412TW-PA-18568

DEVELOPING C-17A CONTROL LAWS IN-FLIGHT

4
1
2
T
W

MAJ PATRICK RIS
MAJ DUNCAN REED
MAJ DANIEL EDELSTEIN

AIR FORCE TEST CENTER
EDWARDS AFB, CA

SEPTEMBER 2018

412TW-PA-18568

412TH TEST WING
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 21-09-2018	**2. REPORT TYPE** Briefing slides	**3. DATES COVERED** *(From - To)* 9/26/2018-9/29/2018
4. TITLE AND SUBTITLE Developing C-17A Control Laws In-Flight		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Maj Patrick Ris Maj Duncan Reed Maj Daniel Edelstein		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) 412th Test Wing 195 E Popson Ave Edwards AFB CA 93524		**8. PERFORMING ORGANIZATION REPORT NUMBER** 412TW-PA-18568
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 412th Test Wing 195 E Popson Ave Edwards AFB CA 93524		**10. SPONSOR/MONITOR'S ACRONYM(S)** N/A
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release A: distribution is unlimited.

13. SUPPLEMENTARY NOTES
Society of Experimental Test Pilots Annual Symposium, Anaheim, CA. 26-29 Sep 2018

14. ABSTRACT
The C-17A was known for Level 2 handling qualities during aerial-refueling and extensive turbofan time delay during both aerial-refueling and powered-lift configuration landing. This increased the pilot compensation required for aerial-refueling and decreased safety margins for adverse wind condition landings. The Aerial-Refueling Handling Qualities Improvement (ARHQI) was a three-axis control law designed to improve HQ with a vertical-speed feedback loop. Additionally, ARHQI implemented flap and spoiler bias with elevator feedback to create a throttle-controlled drag differential, with zero net pitching moment, to augment relative fore-aft control and reduce time delay. Robust Flight Path Control was a control law designed to reduce time delay by mixing flap, spoiler, and elevator with throttle movement to increase powered-lift control. These two control laws were developed in a risk-reduction program including control law first-flight, safety build-up, in-flight control law tuning, offset landings, tanker contacts, and lessons learned for future flight control developmental testing.

15. SUBJECT TERMS
C-17A, Control Laws, Aerial Refueling (AR), Landing, Robust Flight Path Control (RFPC), Change-A-Gain (CAG), Handling Qualities (HQ)

16. SECURITY CLASSIFICATION OF: Unclassified			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** 412 TENG/EN (Tech Pubs)
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	None	2	**19b. TELEPHONE NUMBER** *(include area code)* 661-277-8615

[DISTRIBUTION STATEMENT A. Approved for public release; Distribution is unlimited 412TW-PA-18545]

Developing C-17A Control Laws In-Flight

3-AXIS AERIAL-REFUELING & ROBUST FLIGHT PATH

Maj Patrick Ris, Maj Duncan Reed, & Maj Dan Edelstein — 27 September 2018

C-17A Legacy Control Laws

- *Air-refueling*
  - *Thrust axis: computer controlled engines*
  - *Pitch rate command*
  - *Roll rate command*

- *Approach & landing*
  - *Pitch attitude command*
  - *Augmented powered lift*

New Control Law Requirement: Air-Refueling

HQR Air-Refueling Pilot Comments During Full Scale Engineering & Development

- “Training would not significantly improve pilot’s ability to compensate”
- “Engine throttle response was marginal. Small throttle changes resulted in large thrust changes…increasing pilot workload”
- “Delay between throttle movement and thrust response contributed to throttle sensitivity deficiency…lag time unavoidable with high bypass turbofan engines”
- “Lack of predictability in pitch…tendency toward moderate, periodic, pitch excursions or bobbles increased workload”
- “Aircraft moved rapidly around envelope…nearly impossible to stabilize without constant correction”

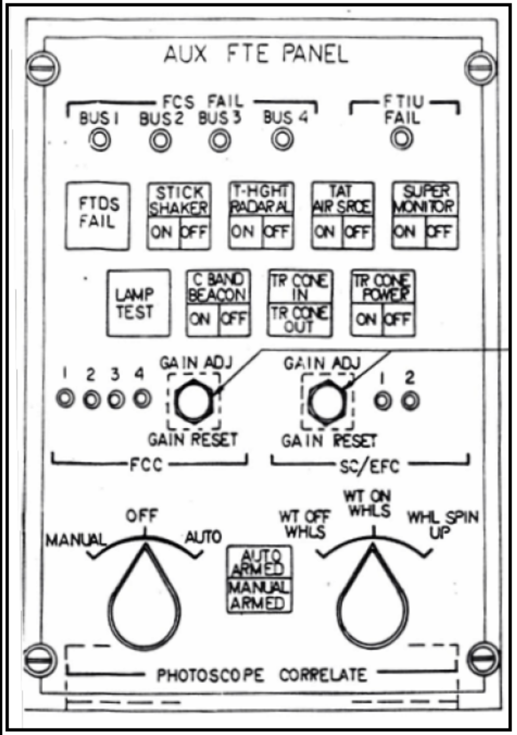
New Control Law Requirement: Landing

HQR Approach Pilot Comments During Full Scale Engineering & Development

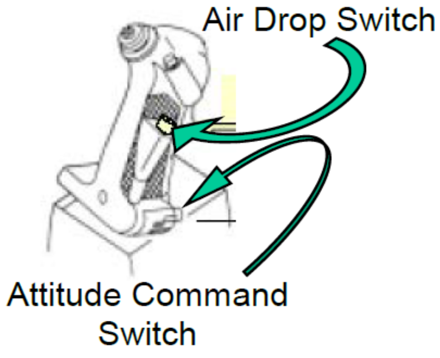
- “Moderate workload in thrust axis”
- “Workload tolerable, compensation moderate, struggle to match [Flight Path Vector] response”
- “Thrust is difficult to control”
- “Gusty winds/thermals make stabilization on final difficult”
- “Crosswind landing: thrust axis hard to control, workload high for task with gusty winds”
- “Throttles are unpredictable”
- “[Flight Path Vector] control sluggish”
- “Lots of throttle, drives up workload – concentrated more on throttle than lateral or pitch”

