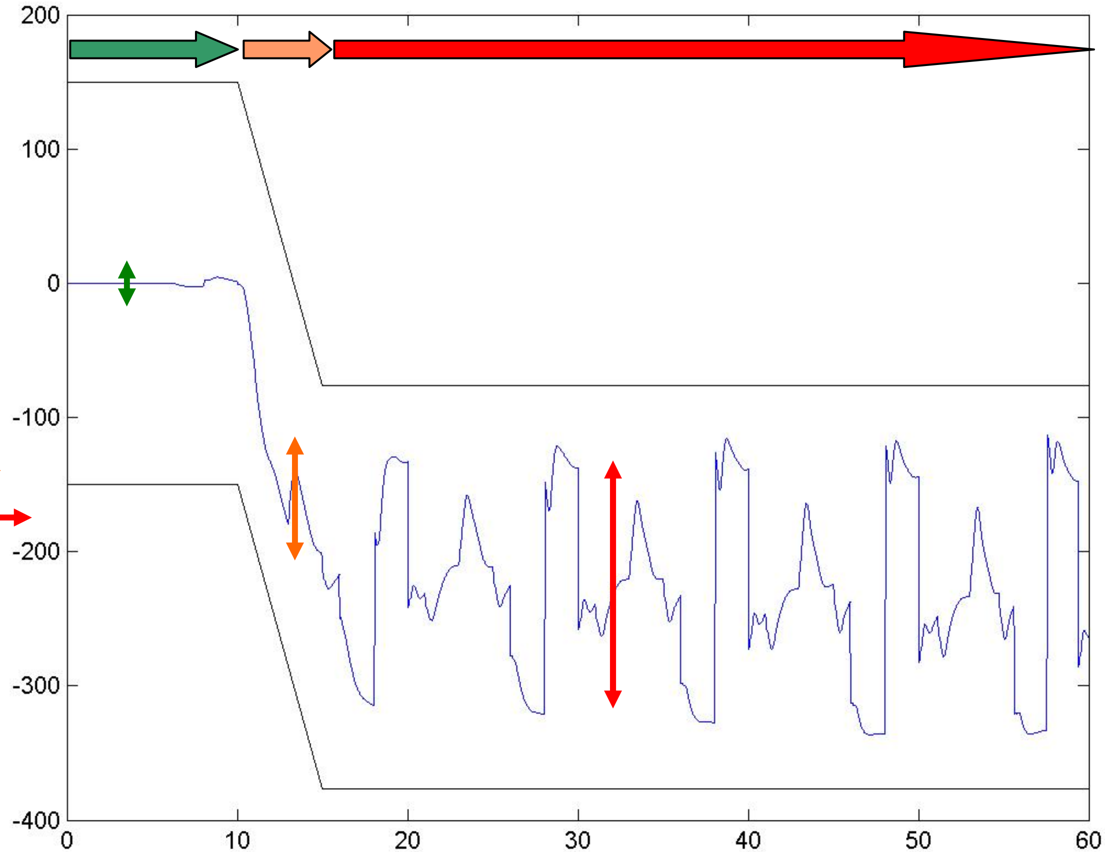
Floating Limiter Metrics



Floating Limiter Regions

Initial; no fail
Transition
Final; after fail

Slow drift
Moderate drift
Fast drift



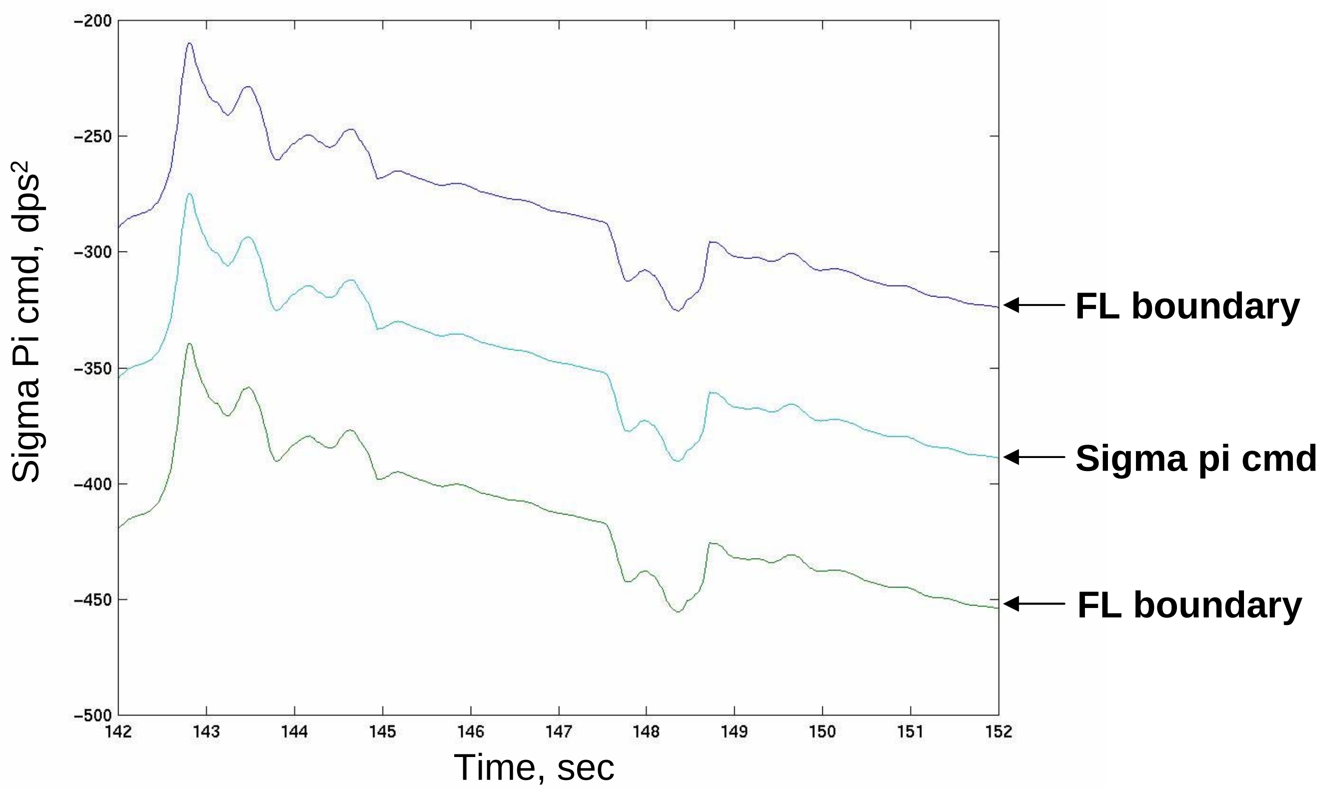
Simulation Testing

- **Flight conditions (2 design points)**
  - **.75M/20Kft**
  - **.90M/25Kft (worst case)**
- **Maneuvers**
  - **Straight & level with pqr doublets**
  - **3g WUT with pqr doublets**
  - **Simulated failures**
    - **Straight & level with pqr doublets**
    - **3g WUT with pqr doublets**
  - **Loads maneuvers**

