X-48B Flight-Test Progress Overview

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The results of a series of 39 flight tests of the X-48B Low Speed Vehicle (LSV) performed at the NASA Dryden Flight Research Center from July 2007 through December 2008 are reported here. The goal of these tests is to evaluate the aerodynamic and controls and dynamics performance of the subscale LSV aircraft, eventually leading to the development of a control system for a full-scale vehicle. The X-48B LSV is an 8.5%-scale aircraft of a potential, full-scale Blended Wing Body (BWB) type aircraft and is flown remotely from a ground control station using a computerized flight control system located onboard the aircraft. The flight tests were the first two phases of a planned three-phase research program aimed at ascertaining the flying characteristics of this type of aircraft. The two test phases reported here are: 1) envelope expansion, during which the basic flying characteristics of the airplane were examined, and 2) parameter identification, stalls, and engine-out testing, during which further information on the aircraft performance was obtained and the airplane was tested to the limits of controlled flight. The third phase, departure limiter assaults, has yet to be performed. Flight tests in two different wing leading edge configurations ("slats extended" and "slats retracted") as well as three weight and three center of gravity positions were conducted during each phase. Data gathered in the test program included measured airplane performance parameters such as speed, acceleration, and control surface deflections along with qualitative flying evaluations obtained from pilot and crew observations. Flight tests performed to-date indicate the aircraft exhibits good handling qualities and performance, consistent with pre-flight simulations.

Nomenclature

BIT = Basic Integrated Test
BWB = Blended Wing Body
DFRC = Dryden Flight Research Center
ECU = Engine Control Unit
FCC = Flight Control Computer
FTS = Flight Termination System
GCS = Ground Control Station
GPS = global positioning system
HDD = head-down display
HUD = head-up display
IMU = Inertial Measurement Unit
LSV = Low-Speed Vehicle
MEHPR = Minimum Effective Height for Parachute Recovery

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MFTS = Multiple Frequency Tracking System
MSL = mean sea level
NASA = National Aeronautics and Space Administration
PID = parameter identification [maneuver]
RF = radio frequency
RPM = revolutions per minute
RSO = Range Safety Officer
RTSM = Real-Time Stability Margin
SAD = structural aerodynamic dampening
SPORT = Space Positioning Optical Radar Tracking
TM = telemetry
V&V = verification and validation
WATR = Western Aeronautical Test Range

I. Introduction

The Blended Wing Body (BWB) aircraft configuration, employing a radical new design of the traditional tube-and-wing aircraft, offers the potential for revolutionary improvement in performance and efficiency over current-day airframe configurations. A blended-wing configuration is characterized by an overall aircraft design that provides minimal distinction between wings and fuselage and fuselage and tail. It closely resembles a flying wing configuration, but concentrates more volume in the center section of the aircraft than does a traditional flying wing.

The unique configuration of the BWB offers several promising advantages over other conventional configurations including: high internal volume, aerodynamic efficiency, structural efficiency, and lower noise. In a civil transport role, the BWB offers a large improvement in cost-per-seat-mile, which is a critical parameter for airline viability measurements. As a freight transporter, the configuration combines a large cargo volume with high operating efficiency. Finally, as a tanker, the configuration shares the same advantage as the freighter and is even more well-suited for transporting the low-density methane and hydrogen fuels that are currently being considered for future propulsion concepts.

The X-48B Low Speed Vehicle (LSV) is an 8.5%-scale version of a full-scale blended-wing-body aircraft designed to investigate the stability and control characteristics of this aircraft configuration. Two flight vehicles have been built. The first vehicle (LSV-1) was tested in wind-tunnel tests to obtain aerodynamic and stability data. The second vehicle (LSV-2) was constructed as the primary flight vehicle and is the subject of the flight-test program documented here.

The first flight of the X-48B LSV occurred on July 20, 2007, at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC) (Edwards, California). A total of 39 flights have been conducted in two leading-edge configurations: the first in a “slats extended” configuration and the second with a clean leading edge (the “slats retracted” configuration). In addition, flights were conducted at three different weight conditions and at three different center-of-gravity locations. Typical flight durations were approximately 35 minutes and were limited by the approximately 13-gallon fuel capacity of the aircraft.

II. Program Structure

The X-48B flight-test program is a joint partnership between NASA, the Air Force Research Laboratories, and The Boeing Company (Chicago, Illinois). The NASA project funding is provided by the Subsonic Fixed Wing Project of the Aeronautics Research Mission Directorate’s Fundamental Aeronautics Program.

As defined by a signed Memorandum of Agreement, NASA is responsible for providing the facilities, equipment, and range assets for flight-testing as well as being responsible for range and ground safety. Under the agreement, Boeing provides the X-48B aircraft and ground station and is responsible for flight safety, airworthiness, and mission success.

The flight-test program is being conducted in three phases comprising six separate test blocks, as shown graphically in Fig. 1. Each odd-numbered block represents the X-48B aircraft configured in the “slats extended” configuration, while in the even-numbered blocks the aircraft is configured in the “slats retracted” configuration. The first two blocks comprise the envelope-expansion test phase. In this phase, the aircraft is flown through a variety of maneuvers intended to define the overall flight capabilities away from stall regimes and to discern the general stability and flight handling characteristics of the aircraft. These two blocks are completed.

In the second phase, more aggressive maneuvers to assess the aircraft capabilities under more demanding flight conditions, such as stalls and limited engine power, were conducted. In the second phase, the aircraft was taken to the limit of controlled flight. Note, however, that envelope-expansion work continues in this phase, especially in the stall regime and therefore Blocks 3 and 4 are not yet completed.

The third and final phase, yet to be performed, is termed "departure limiter assaults." The ability of the aircraft to prevent entry into uncontrolled flight regimes will be investigated in this phase. The outcome of these tests will be validated software algorithms for the computerized flight control system to prevent such entry into the uncontrolled flight regimes.

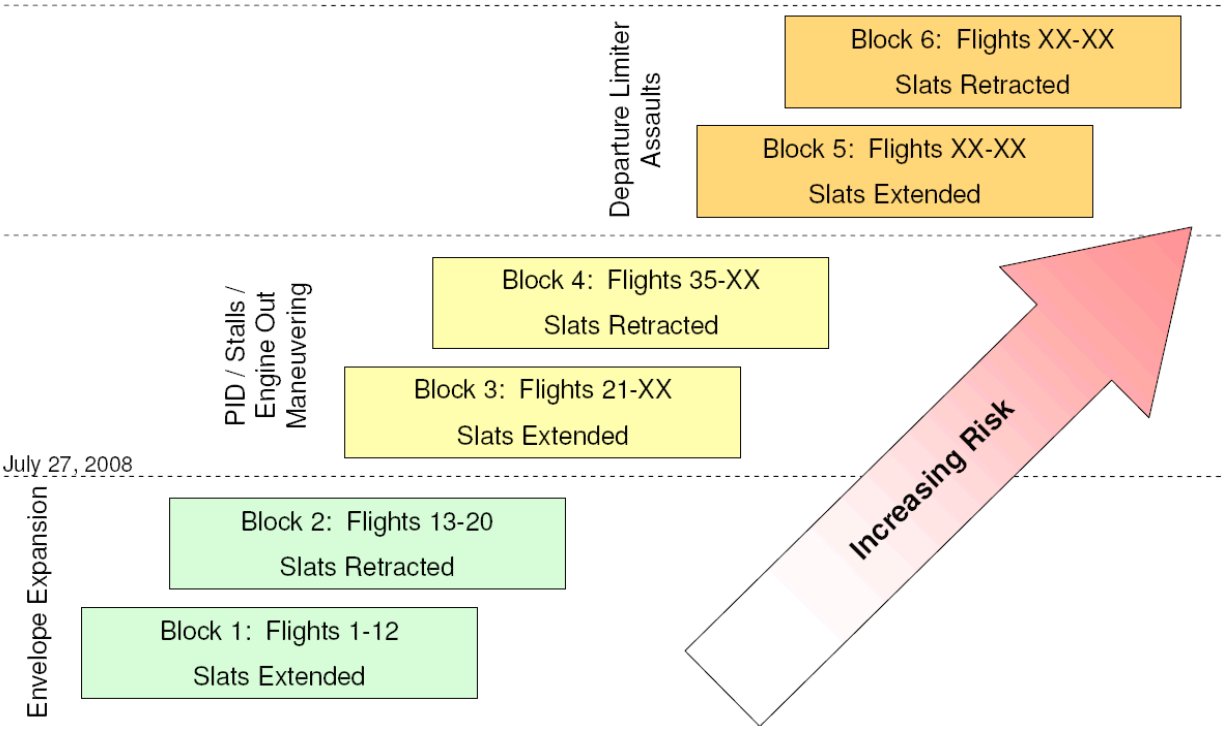

Figure 1. Definition of the flight-test blocks for the X-48B test program.