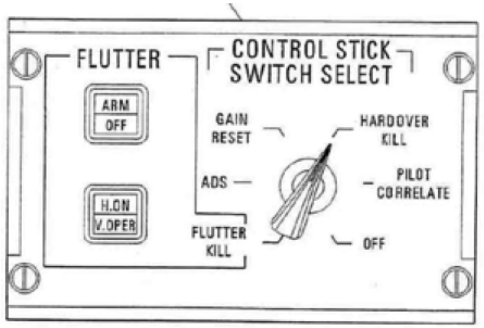
New Design: 3-Axis AR & Robust Flight Path

- *Air-refueling: thrust axis*
  - *Spoiler, flap & elevator augmentation*
- *Air-refueling: pitch rate command*
  - *Short input: attitude command*
  - *Sustained input: rate command*
  - *Vertical speed feedback*
- *Air-refueling: roll rate command*
  - *Precision azimuth tracking*
- *Approach: pitch attitude command & augmented powered lift*
  - *Closed loop system*
  - *Flap augmentation*

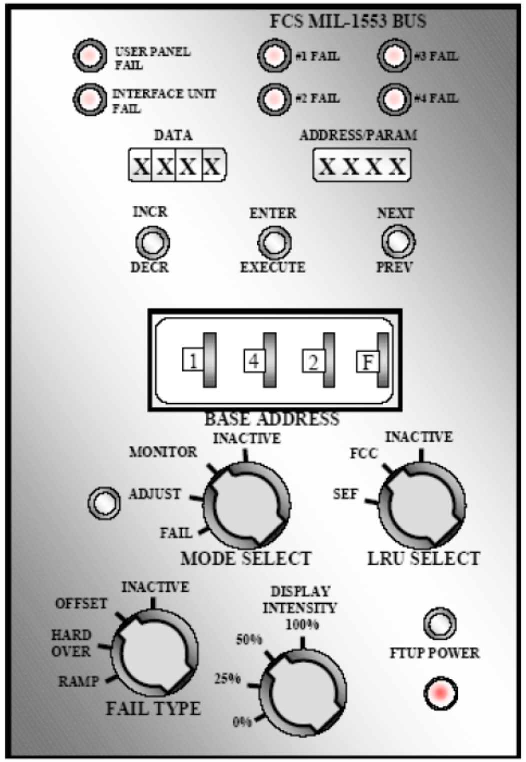


Aux FTE Panel





Center Console Control Switch Select Panel



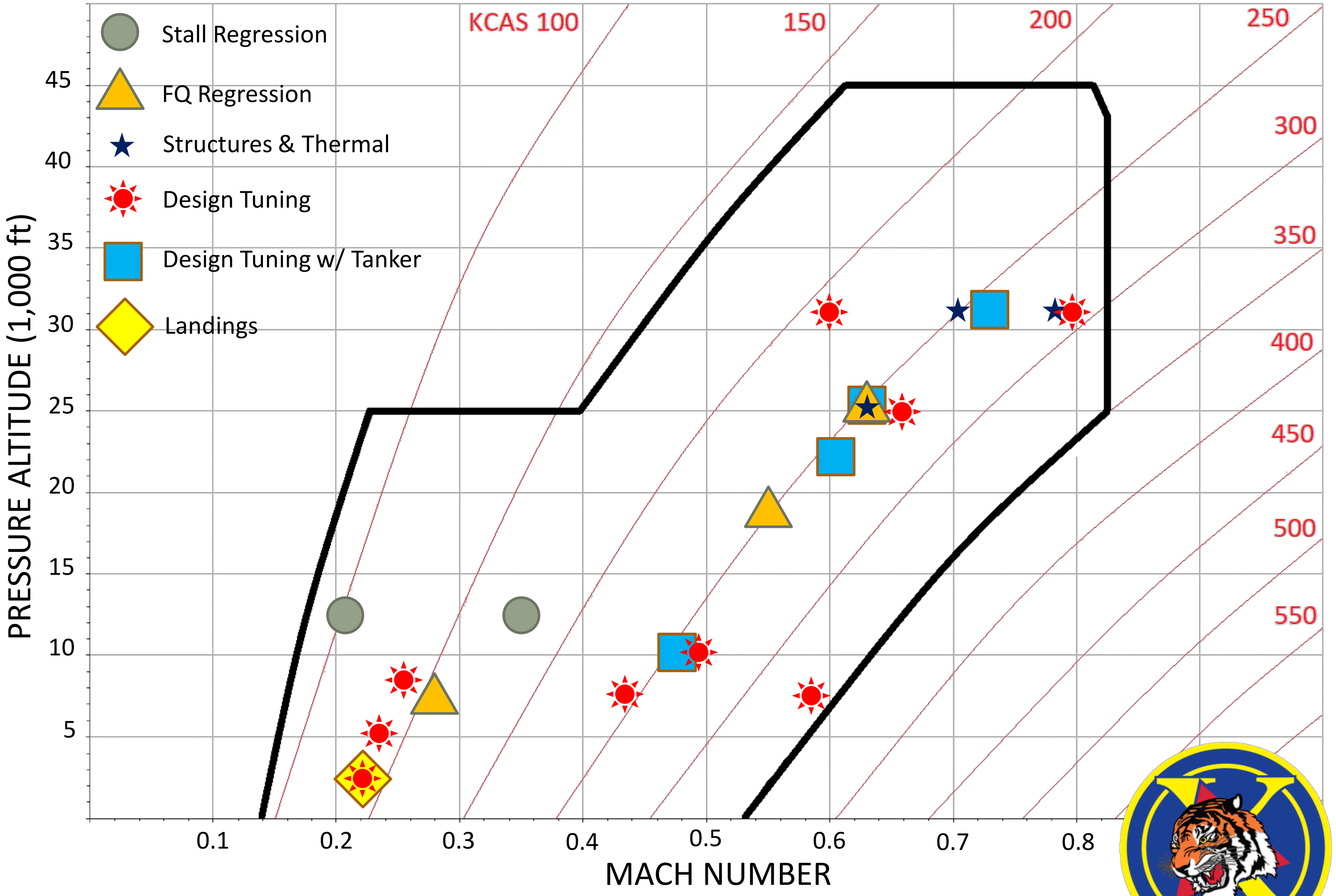
Flight Test User's Panel

Change-A-Gain System