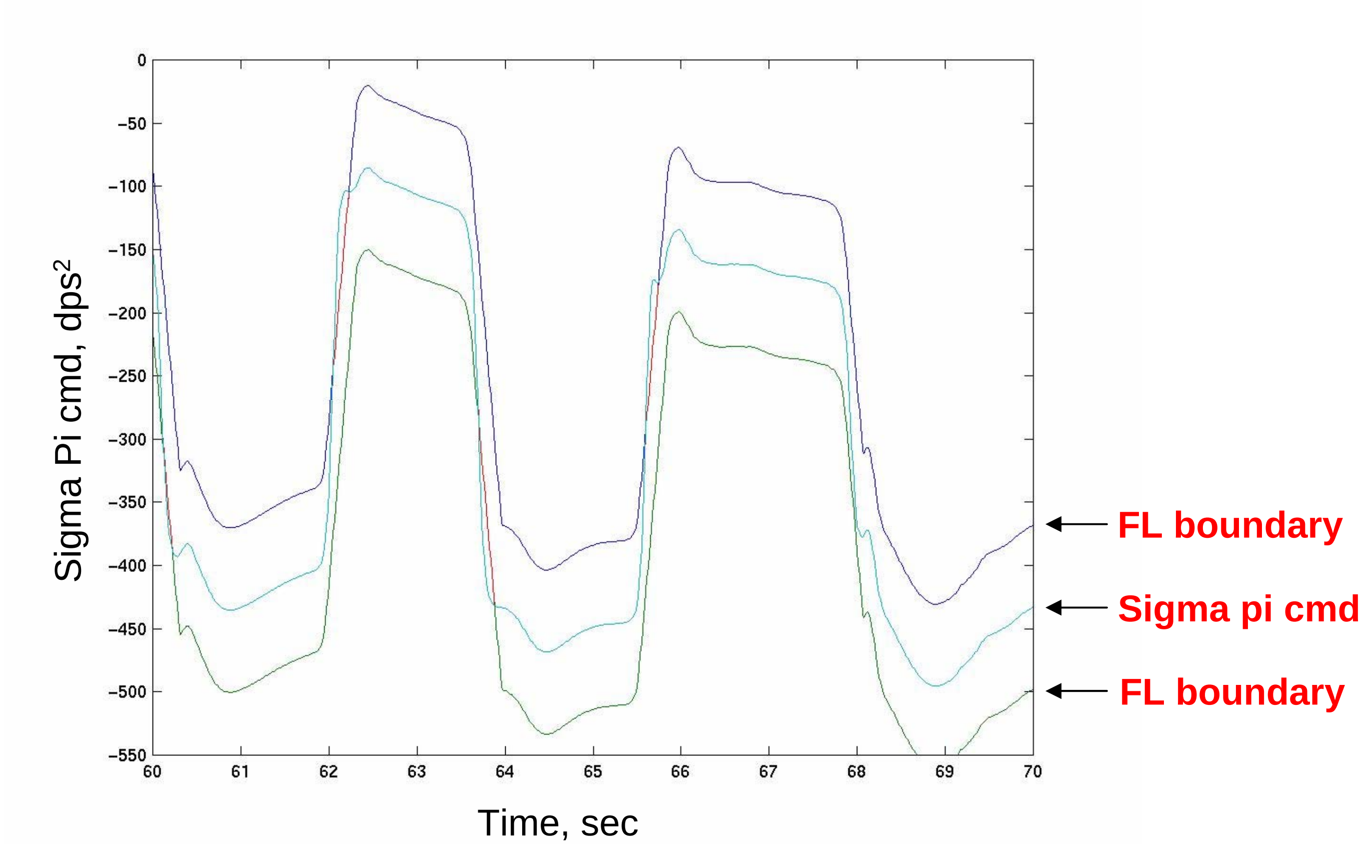
Software Testing Maneuvers

Bank angle captures (60 deg)
P doublets
Q doublets
R doubles
Stab fails; 0 from trim
Stab fails; +2 from trim
Stab fails; -2 from trim
Stab fails; +4 from trim
Stab fails; -4 from trim
Stab fails; +4 from trim with p doublet
Stab fails; +4 from trim with q doublet
Stab fails; +4 from trim with r doublet
Sigma Pi hardover from trim; +p no fail
Sigma Pi hardover from trim; -p no fail
Sigma Pi hardover from trim; +q no fail
Sigma Pi hardover from trim; -q no fail
Sigma Pi hardover from trim; +r no fail
Sigma Pi hardover from trim; -r no fail
Sigma Pi hardover from trim; +p, 4 deg fail
Sigma Pi hardover from trim; -p, 4 deg fail
Sigma Pi hardover from trim; +q, 4 deg fail
Sigma Pi hardover from trim; -q, 4 deg fail
Sigma Pi hardover from trim; +r, 4 deg fail
Sigma Pi hardover from trim; -r, 4 deg fail
Sigma Pi hardover from 3g WUT; +p, 4 deg fail
Sigma Pi hardover from 3g WUT; -p, 4 deg fail
Sigma Pi hardover from 3g WUT; +q, 4 deg fail
Sigma Pi hardover from 3g WUT; -q, 4 deg fail
Sigma Pi hardover from 3g WUT; +r, 4 deg fail
Sigma Pi hardover from 3g WUT; -r, 4 deg fail
Roll doublet in 3g WUT
Pitch doublet in 3g WUT
Yaw doublet in 3g WUT

