LESSONS LEARNED DURING DEVELOPMENTAL TEST OF THE X-47B AIRCRAFT

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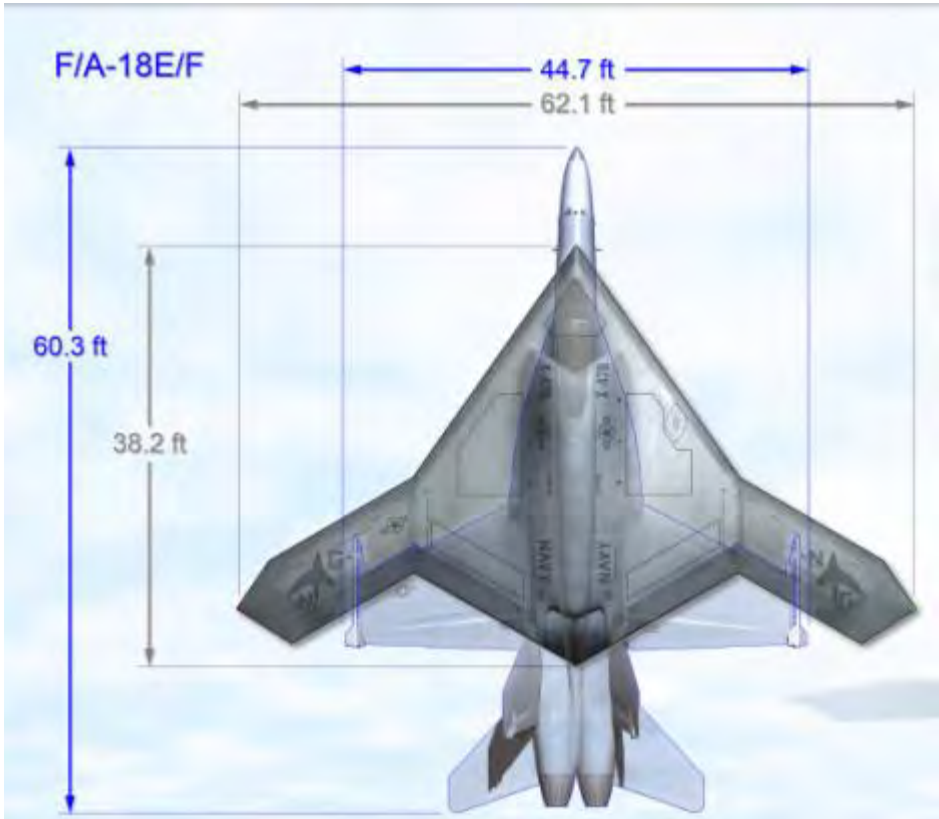
First Flight Video

UCAS-D Air Vehicle System (X-47B) in Focus



Design	*Tailless, cranked-kite*
Plan form	*LO relevant features*
Structure	*Carrier approved*
Take-off gross weight (demo)	*44,000 lbs*
Engine	*PW F100-PW-220U*
Twin Internal Weapons Bays	*4,500 lbs payload*
Aerial refueling provisions	*USN / USAF style*
CV launch OPWOD	*+2.2 knots*
CV recovery WOD	*+7.2 knots*
Spot factor (F/A-18C)	*0.87*