III. Program and Flight-Test Objectives

Both general program goals and the specific flight-test objectives drive program execution. General program goals come from NASA in terms of high-level objectives for the development of future air transport systems. Flight-test objectives, generated within the program, define the specific flight tests required to meet the higher-level goals.

A. General Program Goals

The Subsonic Fixed Wing Project of the NASA Fundamental Aeronautics Program[1] is tasked to develop concepts/technologies for enabling dramatic reductions in noise and emissions, and improved performance characteristics, of subsonic/transonic aircraft. The development and characterization of a highly fuel efficient and quiet flight vehicle, such as a BWB-class vehicle, clearly meets these objectives. Specifically, the X-48B flight research program will validate the flight control system of the X-48B vehicle by September 2009. The completion of this milestone will provide confidence that the development of a control system for a full- or near full-scale X-48B vehicle is technically feasible.

B. Specific Flight-Test Objectives

The flight-test program objectives are summarized in the X-48B flight-test plan, which has been developed to assess three main areas of research: 1) stability and control, 2) flight controls, and 3) prediction and test methods. For each of these areas, the main issues and associated objectives are summarized by the following:

1. *Stability and Control*

   Issue – Stability and control characteristics of a BWB-class vehicle in free-flight conditions
   - Assess stability and controllability about each axis at a range of flight conditions. Hypothesis is that roll control is good but diminishes near stall, yaw control is poor throughout the flight envelope, and pitch is unstable at various flight conditions.
   - Characterize departure onset boundary (the point at which the pilot begins to lose control)
   - Assess dynamic interaction of all 20 control surfaces
   - Assess control requirements to accommodate asymmetric thrust

   Program Objectives – Stability and control
   - Determine via parameter identification (PID) techniques the static and dynamic stability and control derivatives at a range of flight conditions. (e.g., control doublets, frequency sweeps of individual control surfaces)
   - Determine via aircraft flight-test maneuvers and dynamic-scaling relationships the full-scale BWB low-speed flight characteristics and departure onset boundaries
   - Determine via PID techniques the aerodynamic interaction of control surfaces
   - Determine via aircraft flight-test maneuvers the control requirements under worst case asymmetric thrust condition (low-speed, takeoff configuration, minimum operating empty weight, one outboard engine out).

2. *Flight Controls*

   Issue – Flight control algorithms designed to provide desired flight characteristics
   - Assess control surface allocation and blending
   - Assess edge of envelope protection schemes
   - Advance the state of the art in control theory via application of embryonic technologies, particularly in regions of nonlinear aerodynamics and during rapid maneuvers
   - Assess takeoff and landing characteristics

   Program Objectives – Control law development
   - Test experimental control laws and control design methods.

3. *Prediction and Test Methods*

   Issue – Prediction and test methods for BWB-class vehicles
   - Correlate flight measurements with ground-based predictions and measurements
   - Develop the process and associated infrastructure to allow for a seamless transfer of the aircraft to DFRC and efficacious final verification and validation (V&V) of flight control system

   Program Objectives – Prediction and test methods
   - Assess flight data via comparison with predicted results from ground-based experiments.
   - Expedite final X-48B aircraft V&V at DFRC with hardware-in-the-loop V&V Capability.

From the above general objectives, 53 specific flight-test objectives were developed as summarized in Table 1. Flight-test objectives are managed and selected during the flight-planning phase prior to each flight. The list of flight-test objectives is extensive and covers a broad range of aircraft performance goals. Because of the limited duration, only a small portion of the flight-test objectives can be covered in each flight. In order to complete the flight objectives efficiently during the flight-test program, not all objectives are required to be completed in every aircraft configuration. Appendix A contains definitions of the flight-test maneuvers listed in Table 1 and helps to clarify the flight-test objectives and the rationale for their inclusion in the test program.

Table 1. The X-48B flight-test objectives, showing all maneuvers planned and completed by flight.

		Flight																																				
		Block 1											Block 2									Block 3														Block 4				
Objective	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
X-48B-FLT-1	Takeoff - All Engine	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-2	Climb - Normal All Engine	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-3	In-Flight Instrumentation Phase Check	2	2	2	2		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-4	Approach	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-5	Landing	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-6	Structural Aerodynamic Dampening (SAD)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-7	Static Longitudinal Stability - Low Speed Cruise	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-8	Maneuvering Stability - Low Speed Cruise	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-9	Maneuvering Stability - Speed Brake Deployment	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
X-48B-FLT-10	Static Lateral Directional Stability Sideslips	1	2	2	2	2		1	2		2	2	2	1	2	2	2	2	2		2			2			1	2	2		2		2	2		2	2	2		
X-48B-FLT-11	High Speed Characteristics – Vd																																							
X-48B-FLT-12	Handling in Ground Effect																												2	2										
X-48B-FLT-13	Departure Limiter Effectiveness - Limiter ON																																							
X-48B-FLT-14	Asymmetric Thrust Controllability –Static																																							
X-48B-FLT-15	Asymmetric Thrust Controllability – Dynamic																																							
	Parameter Identification - All Axes																																							
X-48B-FLT-16	RTSM		1	2	2		2			2			2						2			2		2			1	2		2								2		
X-48B-FLT-16	Doublets																																							
	Pitch	1	2	2	2	2		2	2	2			2			1	2	2	2			2					1	2	2	2			1	2						2
	Roll	1		2	2	2		2	2	2			2			1	2	1	2			2					1	2	2	2			1	2	2	2	2	1		2
	Yaw	1		2	2	2		2	2	2			2			1	2	2	2			2					1	2	2	2			1	2						2
X-48B-FLT-16	Frequency Sweeps																																							
	Pitch		2	2	1	2			2	2	1	2	2	2	2	2	1	2		2	2	1	2	2			1	2		2									2	
	Roll		2	2	1	2			2	1	1	2	1	2	1	2	1	2		2	2	1	1	1	2		1	2		2									2	
	Yaw		2		1	1	2		2	1	1	2	1	2	1	1	2	2		2	2	1	1	1	2		1	2		2										
X-48B-FLT-17	Autothrottle IAS Evaluation	2			2		2																																	
X-48B-FLT-18	Autopilot Altitude Hold Evaluation						2																																	
X-48B-FLT-19	Autopilot Heading Evaluation						2										2	2					2						2											
X-48B-FLT-20	Autonomous Mode Evaluation																																							
X-48B-FLT-21	Stall Speeds																																							
X-48B-FLT-22	Stall Characteristics - Straight Flight - Power ON																																							
X-48B-FLT-23	Stall Characteristics - Straight Flight - Power OFF																								2	2						2							2	
X-48B-FLT-24	Stall Characteristics - Turning - Power ON																																							
X-48B-FLT-25	Stall Characteristics - Turning - Power OFF																																							
X-48B-FLT-26-30 RESERVED																																								
X-48B-FLT-31	Bank to Bank Turns					2					1	2		2	1	1	2	1	2		2	2		2							2					2	2	1		2
X-48B-FLT-32	Combined Axis Maneuvers / Lazy 8's								2	2	1			1																										
X-48B-FLT-33	Maneuvering Stability - Wind Up Turns						2							1	1	1	2	2	2		2			1							2									
X-48B-FLT-34	Air Speed Calibration					1	1	2	2	2		2		2	1	1	2	2		1		1	2																	
X-48B-FLT-35	Maneuvering Capability Nose-Down Pitch/Approach to Stall					2		1			1	1	2	1					2			2	2	2							2									
X-48B-FLT-36	Maneuvering Capability - Vmo																																							
X-48B-FLT-37	Maneuvering Capability - VSR + 5																																							
X-48B-FLT-38	Approach Speedbrake HQ Evaluation							2																																
X-48B-FLT-39	Landing / Go-Around Evaluation					1																				1		2		2	2									
X-48B-FLT-40	Level Acceleration / Ps Mapping							2	2				2																											
X-48B-FLT-41	Level Deceleration / Ps Mapping								2				2																											
X-48B-FLT-42	Offset Approach - Control Interaction / PIO Eval																																							
X-48B-FLT-43	Pitch Tracking Tasks - Control Interaction / PIO Eval																																							
X-48B-FLT-44	Roll Tracking Tasks - Control Interaction / PIO Eval																																							
X-48B-FLT-45	Simulated Engine Out					1	2																																	
X-48B-FLT-46	Autopilot Functionality Check						1																				1	2												
X-48B-FLT-47	Simulated Approach at Altitude	2					2	1		2									2					2							2									
X-48B-FLT-48	VMS Level Evaluation															2	1					2																		
X-48B-FLT-49	Pitch/Throttle/Trim setting for loss of TM															2	1	1		1				2																
X-48B-FLT-50	Auto Trim Evaluation							2																																
X-48B-FLT-51	Handling Qualities Evaluation (control harmony)							2														2	2		2		2													
X-48B-FLT-52	Alpha Limiter Assault																																							
X-48B-FLT-53	In-Flight Load DOF																																						2	

