F-35 AGCAS Testing
Agile Implementation of Collision Avoidance Systems

Katie Peticolas (Project Team Lead)

Marcea Ascencio (Project Engineer)

LCDR Jonathan Beaton (Test Pilot)

Maj Jonathan Bearce (Test Pilot)

Lt Col Raven LeClair (Test Pilot)

Mr. Andrew Soundy, Test Pilot, Lockheed Martin Corp

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Overview

- F-35 AGCAS (Automatic Ground Collision Avoidance System) Programmatic Timeline
- Test Item Description
- Agile Testing Approach
- Types of Testing and Measures vs Requirements
- Issues Found
- Lessons Learned

F-35 AGCAS Programmatic Timeline

F-35 AGCAS History/Timeline

- **F-35 AGCAS was originally scheduled for Block 4.3, late 2025 testing. This schedule was based on assumed VMC hardware limitations.**
- **Jan 2017 -** AGCAS Summit organized by Edwards F-35 test team
- **March 2017-** AFRL funded a study to prove existing VMC hardware capable of hosting AGCAS. The study was successful.
- **31 Oct 2018 -** F-35 AGCAS testing begins
- **Friday, 02 Nov 18 -** AGCAS released to unmonitored flight on all DT sorties only three days after first test.
- **5 December 18 -** Test Surge complete: most flight test questions answered (measures)

F-35 AGCAS Timeline

Planned F-35 AGCAS testing is moved left by *7 years*.

AFRL funded a study to prove existing VMC hardware was capable of hosting AGCAS. The study was successful.

MAR

F-35A testing completed.

APR

2017 2018 2019 ... 2025

JAN

AGCAS Summit organized by Edwards F-35 ITF.

OCT

AGCAS testing begins at Edwards AFB.

AGCAS was released for unmonitored DT flight *3 days* after start of test.

F-35 AGCAS Test Item Description

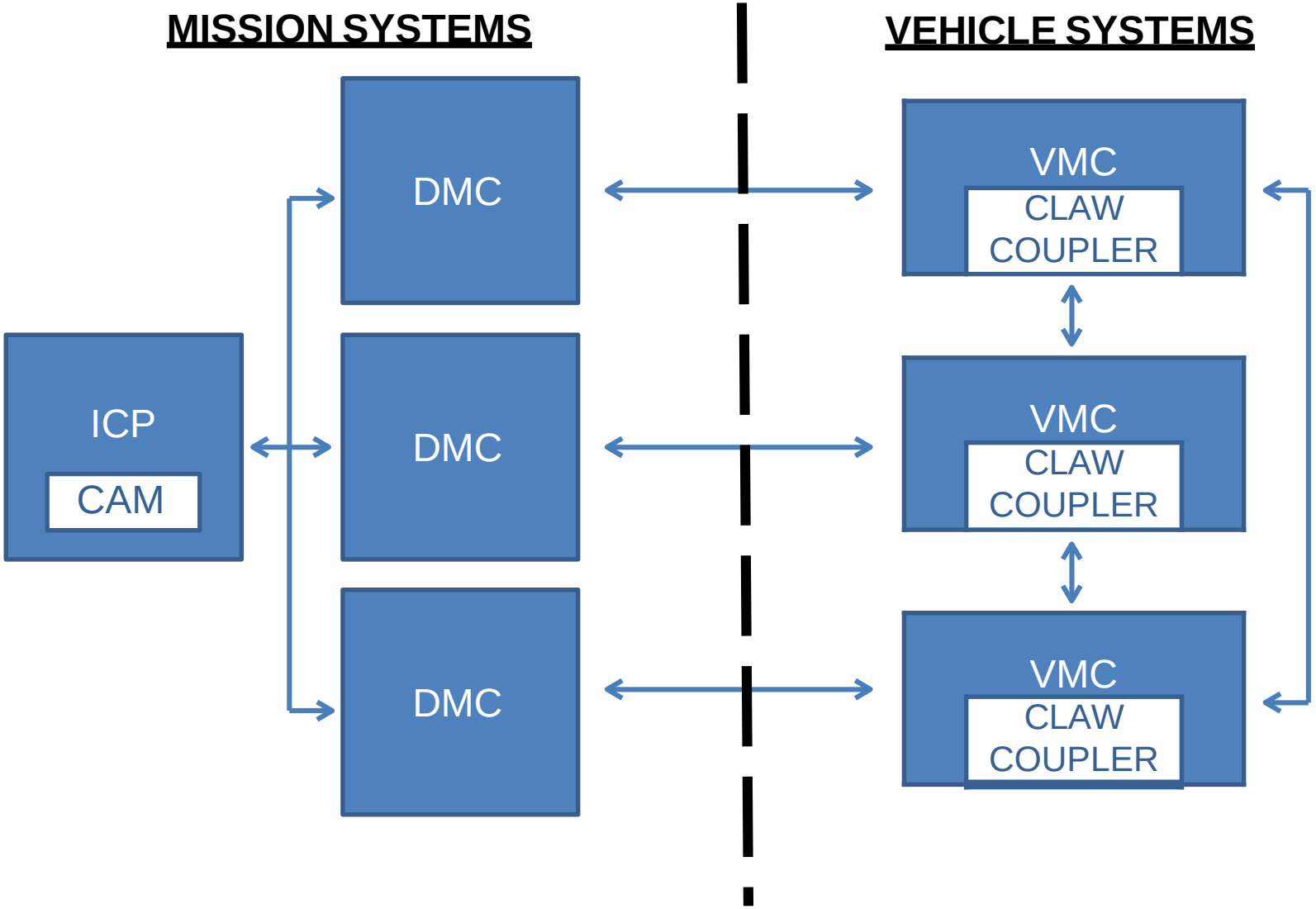
Rapid Implementation on the F-35

- **F-16 implementation established that AGCAS increases overall military utility**
  - Confidence in proven system convinced stakeholders to provide the means for rapid integration
- **F-35 required a reduced scope of flight test and was focused primarily on integration because of existing system maturity**
  - F-35 AGCAS is very similar to F-16 design
    - Extensive F-16 testing helped refine the system design, characterize system performance, and determine nuisance potential
  - F-35 MGCAS testing improved the collision avoidance model implementation prior to the integration with the control laws

F-16 Lessons Learned

- **Results from F-16 testing and fielding influenced design**
- **Auto-throttle functionality**
  - F-16 had a low speed interlock because of limited aircraft performance
  - Low speed recoveries are now possible because of the ability to automatically increase throttle setting
  - Helps reduce nuisance potential for steep recoveries because of the ability to decrease throttle setting
- **Pull-through recovery logic**
  - Both CAM and CLAW coupler utilize pull-through logic
  - Reduces nuisance potential during high G split-S maneuvers by reducing predicted altitude loss in recovery

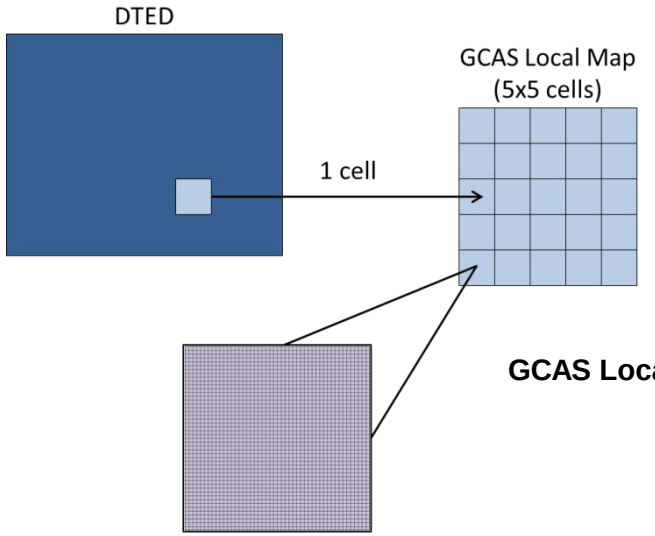
F-35 AGCAS Architecture



GCAS Modes of Operation

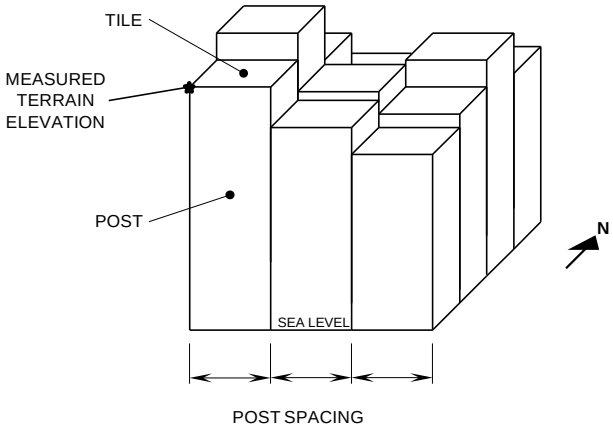
- **AGCAS and MGCAS do not operate simultaneously**
- **GCAS mode initializes to best available option**
  - Default GCAS mode is AGCAS
  - If aircraft cannot support AGCAS, GCAS mode reverts to MGCAS
    - Once aircraft can support AGCAS again, GCAS mode reverts to AGCAS without pilot action
- **Pilot can also manually change GCAS mode**

AGCAS Digital Terrain



GCAS Local Map Creation

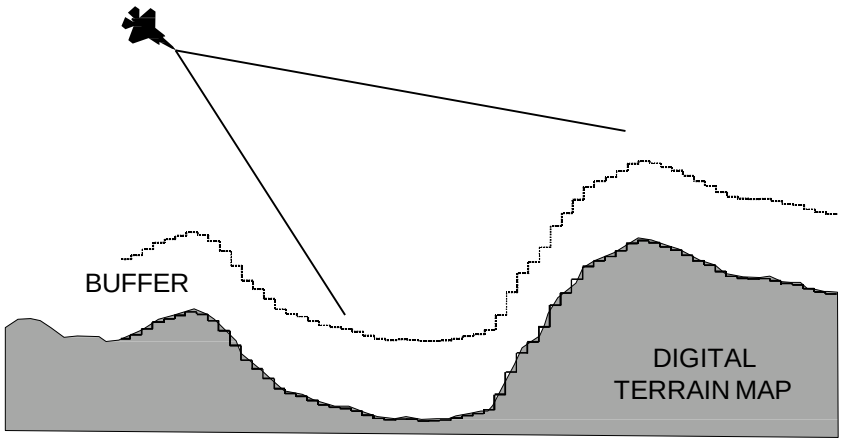
TED Posts and Tiles



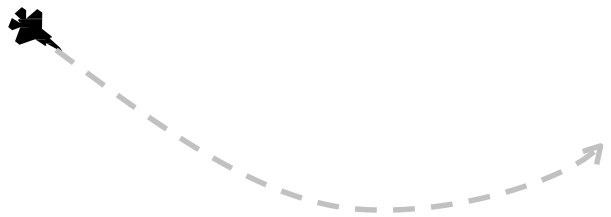
AGCAS Functionality

COLLISION AVOIDANCE MODEL

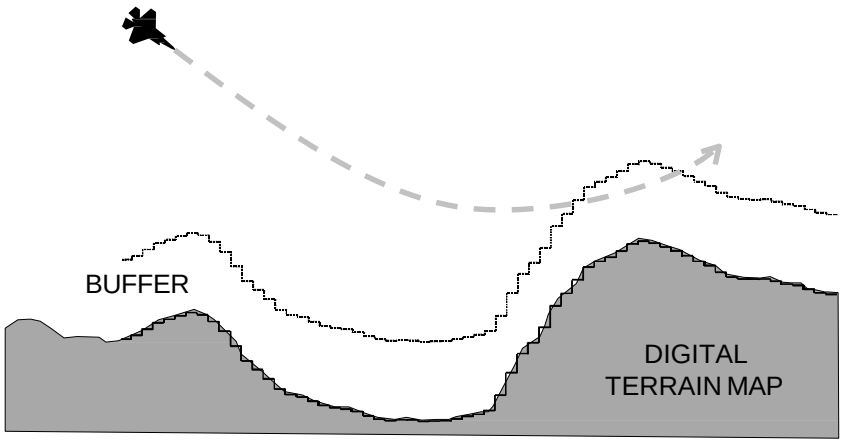
1. Process the digital terrain map.



