AME Seminar

Flight Testing the X-48B at the NASA Dryden Flight Research Center

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Lead Flight Operations Engineer
March 25, 2010

X-48B Project Credits

The work you are about to see is the result of a cooperative partnership between:

- The Boeing Company
- NASA
- Air Force Research Laboratory
- and under contract to Boeing, Cranfield Aerospace, of Bedford, England

Special thanks are due to my colleagues and friends:

- Mr. Michael Kisska, Boeing X-48B Project Manager
- Mr. Timothy Risch, NASA Dryden X-48B Project Manager
- Mr. Norman Princen, Boeing X-48B Chief Engineer
- Dr. Fayette Collier, NASA Sponsor
- Many, many others…

Outline

- UAV's at NASA Dryden, Past and Present
- Why Do We Flight Test?
- The Blended (or Hybrid) Wing-Body Advantage
- Program Objectives
- The X-48B Vehicle and Ground Control Station
- Flight Test Highlights & Video
- Questions

NASA Dryden/Edwards Air Force Flight Test Center Complex

UAV's at Dryden

Perseus B

- **Aurora Flight Sciences Perseus B HALE Aircraft:**
  - Piston-powered, turbocharged with intercooling
  - Designed and built as a remotely piloted aircraft for high altitude science missions
  - Flight tested at Dryden in late 1990's

Altus II

- **General Atomic Altus II HALE Aircraft:**
  - Piston-powered, turbocharged with intercooling
  - Designed and built as a remotely piloted aircraft for high altitude science missions
  - Flight tested at Dryden in the late 1990's
  - Successfully conducted several science missions and is still in flyable storage

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC98-44684-1 Date: 29 Jun 1998 Photo by: General Atomics

Altus II aircraft flying over southern California desert

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC99-45006-2 Date: May 1999 Photo by: Sandia Labs/Dick Jones
Altus II high altitude science aircraft decending toward U.S. Navy's Pacific Missile Range Facility on Kauai, Hawaii

Altair

- **General Atomics Altair HALE Aircraft:**
  - High-altitude long endurance variant of early version of Predator B aircraft
  - Designed and built as a remotely piloted aircraft for high altitude science missions
  - Turbine powered (turboshaft engine)
  - Successfully conducted several science missions and is still in flyable storage

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED03-0078-4 Date: March 7, 2003 Photo By: GA-ASI/Alan Waide

Long wings, a V-tail with a ventral fin and a rear-mounted engine distinguish the Altair, an unmanned aerial vehicle built for NASA by General Atomics Aeronautical Systems, Inc.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED06-0208-1 Date: October 25, 2006 Photo By: General Atomics Aeronautical Systems, Inc.

A high-tech infrared imaging sensor in its underbelly pod, the Altair UAS flew repeated passes over the Esperanza fire to aid firefighting efforts.

Ikhana

- **General Atomics NASA Predator B “Ikhana” Aircraft:**
  - Based very closely on production Predator B aircraft
  - Designed and built as a remotely piloted aircraft for science missions and payload experiments
  - Turboshaft powered
  - Fully operational Dryden-owned aircraft

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED08-0151-07 Date: July 2, 2008 Photo By: Tony Landis

Ground crewmen prepare NASA's Ikhana remotely piloted research aircraft for another flight. Ikhana's infrared imaging sensor pod is visible under the left wing.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED07-0038-028 Date: March 5, 2007 Photo By: Tony Landis

Narrow wings, a Y-tail and rear engine layout distinguish NASA's Ikhana aircraft, a civil variant of General Atomics' Predator B unmanned aircraft system.

Global Hawk

- **Northrop-Grumman NASA Global Hawk Aircraft:**
  - ACDT Global Hawks AV-1 and AV-6 aircraft turned over to NASA from Air Force
  - Designed and built as fully autonomous aircraft for science missions and payload experiments
  - Turbofan powered
  - Soon-to-be fully operational Dryden-owned aircraft

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED07-0244-78 Date: December 3, 2007 Photo By: Tony Landis

In its new white-and-blue NASA livery, an early development model of the Global Hawk unmanned aircraft rests on the ramp at the Dryden Flight Research Center.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED08-0309-24 Date: December 11, 2008 Photo By: Tony Landis

This and a companion Global Hawk unmanned aircraft are used by NASA for Earth science missions and by Northrop Grumman for developmental testing.

X-36

- **X-36 Tailless Fighter Agility Research Aircraft:**
  - 28% scale of a notional tailless fighter aircraft
  - Designed and built as a remotely piloted aircraft to demonstrate controllability and agility
  - Used “CFD-to-Flight” methodology for design and analysis, wind tunnel testing as verification
  - Proved definitively that fighter agility levels possible without vertical tail surfaces

X-36 Flight Summary

Flight Test Highlights

- 31 Flights May 17 - November 12, 1997
- 4.8 G's maximum
- 52 to 206 KEAS
- 3 Pilots from Boeing and NASA
- 15 hrs 38 mins Flight Time
- 3^{deg} to 40^{deg} Angle of Attack
- 20,200 ft. Max Altitude
- All Program Objectives Met or Exceeded

X-45A

- **Unmanned Combat Air Vehicle (UCAV) Demonstrator:**
  - Full scale of a notional tailless unmanned combat system aircraft
  - Designed and built as an autonomous aircraft to demonstrate concept
  - Used “CFD-to-Flight” methodology again with great success
  - Demonstrated many UAV “firsts” such as internal carriage weapons deployment, autonomous coordinated taxi and flight operations, and storage and transportability concepts

X-45A in Flight

X-45A Flight Summary

Flight Test Highlights

- 64 Flights May 22, 2002 - August 10, 2005
- Many, many UAV firsts achieved
- 12 flights dual-vehicle
- Max speed Mach 0.75
- X-45A-1 40 flights total
- X-45A-2 24 flights total
- 63.4 hours flight time total
- 35,000 ft. Max Altitude

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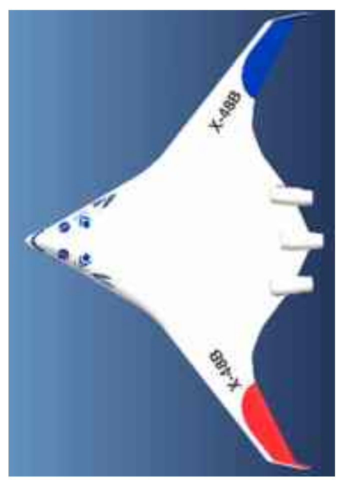
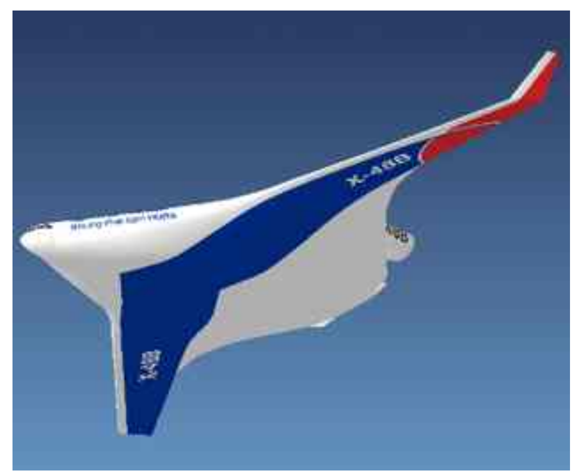
Why Do We Flight Test ?