Key: 1 = planned, 2 = accomplished.

IV. The X-48B Flight-Test Components

The X-48B flight-test system consists of the ground control station (GCS), DFRC Range Assets, chase aircraft, and the X-48B LSV-2 flight vehicle itself.

A. The X-48B LSV-2 Vehicle

The X-48B LSV-2 vehicle, as shown in Fig. 2, was constructed for The Boeing Company (Boeing Phantom Works, Huntington Beach, California) by Cranfield Aerospace Ltd. (Bedford, United Kingdom). The X-48B aircraft has a wingspan of 20.4 ft, maximum weight of 525 lb, and fuel-carrying capacity of approximately 13 gallons. The aircraft uses three modified JetCat USA® (Paso Robles, California) P200 turbojet engines and Engine Control Units (ECUs), each capable of 54 pounds-force of installed thrust. The aircraft takes off and lands conventionally with fixed tricycle-type landing gear. The flight duration during initial flight tests has been 30-35 min per flight, only a fraction of which is available for flight-test maneuvers. There is also a flight termination system (FTS) and emergency landing system on the aircraft that includes a parachute and air bag system. A cutaway view of the top of the LSV is shown in Fig. 3 and a bottom view in Fig. 4.

Access to battery switches, a laptop interface for data download and flashing of the onboard volatile memory, FTS system status and servicing, engine start, and transponder access is provided through the Basic Integrated Test (BIT) panel located on the side of the aircraft.

A similar vehicle (LSV-1) was tested in the NASA Langley 30- by 60-ft low-speed wind tunnel to obtain measured lift and drag coefficients along with stability and dynamic coefficients. One of the flight-test goals is to compare the measured wind-tunnel data with the same parameters derived from flight tests. Such comparisons will provide insight into those tests and parameters that can be more economically obtained from wind-tunnel tests as opposed to those that must be measured in actual flight-testing for this class of vehicle.

1. *Main Vehicle Structure*

The majority of the X-48B structure is manufactured from carbon fiber face sheets with honeycomb core and infused with composite matrix resins. The Boeing Company furnished the loft data for the outer mold line that Cranfield Aerospace used to construct the vehicle. Leading edge slats were used to increase maximum lift for takeoff and landing. The leading edge slats have only an extended and retracted position and cannot be modified in flight. For the aircraft, the slats were bolted in either the extended or retracted position before takeoff and were not actuated during the flight. There are 20 individually-actuated control surfaces along the trailing edge of the wing and winglets. These 20 control surfaces provide all the control power for flight.

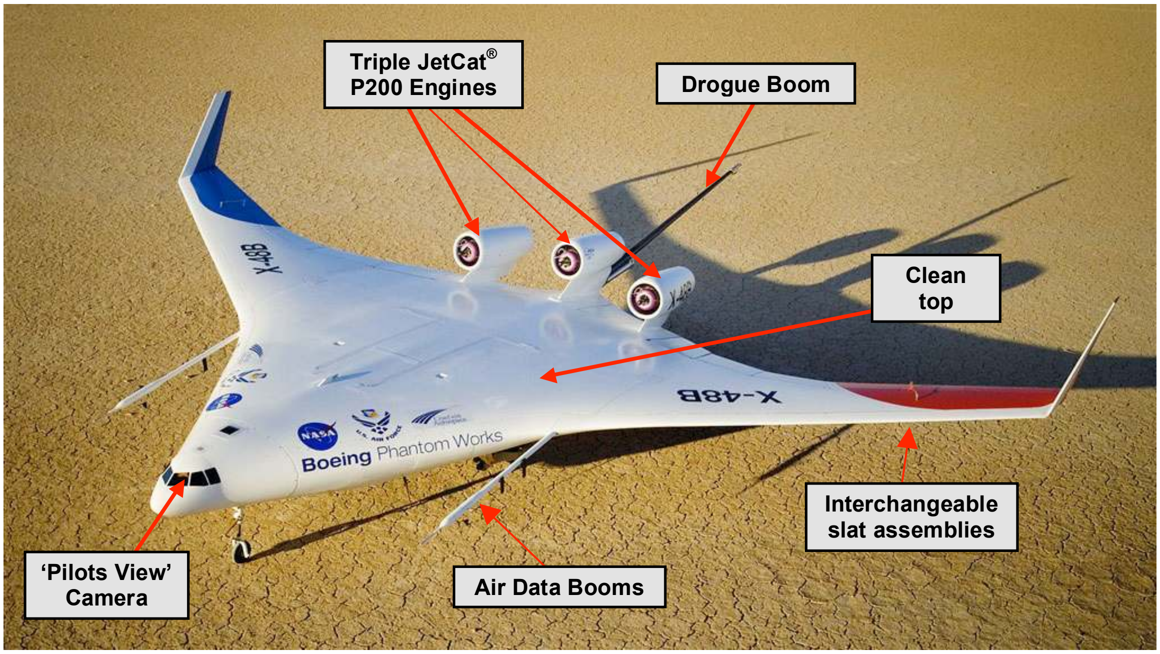

Figure 1. The X-48B LSV-2 on the Edwards Air Force Base dry lake bed.