Test Unique Hardware

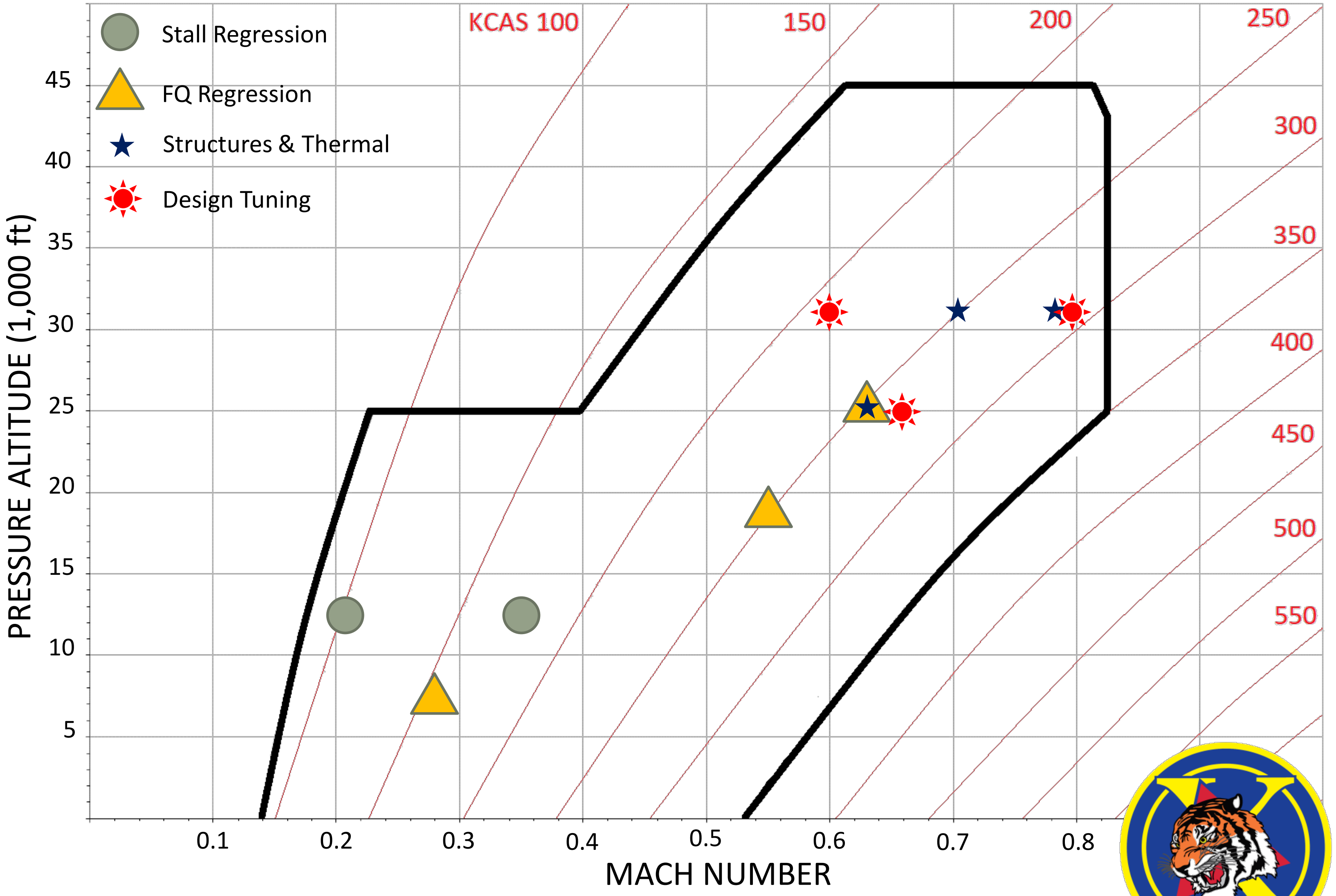
Test Methodology

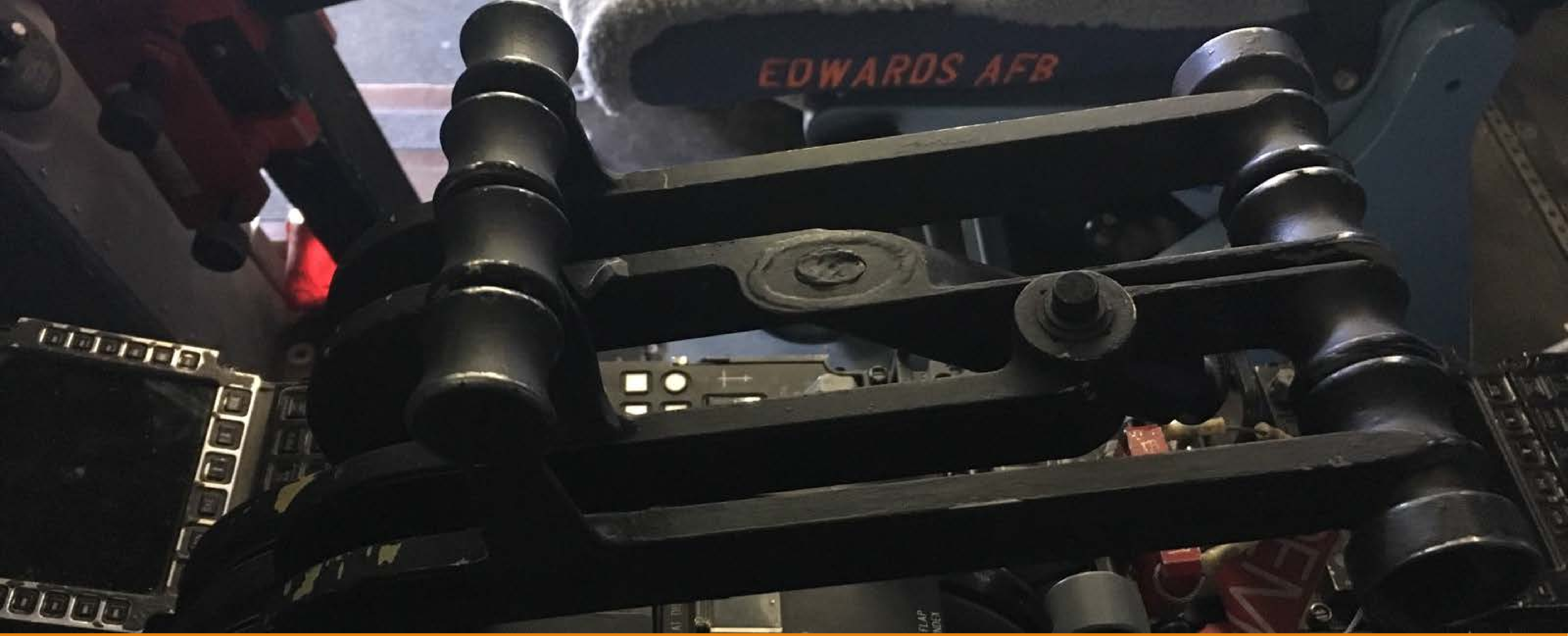
- *Single Ship*
- *Tanker/Receiver Formation*
- *Robust Flight Path Landings*



Test Methodology

- *Single Ship*
  - *Safety Buildup*
  - *FQ Data Collection*
- *Tanker/Receiver Formation*
- *Robust Flight Path Landings*