- **Flight test is justified when required data cannot be obtained via ground-based analyses and testing:**
  - Computational fluid dynamics
  - Wind tunnel testing
  - Flight control law simulation and ground based simulators
- **All have limitations and require simplifying assumptions be made**
- **Flight research provides:**
  - Flight Control System risk reduction
  - Required to ensure BWB configuration is as safe as a conventional airplane
- **Investigate:**
  - Stall Characteristics
  - Departure Onset Boundaries
  - Asymmetric Thrust Control
  - Flight Control Algorithms
  - Envelope Protection Schemes
  - Dynamic Ground Effects
  - Control Surface Hinge Moments





Why Do We Flight Test ?

- **However, if flight testing is sub-scale:**
  - Meaningful comparisons require that the vehicle be dynamically scaled
  - Ensures that the angles between the 6 force and moment vectors are independent of scale
  - Requirement adds greatly to the cost and complexity of the engineering solution
- **Dynamically scaled flight research vehicles:**
  - Critical weights and inertias must be controlled in design/assembly process
  - Limits efficient usage of volumes and structures
  - Can add difficultly to selection of internal components and packaging
  - Measuring weight of finished vehicle one thing, measuring its inertias is another!

- **Generally, you accept the best compromise you can afford**

- **Often, during X-48 flight test, we have seen behaviors in flight not predicted by analysis nor wind tunnel data, and just as often, the behavior of the aircraft in flight is *better* than our predictions**

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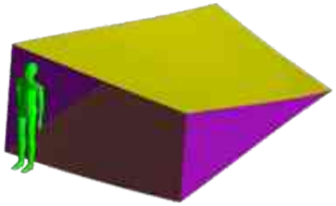
The Hybrid Wing-Body Advantage

- The unique shape offers promise in several relevant areas:
  - Higher aerodynamic efficiency
  - Reduced environmental noise
  - Significantly reduced fuel burn (30+ %) per unit useable volume
  - Aerodynamically efficient way of moving a large volume through the air

The Future ?

The Vision

BWB Elevon #1



Flying Wing Spin & Tumble Departures

Then...

- Flying wing dynamics dominated by minimal aerodynamic pitch and yaw damping
- Post-stall, this could lead to unrecoverable spin and tumble modes

Northrop XB-35 in 20 Foot Spin Tunnel
NASA Langley Research Center 10/11/1943 Image # EL-2000-00235

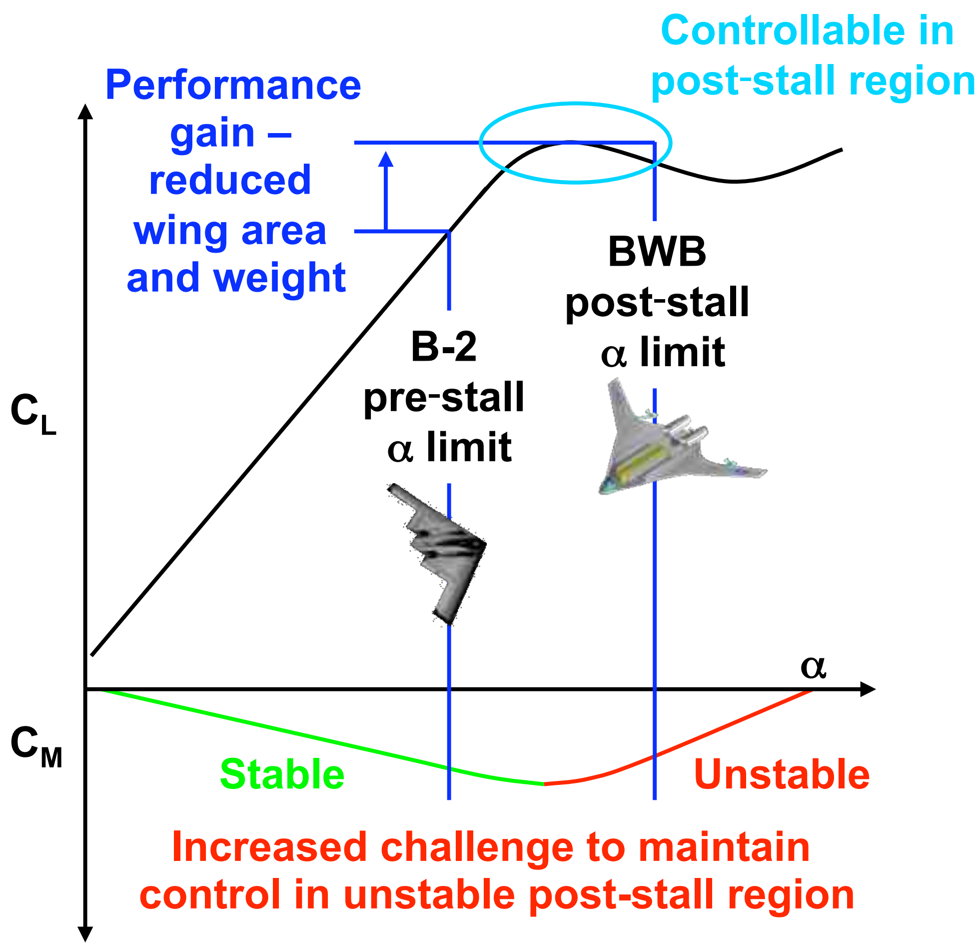
Air Flow

Now...