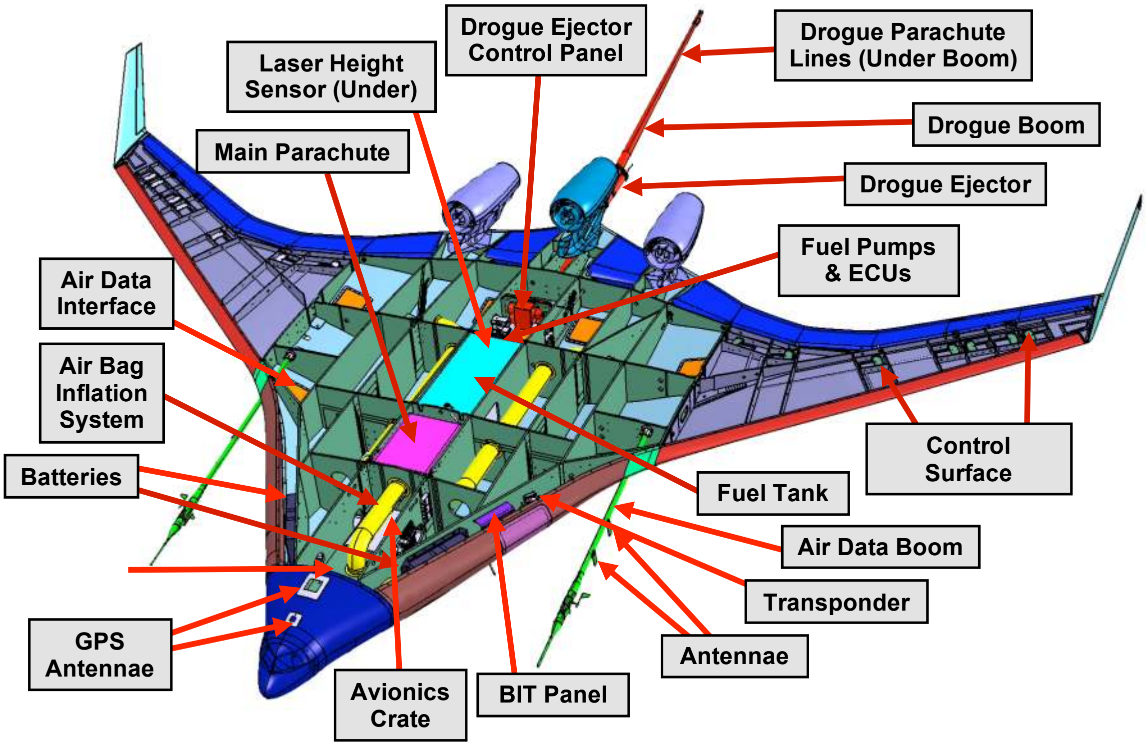

Figure 2. A cutaway view of the top of the X-48B LSV.

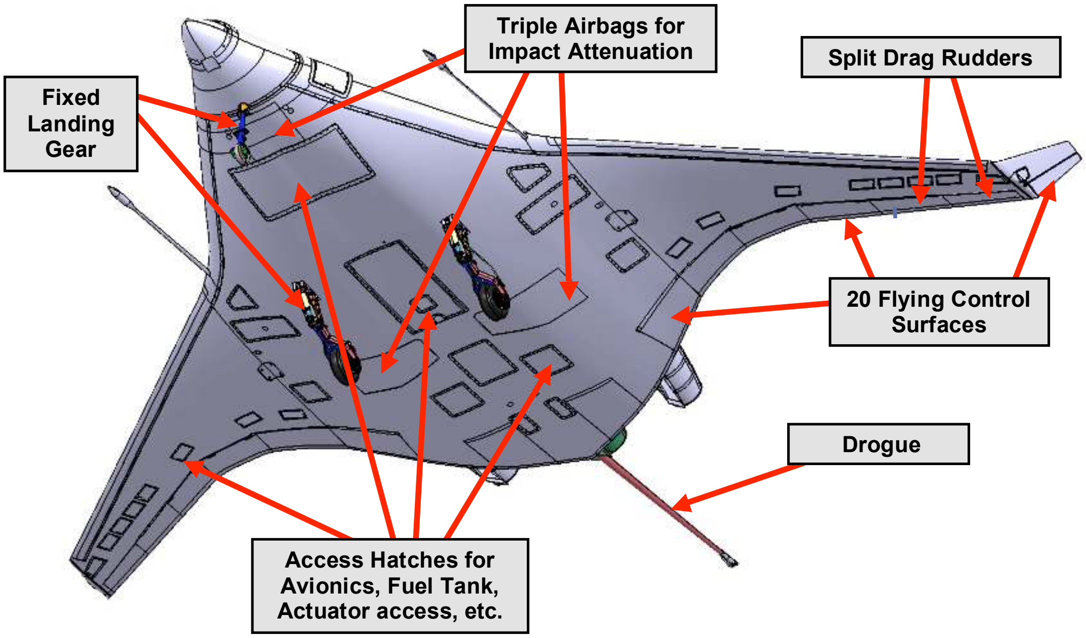

Figure 3. The bottom of the LSV.

2. *Flight-Control and Data-Recording Computer*

The flight control system of the X-48B aircraft contains a custom-built Flight Control Computer (FCC) to process the pilot commands and vehicle sensor inputs to command the control surfaces. The FCC hosts an advanced Vehicle Management System (VMS), developed by The Boeing Company. The VMS has a 200-Hz frame rate and includes navigation, guidance, sensor processing, and flight control subsystems. Approximately 300 critical parameters are recorded on the aircraft from the FCC at 200 Hz for the duration of the mission.

3. *Electrical Power System*

The electrical power system consists of three different power subsystems: a 32-V avionics subsystem, a 32-V actuators subsystem, and a 6-V actuators subsystem. The 32-V avionics and 32-V actuators subsystems get power from either an external power supply (for use when the aircraft is trailer-towed or stationary on the ground), or on-board Lithium-Polymer battery packs (for taxi or flight). The 6-V actuators system receives power from either an external power supply (for use when the aircraft is trailer-towed or stationary on the ground), or on-board Nickel Metal Hydride battery packs (for taxi or flight). All batteries are charged via benchtop battery "smart" chargers, and reinstalled prior to a test operation.

4. *Recovery Systems*

Flight of the X-48B aircraft can be terminated via a drogue chute that deploys out of the aft end of the vehicle; the drogue chute riser lines are connected to a spin-recovery boom that extends from the aft center of the aircraft. The FTS can be activated by the designated Range Safety Officer (RSO) via dual-redundant paths to the vehicle (one path through the Range FTS tone system, and one through a telecommand uplink). Upon activation of the FTS, the fuel flow to the engines is stopped, the drogue chute deploys out of its canister, and the aerosurfaces of the X-48B aircraft go in to a high-drag, slightly aircraft-nose-down configuration. The drogue chute is ejected out of the drogue canister by a pressurized charge of compressed nitrogen gas.

The X-48B aircraft uses a recovery parachute system with airbags to allow a reasonable chance of recovering the airplane after initiation of the FTS. The recovery system is made from conventional nylon fabric parachutes consistent with industry standards for emergency egress equipment. Three airbags (two aft of the main landing gear and one in front of the nose gear) deploy after main parachute deployment and are inflated by ducted fans. After touchdown, the main parachute is discarded so as to avoid dragging the aircraft along the ground. A self-contained pyrotechnic line cutter with a small contained charge is housed in the main parachute bridal assembly. The pyrotechnic charge is electrically activated via a pressure-pulse touchdown sensor inside one of the airbag housings.