Within floating limiter: no rate limiting

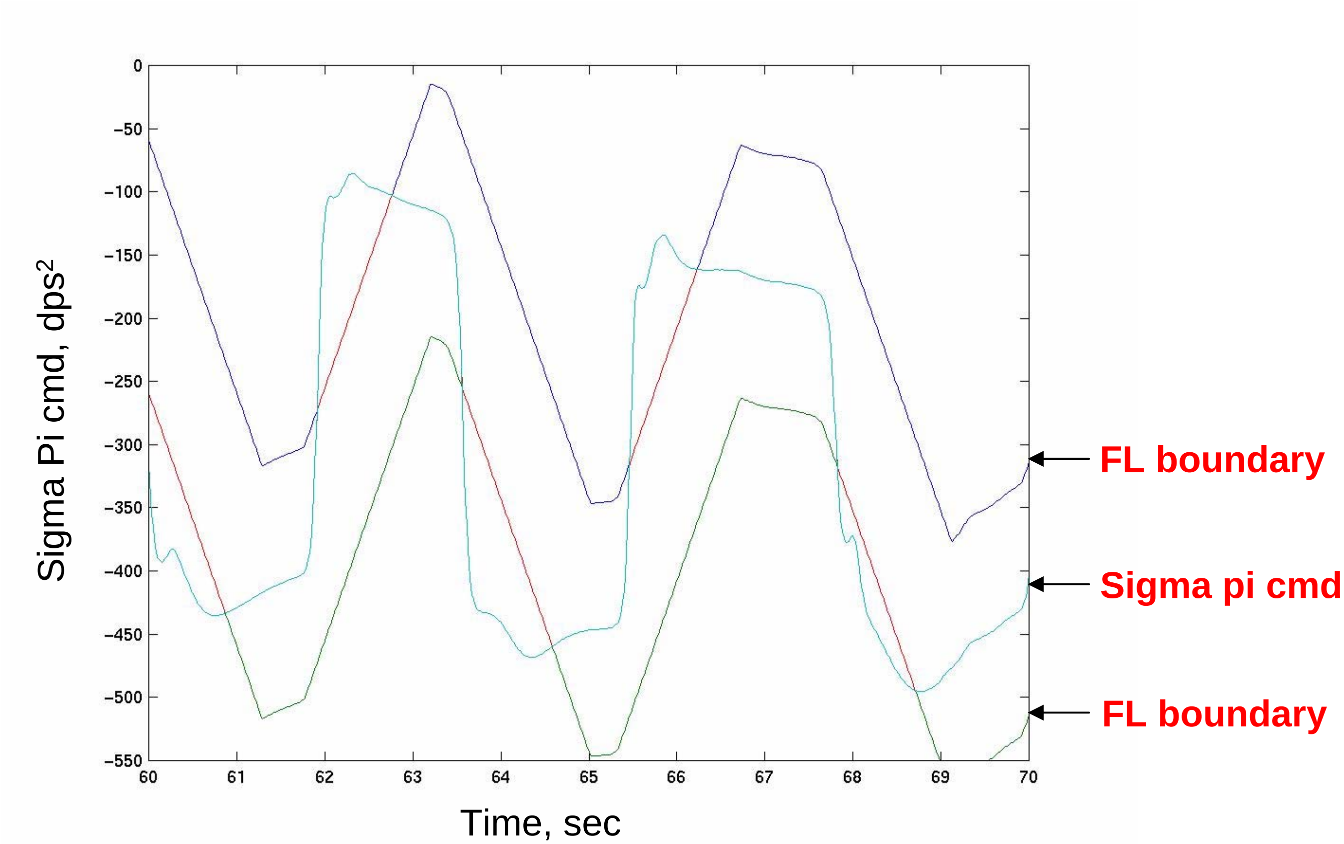


Outside floating limiter: Minor Rate Limiting



Red indicates rate limit

Outside floating limiter: Moderate Rate Limiting



Red indicates rate limit

Floating Limiter Constants

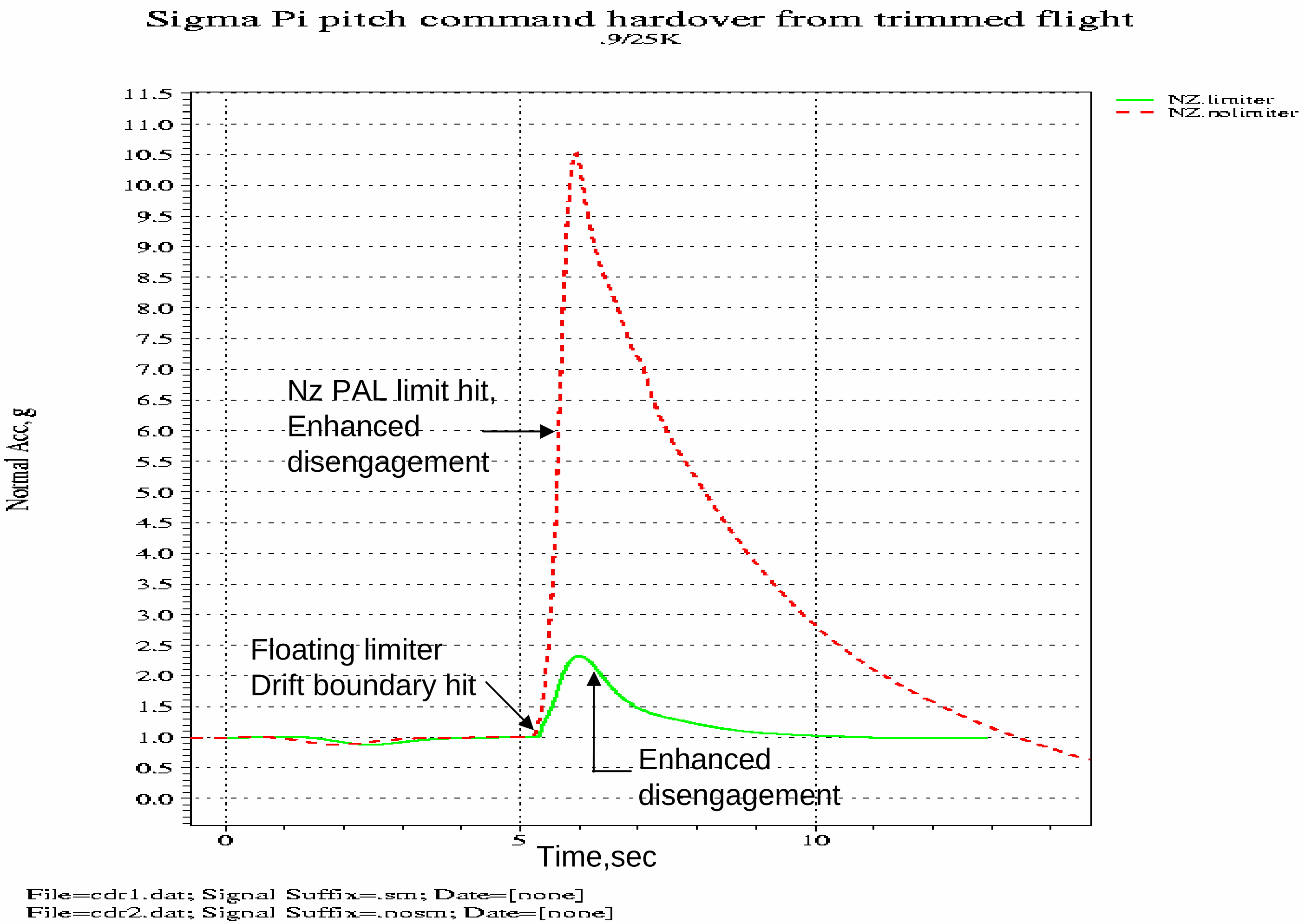
Rt Stab Failure from Trim *fl_drift_table_conf_file*	P axis	Q axis	R axis
0 deg, dps^3			
Transition	150	50	0.03
Final	500	90	0.01
+2 deg, dps^3			
Transition	230	60	0.03
Final	700	60	0.02
+4 deg, dps^3			
Transition	430	60	0.03
Final	850	60	0.02
-2 deg, dps^3			
Transition	230	60	0.03
Final	525	60	0.09
-4 deg, dps^3			
Transition	430	60	0.03
Final	550	60	0.09

Canard AOA fails	P axis	Q axis	R axis
Set 1; dps^3			
Transition	100	1	0.03
Final	100	1	0.03
Set 2; dps^3			
Transition	100	20	0.03
Final	100	20	0.03
Metrics			
Initial drift, dps^3	1.0	1.0	0.01
Delta, dps^2	200	52	0.10
Range limit, dps^2	1000	500	0.10
Persistence time, sec	0.75	1.25	0.75
Transition time, sec	3		