Spin testing shows that the BWB potentially has unrecoverable spin and tumble modes

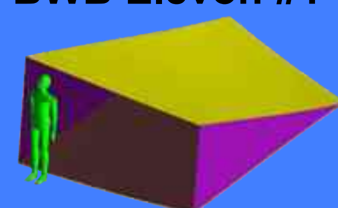
Need to prove that an advanced flight control system will prevent entry into departure regions

Critical Flight Control Technology



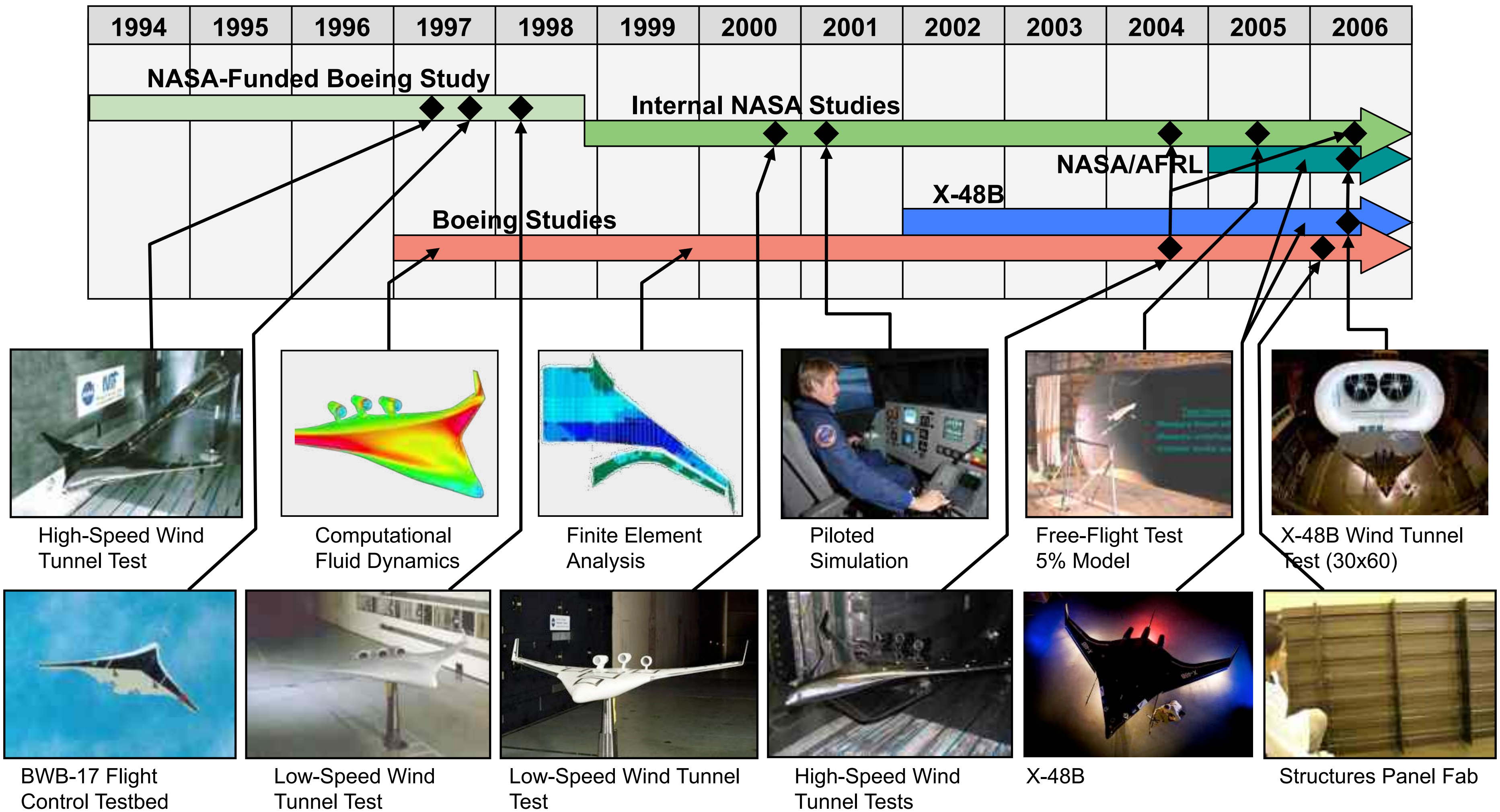
High-rate large control surfaces create large secondary power demands

BWB Elevon #1



Need to Prove that the BWB is as Robust as a C-17

BWB Development



Extensive technology development background

X-48B 30x60 Wind Tunnel Test

- NASA / AFRL contributed test time in ODU Langley Full-Scale Tunnel
- Wind tunnel test completed April / May 2006
- 250 hours of testing with flight control hardware active
- Data used by Boeing for X-48B simulation and flight control software

X-48B 30x60 Wind Tunnel Test

X-48B Project Schedule

• Program Start	December 2001
• Completed PDR	June 2002
• Completed CDR	December 2002
• LSV1 Delivery	March 2006
• 30x60 Tunnel Test	April 2006
• LSV2 Delivery	May 2006
• First Flight	July 2007
• Flight Testing	Mid 2008

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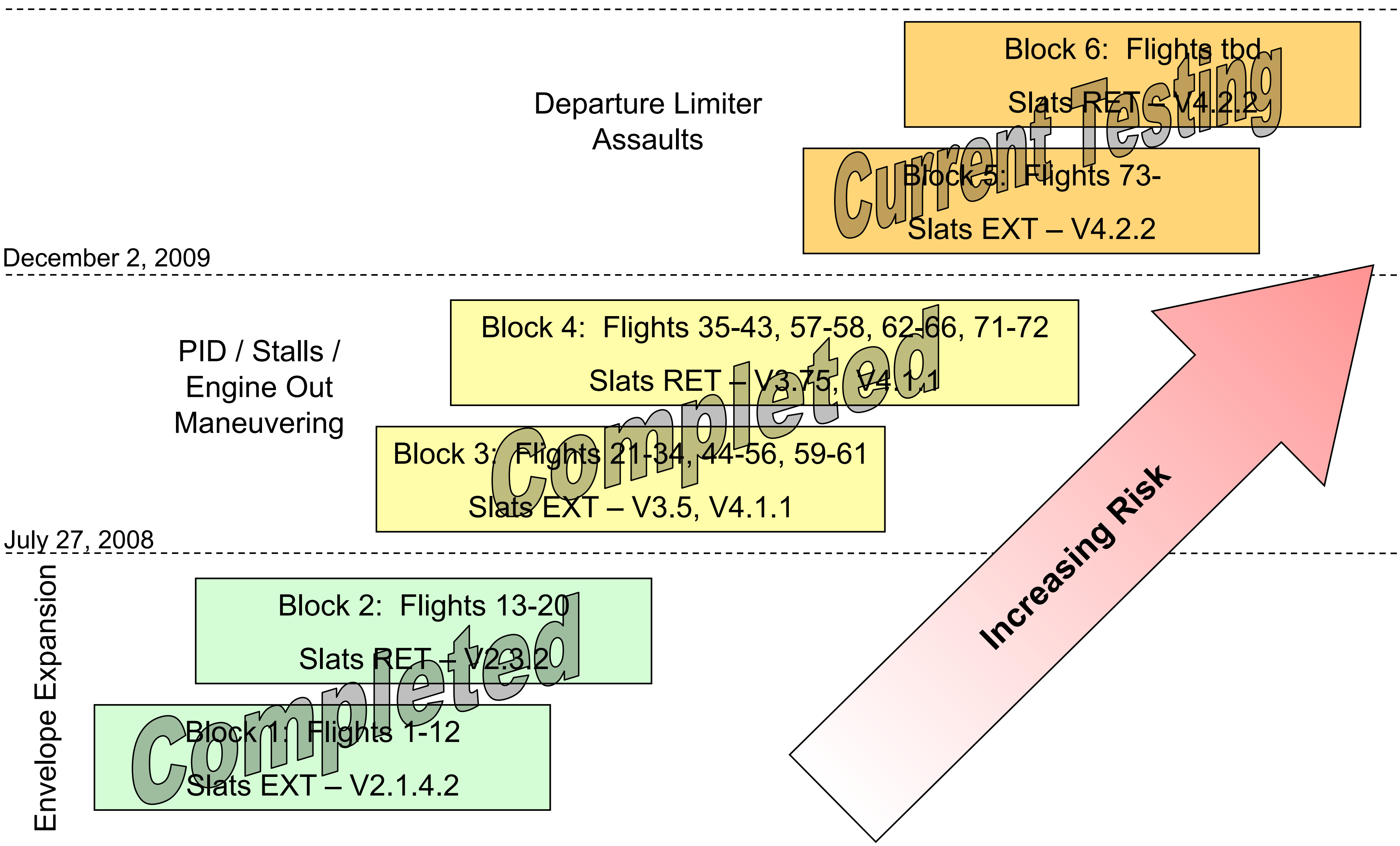
Program Objectives