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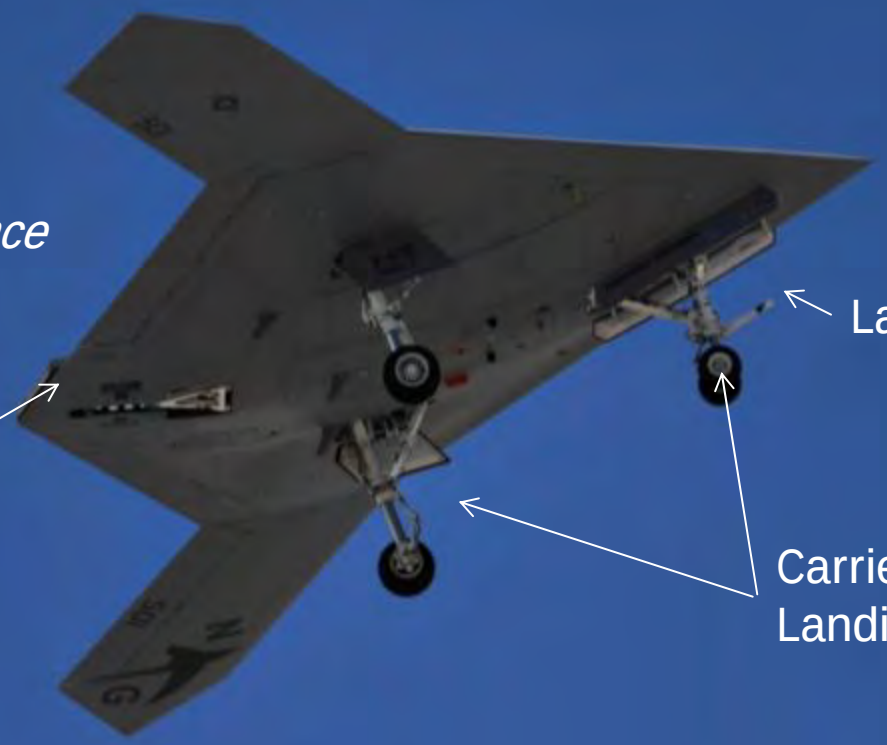
System Description – Design Features

Carrier Suitable System

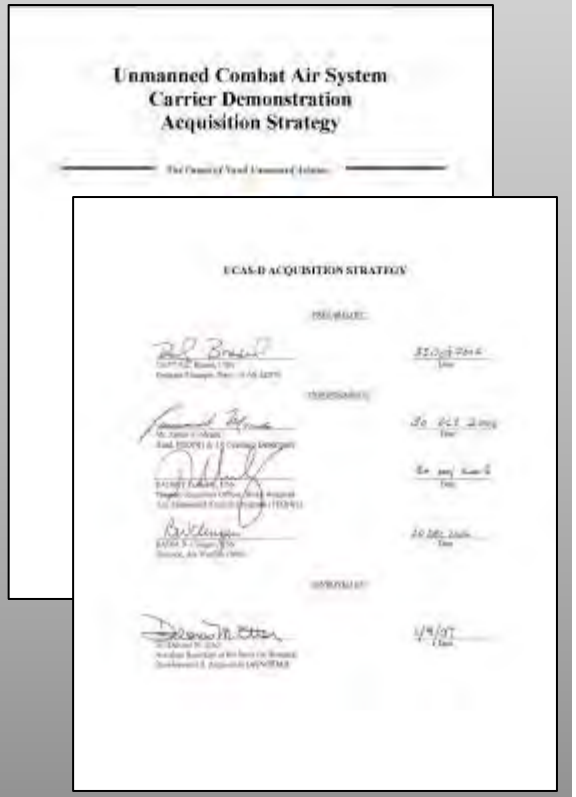
- *Strength, Durability, and Damage Tolerance to NAVAIR Requirements*
- *Carrier Suitable Vehicle Management and Flight Control System*
- *Carrier Suitable Performance and Flying Qualities*

LO relevant design



UCAS Demonstration Objectives

- Demonstrate critical technologies for a Carrier Suitable, Low Observable (LO) Unmanned Air System in a relevant CVN environment (TRL-6)
  - Carrier Control Area (CCA) Operations
  - Catapult Launch and Departure Performance
  - Arrested Landing Performance Including Approach, Wave off and Bolter
  - Mission Control Segment (MCS) CVN Integration
  - UCAS interface to CVN and associated systems
- Critical Technologies include:
  - Autonomous CV/Tanker Airspace Ops
  - Guidance/Navigation/Control
  - Flush Air Data Systems
  - Tailless Vehicle Aero/ Control
  - Low Latency Safety of Flight C2
  - Precision Navigation in CCZ
  - Deck Handling/Deck Operations



TRL - 3

TRL - 6

Lab Testing	C-12 & F/A-18 Surrogate	Airworthiness Testing	Shore-Based Ship Suitability Testing	Carrier Control Area Testing	Sea-Trials

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Test Program Scope & Buildup