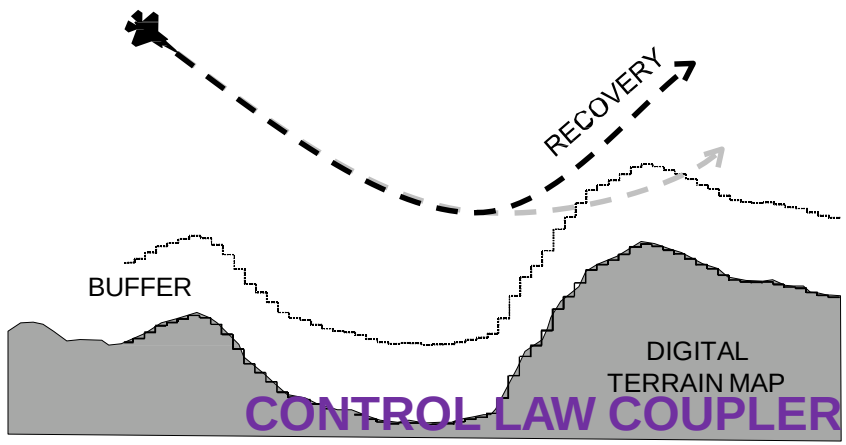
2. Calculate aircraft trajectory.



3. Determine if recovery is required.



4. Execute recovery when required.



CONTROL LAW COUPLER

Collision Avoidance Model

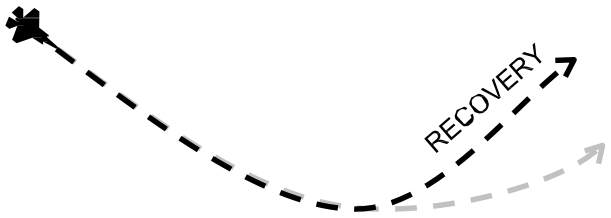
- **CAM collects aircraft state information and uses it to determine when a recovery is required**
  - Digital Terrain Map
    - Determines aircraft position with respect to surrounding terrain
  - Aircraft Trajectory Prediction
    - Uses aircraft state information and attitude to predict trajectory
  - Collision Estimation
    - Combines the digital terrain map and aircraft trajectory prediction to determine when a recovery is required
- **Once it has been determined that a recovery is required, a fly-up request is sent to the CLAW coupler**

CLAW Coupler

- **Commands pitch, roll, and throttle inputs as required to recover based on aircraft state at recovery initiation**
  - Pitch commands
    - Will always be below the symmetric and asymmetric structural Nz limitations
    - Lower Nz commanded for a Standard Recovery
    - Higher Nz commanded for a Pull-Through Recovery
  - Roll commands
    - Maximum possible roll rate will be commanded
    - Direction will be based on aircraft state at recovery initiation
  - Throttle commands
    - Initial command is MAX, IDLE, or control remains with pilot
    - Command can be changed to MAX mid-recovery
- **The pilot can manually end a recovery at any time**

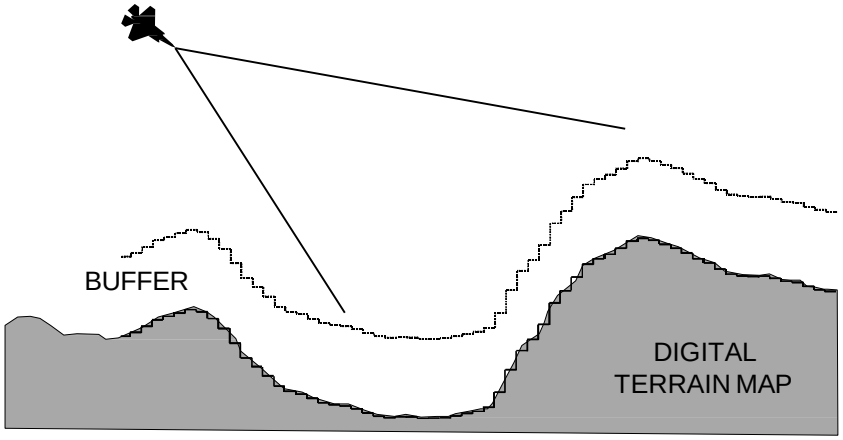
Pilot Initiated Fly-Up (PIF)

- **Pilot can manually initiate a recovery regardless of surrounding terrain**

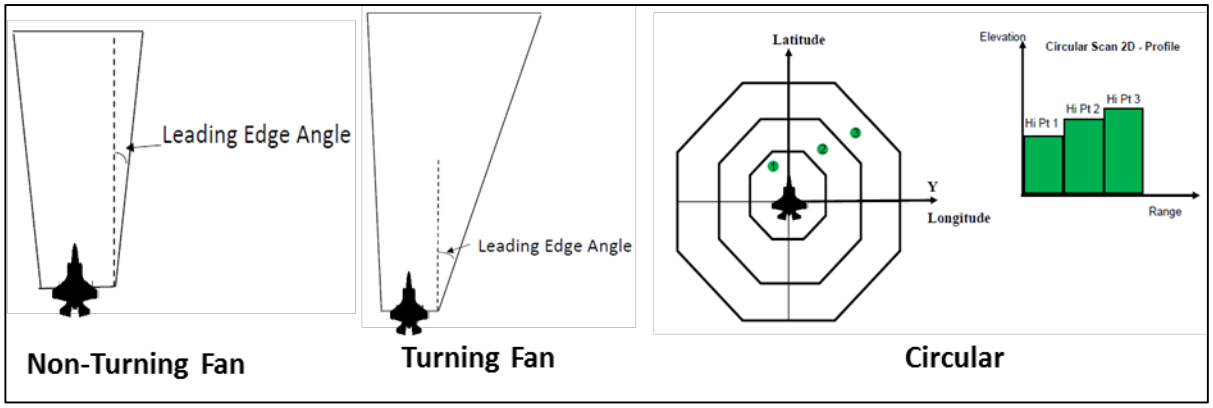


- **Does not require CAM and is not dependent on AGCAS**
- **PIF recovery is very similar to an AGCAS recovery**
  - Only entry and exit criteria are different

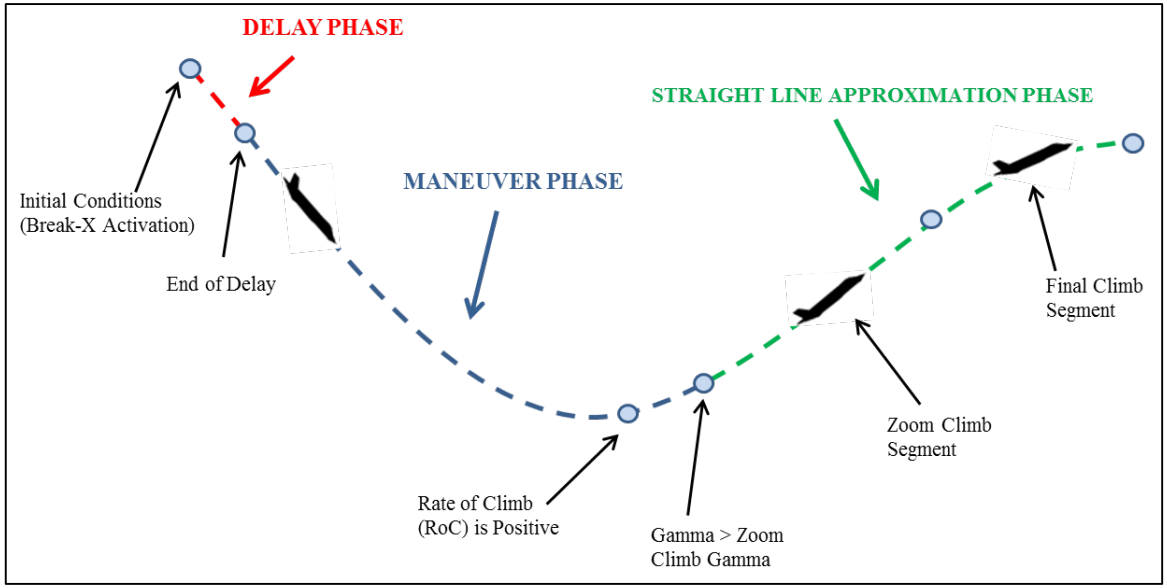
Digital Terrain Map



- **Three different “scan patterns” used to develop the digital terrain map**
- **Type of “scan pattern” is based on aircraft state**



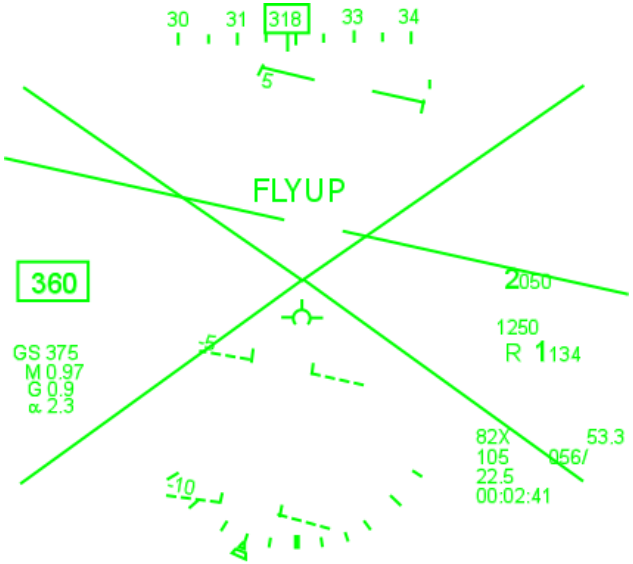
Trajectory Prediction Phases



PVI during Recovery

HMD

- Chevrons appear 3 seconds before AGCAS recovery
- Converge to an X at AGCAS or PIF recovery
- “FLYUP” displayed during recovery
- No up arrow



PCD

- Red X displayed on each portal at 1.1 seconds to AGCAS recovery
- No indication on PCD for PIF

Audio “Fly-up, fly-up” occurs during AGCAS and PIF recoveries

AGCAS Auto Throttle

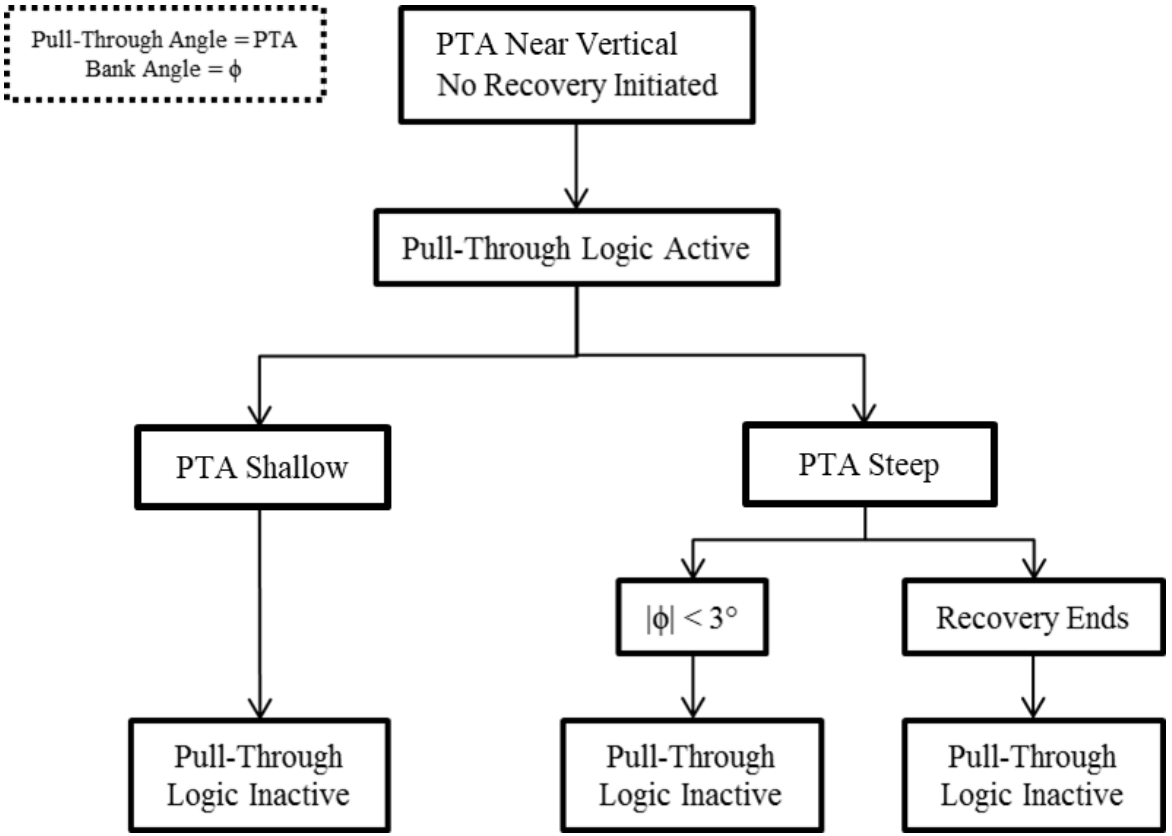
- **With auto throttle capability, low speed recoveries are now possible and no low speed interlock is required, which is present on F-16.**