- **Explore the stability & control characteristics of a BWB class vehicle in free-flight conditions to better understand the unique flight control issues:**
  - Assess dynamic interaction of control surfaces
  - Assess control requirements to accommodate asymmetric thrust
  - Assess stability and controllability about each axis at a range of flight conditions

- **Assess flight control algorithms designed to provide desired flight characteristics:**
  - Assess control surface allocation and blending
  - Assess edge of envelope protection schemes
  - Assess takeoff and landing characteristics
  - Test experimental control laws and control design methods

- **Evaluate prediction and test methods for BWB class vehicles:**
  - Correlate flight measurements with ground-based predictions and measurements

Definition of Test Flight Blocks



Major Program Accomplishments

- 74 successful flights beginning July 20, 2007 to present
- 2 flights in 1 day many times
- Completion of envelope expansion phases in both slats extended and slats retracted configurations, approach to stall and beyond tested
- Aircraft capable of operating from hard surface and lakebed runways at Dryden
- Both Boeing and NASA pilots trained to fly aircraft
- High quality data for various maneuvers recorded and archived for future use
- Preliminary data analysis ongoing with final data report due late 2010
- High AOA flights (near and beyond stall) performed in slats extended and retracted configurations and stable AOA limits found
- Takeoffs, landings, low approaches, and go-arounds are routine operations

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X-48B

- **Blended Wing-Body (BWB) Demonstrator Aircraft:**
  - 8.5% scale of a notional future “hybrid” wing-body cargo/tanker/transport aircraft
  - Designed and built as a remotely piloted research aircraft for controllability studies
  - Designed originally 20 years ago by McDonnell-Douglas Long Beach as future transport
  - Designed and built to be dynamically scaled to a notional full-size aircraft
  - Two copies built by Cranfield Aerospace in the UK under contract to Boeing

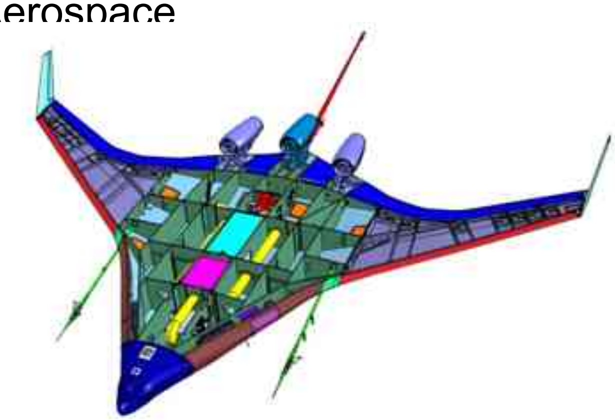
8.5% Dynamically Scaled X-48B

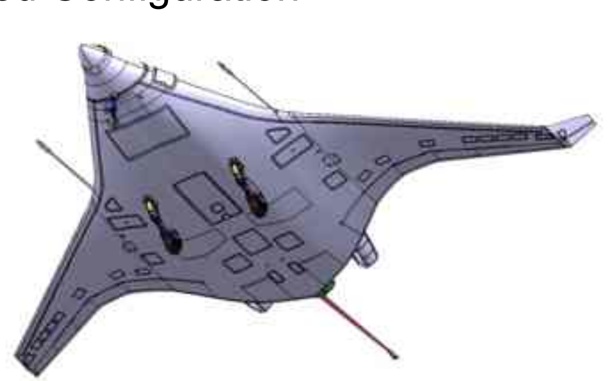
- **Vehicle Characteristics**

– Wing Span	20.4 ft
– Wing Area	100.5 ft2
– Maximum Weight	523 lbs
– Static Thrust	162 lbs
– Maximum Airspeed	118 kts
– Maximum Altitude	10,000 ft MSL
– Load Factor Limits	+4.5 g's to -3.0 g's
– Flight Duration	35 minutes + 5 minute reserve

X-48B BWB Low Speed Vehicle

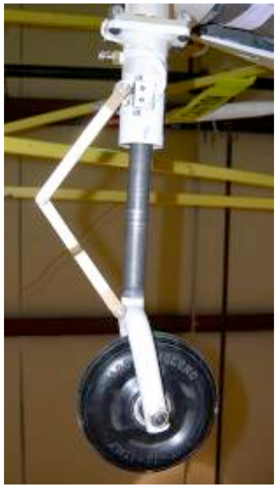
- **Two X-48B Aircraft and Ground Control Station (GCS)**
  - Research Partnership of Boeing, NASA, and AFRL
  - Design and fabrication contracted to Cranfield Aerospace
- **Air Vehicle Highlights:**
  - Dynamically Scaled
  - Uninhabited Air Vehicle
    - Flown by Pilot from Ground Station
  - Powered by 3 Small Turbojets
    - ~52 lbs. of Thrust Each
  - Conventional takeoff and landing
    - Non-retractable Tricycle Gear
    - Slats are Fixed for either Extended or Retracted Configuration
  - Recovery System
    - Drogue, Parachute, and Air Bags





X-48B Vehicle

- **Design Approach:**
  - Use low cost (COTS) equipment where possible
    - Engines - JetCat P-200
    - Landing Gear - mountain bike shocks & brakes
  - Use normal industry practice for electronic equipment
  - Use aircraft spec equipment where necessary
    - Radios, IMU, Actuators, Flight Termination System (FTS) parts
  - Save weight to meet dynamic scaling requirements