5. Avionics and Sensors

A complete avionics package is required to fly the X-48B aircraft. High-quality sensors are used to collect information about the state of the airplane for use in airplane control and post-test data analysis. An onboard Command Receiver and an onboard Telemetry Downlink Transmitter operate in the L-Band frequency spectrum. Nose camera video and on-board audio are relayed to the GCS via a transmitter that operates in the S-Band frequency spectrum along with an air traffic controller transponder installed onboard the aircraft to enhance the X-48B aircraft position on the Air Force Radar Control Facility's Space Positioning Optical Radar Tracking (SPORT) system. There is a primary global positioning system (GPS) receiver and a completely independent secondary GPS source incorporated into the avionics pallet. The primary GPS receiver provides aircraft position and velocity information through the telemetry downlink. The secondary GPS source transmits to a receiver on the ground, used by the RSO.

The control system actuators contain built-in position sensors to provide positional feedback to the control system. There are 20 control surface sensor inputs to the FCC. Two air data booms are used on the X-48B aircraft, each incorporating instruments to measure total pressure, static pressure, static temperature, angle of attack, and angle of sideslip. The laser altimeter is used for control law mode changes during takeoff and landing, and gives the pilot a height-above-ground reading at heights below 70 ft. An Inertial Measurement Unit (IMU) is installed in the vehicle. The IMU provides enhanced accuracy vehicle position and orientation by merging three axis accelerations and three axis rotational rates, with GPS data in real time. Engine speed (RPM) and exhaust gas temperature are measured for each engine. The data comes directly from the JetCat® ECUs through serial interfaces and is telemetered to the GCS.

B. Ground Control Station

The GCS can be operated in three modes: 1) aircraft flight mode, 2) flight simulation mode, and 3) hardware simulation mode. The aircraft flight mode supports the flight operations reported here. In this mode, the pilot and flight crew control the functionality of the aircraft remotely through the telecommand and telemetry systems. In flight simulation mode, the ground control system acts as a realistic software simulator to aid in training of pilots and crew. Simulation mode was used to rehearse all of the flight missions prior to the actual flight tests. This is a key safety procedure, one that has been developed from the experiences of many remotely-piloted vehicle programs. Finally, in hardware simulation mode, the GCS is connected to hardware simulation bench consisting of all the control system hardware components and most of the key instrumentation. This mode is used to verify and validate new software releases and for hardware integration and validation work.

The GCS also accommodates four operators internally and three external monitoring stations. The internal stations are the Pilot, RSO, Test Conductor, and Flight Test Engineer. The external monitoring stations are for the GCS Engineer, Vehicle Tracking Operator, and Real-Time Stability Margin (RSTM) Engineer. The pilot operates the X-48B aircraft using conventional stick, rudder, and throttle controls.

There are five display types in the GCS. The pilot's primary flight display is the head-up display (HUD). The HUD uses the vehicle nose camera video with an overlay of typical HUD symbology to display critical parameters to the pilot. Below the HUD is a head-down display (HDD), which contains similar data to the HUD and does not use the nose camera video. A map display, mounted to the right of the HUD, provides situational awareness of the aircraft's location and trajectory. The map display contains area boundaries, runway markers, and the predicted impact area in the event the emergency parachute recovery is initiated. A dedicated display for warnings, cautions, engines status, fuel state, and battery condition is mounted to the left of the HUD. An additional touchscreen display is mounted below the map display; the touchscreen provides software buttons for commanding operating modes and programmed maneuvers. A view of the GCS during a flight operation is shown in Fig. 4.

Figure 4. The ground control station in use. The pilot (center) uses both the head-up display, providing a view out the aircraft nose, plus key aircraft performance indicators along with the lower head-down display. The test engineer, on the right, interacts with the aircraft through the touchscreen display panel. The Range Safety Officer, just visible on the left, ensures that the aircraft remains safely inside the range boundary.

C. Real-Time Stability Margin Station

The RTSM station consists of a desktop personal computer running MATLAB® (The MathWorks, Natick, Massachusetts) software for monitoring of the RSTMs of the vehicle in flight. The RTSM system has the ability to process data collected from the telemetry stream in near real-time. The RTSM operator can view the results immediately after processing while the plane is still in flight. Further information on the background and procedure for RSTM measurements can be found in Ref. 2.

D. Chase Aircraft

The NASA Dryden T-34 airplane was used in selected flights to provide chase coverage of the flight tests. The primary purpose of the chase aircraft is to provide an additional source of situational awareness to the pilot. A secondary benefit of the chase aircraft was that it provided the position and trajectory of the X-48B aircraft to the RSO, further enhancing flight safety. Throughout the flight, the chase pilot was in direct contact with the X-48B pilot and could relay such information as the position, orientation, and general flight characteristics of the X-48B aircraft. In addition, selected flights with the chase aircraft also provided photographic and video coverage of the X-48B aircraft throughout the flight.

E. Test Range

All flights in the test program were performed at NASA DFRC and supported by NASA DFRC’s Western Aeronautical Test Range (WATR). The WATR utilizes the airspace and ground flight-test facilities provided by Edwards Air Force Base and provides logistic and communication resources for the flight tests. The WATR provides telemetry, optical tracking, range safety, and communication facilities.

All test flights were conducted within the Remotely Operated Aircraft (ROA) work area on the north side of Edwards Air Force Base. The ROA work area consists of an irregularly-shaped, sterilized, controlled airspace from ground level to 10,000 ft mean sea level (MSL) between 34.92 and 35.02 degrees north latitude and -117.78 to -117.88 degrees west longitude. The available working area is shown in Fig. 5. For reference, the longest straight distance across the work area is approximately 5.5 nautical miles.

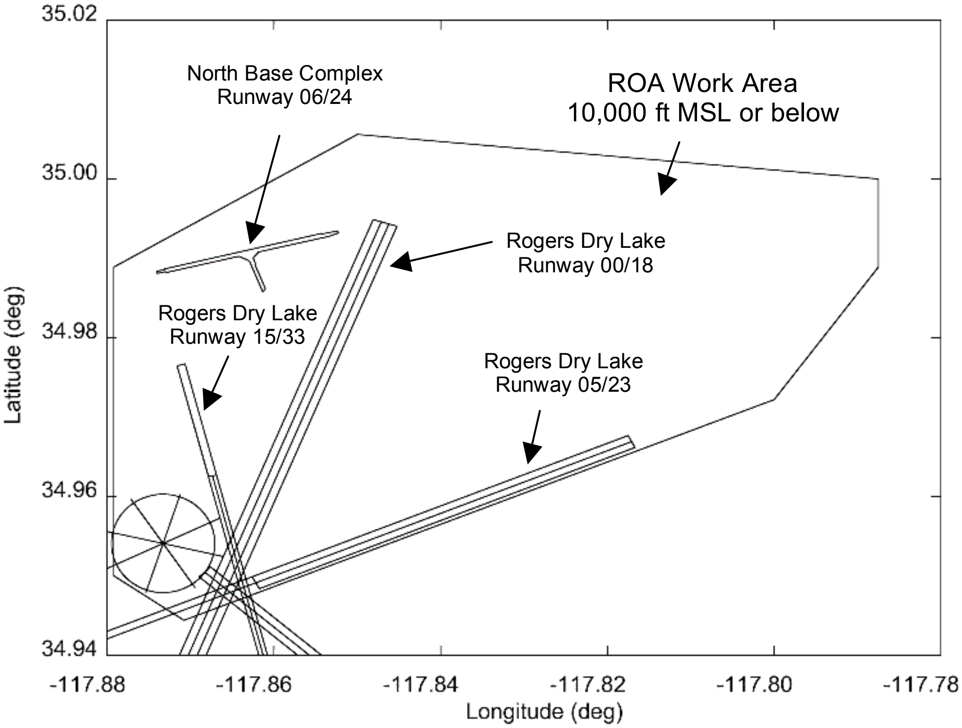

Figure 5. The Edwards Air Force Base Remotely Operated Aircraft (ROA) work area.