- **Extensive Shore-based Lab Integration, M&S**
- **X-47B VMS Surrogate Flight Test**
  - **Vehicle Management System**
  - **MCS Integration**
- **A/SI Surrogate Flight Test**
  - **CV Segment Verification**
  - **Shipboard TTNT, PGPS Testing**
  - **CCA Operations**
  - **Approach, Bolter, Wave off, Departure**
- **Surrogate Shore Launches**
  - **CV Segment Verification**
  - **Shipboard TTNT, PGPS Testing**
  - **Shipboard MCS Testing**
  - **CCA Operations**
  - **Approaches, Touch and Go's**
  - **Nominal & Off-nominal Tests**
- **Airworthiness/Envelope Expansion**
- **Shore-based Ship Suitability Tests**
  - **Catapult Launch, Arrested Landing**
  - **Deck Handling**
  - **Landing System Tests**
  - **Simulated CCA Operations**
  - **E3 Testing for CV Environment**
  - **Hoist Aboard**
- **UCAS Shore Launches**
  - **CCA Operations**
  - **Approaches, Touch and Go's**
  - **Build down to first trap**
- **UCAS CVN Operations**
  - **Deck Operations, Catapult Launch, Departure, CCA Ops, Approach, Trap, Wave off, Bolter**

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X-47B Block 1 Edwards AFB

- Taxi, airworthiness testing
- Command and control data link verification
- Ground handling
- Navigation performance

- Airworthiness
- Flying qualities
- Approach and landing performance

Surrogate Aircraft Testing

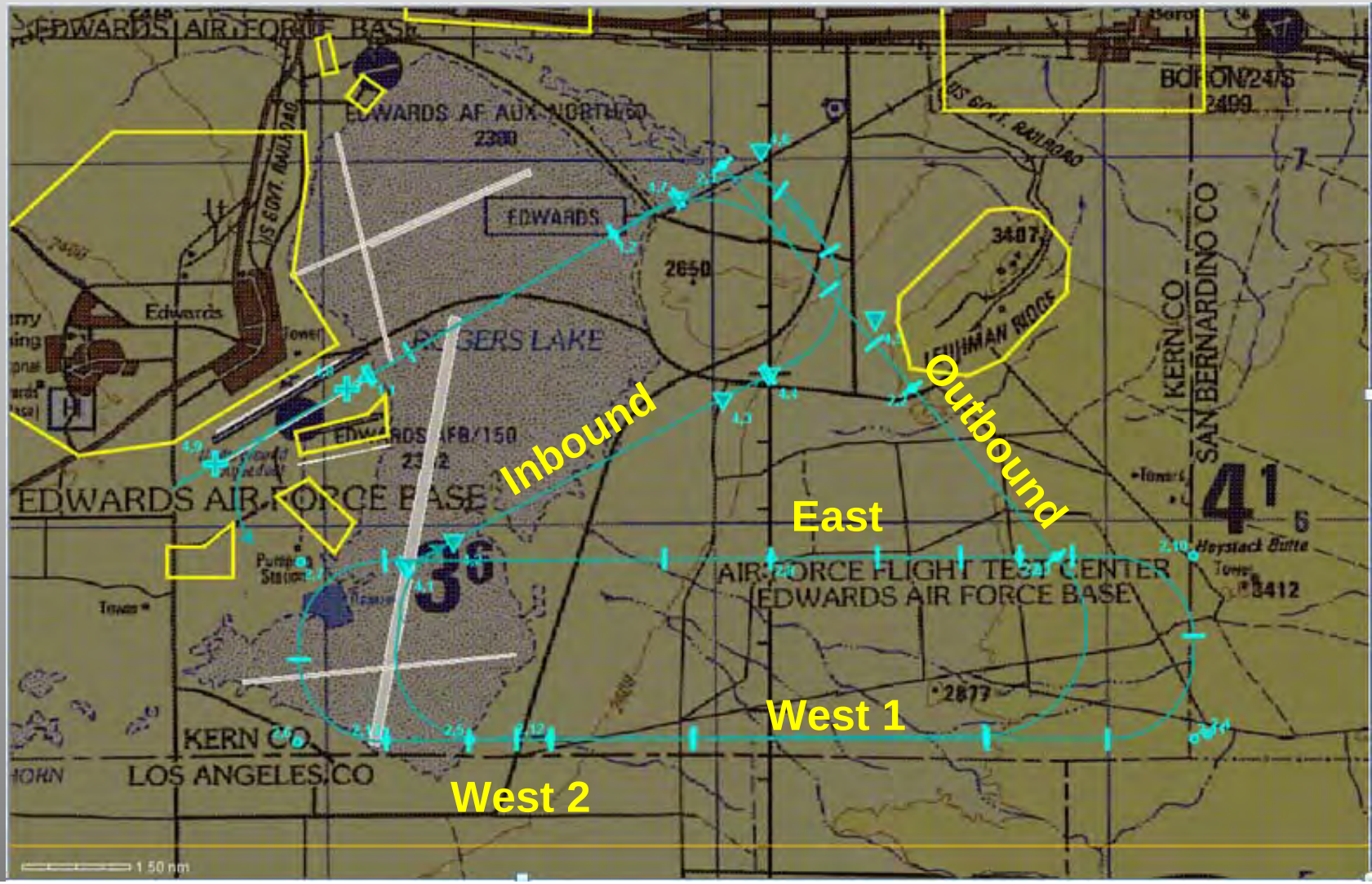
- Manned surrogate testing used to mature and validate critical technologies for the UCAS demo
  - King Air, Lear Jet, F/A-18D, and K707 Tanker aircraft modified with UCAS hardware and software
  - Several aircraft carriers modified with the systems to support UCAS operations for the demo program
- Aircraft Carrier Systems surrogate testing
  - USS HARRY S. TRUMAN (CVN-75) test detachment in February 2010
  - USS DWIGHT D. EISENHOWER (CVN-69) test detachment in July 2011
- Autonomous Aerial Refueling surrogate testing
  - Niagara falls test detachment in October 2010
  - Upcoming test detachment in St. Augustine Dec 2011