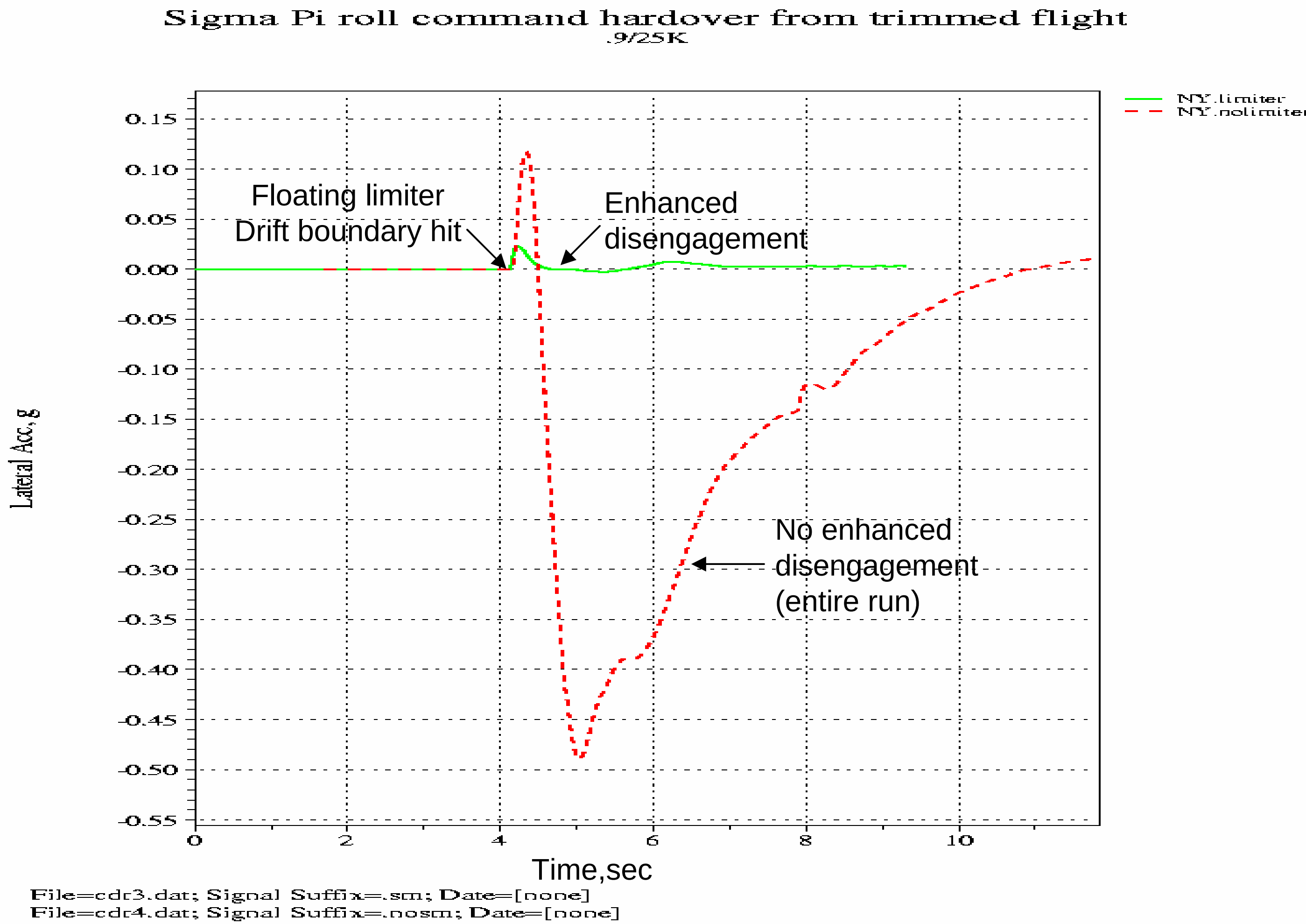
Floating Limiter Outputs

Parameter	Description	Units	Bus	RT	SA	W	Bit
fl_dmode_flag (0), p	fl_plim_flag(0) or fl_hrange_flag(0)	bit	FC	15	2	25	00
fl_dmode_flag (1), q	fl_plim_flag(1) or fl_hrange_flag(1)	bit	FC	15	2	25	01
fl_dmode_flag (2), r	fl_plim_flag(2) or fl_hrange_flag(2)	bit	FC	15	2	25	02
fl_drift_flag (0), p	NN cmd (p) is limited	bit	FC	15	2	25	03
fl_drift_flag (1), q	NN cmd (q) is limited	bit	FC	15	2	25	04
fl_drift_flag (2), r	NN cmd (r) is limited	bit	FC	15	2	25	05
fl_plim_flag (0) p	persistence ctr (p) is max – downmode	bit	FC	15	3	2	10
fl_plim_flag (1) q	persistence ctr (q) is max – downmode	bit	FC	15	3	2	11
fl_plim_flag (2) r	persistence ctr (r) is max – downmode	bit	FC	15	3	2	12
fl_hrange_flag (0), p	NN cmd (p) is at hard range limit - downmode	bit	FC	15	3	2	13
fl_hrange_flag (1), q	NN cmd (q) is at hard range limit - downmode	bit	FC	15	3	2	14
fl_hrange_flag (2), r	NN cmd (r) is at hard range limit - downmode	bit	FC	15	3	2	15