FTT: Throttle Frequency Sweeps

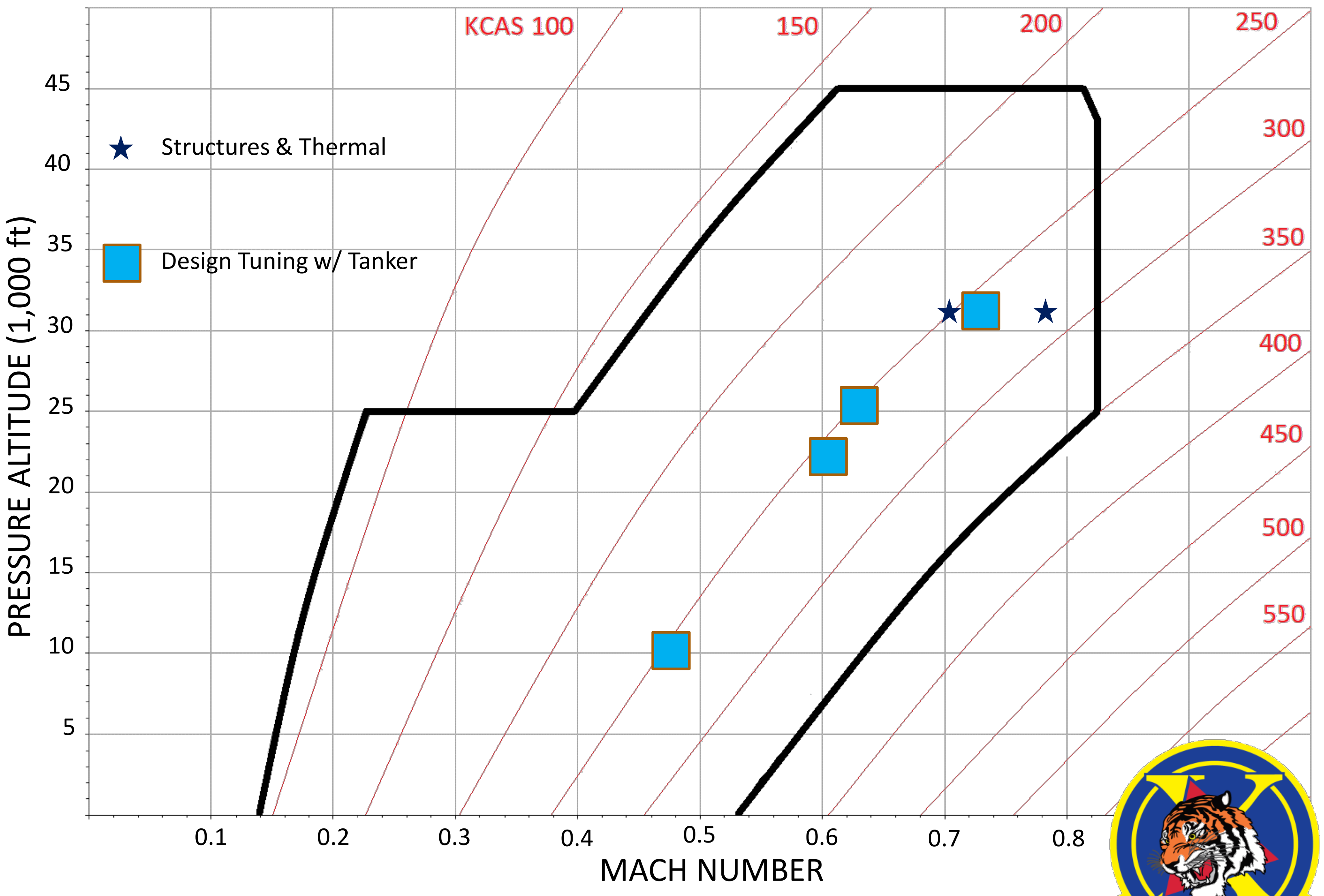
0.1 – 5 Hz ½ INCH AMPLITUDE

Test Methodology

- *Single Ship*

➢ *Tanker/Receiver Formation*
  - ➢ *Safety Buildup*
  - ➢ *HQ Evaluation*

- *Landings*

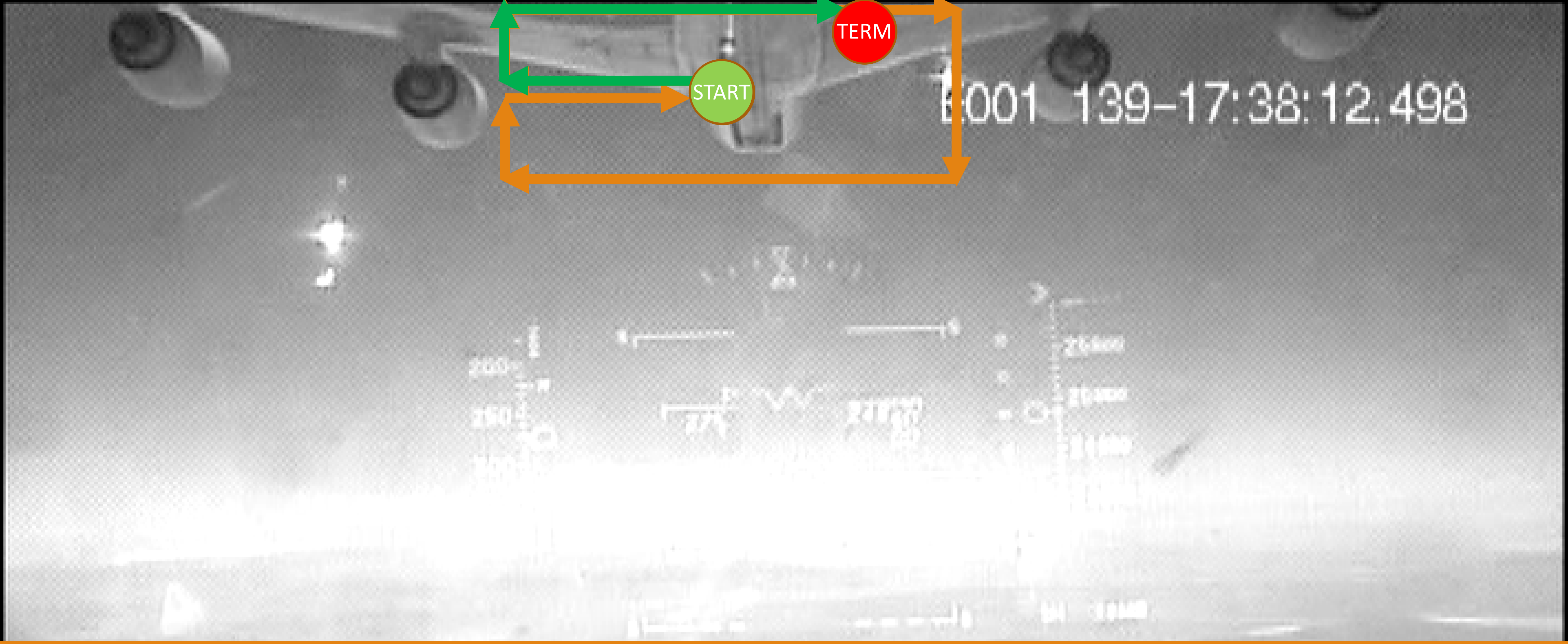