Flight operations 1 through 6 and 28 through 39 were conducted from Rogers Dry Lake runways; flight operations 7 through 27 were conducted from the paved, hard surface runway at the North Base Complex. In either case, access to the airspace was controlled by Edwards Air Force Base tower flight operations, and in-flight movements were controlled and monitored by the Air Force Radar Control Facility's SPORT, the Department of Defense operated air traffic controller for the R2515 restricted airspace encompassing the airfield.

Several different antennas were used to support the various communication needs of the flight missions. The GCS is interfaced to WATR range antenna dishes via fiber optic modems and fiber optic cable runs to one of three possible antenna sets. The Multiple Frequency Tracking System (MFTS) and Triplex antennas are 7-meter assets capable of supporting telemetry and video signals in the L-, S-, and C-Band. These two antennas are used for flights originating out of North Base. The Building 4800 Rooftop antenna is a 3.7-m asset and was used for tests originating on the lakebed if the MFTS or Triplex systems were unavailable. Antenna selection is performed prior to all flight operations and any one of the three antennas may be used. Each antenna can be patched into the radio frequency (RF) path as required. Telecommand uplinks and telemetry downlinks are in the L-Band RF spectrum. Vehicle video and audio are downlinked in the S-Band RF spectrum.

The Range FTS transmitters are used in the event of a need to terminate the flight of the X-48B aircraft. The manual termination command via the Range FTS transmitters is executed by the RSO through the FTS panel in the GCS. Redundant 1-kilowatt transmitters, in the UHF frequency band supported all test flights. Concurrently, technicians at the transmitter site monitor system health status, and provide assistance should a failure occur. Additionally, system health status is time-stamped and recorded on a personal computer-based data-logger in real-time. Depending on mission requirements, various flight termination antennas are available for use. These include gained Yagi antennas, omnidirectional antennas, and a high-gain directional parabolic array.

Both fixed and mobile camera systems were used to acquire mission video for flight monitoring and safety concerns. These systems include one long-range, broadcast-quality, high-definition optical tracking system and a mobile broadcast quality television video van. Mission video is routed to the GCS by the use of a digital video switcher. Video was recorded digitally and archived on DVDs.

V. Flight-Testing Summary

A total of 39 flights were completed in Blocks 1 through 4 of this flight-test program. A summary of the various flights is provided in Table 2. Eleven of the flights were flown under Block 1, 9 flights under Block 2, 14 flights under Block 3, and 5 under Block 4. The required objectives for Blocks 1 and 2 have been met, therefore, these blocks are deemed complete. Blocks 3 and 4 are still in progress, and additional flights will be conducted in the future to complete the flight program objectives.

Some of the information contained in Table 2 requires further description. The slat configuration defines whether the bolt-on slats were used in the "slats extended" configuration or the "slats retracted" configuration. The weight designation (either "light," "mid," or "heavy") indicates the amount of ballasted weight added to the aircraft. The empty aircraft in the "light" configuration weighed approximately 395 lb, 405 lb in the "mid" weight configuration, and 430 lb in the "heavy" configuration.

Three center of gravity (CG) configurations were also tested. Ballast weight in different locations on the aircraft was used to modify the CG location. The reference location for the CG was taken from the mean aerodynamic chord (MAC) leading edge. There was a four-inch difference in the CG location between the forward and aft locations.

Table 2 also indicates the aircraft flight time from liftoff to touchdown and whether a chase aircraft was utilized during the flight. The X-48B aircraft was flown by pilots employed by The Boeing Company as well as by a NASA pilots. All pilots had extensive aircraft flight-testing experience. Having multiple pilots gave the program different perspectives which were especially valuable in the handling qualities evaluation where the results are generally qualitative.

Table 2. Flight summary table showing flight history and aircraft configuration.

	Flight No	Date	Duration (min)	Slats	Weight	CG Location	Location	Takeoff Runway	Landing Runway	Chase Aircraft	Cumulative Time
Block 1	1	7/20/2007	31	Extended	Mid	Mid	Lakebed	23	23	Yes	0 hr 31 min
	2	7/30/2007	33	Extended	Mid	Mid	Lakebed	23	23	Yes	1 hr 04 min
	3	8/2/2007	31	Extended	Mid	Mid	Lakebed	23	23	Yes	1 hr 35 min
	4	8/8/2007	35	Extended	Mid	Forward	Lakebed	23	23	Yes	2 hr 10 min
	5	8/14/2007	36	Extended	Mid	Forward	Lakebed	23	23	Yes	2 hr 46 min
	6	8/28/2007	34	Extended	Mid	Forward	Lakebed	23	23	Yes	3 hr 20 min
	7	1/18/2008	35	Extended	Heavy	Mid	North Base	06	24	Yes	3 hr 55 min
	8	1/31/2008	36	Extended	Heavy	Aft	North Base	06	24	Yes	4 hr 31 min
	9	2/8/2008	32	Extended	Heavy	Aft	North Base	06	24	No	5 hr 03 min
	10	2/29/2008	38	Extended	Heavy	Aft	North Base	06	24	No	5 hr 41 min
	11	3/6/2008	35	Extended	Heavy	Aft	North Base	06	24	Yes	6 hr 16 min
Block 2	12	4/4/2008	33	Retracted	Light	Mid	North Base	24	24	Yes	6 hr 49 min
	13	4/17/2008	36	Retracted	Light	Mid	North Base	06	06	No	7 hr 25 min
	14	5/8/2008	28	Retracted	Light	Mid	North Base	24	24	Yes	7 hr 53 min
	15	6/12/2008	35	Retracted	Mid	Forward	North Base	06	06	Yes	8 hr 28 min
	16	6/19/2008	34	Retracted	Mid	Forward	North Base	24	24	Yes	9 hr 02 min
	17	7/3/2008	28	Retracted	Mid	Forward	North Base	24	24	No	9 hr 30 min
	18	7/21/2008	31	Retracted	Heavy	Aft	North Base	24	24	Yes	10 hr 01 min
	19	7/21/2008	28	Retracted	Heavy	Aft	North Base	24	24	Yes	10 hr 29 min
	20	7/25/2008	32	Retracted	Heavy	Aft	North Base	24	24	Yes	11 hr 01 min
Block 3	21	8/11/2008	37	Extended	Mid	Forward	North Base	24	24	No	11 hr 38 min
	22	8/11/2008	35	Extended	Mid	Forward	North Base	24	24	No	12 hr 13 min
	23	8/13/2008	34	Extended	Mid	Forward	North Base	24	24	No	12 hr 47 min
	24	9/4/2008	38	Extended	Mid	Forward	North Base	24	24	Yes	13 hr 25 min
	25	9/11/2008	37	Extended	Mid	Forward	North Base	06	06	Yes	14 hr 02 min
	26	9/18/2008	12	Extended	Mid	Forward	North Base	24	24	Yes	14 hr 14 min
	27	9/18/2008	36	Extended	Mid	Forward	North Base	24	24	Yes	14 hr 50 min
	28	9/24/2008	35	Extended	Mid	Forward	Lakebed	15	15	Yes	15 hr 25 min
	29	10/6/2008	35	Extended	Mid	Forward	Lakebed	33	33	Yes	16 hr 00 min
	30	10/6/2008	33	Extended	Mid	Forward	Lakebed	33	33	No	16 hr 33 min
	31	10/15/2008	36	Extended	Mid	Forward	Lakebed	05	05	No	17 hr 09 min
	32	10/16/2008	34	Extended	Mid	Forward	Lakebed	05	05	No	17 hr 43 min
	33	10/23/2008	36	Extended	Mid	Forward	Lakebed	05	05	Yes	18 hr 19 min
	34	10/23/2008	29	Extended	Mid	Forward	Lakebed	23	23	Yes	18 hr 48 min
Block 4	35	10/29/2008	36	Retracted	Mid	Forward	Lakebed	05	05	Yes	19 hr 24 min
	36	10/30/2008	36	Retracted	Mid	Forward	Lakebed	05	05	Yes	20 hr 00 min
	37	11/21/2008	32	Retracted	Mid	Forward	Lakebed	05	05	Yes	20 hr 32 min
	38	11/21/2008	38	Retracted	Mid	Forward	Lakebed	05	05	No	21 hr 10 min
	39	11/25/2008	34	Retracted	Mid	Forward	Lakebed	18	18	Yes	21 hr 44 min

A list of planned and completed flight objectives for each flight is given in Table 1. Note that the list of flight-test objectives is extensive and not all of the flight objectives have been completed. A successful flight-test program is possible if only a select portion of these objectives is completed during tests.