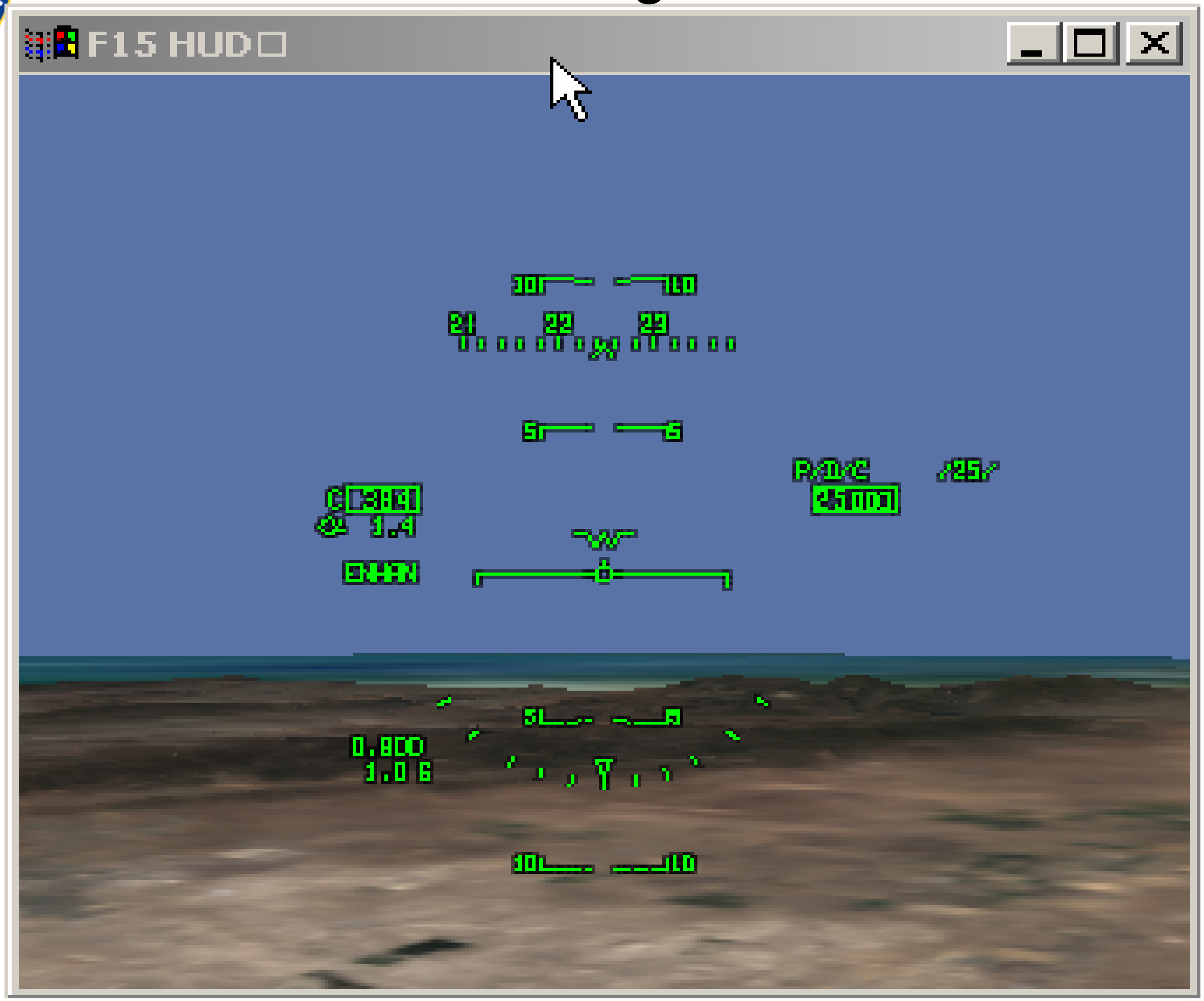
Sigma Pi Pitch Hardover



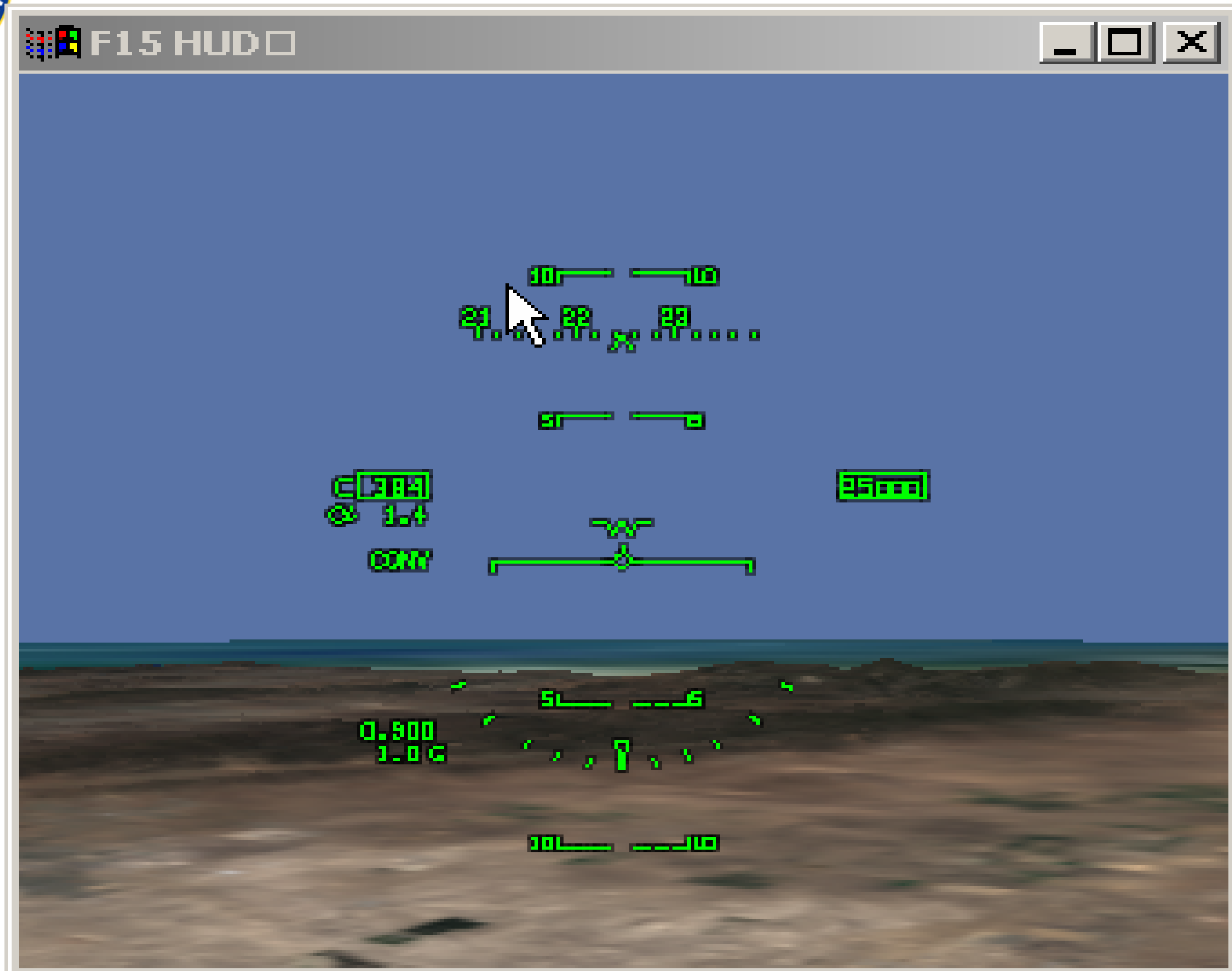
Sigma Pi Roll Hardover



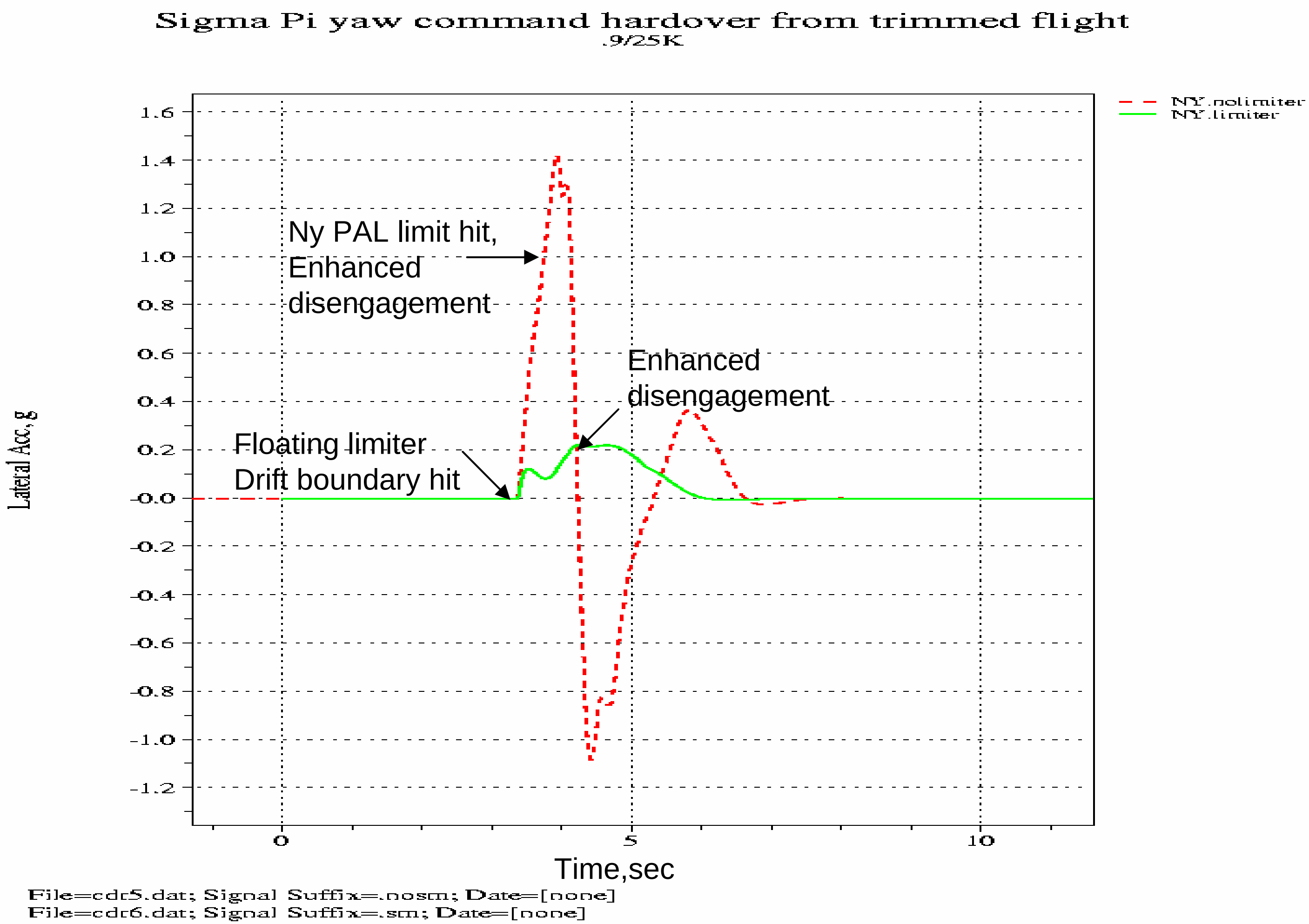
Sigma Pi Roll Hardover:
no floating limiter