Decision Criteria for ETR Setting at Recovery Initiation		
Flight Path Angle – Termination Angle	**Airspeed**	**Decision**
Small Change	Near Low Corner	ETR to MAX
Large Change	Near High Corner	ETR to IDLE
N/A	Corner Velocity Region	Pilot Retains Control

Decision Criteria for ETR Setting Mid-Recovery			
Initial Decision	Airspeed Trigger	Angle of Attack	Decision
Pilot retains control	Very Slow	-	ETR to MAX
Pilot retains control	Low Corner	Max Alpha Target	ETR to MAX
ETR to IDLE	Low Corner	-	ETR to MAX

Pull-through Logic

- **F-16 had an issue with nuisance activations during high G split-S maneuvers. Pull through logic solves this problem.**



20 Deg AOA Limit

- **Why choose a 20 deg AOA limit?**
  - F-16 design was copied for rapid implementation
  - Heart of the AOAenvelope
- **How CLAW changes > 20 deg**
- **Transonic vs. slow speed**

Types of Test

Summary of Testing

- **Legacy Airworthiness**
- **Safety Critical Interlocks**
- **Functional Interlocks**
- **MGCAS Regression**
- **Human Factors Evaluation**
- **Mission Debrief Capability**
- **AGCAS Performance**
- **AGCAS Nuisance**

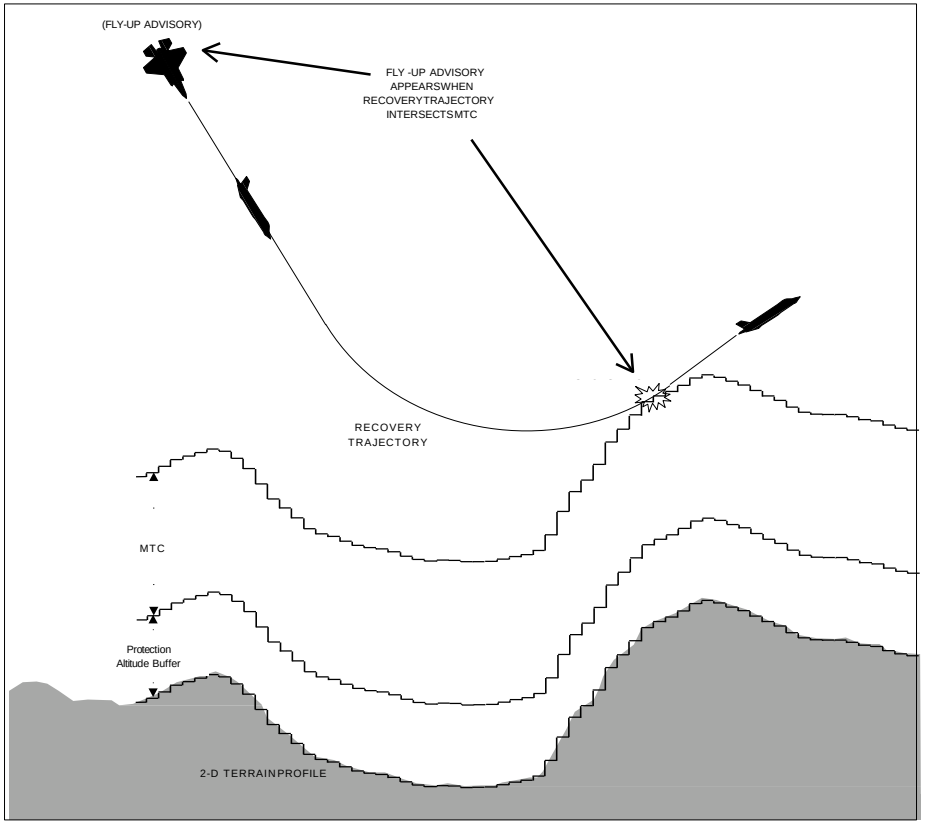
First: Do No Harm

Third: Avoid the Ground

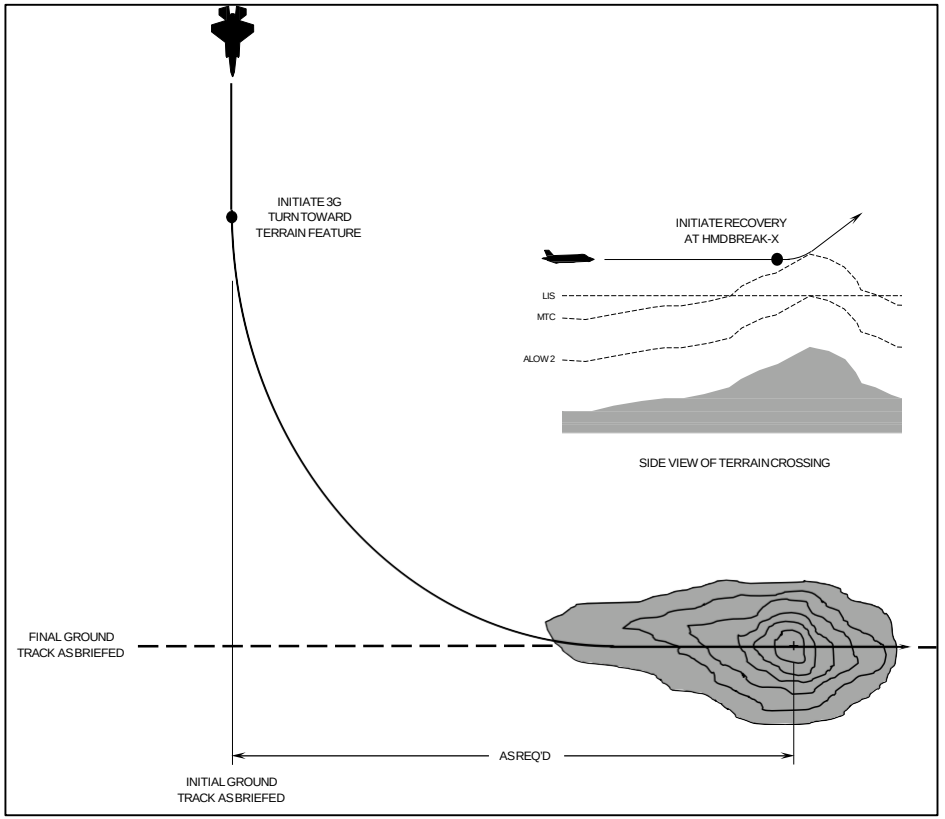
Second: Do Not Interfere

Performance Maneuver Types

Dive Towards Smooth Terrain



Flight Towards Elevated Terrain



Nuisance Evaluation Maneuver Types

- High Angle Strafe
- Low Angle Strafe
- Low-Level Flight
- Split-S
- Sliceback
- Loop
- BFM
- US Navy Low Altitude Training Matrix
- Tower Fly-by
- High-to-Low Tactical Intercept
- Safety Chase

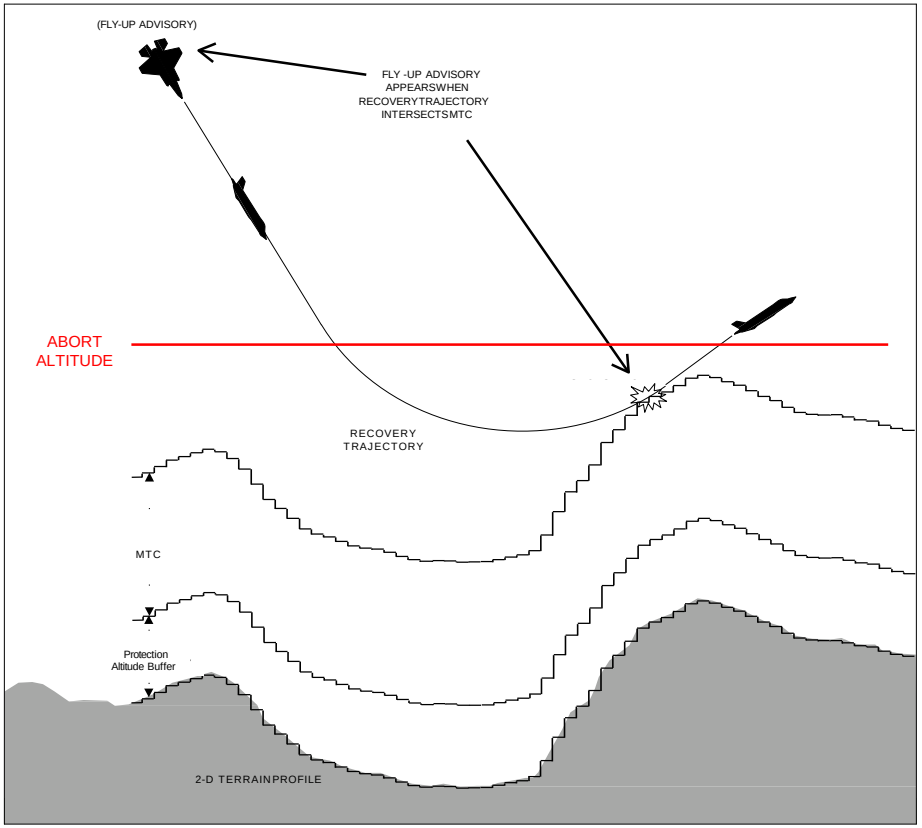
All are operationally representative maneuvers

Dive Planning

A New Approach

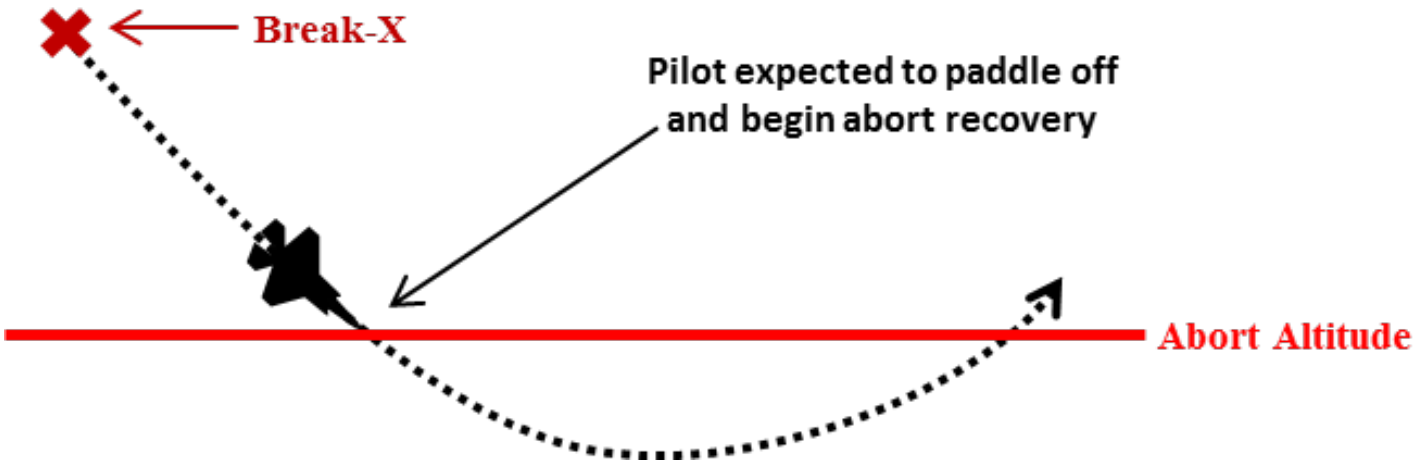
Writing the Safety Plan

- **Considered lessons learned from previous AGCAS testing efforts (F-16 and F-22)**
  - Did not always use the same solution as previous teams
- **Extensive discussion within the test team and at the safety review board regarding what the pilot action should be when an “Abort” call was made**



Sanctity of “Abort”