A systematic approach to envelope expansion has been used throughout the flight-test program. The general test process for all envelope expansions was to begin maneuvers at moderate speeds in near-straight-and-level flight, gradually expanding the allowable operating conditions in terms of airspeed, angle of attack, and sideslip angle. In this way, low-risk test conditions were investigated first and then the operating envelope was expanded to higher-risk conditions.

At this time, analysis of the detailed flight results is ongoing. The results will be used to compare flight-derived stability and dynamic coefficients with those obtained in prior wind-tunnel tests. Preliminary results are expected to be available in early- to mid-2009.

Prior to each actual flight mission, the flights were rehearsed using the simulator capabilities of the GCS. The simulator was updated periodically throughout the flight program using information gathered during each flight test to ensure that the simulations were representative of the planned flight tests.

Maneuvering evaluations relied upon a simple “satisfactory” or “unsatisfactory” judgment from the pilot. A systematic criterion for evaluation of remotely-piloted-vehicle handling qualities, such as those that exist for manned vehicles,[3] is lacking. Here, the “satisfactory” or “unsatisfactory” judgment is simply an assessment by the pilots relative to their own anticipation as developed through flight rehearsals in the simulation. A more comprehensive approach to flight-testing and analysis methods for handling quality assessment of remotely-piloted vehicles is needed to justify a more robust evaluation method. This is an area of research that would be of great value to the remotely-piloted-vehicle research community.

The following provides a brief summary of each flight block.

A. Envelope Expansion Phase: Blocks 1 and 2: Flights 1 through 20

The primary flight objectives of Blocks 1 and 2 were to verify the operation of key aircraft systems and assess the general performance characteristics of the aircraft in order to clear a portion of the flight envelope for further testing. Specific maneuvers were conducted to demonstrate vehicle controllability and stability during the takeoff, climb, cruise, approach, and landing phases. The first flights of the X-48B aircraft in Block 1 were conducted in the leading-edge “slats extended” configuration followed by flights in Block 2 in the “slats extended” configuration.

In general, the pilot reported that the aircraft performed extremely well and matched well with the simulator behavior. The image from the “pilot’s view” camera out the nose was acceptable and the sun did not obscure the pilot’s vision. Engine thrust response was very good. The speedbrake function resulted in symmetric drag with no noticeable directional effects. There was good speed stability on approach. The pilot deemed the laser altimeter instrument necessary to conduct a proper landing.

Envelope expansion for Block 1 consisted of a variety of maneuvers. Steady-heading sideslip maneuvers were performed to determine the static roll and yaw characteristics and to expand the crosswind landing limits. Bank-to-bank maneuvers were flown to evaluate the dynamic roll and yaw characteristics. Wind-up turns were conducted to evaluate the handling qualities during loaded flight up to the test maneuver load factor limit. In addition, frequency sweeps, doublets, and RTSM maneuvers were performed to collect data for quantitative comparisons between simulation predictions and flight results. All maneuvers were evaluated satisfactorily by the pilots during flight.

Simulated engine-out handling qualities were evaluated at a benign flight condition. Each engine was reduced to idle thrust individually, with a minor controllability check conducted to evaluate flight characteristics. The center engine and left engine were reduced simultaneously to further evaluate the vehicle performance. Vehicle response and engine response were found to be satisfactory.

A control law update occurred prior to Flight 7, incorporating lessons learned from the first six flights. This update also coincided with a change from operations on the lakebed to the North Base hard surface runway. The pilot commented that with the new control laws the aircraft appears much more stable in flight at higher speeds, and speedbrake extension at higher speeds made the vehicle more stable in pitch. The pilot also remarked that ground-handling characteristics, including braking and directional control with braking, are much better on the hard surface runway than on the lakebed.

The first flight of Block 2, Flight 12, was the first flight in the “slats retracted” configuration. The configuration change to “slats retracted,” necessitated a flight control law update. Because of the change in the slats configuration and the flight control update, Flight 12 was approached as a first flight, with all of the applicable first-flight restrictions.

Envelope expansion in Block 2 proceeded in a similar fashion to the Block 1 envelope expansion. Steady-heading sideslip, bank-to-bank, and wind-up turns were performed, as well as frequency sweeps, doublets, and RTSM maneuvers. Similar to Block 1, all maneuvers were evaluated satisfactorily by the pilots during flight and were reported to be similar to the simulation results.

Completion of Blocks 1 and 2 resulted in a preliminary flight envelope adequate for transition to higher-risk testing.

B. PID/Stalls/Engine-Out Maneuvering Phase: Blocks 3 and 4: Flights 21 through 39

Block 3 returned to the "slats extended" configuration with the goal of taking the aircraft to the limit of controlled flight. The aircraft was also returned to the "mid" weight, forward CG configuration because of the predicted improved stability with a forward CG. At the time of this report, this Block 3 is partially complete.

Similar to Blocks 1 and 2, a systematic approach to investigate and expand the angle-of-attack envelope was followed. The focus of Block 3 was to expand the Block 1 envelope to higher angles of attack. An initial expansion proceeded in much the same way as the Block 1 expansion, incorporating bank-to-bank rolls, steady-heading sideslips, frequency sweeps, and RTSM maneuvers. This initial expansion was performed in one-degree increments up to an intermediate angle of attack that provided protection from uncertainty in the predicted stall angle of attack.

After envelope expansion to the intermediate angle of attack, the final expansion to the stall angle of attack was performed. The initial stall approaches were performed while descending at idle thrust; this was determined to be the lowest-risk flight condition for initial probing of uncontrollable flight. Again, the angle-of-attack expansion was performed in one-degree increments. At each angle of attack, the controllability in all three axes and the pitch-over recovery were evaluated by the pilot. As the angle of attack was increased to just below the predicted stall angle of attack, the aircraft became relatively difficult to hold steady because of a sustained and continual pitch bobble. At each angle of attack during the expansion, the pitch-over recovery maneuver was performed successfully.

Finally, a limiting angle of attack was reached, resulting in uncommanded wing roll-offs from the high-angle-of-attack state. At this angle of attack the pitch bobbling subsided and was no longer evident. During the initial observation of the uncommanded wing roll-offs the pilot performed the pitch-down recovery by releasing aft stick pressure. Subsequent tests allowed the pilot to attempt to counter the roll-off with lateral stick inputs; this slightly delayed the roll-off and resulted in a more abrupt wing drop. The limiting angle of attack was achieved six times during three flights with three separate pilots; the pitch-over recovery maneuver was performed successfully each time.

Investigation of the flight characteristics between the intermediate and limiting angle of attack was performed to provide quantitative information useful for understanding the roll-off behavior. Doublets and frequency sweeps in all three axes, doublets at the control surfaces, and RTSM maneuvers were performed at an angle of attack just below the limiting angle of attack. The data are currently being reviewed, along with the behavior at the limiting angle of attack, to determine the cause of the effects observed.