Overview of Test Results to Date

- Hundreds of hours of on-aircraft Systems Check Out (SCO) and VMS 0015 check out
- Dozens of tow tests – now a standard maintenance evolution
- Full EMC/SOF evaluation of the Edwards AFB environment
- Over 100 mission rehearsals, simulator sessions, etc
- Over 100 Low, Medium and High Speed Taxi test events
- 18 Flights on the X-47B
- Hundreds of flight hours across 4 manned surrogate aircraft

X-47B Test Flight Route

Gear Down, 29 minutes total time en route



X-47B Flight 1-5 Highlights

- Testing accomplished:
  - 140 -180 KCAS in PA configuration, 160 – 180 in TO configuration at 5,000 and 7,500 ft
  - Pitch/Yaw/Roll doublets, steady heading sideslips, throttle burst and chop
- Nominal performance during all three flights
  - Cross track error, altitude error, and air speed control were very precise
- Acceptable Air Data System performance
  - Flush Air Data System , no flight test boom
- No system failures or faults
- Excellent touchdown dispersion and braking results
- RTB on Flight 3 due to indicated structural wing bending load measurement exceeding limit during final sideslip maneuver
  - Post test analysis indicated strain gage drift and no limit was exceeded
  - Effective drill for the test team!

Surrogate Testing Highlights

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- Completed initial field performance testing of the UCAS carrier landing systems
  - Precision (Differential) GPS guidance using high speed data-link (Tactical Targeting Network Technology (TTNT)
  - Straight-in (Case 3) and approach turn (Case 1) automatic (coupled) landings
  - Field results were nominal with acceptable performance to test at CV at sea.
- Completed initial at-sea testing using surrogate aircraft on CVN-69
  - Build up approach – manual then automatic approaches
  - Completed first ever coupled arrestments to an aircraft carrier using GPS only guidance
  - Completed first ever coupled landings and arrestments in a Case 1 (approach turn) pattern to an aircraft carrier

First coupled arrestment

LESSONS LEARNED

Lesson Re-Learned #1
Software, Software, Software

- Airplane built and ready to fly/test on schedule, however, well ahead of software certification readiness
  - Over 2.5M executable lines of code
- V&V takes longer than anticipated after fixes to address discoveries
- Lab/Hardware In The Loop (HITL) testing is critical and can be a choke point
  - Program Action Request (PAR) burn down rate was affected
  - Manpower can be a limiting factor; 24/7 operations at times