- **F-35 AGCAS safety plan**
  - GMP - AGCAS and MGCAS are the *systems under test*; they are not to be relied upon for terrain avoidance cues
  - GMP - If the aircraft is in the middle of an AGCAS or PIF recoverywhen it reaches or exceeds any of the abort criteria, the pilot shall activate the paddle switch to end the AGCAS or PIF recovery and manually perform an abort recovery



Results in Test Execution

- **No ambiguity regarding expected pilot actions when an "Abort" call was made by the control room**
- **Removed requirement for the test team and/or pilot to make a real-time evaluation of whether or not the system under test is operating as expected**
- **All test points planned so that full AGCAS recovery would occur within the dive planning abort criteria**

Results in Test Execution (cont'd)

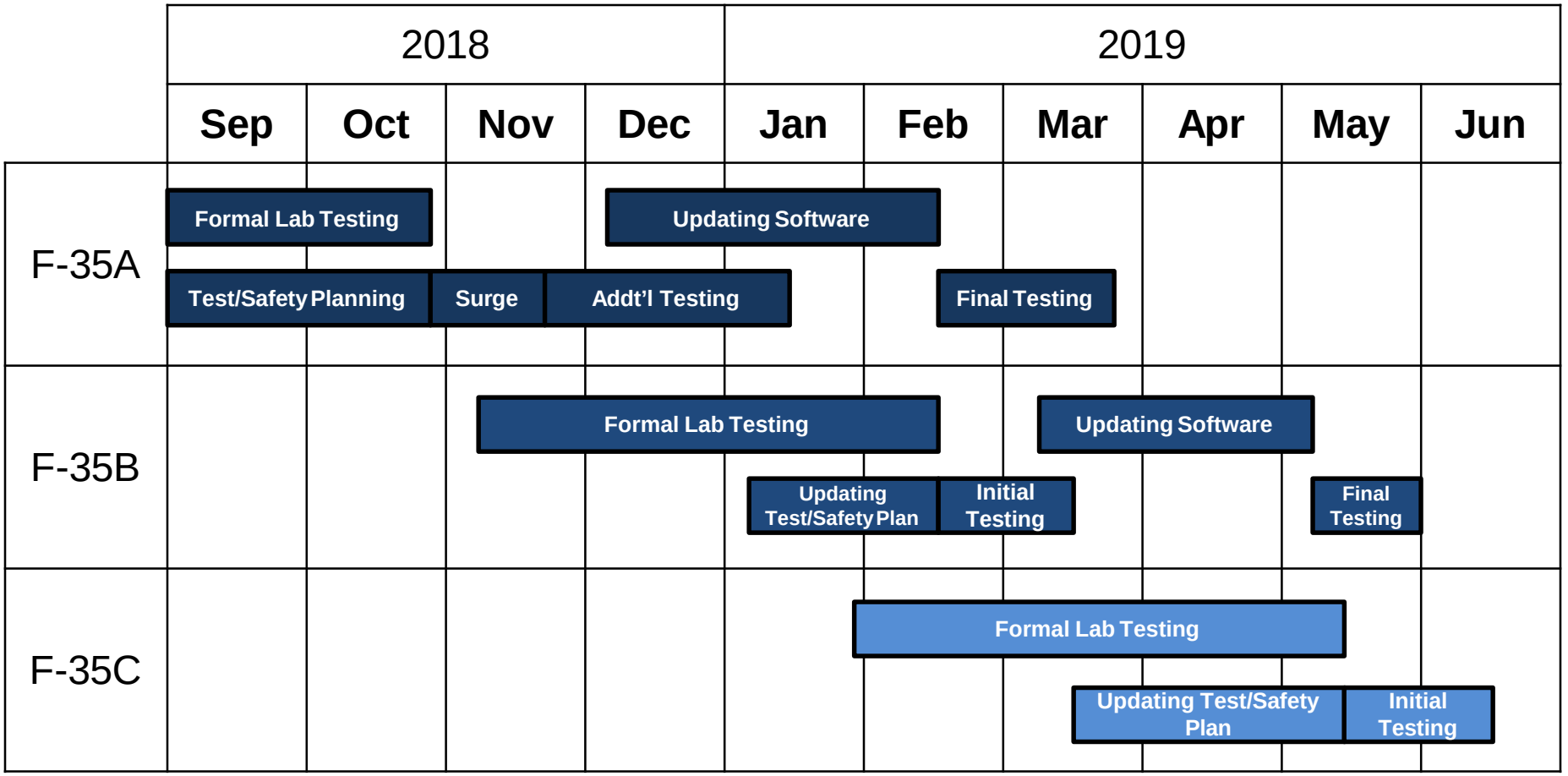
- **Ensures "real TSMs" are communicated**
- **Even utilizing maximum MTC setting, some test points had TSMs that were less than 4 seconds**
  - To reduce the likelihood of reaching the abort criteria the following minimizing procedures were incorporated:

  - Pre-Test Planning
    - Determined expected altitude loss with simulator
    - Add 50% altitude loss to card
    - Mission rehearsal with pilot
    - Discussed in brief

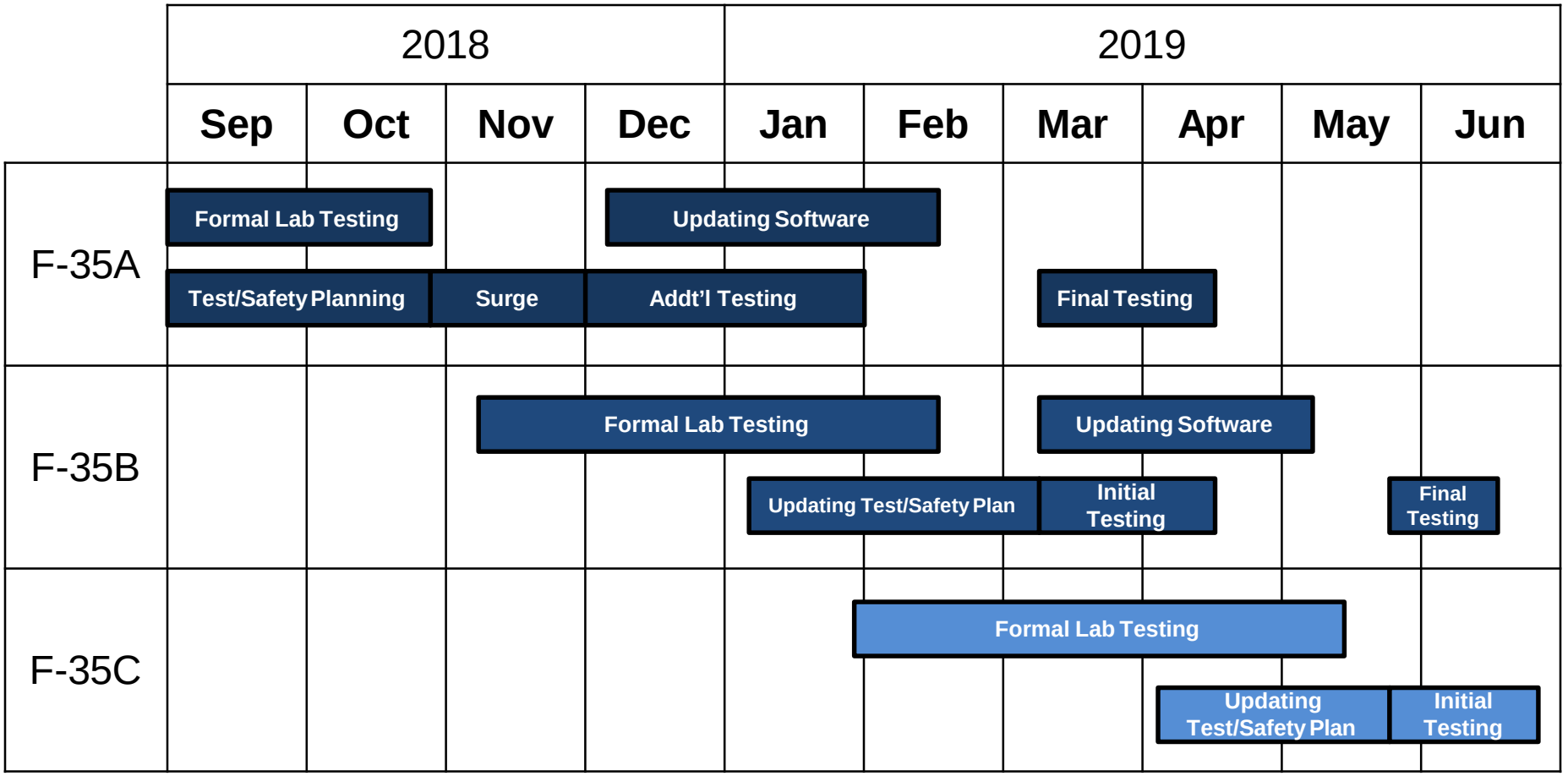
  - Test Execution
    - "Recover" call made by control room at 50% altitude loss
    - Pilot would acknowledge control room call
      - If already in an AGCAS recovery, pilot would allow AGCAS to continue
      - If AGCAS recovery has not started, pilot would manually recover the aircraft

Test Execution

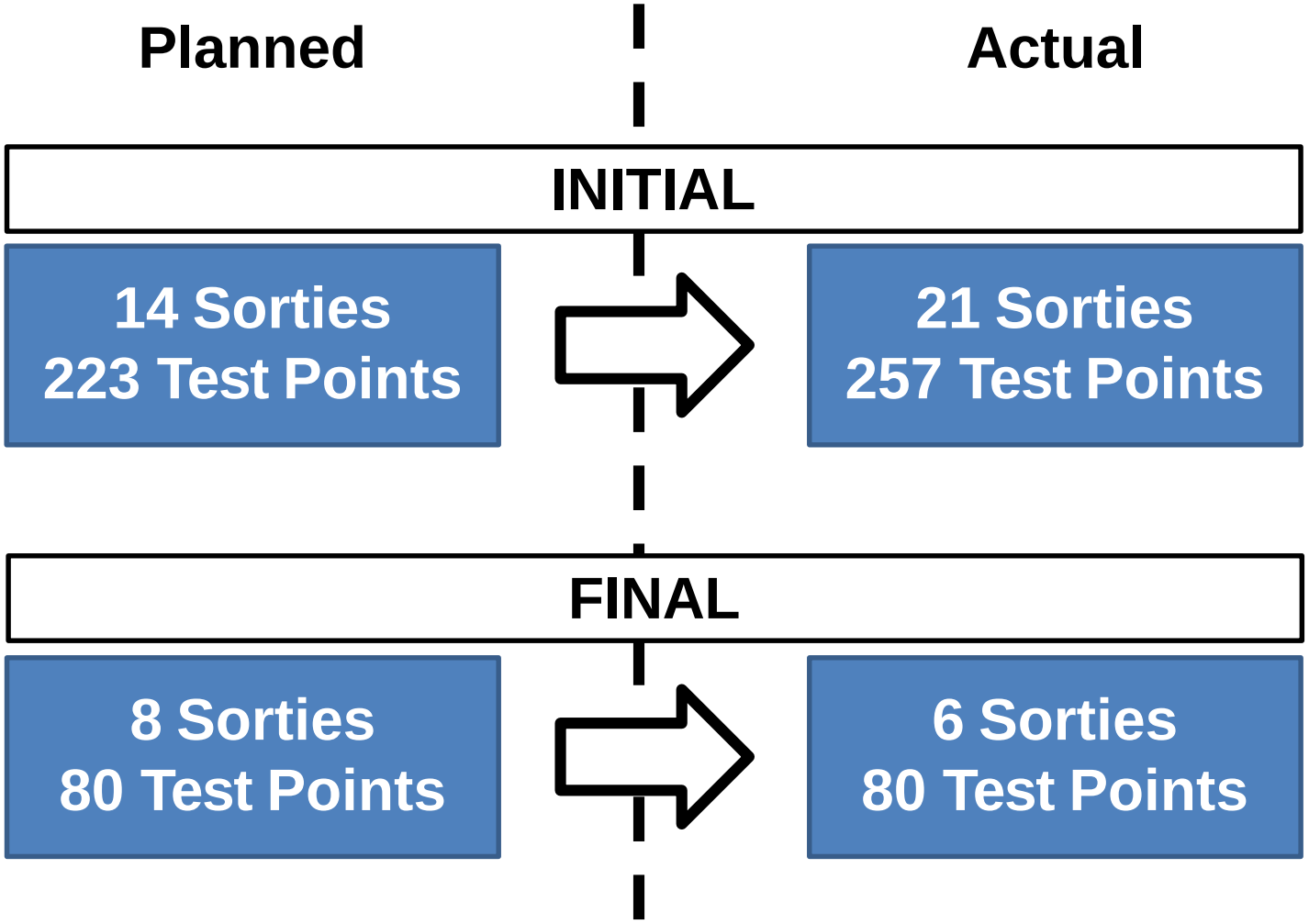
Planned AGCAS Schedule



Actual AGCAS Schedule



Summary of F-35A Testing



F-35A AGCAS Test Execution

- **Motivation for accelerated test timeline**
  - 2 - 3 weeks to gather data to effect future software changes
  - Initial testing required to allow release to operational test before fielding
- **Prioritize test points to ensure critical data is gathered as soon as possible**
  1. Airworthiness/safety critical interlocks
  2. Performance/nuisance test points required by Lockheed Martin
  3. Performance/nuisance test points tied to requirements verification/airworthiness certification/ operational test release
  4. Remaining interlock testing
  5. MGCAS regression