Block 4 returned to the "slats retracted" configuration with the same objectives as Block 3. The initial flight envelope cleared during Block 2 testing was augmented with minimal additional testing to provide a sufficient flight envelope for final approach to the limiting angle of attack. Steady-heading sideslips, bank-to-bank turns, doublets, and RTSM maneuvers were performed to reestablish a safe flight envelope.

The Block 4 approach to stall was conducted in a similar fashion to the Block 3 approach. The approaches were performed in a descent, with idle thrust, and increasing angle of attack in one-degree increments. At each angle of attack, the controllability in all three axes and the pitch-over recovery were evaluated by the pilot. The limiting angle of attack, for the "slats retracted" configuration, was reached, again resulting in uncommanded wing roll-offs. The pilot commented that it felt like he was attempting to balance the aircraft on the head on a pin. The limiting angle of attack was achieved twice in the "slats retracted" configuration; the pitch-over recovery maneuver was performed successfully each time.

At the time of this report, the Block 4 objectives are minimally complete. Further investigation into the uncommanded high-angle-of-attack flight regime will be conducted in subsequent flights.

VI. Conclusion

Thirty-nine flights of the X-48B subscale Blended Wing Body aircraft were conducted from the period of July 2007 through December 2008. The flight tests were conducted in four blocks of a planned six-block (three-phase) test program. Significant results of the flight program included validating the stability and control of the full-scale Blended Wing Body aircraft across a significant portion of the low-speed flight regime and demonstrating recovery from idle thrust stalls in both the "slats extended" and "slats retracted" configuration. Future reports will provide more detailed analysis and interpretation of these observations as well as the interpretation of quantitative data collected. Overall, the flight tests performed to-date indicate that the aircraft exhibits good handling qualities and performance, consistent with pre-flight simulations.

Appendix
Glossary of Flight-Test Terms

- **Airspeed Calibration** – The determination of actual airspeed by measuring the time required to cover a specified distance along the ground and then correcting this measurement to account for wind effects. An airspeed calibration is used to correct basic pitot-static measurements to account for the effects of the airplane body on the freestream flow.
- **Autopilot/Autotrim/Autothrottle Maneuvers** – Maneuvers designed to ascertain the effectiveness and capabilities of the autopilot system. For example, an autopilot engage/disengage check verifies that the autopilot can be engaged (activated) and disengaged (inactivated) using the airplane control system.
- **Bank-to-Bank** – A maneuver designed to test the roll/yaw damping characteristics of the airplane. The maneuver is started from a bank angle in one direction and the pilot tries to capture a bank angle in the opposite direction. The level of capture accuracy/crispness depends on the level of entry roll-rate/aggressiveness and roll/yaw damping characteristics. The more aggressive the entry roll-rate or the less the roll/yaw damping characteristics, the more the bank angle oscillates at capture. There are accepted levels of entry aggressiveness for different category (transport/fighter) aircraft against which the handling quality is determined.
- **Departure** from controlled flight – This refers to airplane response outside the pilot commands. Small departures not corrected/stopped in time could lead to large departures in roll pitch or yaw, or combinations there of. Usually departures are characteristics of high-angle-of-attack flight, approaching stalls or beyond.
- **Doublet** – A series of two opposite control inputs testing the dynamic response of the plane in a particular axis. For example, a pitch doublet is the consecutive application of pitch-up input followed by a pitch-down input and then a return to neutral conditions.
- **Engine-Out Maneuver** – A maneuver in which the engine speed is reduced to idle to determine the simulated effect of a lost engine on airplane performance. For the X-48B LSV at idle, the engine thrust is expected to be 5 lbf or less compared to the approximately 50-lbf thrust at full throttle.
- **Frequency Sweep** – A time-varying sinusoid signal with increasing frequency as a function of time applied to the airplane control system to induce an aerodynamic response. The signal can occur to produce a response primarily in any one of the three orthogonal axes (roll, pitch, and yaw) or can excite a single control surface.
- **Gait Check** – A verification of the airplane's angle of attack during flight. In this program, a gait check determines the location of the horizon on the head-up display at level flight or in climb. In case of a loss of instrumentation, this reference can therefore be used to maintain a specified level of flight or climb.
- **Ground Effect** – The difference in airplane lift, drag and pitching moment characteristics when flying less than one wingspan height above the ground. These characteristics are especially important when designing control systems for an autonomous aircraft.
- **Landing Go-Around** – A maneuver simulating the approach to landing, except that prior to landing, the pilot pulls up and does not physically land the airplane.
- **Lazy-Eight Turn –** A maneuver consisting of two back-to-back wingovers. A wingover consists of a coordinated bank and turn such that the airplane achieves maximum bank at 90 degrees in the turn.
- **Level Acceleration** – A maneuver in which the airplane's speed is increased at constant altitude.
- **Level Deceleration** – A maneuver in which the airplane's speed is decreased at constant altitude. The opposite of level acceleration.
- **Parameter Identification (PID)** – Determination of a system's dynamic performance parameters based on measurements of the system's excitations and the resulting dynamic response. The correlation between input and output is performed offline, after the flight test.
- **Phase Checks** – A series of maneuvers that verify that the airplane's major controls are properly phased with respect to inputs and outputs. For example, a yaw phase check verifies that a pilot's yaw right input is translated into a yaw right output.
- **Pitch-Over Recovery** – Also known as nose-down or stall recovery, pitch-over recovery is a maneuver designed to assess the ability of the airplane to recover from a nose-up orientation. Often this is used to

evaluate an airplane's ability to recover from a stall or near-stall. A pilot gauges the quality of the pitch-over recovery by the forcefulness of the airplane to recovery to a nose-down or nose-level attitude.

- **Real-Time Stability Margin (RTSM) –** A control system input consisting of an optimized mix of time-repeating signals applied to all three axes (roll, pitch, and yaw) simultaneously. The information extracted from an RTSM maneuver is similar to PID analysis, except the analysis results are computed during the flight and are available shortly after the maneuver is completed. RTSM analysis provides phase and gain margins in all three axis.
- **Speedbrake Stability Check** – A maneuver designed to ensure that the application of the airplane's speedbrakes does not activate an undesirable asymmetrical or dynamic response in the airplane's trajectory.
- **Steady-Heading Sideslip** – A maneuver in which the airplane is forced to maintain a set heading with a specified sideslip angle. Sideslip will induce both yawing motion (due to directional stability) and rolling motion (due to dihedral effect). The combined motions in yaw and roll are therefore coupled together, since they are both related to sideslip. The strength of these coupling effects can be found by measuring the amount of rudder and aileron deflection that the pilot must use to hold the airplane in a steady sideslip. The higher the rudder deflection, the higher the directional stability. The higher the aileron deflection, the higher the dihedral effect. Sideslip maneuvers also are useful to determine the airplane's stability in crosswind conditions.
- **Throttle Response Checks** – A maneuver that verifies that the throttle is active and that it provides the proper engine control.
- **Triplet** – A series of three opposite control inputs testing the dynamic response of the airplane in a particular axis. For example, a pitch triplet is the consecutive application of a pitch-up input followed by a pitch-down input followed by a pitch-up input and then a return to neutral conditions.
- **Wind-Up Turn –** A turn requiring the simultaneous application of bank and pitch to produce a descending spiral that becomes increasingly tighter and steeper as the loads on the airplane increase. The wind-up turn is used to establish the value of "stick force per *g*" at a particular Mach number and airspeed.

Acknowledgments

A flight-test program of this size requires a tremendous number of talented contributors, the number being too great to list each participant individually here. We are most grateful for their dedicated work. The authors also would like to acknowledge the funding provided by the Subsonic Fixed Wing Project of the NASA Fundamental Aeronautics Program as well as internal corporate funding from the Boeing Company, Phantom Works that made this work possible.

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