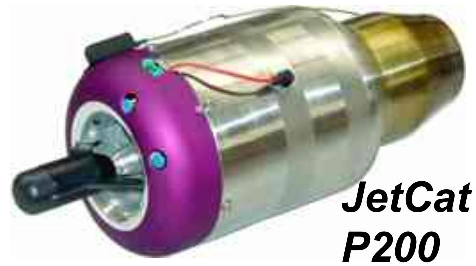
Nose & Main Landing Gear

JetCat P200 Engines

Air Vehicle Configuration

Major Components

Systron Donner C-MIGITS III IMU / GPS



JetCat P200

Drogue Ejector

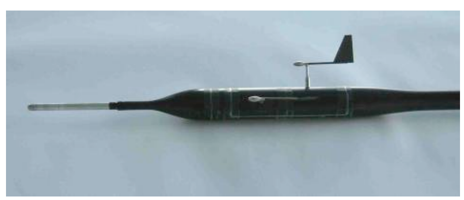
Avionics Crate & Cards

ATL Fuel Tank

Laser Height Sensor

Nose & Main Landing Gear

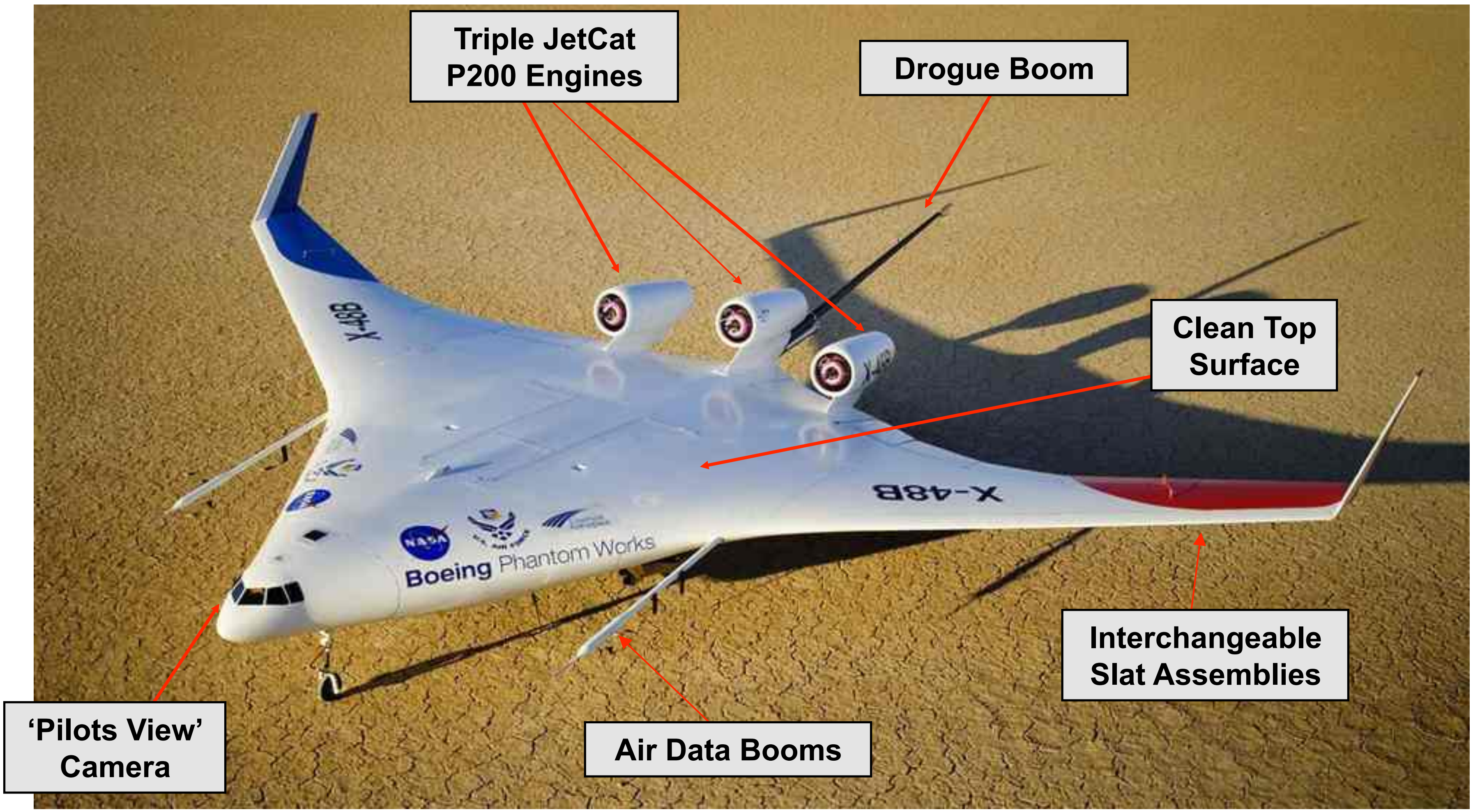
Kearfott K2000 & Volz Actuators



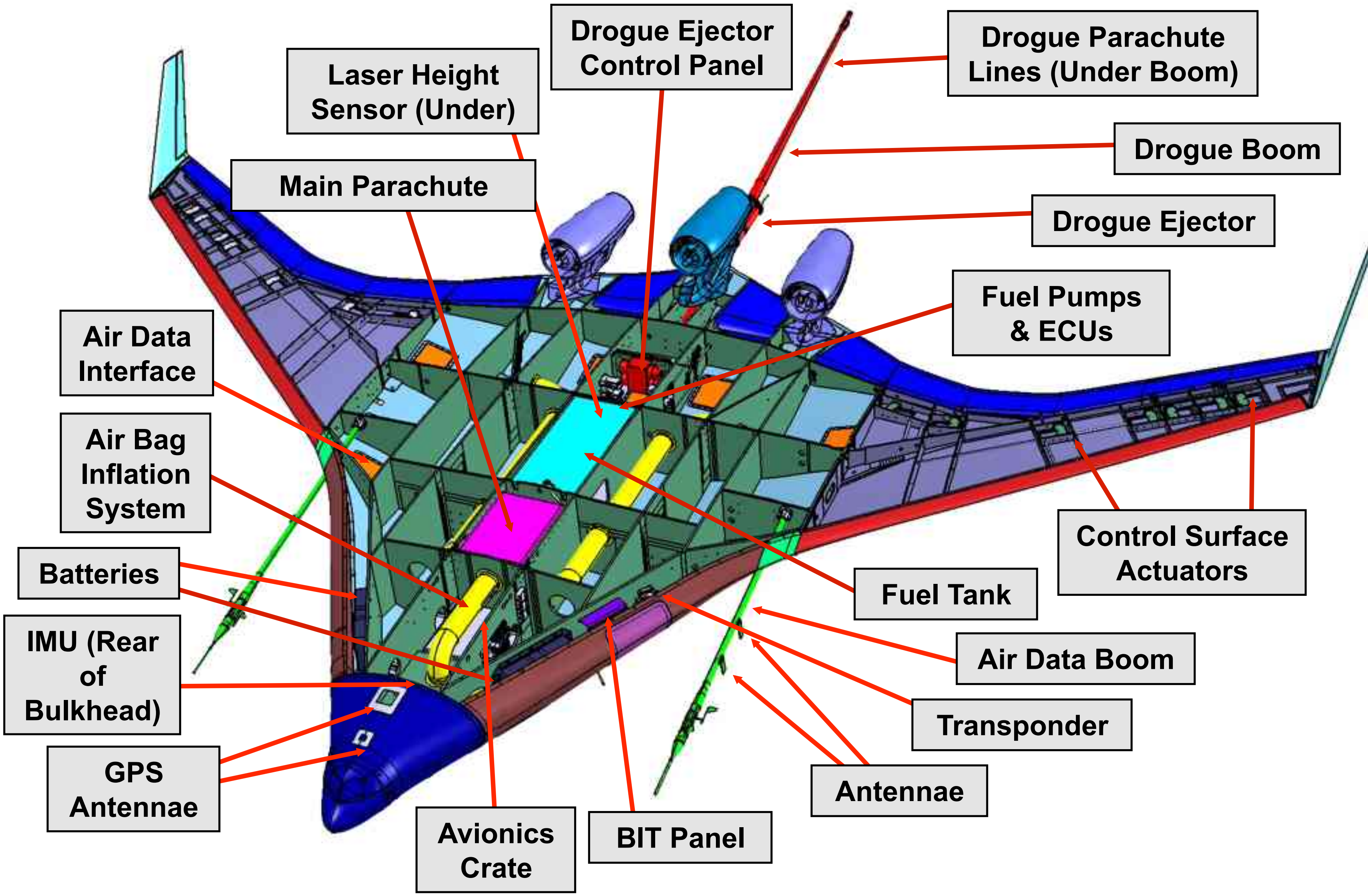
Air Data Probe

Hitachi Camera

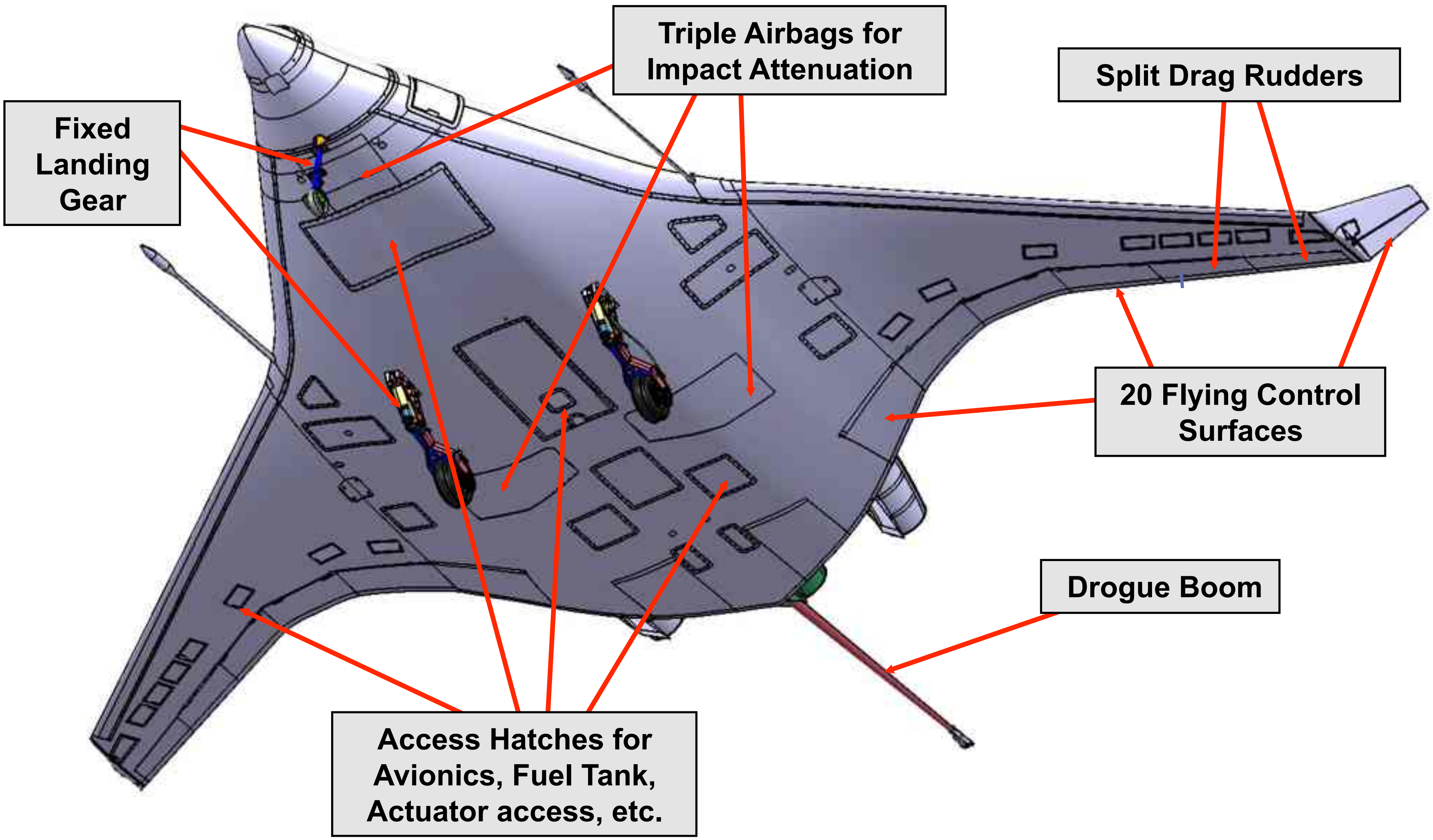
X-48B Configuration – Top View



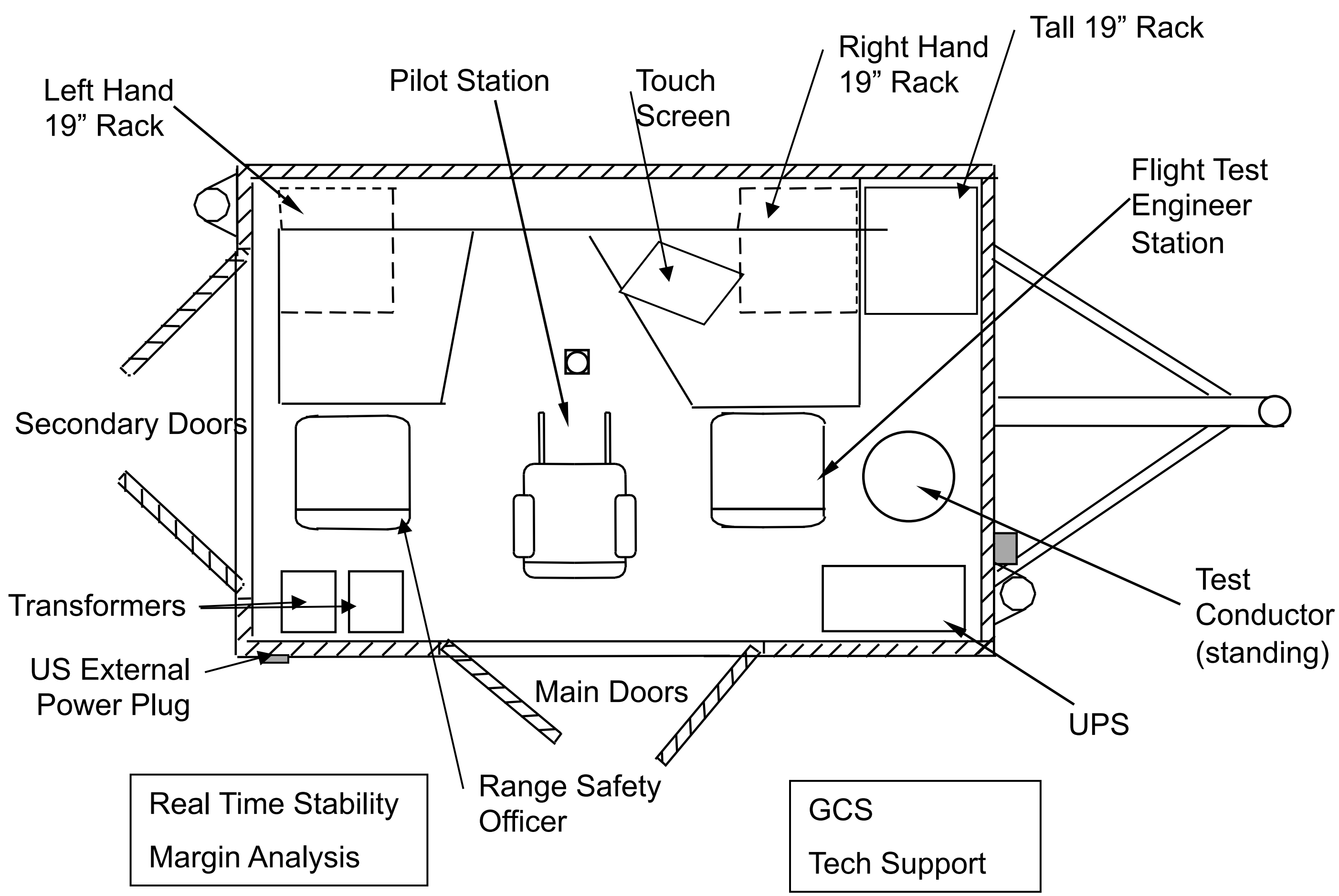
X-48B Configuration – Internal View



X-48B Configuration – Underside View



GCS – Trailer Layout



Ground Control Station

Ground Control Station

GCS – Pilot Station