Test Surge

PLANNED

- **3 week timeline**
- **2 sorties per day twice per week**
  - Two different pilots (both will attend mission brief)
  - Same AGCAS engineering team
  - TC/TD team
- **Utilize two aircraft (one morning sortie and one afternoon sortie)**
  - Delta brief between missions
- **Tanker support desired**
  - Backup plan to use hot pits
- **May require a couple of clean-up sorties**

ACTUAL

- **5 week timeline**
  - Control room discrepancies
    - Control room display setup
    - Data latency
  - Test card development
    - Dive planning constraints
- **2 sorties per day twice per week**
  - Number of sorties per day varied based on available resources
- **Many clean-up sorties required**
  - Less than expected efficiency during surge

Test Execution

Maneuver Development

- Initially can be used for test point matrix development
- Need to have more structured approach once test point matrix is finalized
- Should be used to help develop test cards

Dive Planning

- Squadron dive planning guidance was being updated concurrent to test/safety planning
- Should have a first hack before maneuver development

Test Cards

- Should have a first hack before maneuver development
- Need engineering to review test cards early in development
- Plan order of test point execution and organize card decks accordingly

Mission Rehearsal

- Need to find balance between time spent rehearsing on ground versus executing in the air to maximize efficiency
- Sometimes required by safety planning

Test Execution

Mission Brief

- General AGCAS academics and mission execution strategy could have been presented prior to shorten mission briefs
- Need a notional test point order prior to mission brief
- Applicability of single mission brief for two separate missions

Mission Execution

- Control room monitoring not required for operationally representative maneuvers
- Flexibility during mission execution (e.g. communications, test time, test point order, airspace management, etc.)

Mission Debrief

- Two missions in one day resulted in insufficient time for full debrief of first mission
- Carrying forward lessons learned

SEQNO:	EVENT DESCRIPTION:	TEST POINT:	RISK:

TEST CONFIGURATION

Altitude FAB		GCAS		Instrumentation		Aircraft	
LIS	**Abort Alt**	GCAS	**Auto**	DART Format	**2**	Weight	**<XXK lbs**
ALOW2	AR	LEVEL	**NORM**	Data Pump	**CNI/OKM**		
ALOW1	0		**MTC**				
		8000	**± _____**				

SETUP:

10.6 (K ft MSL) **250** (KCAS/MACH**)**

Power LVL Flight

TEST CONDITIONS AT: BREAK-X OR PIF

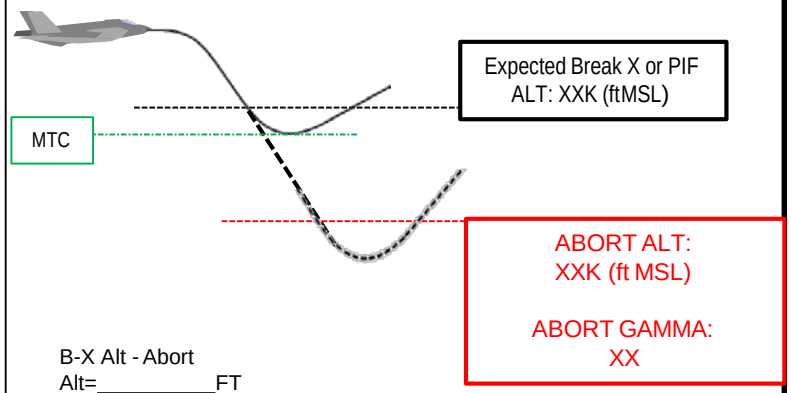
SPEED (KCAS/MACH)	DIVE(°γ)	BANK (°Φ)	Nz (g)
275 ± 25	-30 ± 10	180 ± 30	1 ± 0.5

Maneuver:

Roll 180

Let Nose Fall

To 30° Nose Low



STEP	RUN DESCRIPTION	LIMITS
1	(TP/CR) Verify **GCAS AUTO / MTC / LIS**	
2	(TP) When at initial conditions: initiate descent and establish Break X Conditions	
3	(TP) Observe Auto GCAS Recovery at BREAK-X	

I.C.	H_R	γ_P	γ_R	TSM	Terrain
	9000	-35	-40	**4.0**	3000

4.6G pull, 472 kts, 130 BAC, 54Klb, 1.5G, B35.1(AF), ATG, SPADE v3.7

JTP:	DATE OF LAST UPDATE:	IPT / TC / PROJ PILOT REVIEW:

Required Equipment: F-35A/F-35B , DART pod, CNI, Radar
Required Data: DART, TSPI, PCD/HMD Video and Audio recording
Required Config:
Required Ranges: Local
Required Airspace: 2515 w/ Rogers, Cuddeback, Rosamond, Harper, etc lakebed

Specific Objective:
Verify AGCAS functionality in the external stores config through DTST.

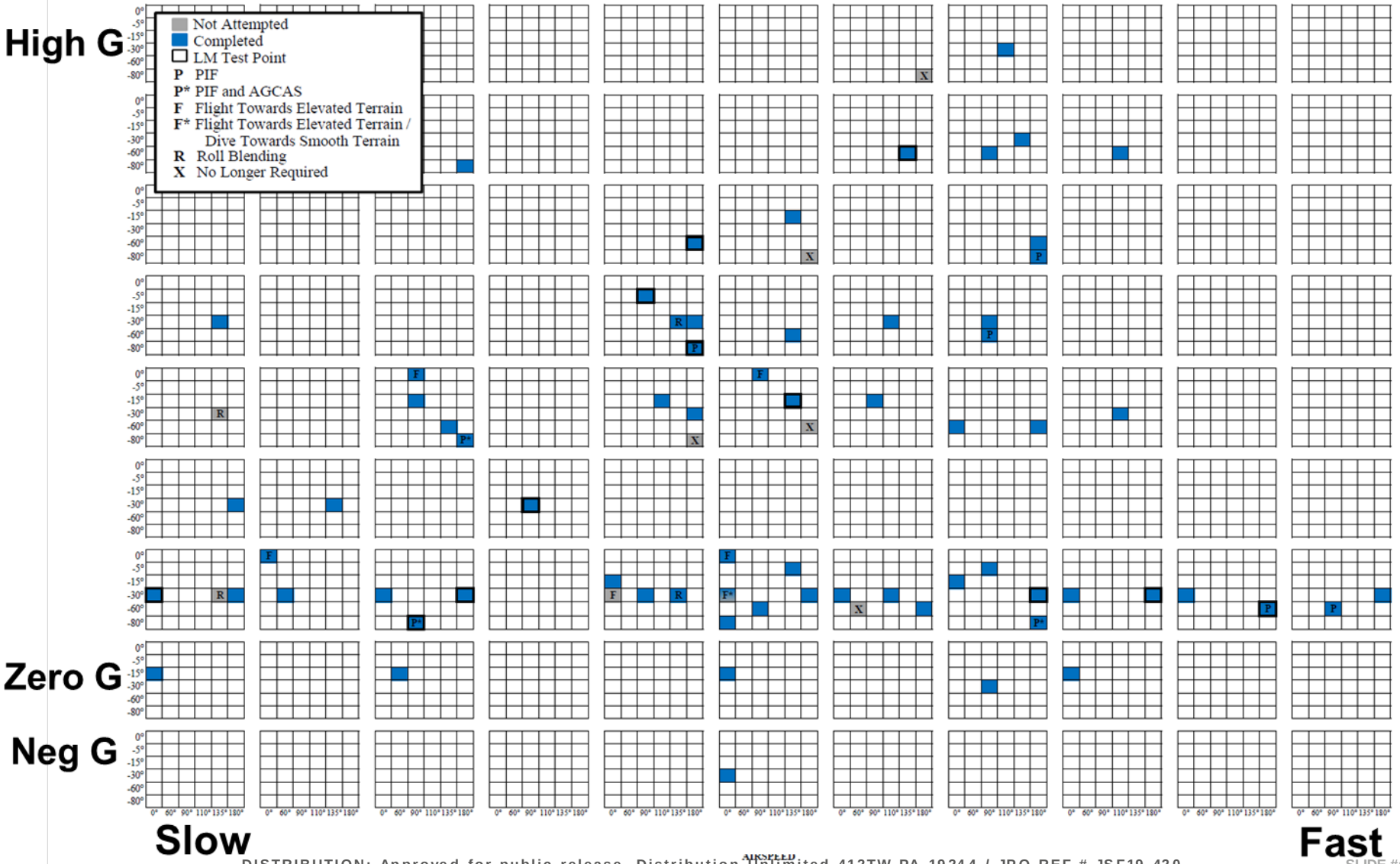
Expected Results:
AGCAS is expected to provide initiate a Fly up before penetrating MTC

Notes:
1.Gross weight and bank angle limitation is due to SPADE calculations. The bank angle limit is not applicable to setup.
2.MD is based off of system alt. View system altitude on INS page.

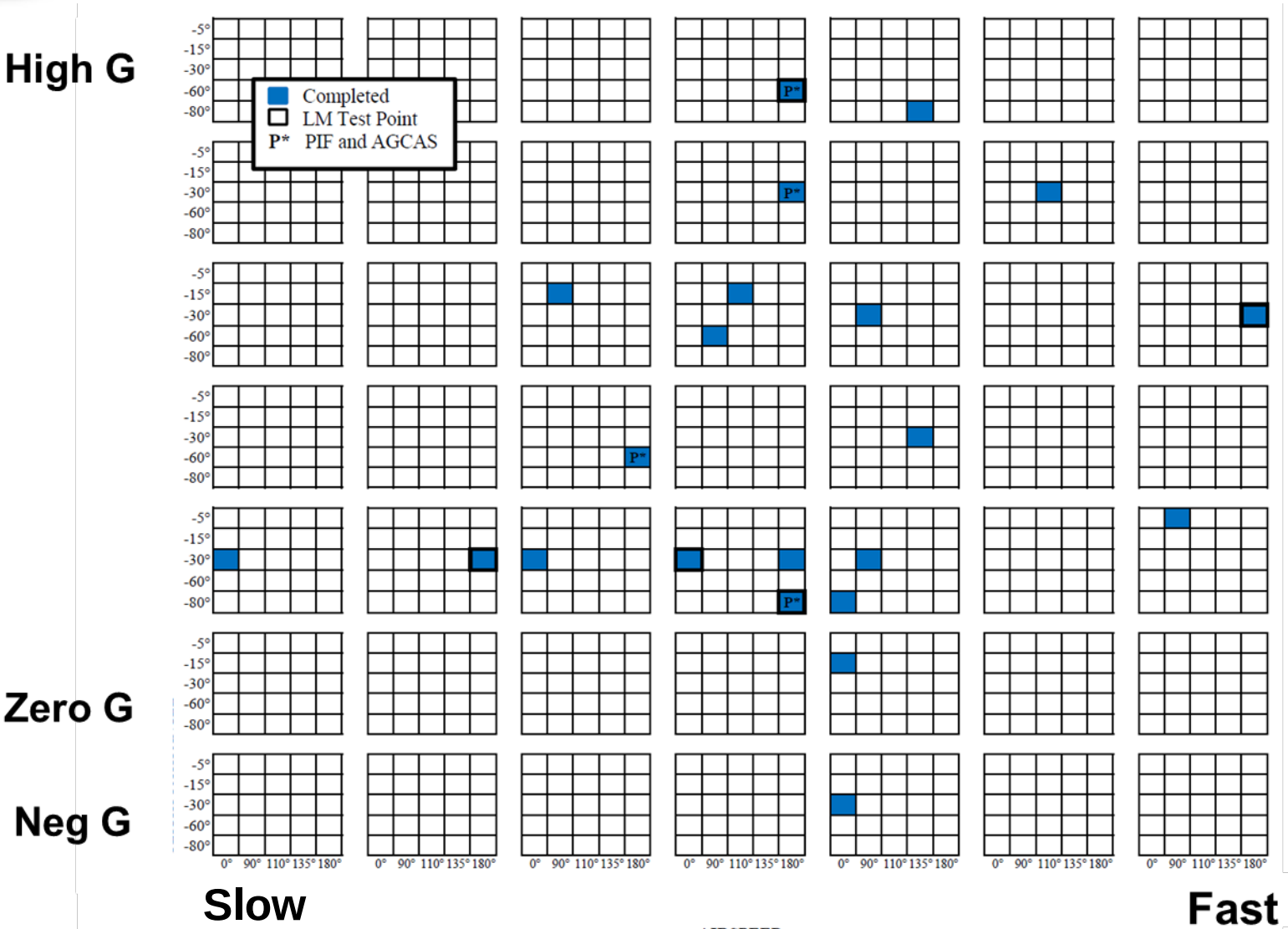
Maneuver Development:

Test Results

Clean Wing Performance Testing



External Stores Performance Testing



CLAW vs. CAM

- **Across all recoveries, the CLAW response and actual recovery outperformed the CAM's prediction**
- **MTC clearance varied from approx. 175 ft - 5000 ft**

  Only one very small MTC penetration was observed
- **Much more sensitive at steeper dive angles**
- **What about at slower speeds?**

Available Reaction Time

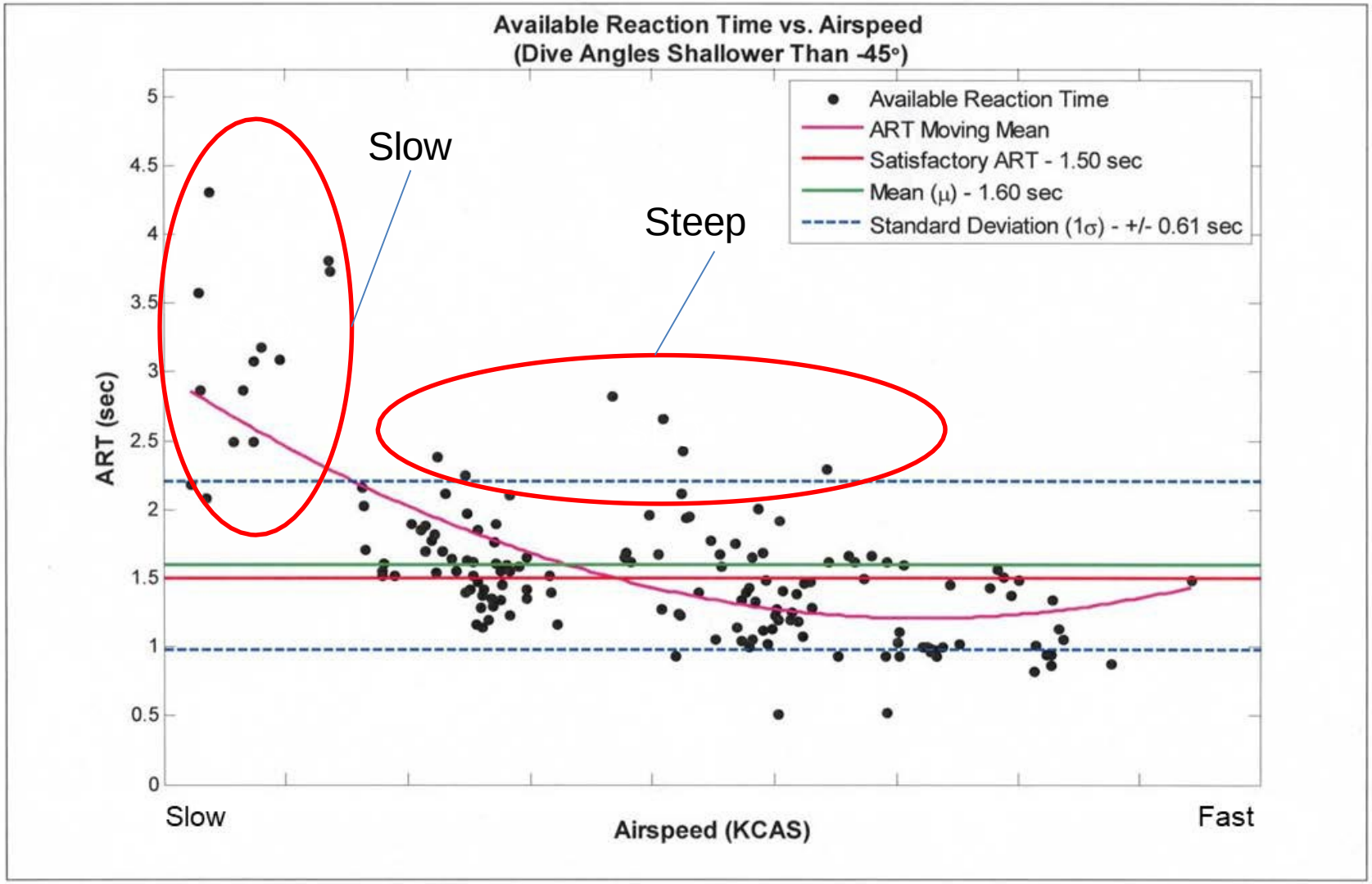
- General requirement for ART to be less than 1.5 seconds
- Team knew from NASA, FRRP, and previous F-16 testing, this criteria only applied during “shallow” dives
- Also, AGCAS recoveries at low speeds(< 2g available for recovery) was a new part of the envelope for ART calculations
- Although the CAM TPA calculations always showed ART less than 1.5 seconds, the implementation of the CLAW always outperformed CAM. Resulting in ART’s > 1.5 sec over 50% of the time.

Available Reaction Time

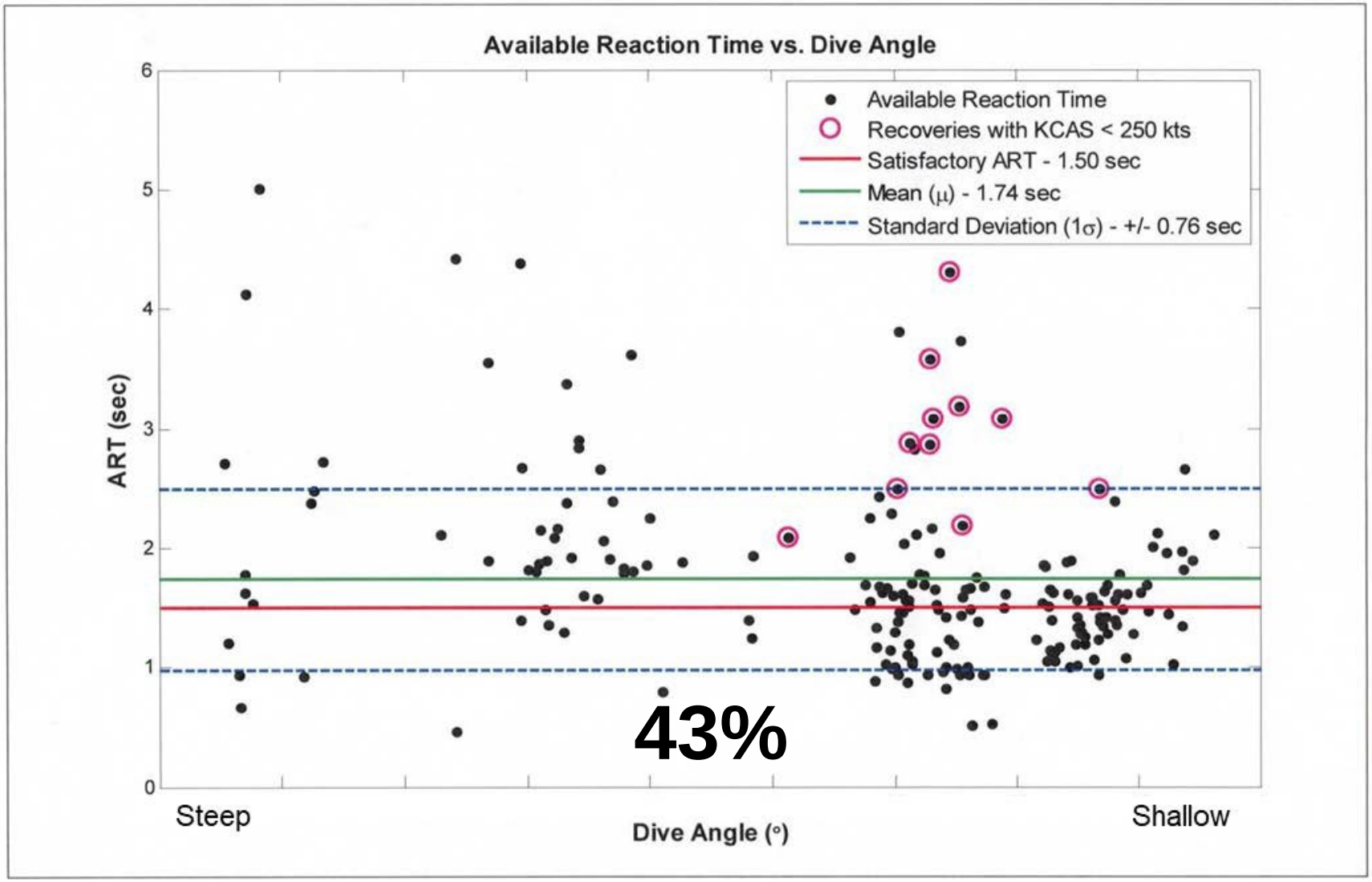
- **Condition 1: All dive angles**
- **Condition 2: Test points shallower than -45°**
- **Condition 3: Test points steeper than -45°**
- **Condition 4: Test points shallower than -20° and a bank angle shallower than ± 140°**

Condition	Recoveries ≤ 1.5 seconds (%)	Mean (seconds)	Maximum ART (seconds)
1	43.1%	1.74	5.01
2	50.6%	1.60	4.31
3	20.0%	2.17	5.01
4	53.6%	1.51	2.67

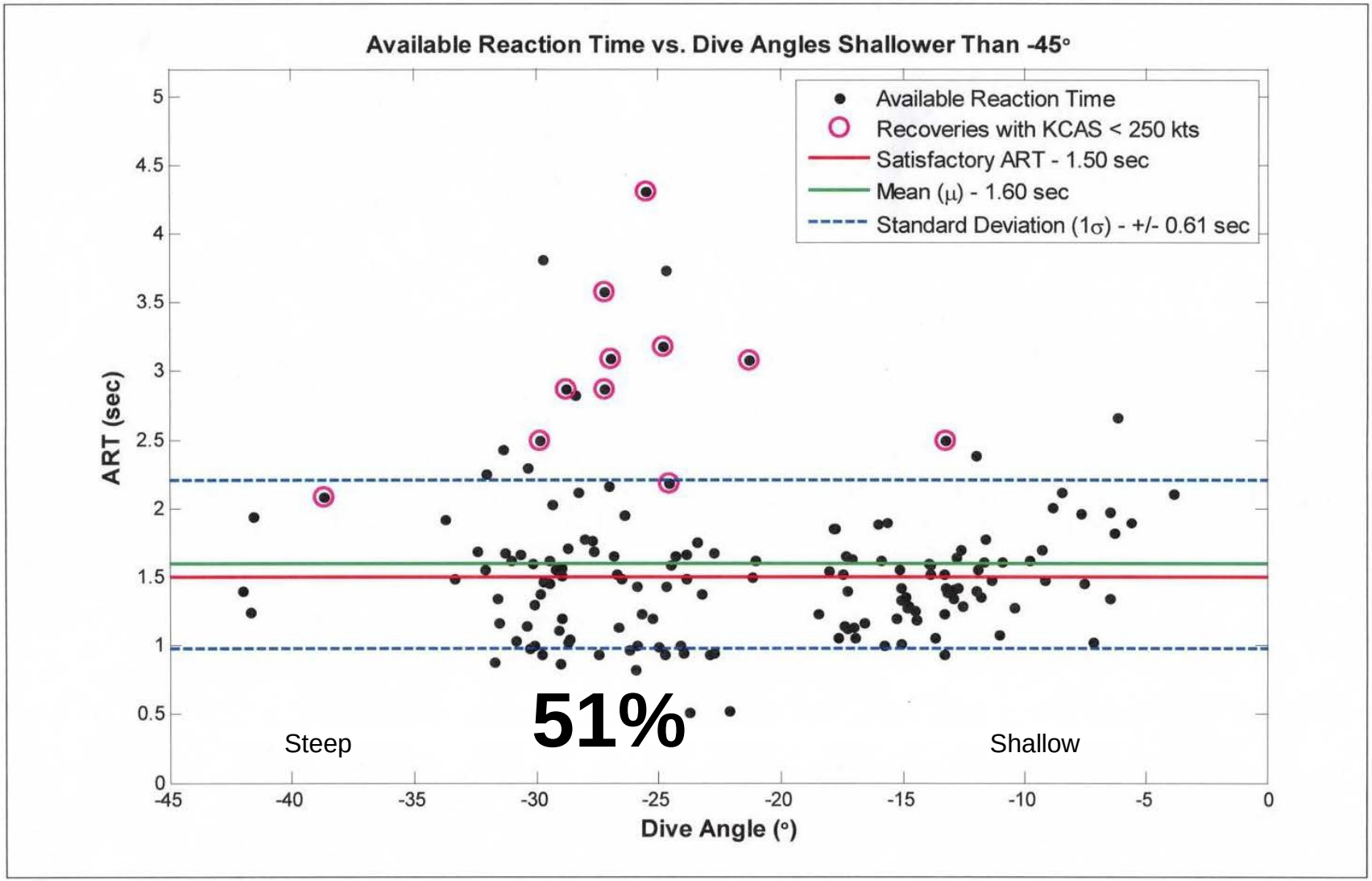
ART vs Airspeed
All test points shallower than -45°