Air-Refueling Control Law Engagement

Initial control law engagement in one nautical mile trail

Qualitative evaluation with target

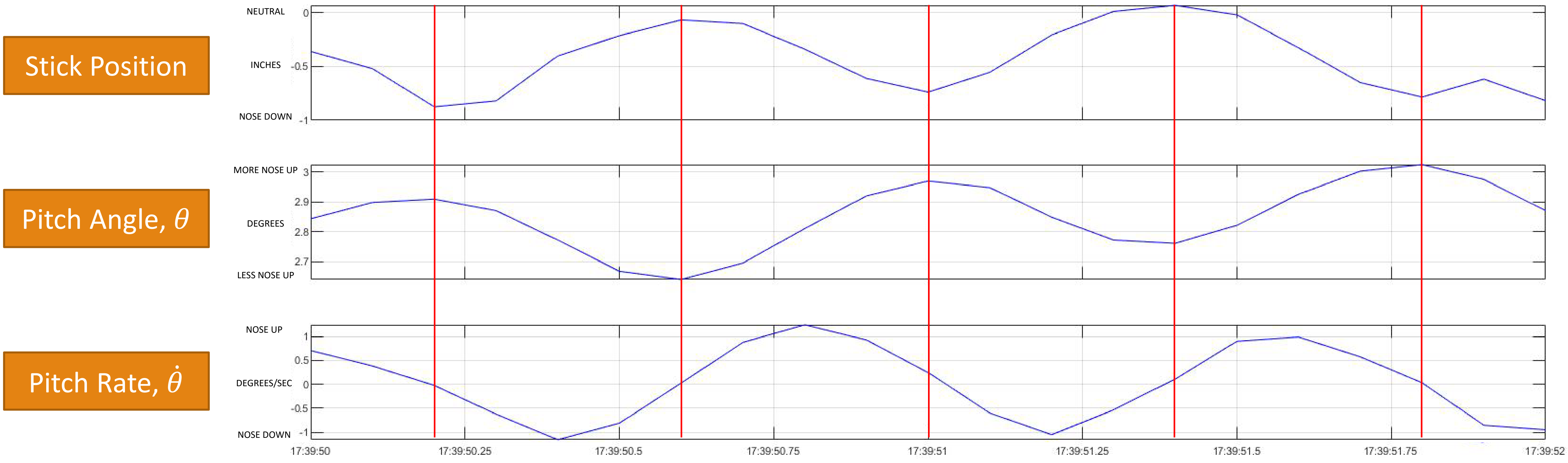
Rejoin in stages



FTT: Boom Tracking

Safety buildup at 50 feet separation (Pre-Contact)