Sigma Pi Roll Hardover:
with floating limiter

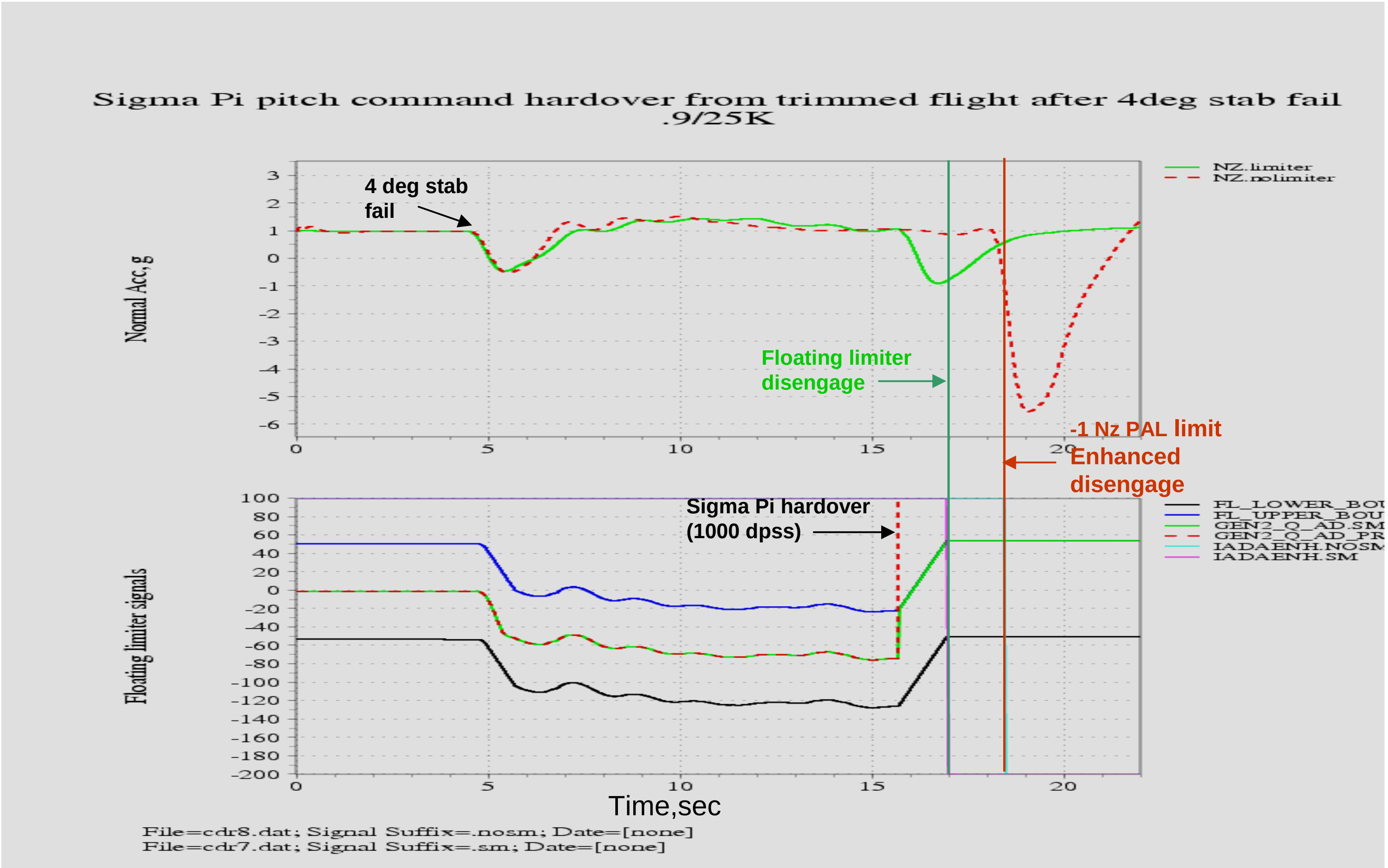


Sigma Pi Yaw Hardover



Sigma Pi Pitch Hardover

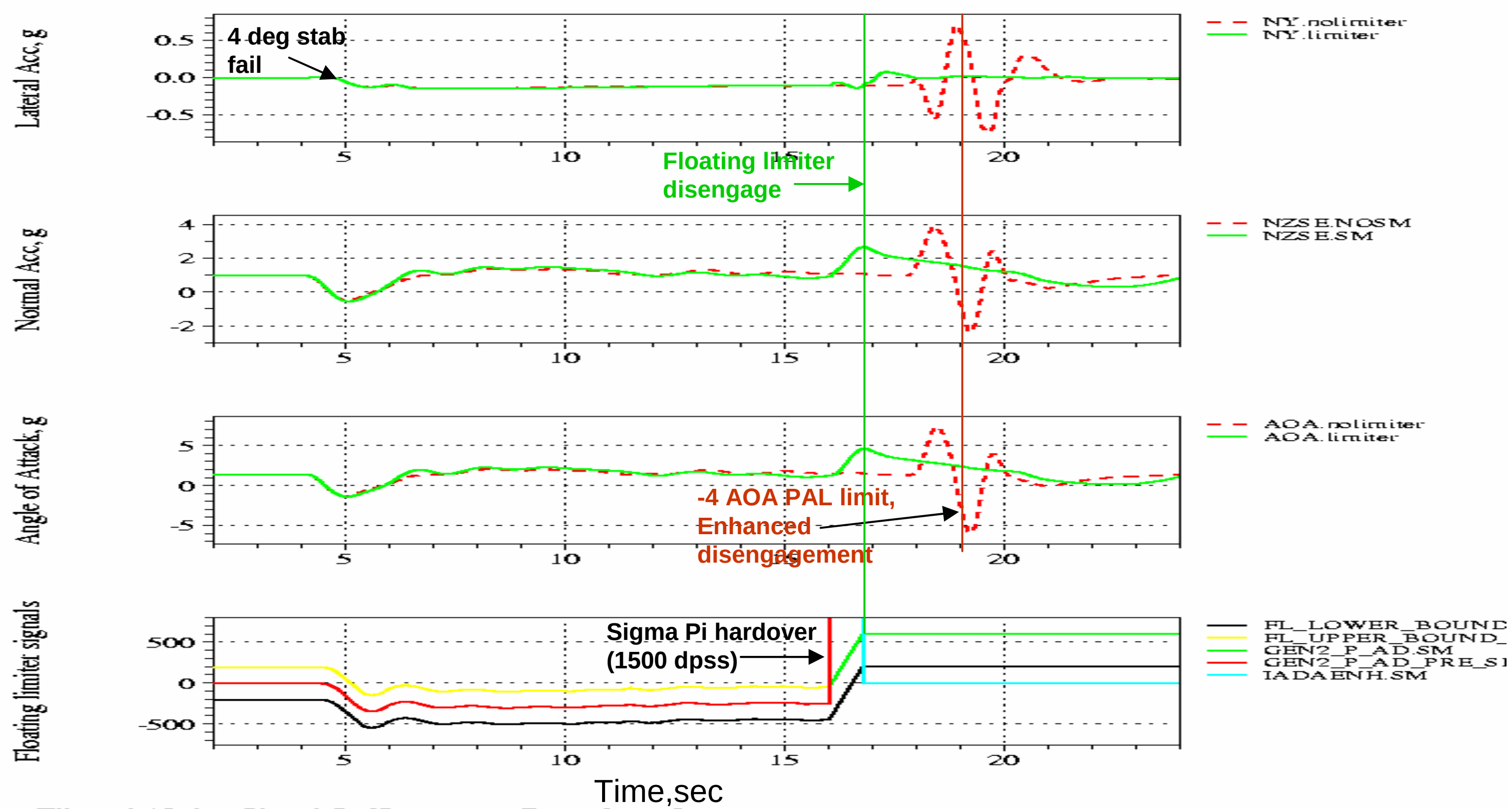
4 deg stab fail



Sigma Pi Roll Hardover

4 deg stab fail

Sigma Pi roll command hardover from trimmed flight after 4deg stab fail
.9/25K



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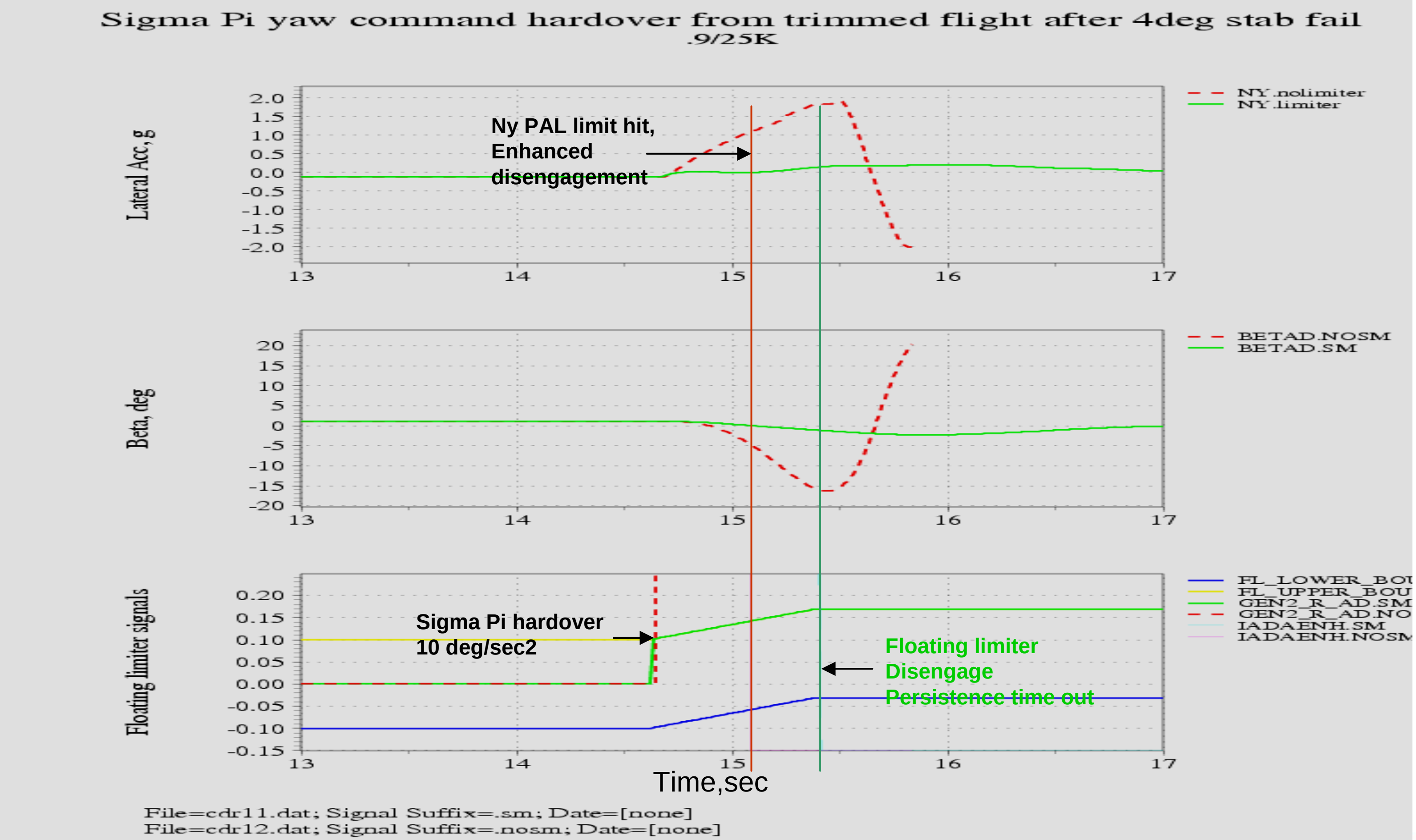
File=cdr9.dat; Signal Suffix=.sm; Date=[none]

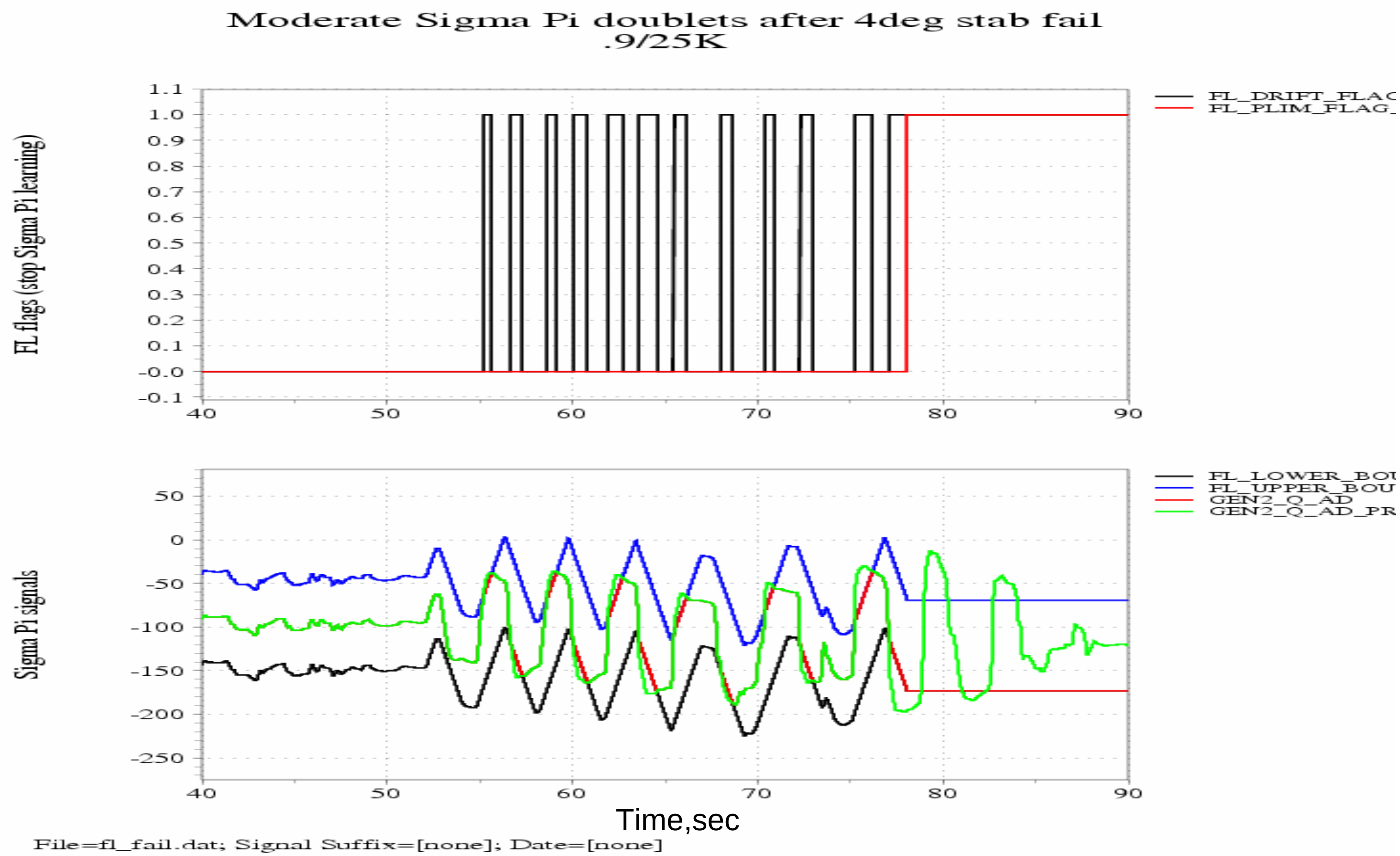
Sigma Pi Yaw Hardover

4 deg stab fail



Sigma Pi - moderate doublets

floating limiter flags

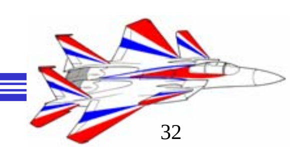


Surprise
An Unexpected Test Anomaly

- **Discrepancy excerpt:**

  “*During dry runs of the supplemental HILS tests on ifcs_051g to simulate ARTSII failure modes, a four channel left stabilator shutdown was experienced as a result of dropping the ARTS_OK_to_Couple Flag in channel 2 with Neural Nets Enabled, and a simulated Stab failure.*
  The test scenario was duplicated five times, one case all four channels of the left stabilator turned off. In all other cases, either just ch 1 and 2 or just ch3 and 4 stabilator failed (2 channel vs four channel fail). The test was run at M.75 @20K with PAL=8 and DAG=21 (4 deg left stab bias).”