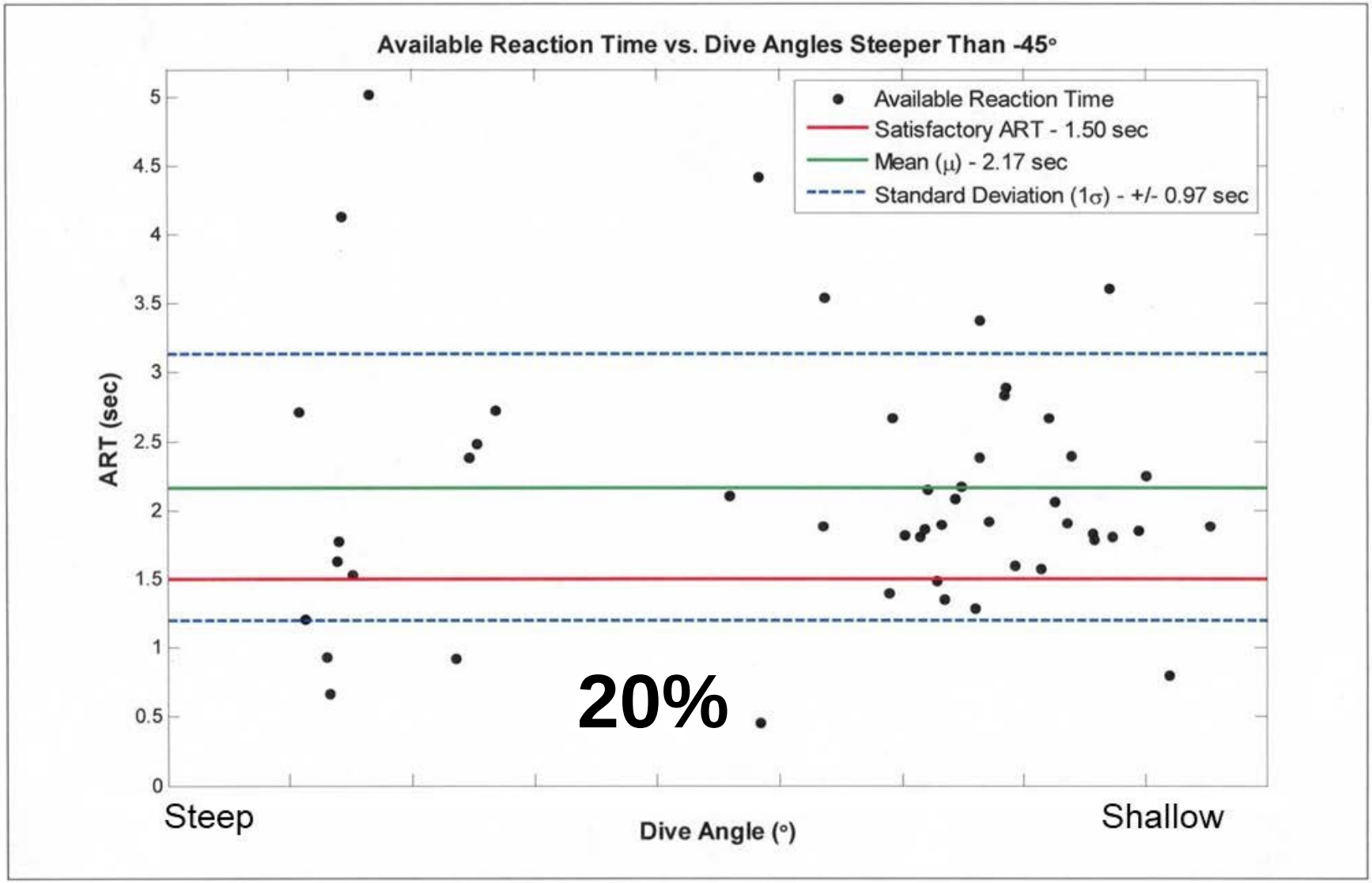
Condition 2: ART vs Dive Angle All Dive Angles



Condition 2: ART vs Dive Angle Shallower than -45°

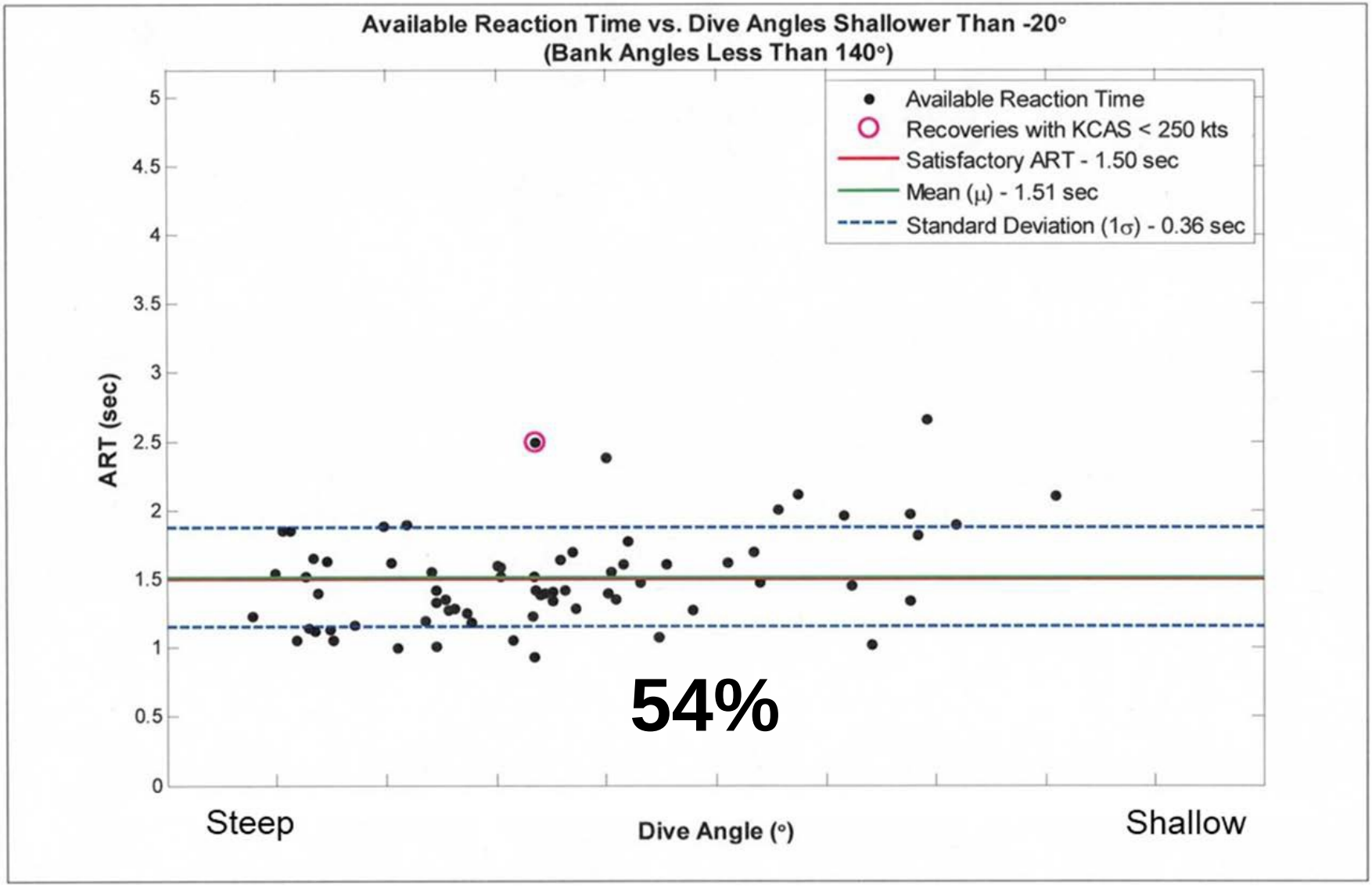


Condition 3: ART vs Dive Angle Steeper than -45°



Condition 4: ART vs Dive Angle

Dive Shallower than -20° & Bank Less than ±140°



Nuisance Evaluation Rating Scale

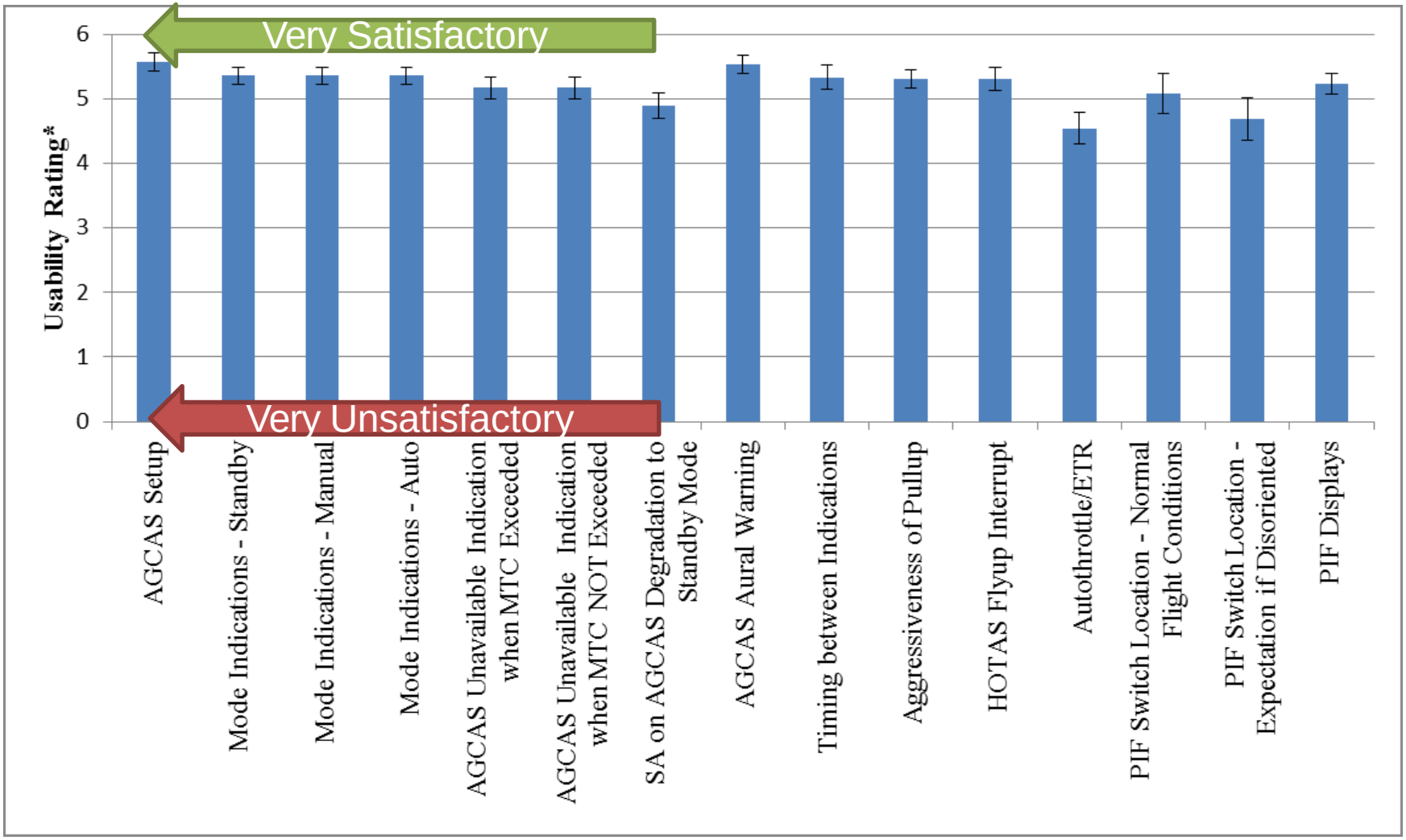
Was the fly-up initiation appropriate and was the fly-up terminated once terrain clearance was assured?
If not, use the scale below to rate each occurrence and provide comments.