Performed at two rates



Boom Tracking Strip Charts

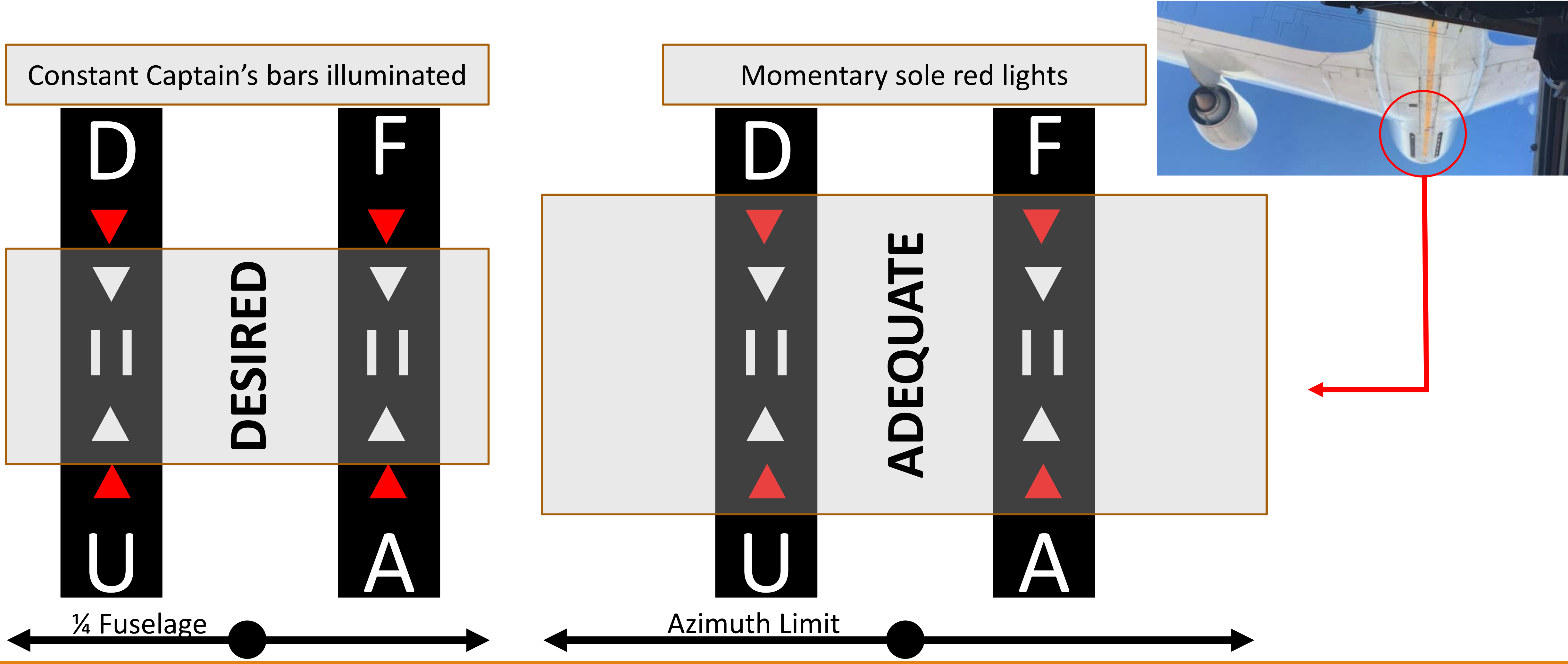
1.25 Hz oscillation

The case for a lesson learned…

- Six month break for data review & design update

- Test methodology review & re-prioritization

➢ ***Design the right flight test: identify and pursue the knowledge test point***



FTT: Sustained Contact HQ Evaluation

Task Criteria

Two minutes straight & level

180 degree turn

FTT: Sustained Contact HQ Evaluation

Control Laws Side-by-side

The case for a lesson learned…

- Test pilots with 1,000s of hours in one platform have inherent bias

- “I used to fly AR just fine, I don’t know how to compensate now, give me back the legacy control law so I know what to do”

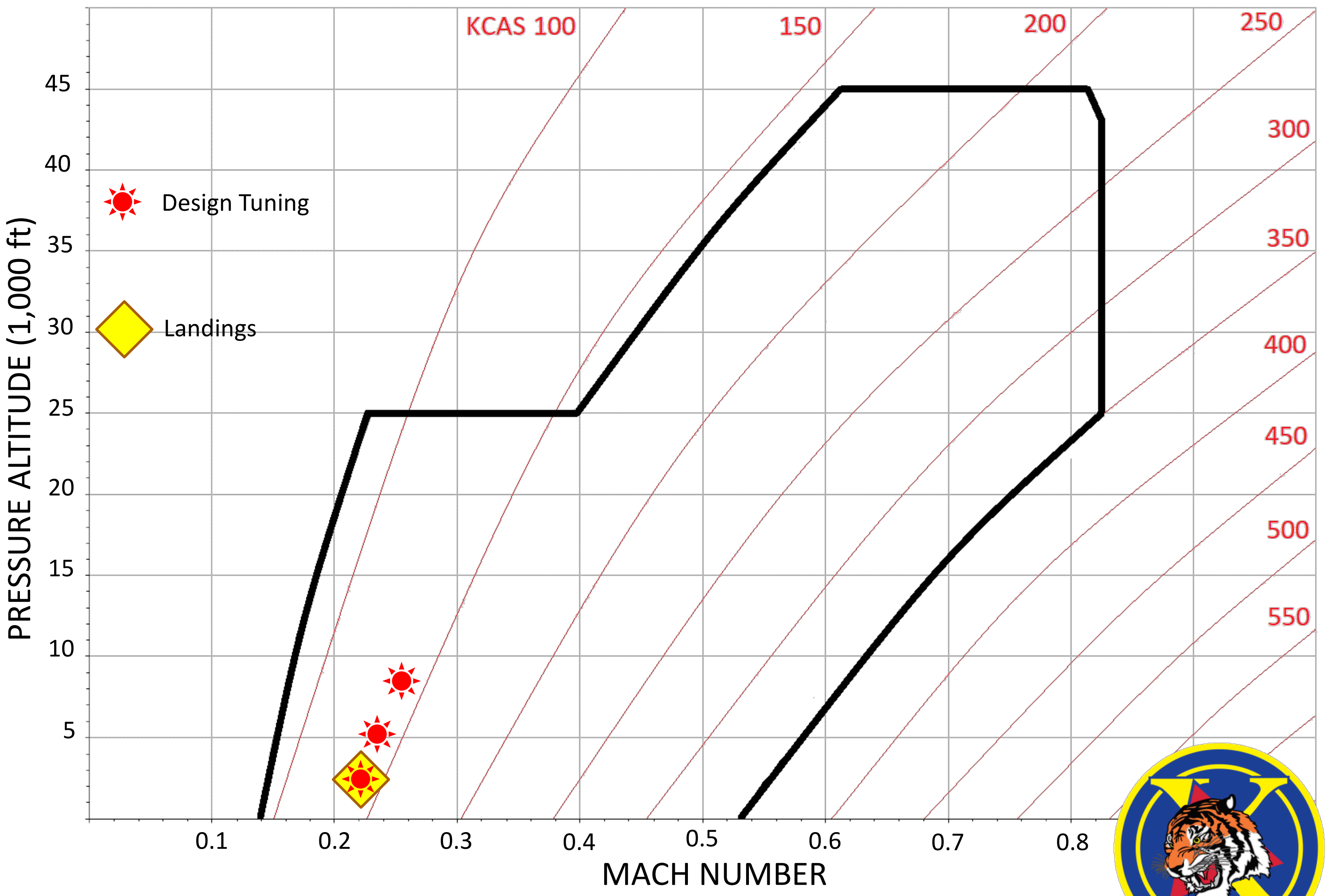
➢ ***Defeat mature aircraft bias: calibrate the test pilot on the ground and in the air***