  BLIN code F143 = left stabilator current disconnect



An Unexpected Test Anomaly

- **Analysis**

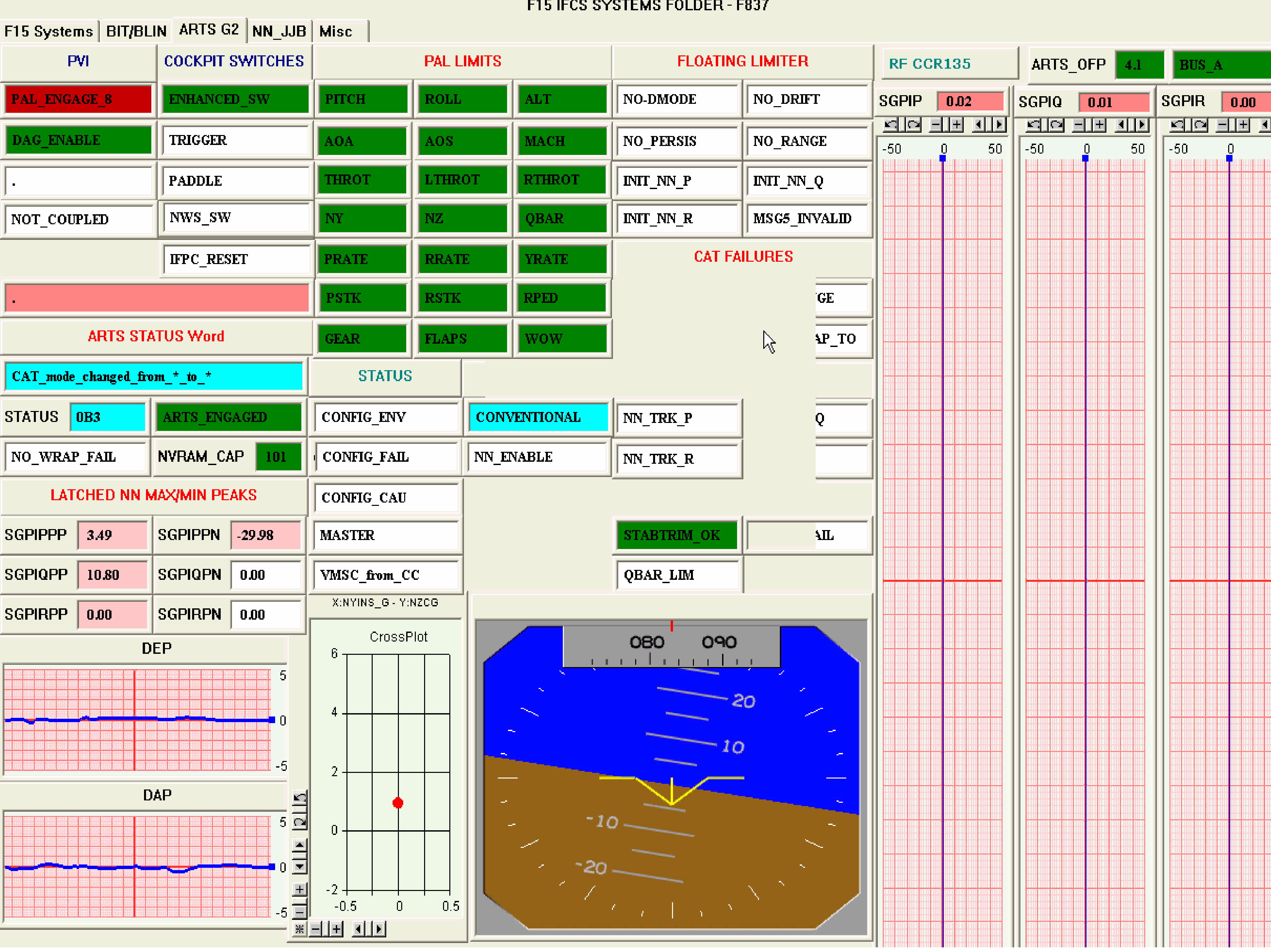
  An FCC fault in channel 2 was created which resulted in that channel initiating the downmode logic from neural net to the conventional control laws. This downmode logic did not occur during the same minor frames in the FCC, resulting in different commands to the 4 channel actuator electronics. Consequently, a force fight was created which triggered the stab current monitor.

- **Corrective Action**

  Add downmode information to the FCC cross channel data link so that all the FCC channels transition in the same frame thereby eliminating the force fight condition

Mission Control Data Display - from flight playback

- IADS display playback showing floating limiter from the neural net pitch command being set
- 3g WUT maneuver with 2 deg left stab lock fail set
- Neural net engaged



F15 IFCS SYSTEMS FOLDER - F837
F15 Systems
BIT/BLIN
ARTS G2
NN_JJB
Misc
PVI
COCKPIT SWITCHES
PAL LIMITS
FLOATING LIMITER
RF CCR135
ARTS_OFP
4.1
BUS_A
PAL_ENGAGE_8
ENHANCED_SW
PITCH
ROLL
ALT
NO-DMODE
NO_DRIFT
SGPIP
0.02
SGPIQ
0.01
SGPIR
0.00
DAG_ENABLE
TRIGGER
AOA
AOS
MACH
NO_PERSIS
NO_RANGE
PADDLE
THROT
LTHROT
RTHROT
INIT_NN_P
INIT_NN_Q
NOT_COUPLED
NWS_SW
NY
NZ
QBAR
INIT_NN_R
MSG5_INVALID
IFPC_RESET
PRATE
RRATE
YRATE
CAT FAILURES
PSTK
RSTK
RPED
ARTS STATUS Word
GEAR
FLAPS
WOW
CAT_mode_changed_from_*_to_*
STATUS
STATUS
0B3
ARTS_ENGAGED
CONFIG_ENV
CONVENTIONAL
NN_TRK_P
NO_WRAP_FAIL
NVRAM_CAP
101
CONFIG_FAIL
NN_ENABLE
NN_TRK_R
LATCHED NN MAX/MIN PEAKS
CONFIG_CAU
SGPIPPP
3.49
SGPIPPN
-29.98
MASTER
STABTRIM_OK
SGPIQPP
10.80
SGPIQPN
0.00
VMSC_from_CC
QBAR_LIM
SGPIRPP
0.00
SGPIRPN
0.00
X:NYINS_G - Y:NZCG
CrossPlot
DEP
DAP

Floating Limiter Summary

- **Meets disengage transients criteria for NN hardover (accelerations and loads)**
  - **Worst case 4 deg stab failure**
  - **Worst case canard failure**
  - **Worst case flight condition**
  - **Aggressive maneuvering flight**
- **Piloted simulation shows disengagements are acceptable, also validated from flight test**
- **No nuisance disengagements**
- **Concept may be applied to any single string controller, not only neural net commands**