Lesson Re-Learned #2A
Autonomous requires mindset change

- Contingency logic / fault response
  - Coding a machine to “react” like a human
  - Need to think of all “what–ifs” ahead of time and code responses
    - Challenge in early development and “unknown unknowns”
    - The desired Autonomous response could be different from what you would want from a manned air vehicle
  - Predictable response / unintended consequences validation

Lessons Re-Learned #2A (cont)
Autonomous requires mindset change

- Contingencies
  - Flight Critical Fault – "It depends"
    - Come back early or have separate profiles for different locations
      - Minimize time aloft
      - Or allow time to deal with emergency
  - Lost Link
    - Have to plan all contingency routing
    - Set Link timers to allow momentary interruptions / regain backup comms
      - Can't be too long in case of other emergency
      - Risk of manually overriding planned flight route with an invalidated comm. configuration
  - General philosophy for contingencies
    - Decide, plan, code for all contingencies on ground
    - Allow AV to execute planned responses and monitor to ensure appropriate
    - **Override as a last ditch if necessary / undesired response**
    - Train for likely contingency scenarios prior to test flights

Lesson Re-Learned #2B
Autonomous requires mindset change

- Flight test maneuvers
  - Developed using standard FTM procedures for airworthiness
    - Multiple conditions and parameters for each condition
      - Coding many combinations for a “menu” of options that can be executed
      - Significant amount of time/effort to validate all maneuvers in simulation
    - FTMs have build up required, so key parameters need to be monitored/instrumented
      - FTE / RE involvement in development and expansion plan
      - Robust test planning
  - No way to change responses airborne or without a software change
    - Significant up front work and planning
    - Anything missed will have to be re-coded or reduced in scope
  - Maneuvers are precise -- minimizes re-fly potential for missed / blown points

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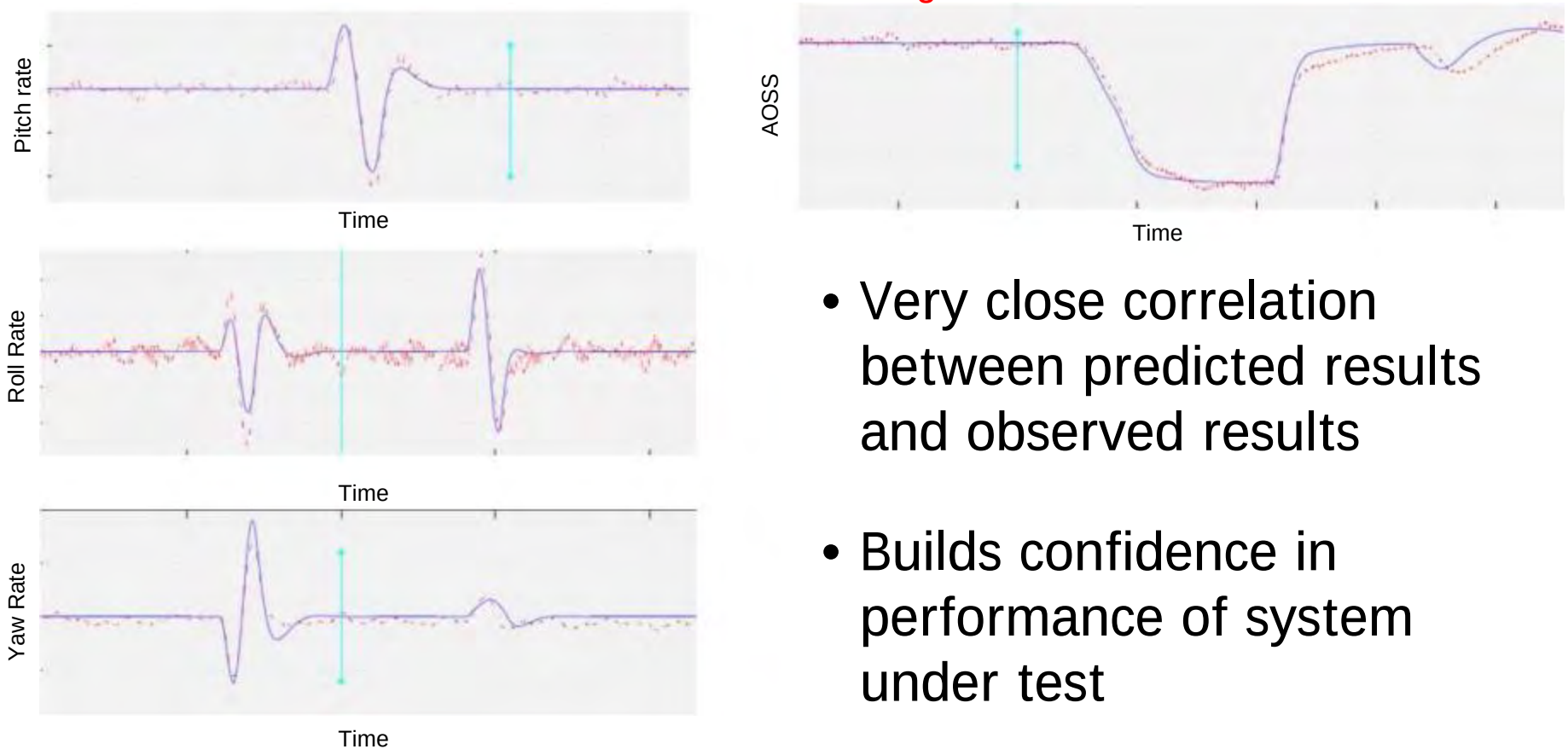
Which of These Data Sets is Actual?