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Ground Vibration Test & Inertia Measurement

Spin Chute Testing

X-48B Initial Flight Test Results

- Extremely Maneuverable in Roll
- Aircraft Very Closely Matches Simulator for Up/Away Flight (and Landing)
    - Recovers from high angle-of-attack/sideslip maneuvers easily
    - Stall AOA matches wind tunnel measurements within 1 degree
    - Stable in pitch at all tested CG locations; very stable in yaw

- Flight Control Design is Very Robust
    - Loss of outboard engine on two flights transparent to pilot (yaw corrected)
- Overall, the Aircraft Flies Extremely Well
    - Despite no peripheral cues (2-D only) / no seat-of-the-pants

X-48B in Flight

X-48B Flight Test Summary

- 74 Flights completed (as of February 2010)
  - 49 Flights w/ Slats Extended
  - 25 Flights w/ Slats Retracted
    - 9 Multi Mission Operational Days

- Test Highlights:
  - Test Maneuvers
    - Real-Time Stability Margins – Envelope Expansion
    - Automated Parameter Identifications (PID) – Freq Sweeps/Doublets
    - Steady Heading Sideslips - Simulate Cross-winds
    - Lazy-8s and Wind-up Turns
    - Airspeed Calibrations
    - Approach to Stalls
    - Stalls & Deep Stall Recoveries (Multiple Vehicle Configurations)
    - Simulated Engine Out Maneuvering (Vmca – Static & Dynamic)
    - Trim in Ground Effect

  - Operations from Hard Surface Runway vs. Lakebed Runway
    - Edwards AFB North Base 6/24 – 3,000 Feet (Eastern End)

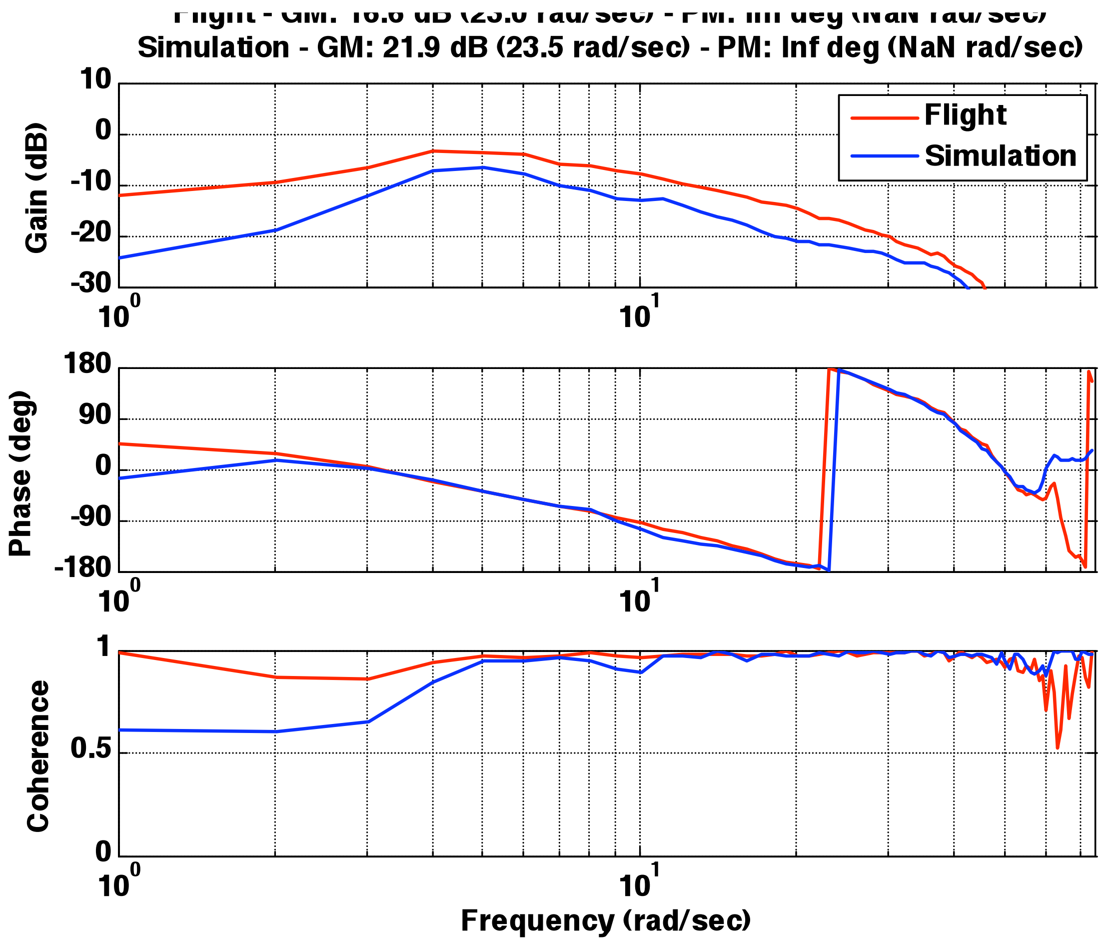
Real Time Stability Margin (RTSM)