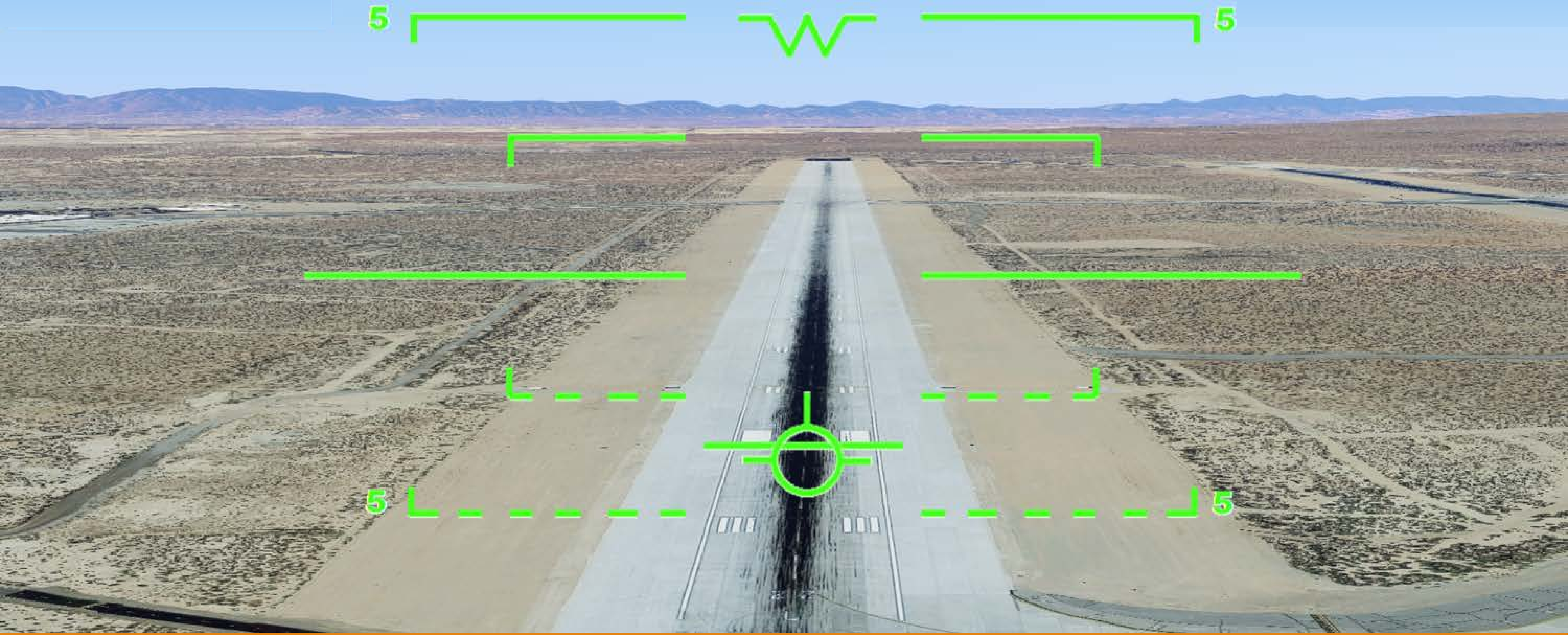
418TH FLIGHT TEST SQUADRON

Test Methodology & Buildup

- *Single Ship*
- *Tanker/Receiver Formation*

- ➢ ***Robust Flight Path Landings***
  - ➢ *Safety Buildup*
  - ➢ *Flight Path Performance*
  - ➢ *HQ Evaluation*





FTT: Vertical Offset Recovery

Stress control law

Increase pilot gain

FTT: Vertical Offset Recovery

Side by side video

Rating	FPV at T/D (°)	A/S at T/D (kt)	T/D from Aim (ft)	Centerline Dev (ft)
Desired	-0.5 to -1.5	+/- 5	+580 / -20	+/- 15
Adequate	0.0 to -2.0	+10 / -5	+880 / -320	+/- 25

FTT: Normal Landing HQ Evaluation

Rating	FPV at T/D (°)	A/S at T/D (kt)	T/D from Aim (ft)	Centerline Dev (ft)
Desired	-1.0 to -2.0	+/- 5	+/- 150	+/- 15
Adequate	0.0 to -2.0	+10 / -5	+/- 250	+/- 25

FTT: Assault Landing HQ Evaluation

Robust Flight Path

Legacy Control Law

FTT: Assault Landing HQ Evaluation

Side by side control law

The case for a lesson learned…

- Test pilots with 1,000s of hours in one platform have inherent bias

- "I used to land just fine, I don't know how to compensate now, give me back the legacy control law so I know what to do"

➢ ***Defeat mature aircraft bias: calibrate the test pilot on the ground and in the air***

Lessons Learned Wrap-up

- ***Design the right flight test: identify and pursue the knowledge test point***

- ***Defeat mature aircraft bias: calibrate the test pilot on the ground and in the air***

A special thanks to:

- Maddie Vega
- James Ortega
- Boggie Wozniak
- Dan Wilson
- Gary Weltz
- Michael Sizoo
- Paul Shank
- Gary Yarosloski
- Susan Choate

…& the everyone at the Global Reach Combined Test Force

For helping us gather data and making this test program a success!