- Data plots from flight number 2 versus simulation results

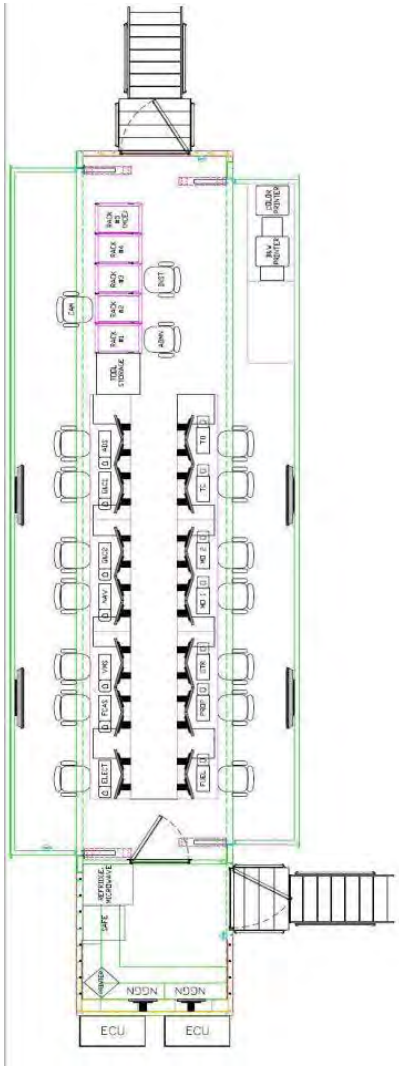
BLUE=Simulation RED=Flight test data



- Very close correlation between predicted results and observed results
- Builds confidence in performance of system under test

Lesson Re-Learned #3
Good Crew Resource Management Critical

- Low speed taxi tests
  - Taxi Test 2
    - Breakdown in communications
      - Cleared for a block of steps, difficulty with radio transmissions
      - Procedural error not caught
    - Only one of the “holes” in the Swiss cheese model
      - Incorrect interpretation/implementation of software requirement
      - Data review pacing test
- Lessons learned
  - Testing continues until the aircraft is secured
  - Plan, practice, then follow good comm discipline
  - Support/maintenance equipment and procedures are part of the “system under test”



Lessons Re-learned #3
Training, Training, Training

- Training as part of validation
  - Ran small test team rehearsals using pre-validated mission plans
    - Work out timing / discover issues / update profile prior to formal validation
    - Practice contingencies
  - Mission operators worked directly with coders to develop / validate plan

- Train nominal mission scenarios and contingencies with entire team
  - Goods
    - Work as a team to iron out solutions
    - Develop cards / procedures / workarounds
    - Identify new anomalies / limits
    - Expose entire team to off-nominals, develop contingency plans with experts
  - Others
    - Coordination logistics of team
    - Experience / background of engineers to practice “cockpit” ORM, SA, assertiveness
    - Decision by committee

Lessons Re-learned #4
Training, Training, Training (cont.)