Flight Path Deviation/ETR Change (Auto throttle) and/or Mission Impact	Nuisance Level	Rating	Improvements
Brief or insignificant deviation from desired flight path. **and/or** Negligible to minor impact to completion of mission tasks.	Non-Nuisance	Satisfactory	Not Needed
Minor to moderate deviation from desired flight path. **and/or** Minor to moderate distraction made completion of mission tasks more difficult but still possible.	Minor Nuisance	Marginal	Warranted
Moderate to severe deviation from desired flight path. **and/or** Ability to complete mission tasks substantially degraded or unable to complete critical mission tasks.	Major Nuisance	Unsatisfactory	Essential
Pilot intervention required for flight safety. **and/or** System induced unsafe handling qualities.	Unsafe	Failed	Mandatory

PVI Evaluation Questionnaire

- AGCAS set up (mode/level selection)
- Mode indications
- Rate the clarity of the AGCAS unavailable indications
- SA on AGCAS degradation to standby mode
- AGCAS aural warning
- Timing between indications
- Aggressiveness of pull-up
- HOTAS fly-up interrupt
- Auto-throttle/ETR
- PIF switch location
- PIF displays
- AGCAS/PIF abnormalities (other than nuisance)
- Military utility of AGCAS/PIF

PVI Evaluation

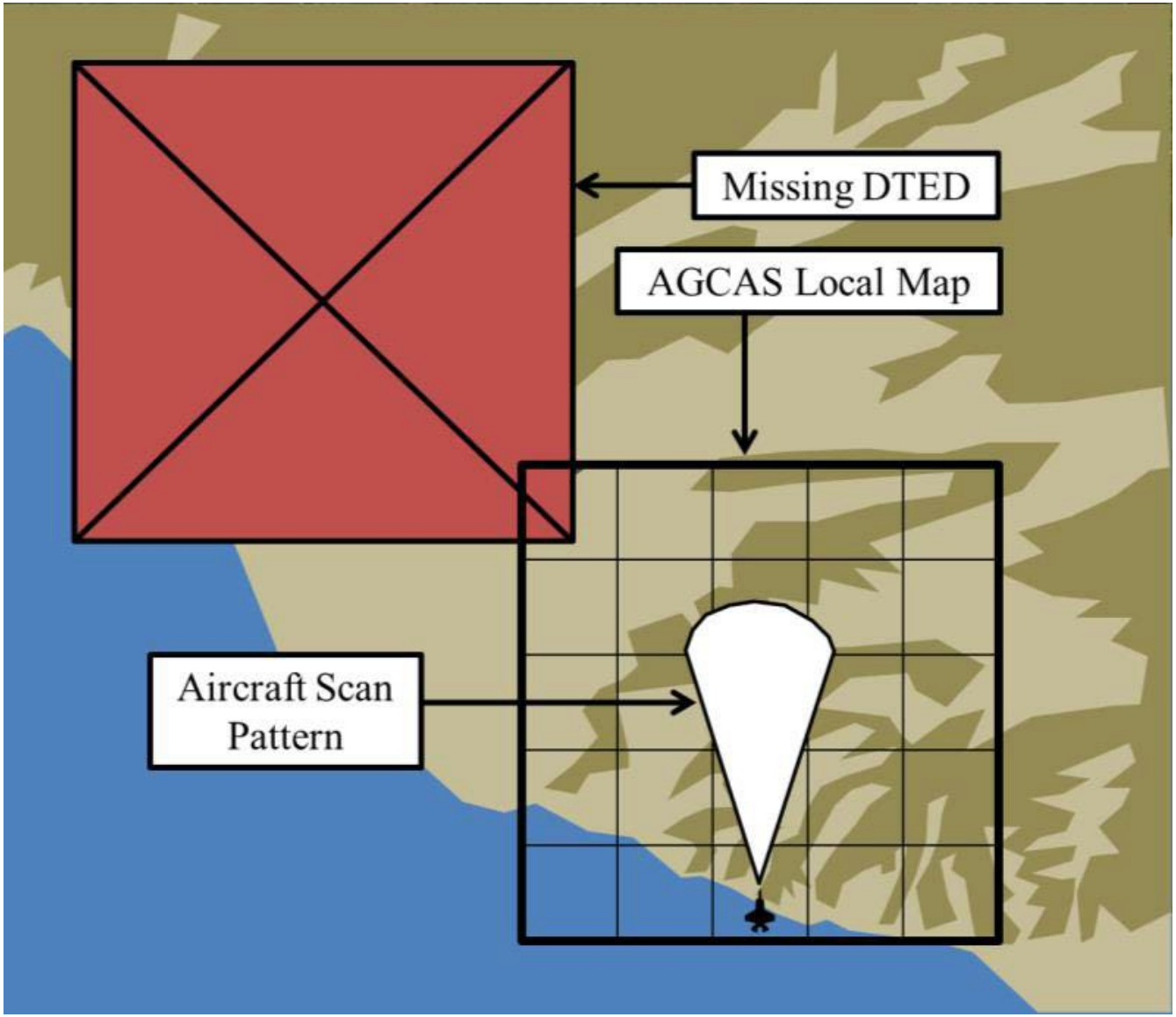


System Anomalies

System Anomalies

- **AGCAS Fail Advisory ICAW**
  - System monitors were excessively sensitive and one particular jet had extra special wiring issue specific to test configuration
- **Pull-through logic** Washout Initialization Error
  - Initial flyup uses default value (1g), Subsequent flyups use the Nz seen at the beginning of a previous roll-and-pull or at pull-through exit from a previous flyup.
- **CAM Declares Off Map** if any tiles of the local map. Scan pattern may include all good tiles but off map status declared, resulting in reversion to 50 ft AGL flat Earth model.
- **Ability to turn off chevrons for specific tasks.** Several pilots found the presence of converging chevrons during low angle strafe distracting with negative impact on the task.

System Anomalies



Lessons Learned

Flight Test Lessons Learned

- **LL1: If you don't know the system design, you don't know what to test -** Test planning/execution requires full understanding of the system under test by the test team. Sometimes it is difficult to know what questions to ask.

- **LL2: The first draft of test point matrix shouldn't be the last -** Agile testing is hard but rewarding. It is important to keep up with model validation and data analysis to amend plan.

- **LL3: Control Room data mismatch –** Know safety of test parameters and have a plan when

Flight Test Lessons Learned

- **LL4: Help draft the requirements and fight for the appropriate language. Available Reaction Time (ART) -** Requirements can provide guidance to produce the desired system performance but misunderstood words can drive less than useful analysis and discussion when attempting to go fast

- **LL5: Some testing is best left to the simulator –**
  - For reasons of safety, efficiency or to answer stupid pilot curiosity, not all testing needs to be done in flight. This requires quick model validation with flight test results.

- **LL6: Don't let safety planning processes make you less safe -** Preserve the sanctity of Abort and make smart team decisions.

Future Testing

Future Safety Considerations

- **Newest software increases range of MTC setting so that maximum is 99,990ft**
  - Allows team to execute with higher TSMs
- **Threshold for “Recover” call could be changed from 50% to a different value**
- **Detailed definition of communications contract between control room and pilot**
- **How to preserve the sanctity of “Abort” during Auto-ACAS or Auto-ICAS testing**

Future Technical Considerations

- **AGCAS on other airframes**
- **ICAS**
- **Combat autopilot**

Questions?

CHANGE LOG

- General: AGCAS never defined. Added to overview slide
- Slide 4: Removed AFRL study $ amount
- Slide 11: Slide heading does not match slide content, includes only figures to include figure numbers. Changed slide heading and removed figure number labels
- Slide 14: For Roll commands could add that roll acceleration is limited. No Change. Statement is correct, max CLAW roll rate is always commanded. G is adjusted to prevent rolling over-g (3.5 target while rolling)
- Slide 16: Slide heading does not match slide content and is the same as Slide 11. Will delete and re-number slides
- Slide 20: Tables B1-B3 are not in presentation, these tables are marked B4 & B5. Removed specific airspeeds. Removed Table labels
- Slide 24: Summary of Testing may not need to include testing not relevant to discussion. No change. Important to remind pilots and future system designers of the true priorities of the system and testing priorities
- Slide 45: Briefing content cannot be assessed. From Jim Baxter and Jeff Harris at LM. "ADP confirmed that don't have concerns with simply quoting the range of MTCs that you observed in test as long as not relating to specifics of initial conditions or anything tactically relevant." "If your making a statement that the F-35 design mimicked the F-16 and set a 20 deg AOA limit, and that leaves some performance on the table….then I would be OK with that."
- Slide 47: suggestion: Number the Conditions above the table to indicated correspondence below. Added Condition # to words to match table
- Slide 55: Could benefit from an indication of usability rating value meaning. Added general label to top and bottom of scale to give general good/bad indicator
- Slide 57: Formatting. Reformatted Lessons Learned
-
- Slide 20: Recommend not using actual design values. Recommend instead "Nominal Recovery Airspeed +20 knots", "Nominal Recovery Airspeed -20 knots", "near AoA limit", "Slow". Changed words to not use design values and be more general.
- Slide 21: Recommend not using actual design values. Removed pitch angle values
- Slide 40: May reveal F-35 performance information. Removed aircraft limits
- Slide 43: May reveal F-35 performance information. Removed airspeed and G
- Slide 44: May reveal F-35 performance information. Removed airspeed and G
- Slide 47: Removed all information not pertinent to ART discussion about requirements language
- Add to previous pictures showing where ART exists prior to recovery
- Slide 48: Figures generated from report with limited releasability as determined by LM. Could remove speeds. Removed Airspeed
- Slide 49: Figures generated from report with limited releasability as determined by LM. Could remove dive angles. Dive angles Removed dive angles
- Slide 50: Figures generated from report with limited releasability as determined by LM. Could remove dive angles. Removed dive angles
- Slide 51: Figures generated from report with limited releasability as determined by LM. Could remove dive angles. Removed dive angles
- Slide 52: Figures generated from report with limited releasability as determined by LM. Could remove dive angles. Removed dive angles
- Slide 40: Still has FOUO marking on the cards. Need confirmation from author that the info can be released. Recommend removing marking if releasable. Removed aircraft limits, system design notes, and removed FOUO label
- Slide 48-52: Chart still has markings for limited release. Need chart author input. Removed airspeeds and dive angles

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Agile Implementation of Collision Avoidance Systems

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Katie Peticolas (Project Team Lead)
Marcea Ascencio (Project Engineer)
LCDR Jonathan Beaton (Test Pilot)
Maj Jonathan Bearce (Test Pilot)
Lt Col Raven LeClair (Test Pilot)
Mr. Andrew Soundy, Test Pilot, Lockheed Martin Corp

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225 N. Flight Line Rd.
Edwards AFB, CA 93524

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195 E Popson Ave
Edwards AFB CA 93524

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14. ABSTRACT

The F-35 enterprise elected to implement AGCAS capability 7 years earlier than originally planned and overcome all real and presumed barriers. This presentation covers some of the lessons learned from jet hardware assumptions to dive planning safety considerations and test methods that have changed forever the way we plan and execute medium to high risk diving test points. Ultimately, this presentation will demonstrate an agile path from the first AGCAS test flight to release to unmonitored active AGCAS system on all squadron jets in three days.

15. SUBJECT TERMS
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