- **In-Flight Stability Margin measurement has a long history at NASA Dryden Flight Research Center**
  - Application to a wide variety of flight programs including X-29, X-36, X-43, X-45, NF-15B 837
  - Method is motivated by inability to break loops on unstable aircraft

- **Dynamic inversion based flight control**
  - Numerous options for on-board excitations

- **Excitation parameters and command sent via command uplink from GCS**
  - Selectable injection points
  - Selectable waveforms
  - Selectable magnitudes

RTSM Results



From: Regan, Christopher, “In-Flight Stability Analysis of the X-48B Aircraft,” AIAA Paper AIAA-2008-6571,AIAA Atmospheric Flight Mechanics Conference and Exhibit, Honolulu, Hawaii, Aug. 18-21, 2008.

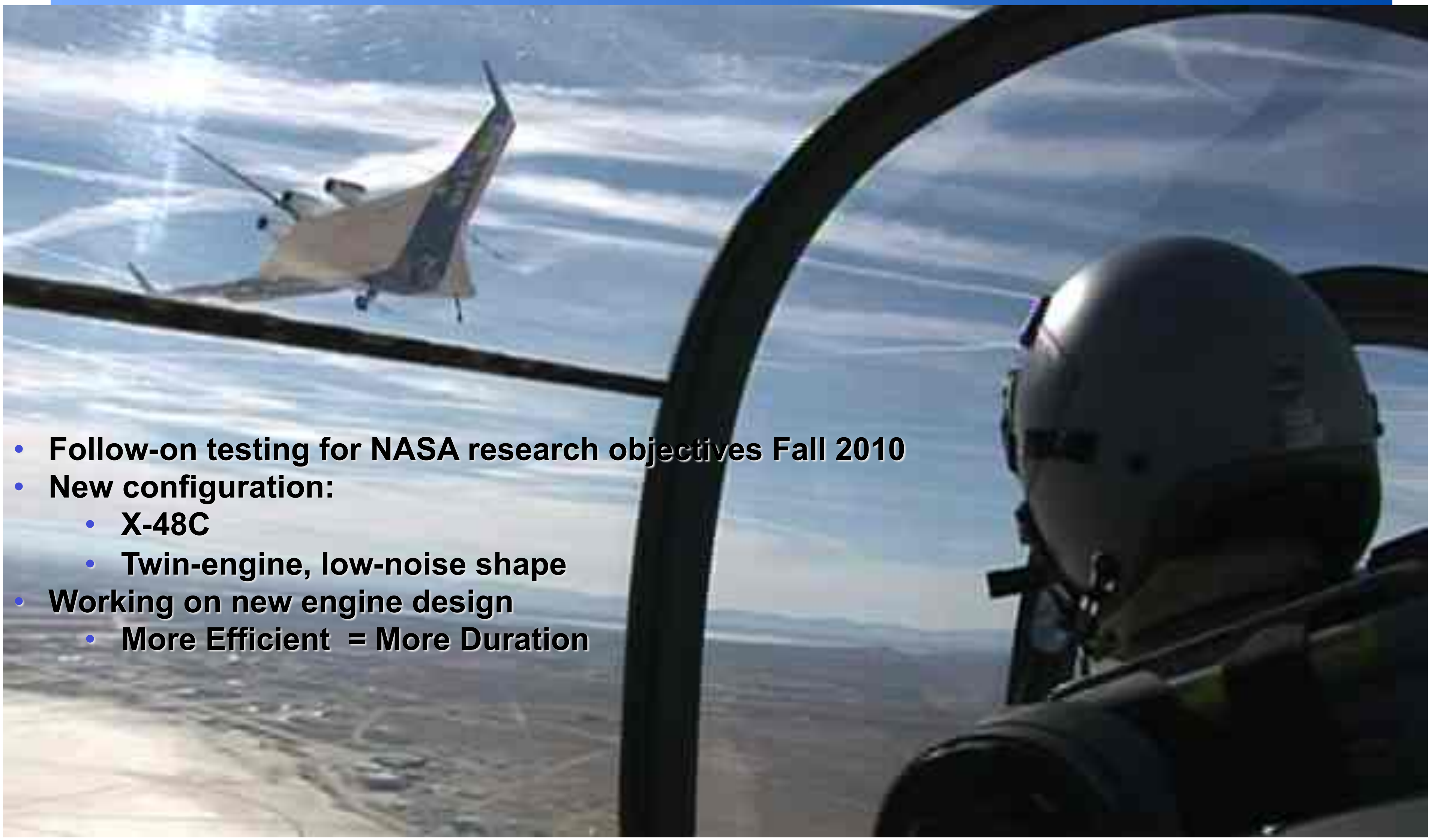
X-48B Blended Wing Body Summary

- **Investigate:**
  - Stall Characteristics
  - Departure Onset Boundaries
  - Asymmetric Thrust Control
  - Flight Control Algorithms
  - Envelope Protection Schemes
  - Dynamic Ground Effects
  - Control Surface Hinge Moments
- **Dynamically Scaled BWB UAV**
  - Vehicle Models & Flight Control Software developed by Boeing
  - Vehicles & Ground Station designed & built by Cranfield Aerospace in UK
  - Joint Boeing / NASA / AFRL Test Program

Video Time!

Seventy-Four Flights Complete
Exhibiting Excellent Flight Characteristics

X-48B What's Next for the Future



- Follow-on testing for NASA research objectives Fall 2010
- New configuration:
  - X-48C
  - Twin-engine, low-noise shape
- Working on new engine design
  - More Efficient = More Duration

Questions?