- Team training highly successful
  - Successes
    - Aircrew (MOs) sit side by side with RE, TC, TD
      - Expose entire team to off-nominal, develop contingency plans with experts
      - Line of sight trust / discussion
      - Aircrew can “see” displays of RE if a question arises
    - On site resident expert who built/developed system
      - Living user manual
      - Work as a team to iron out solutions
      - Develop cards / procedures / workarounds
      - Identify new anomalies / limits
    - One to one training environment with RE/FTE/Aircrew
      - Train and fly in same control center
      - Enhances Crew Resource Management

Lesson Learned #3
Taxi Testing is not Straightforward or Easy

- High Speed taxi tests
  - High risk / a lot of planning discussion
    - Traditionally very low amount of HST done in manned aircraft
      - Verify control power, air data
    - For autonomous system, need to evaluate all of those items plus
      - Interlock response
      - Corrections, response to disturbances, during T/O and landing roll
      - Ground to aero control / braking transition
    - Balanced approach (how much risk is too much)
      - Initially desired 19 HST taxi runs
        - » Concern over the risk/reward
        - » HST runs essentially takeoff aborts
      - Reduced to 11 critical points
        - » Still concern over amount
      - After braking anomaly (separate discussion), reduced to 4 runs

Braking Challenges

- Brake asymmetry
  - No differential braking
  - Asymmetric brake performance creates yaw disturbance
  - Slightly exceeded cross track error SOT limit
  - Saturated NWS control power
- Stop, evaluate
  - Software fix required significant software change / hardware change
  - Reduce contributing factors
    - Brake Control Valve (BCV) mismatch
      - Bring to within acceptable tolerance
      - Monitor
    - Build up in deceleration rate to determine acceptable rate to minimize
- Long term solution versus good enough
  - What is acceptable performance?
    - Characterize system based on design model
    - Update design model based on data
    - Determine if acceptable
  - Deemed okay to continue (at risk)

Lesson learned #6
Surrogates are not exactly like the test article

- Carrier landing systems field testing
  - Simulations do not always translate exactly to the aircraft hardware
    - Command/response polarity and magnitude
      - Initial response different from inputs
      - Smooth versus step response
  - Software coded for precise closed-loop aircraft path
    - Deviations from path at transition to automatic control caused unexpected guidance
    - Usually required airborne troubleshooting, decreasing test efficiency
  - Effects of Datum conversion on a GPS based system

- Testing at sea
  - Precision GPS guidance and satellite DOP
    - Plan events to minimize performance disruptions
    - Sometimes could not avoid due to real world constraints

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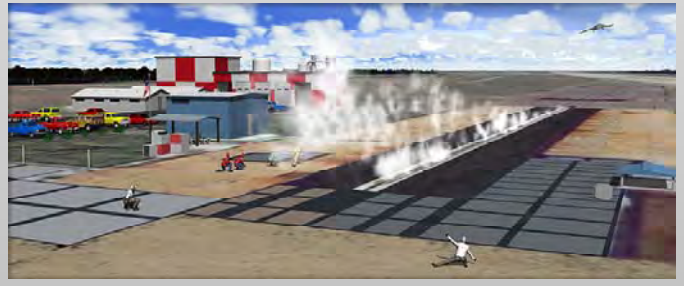
Upcoming Testing



CV Suitability Testing
- EMI Testing
- PA Flying Qualities
- Loads Buildup (Cats/Traps)

Launch and Recovery Bulletin (LRB)
- Cat Steam Ingestion
- Arresting Cable Roll-ins/Roll Over
- Jet Blast Deflector

Carrier Control Area / Zone
- Land Launch – transit to OPAREA
- C2 Handoff
- Marshall / Holding
- Case 1,2 and 3 approaches
- Deck Handling
- Traps and Cats

Autonomous Aerial Refueling
- Rendezvous
- Station Keeping
- Basket and Boom

Summary

- Solid results to date from test aircraft and surrogates
- Modeling and simulation providing valuable insight
- Extensive team training paid off
- Lessons learned are being applied to ensure we have a safe, efficient, and executable test program
- Looking forward to providing update next year

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First Surrogate Coupled Trap