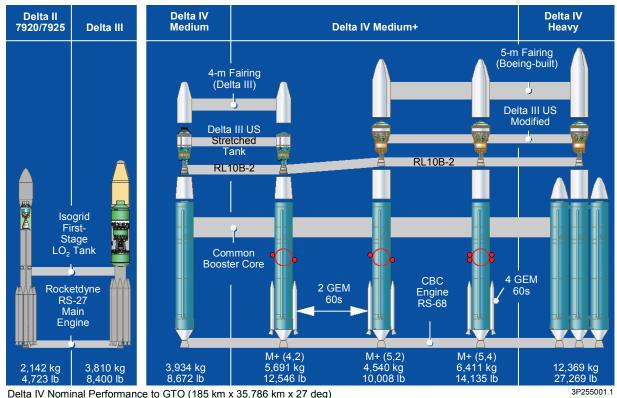
CRITICAL EVENTS OF THE INAUGURAL LAUNCH OF THE BOEING DELTA IV EXPENDABLE LAUNCH VEHICLE

Michael D. Berglund^{*} <u>michael.d.berglund@boeing.com</u> Mark Wilkins[†] Chief Engineer The Boeing Company Huntington Beach, California 92647

ABSTRACT

On 20 November 2002, in its inaugural launch, The Boeing Company's Delta IV expendable launch vehicle lifted off from Cape Canaveral Air Force Station, Florida, at 5:39 EST. The rocket flawlessly deployed its payload (Eutelsat's W5 spacecraft) approximately 35 min later into a geosynchronous transfer orbit. This launch represented the beginning of a new family of rockets, designed to deliver highly reliable, low-cost access to space for military, commercial, and scientific endeavors. Integrating a new launch vehicle with new ground systems and achieving mission success on the inaugural launch posed many unique challenges. This paper summarizes the critical events and challenges of the day of launch, from tanking through spacecraft separation. Liftoff, max Q, solid rocket motor separation, main engine cutoff (MECO), stage I/II separation, and second-stage engine cutoff (SECO) are some of the critical events that are summarized. Also, this paper presents the methodology used in post-flight data reconstruction and analysis.



Delta II Nominal Performance to GTO (185 km x 35,786 km x 28.7 deg)

Note: All Values are Assured Separated Spacecraft Mass and are Derived From the October 2000 Delta IV Payload Planners Guide

Figure 1. The Delta Family of Launch Vehicles

^{*}AIAA Professional Member MS, Delta IV Mission Integration Manager

[†]AIAA Professional Member MS, Delta IV Chief Engineer

INTRODUCTION

The Delta Launch Vehicle Family

Throughout its 40-year legacy, the Delta family of launch vehicles has been evolving to continue to provide a highly reliable, robust solution to satisfy government and commercial access to space needs. The successful Delta IV development represents the most dramatic change in capability during this Delta legacy.

As shown in Figure 1, Delta IV adds five vehicles to the Delta family: the Delta IV Medium, three Delta IV Medium vehicles with solid strap-on rocket motors (Medium-Plus variants), and the Delta IV Heavy with two strap-on first stages serving as liquid rocket boosters.

The Delta IV family is built on a solid foundation of heritage hardware and proven processes in manufacturing, quality, engineering, and supplier management. The Delta IV family evolves to expand the Delta capability while at the same time creating a robust system with improvements in producibility and operability. Figure 1 shows the evolution of the hardware, with the shaded lines connecting common areas across vehicle configurations. The primary avionics system, the 4-m fairing, the 4-m cryogenic second-stage tanks, and the second-stage engine are examples of heritage hardware carried into the Delta IV design. In addition, the strap-on solid rocket motors are derived from the smaller diameter solids used on Delta II and Delta III.

Delta IV enhances hardware integration and checkout processes with the inventive horizontal integration facility (HIF) shown in Figure 2, which enables parallel processing of multiple launch vehicles. In addition, payload fairings and facilities are configured for encapsulation in an offline processing facility and mated to the Delta IV vehicle at the launch pad. This new process enhances payload safety, security, and contamination control and minimizes on-pad time.



Figure 2. Delta IV CCAFS Facilities: Horizontal Integration Facility (HIF)

All configurations of the Delta IV family share the same first stage, the common booster core (CBC). The CBC consists of the interstage, liquid oxygen tank,

centerbody, liquid hydrogen tank, engine section, and the United-States-developed RS-68 engine. The RS-68 engine (Figure 3), clean and environmentally friendly, utilizes liquid oxygen and liquid hydrogen propellants, producing more than 650,000 lb of thrust (sea level).

3P231002



Figure 3. Delta IV First-Stage/RS-68 Engine Static Fire Test

The Medium-Plus variants consist of either two or four 60-in.-diameter graphite-epoxy solid propellant strap-on motors. These motors are designed and manufactured by Alliant Techsystems and have both fixed and vectorable nozzle configurations. The Medium-Plus variants include either a 4- or 5-mdiameter fairing.

The second-stage Pratt & Whitney RL10B-2 engine derives its power from liquid oxygen and liquid hydrogen cryogenic propellants and is used on all Delta IV configurations. Producing 24,750 lb of thrust, the engine possesses an extendible nozzle designed for boost-phase environments and longer second-stage burn durations.

First Flight Vehicle Description

The Alcatel-Space-built W5 telecommunications satellite for Eutelsat, S.A., of France, launched on a Delta IV Medium-Plus variant (Figure 4). The vehicle consisted of a 4-m-diameter second stage and bisector

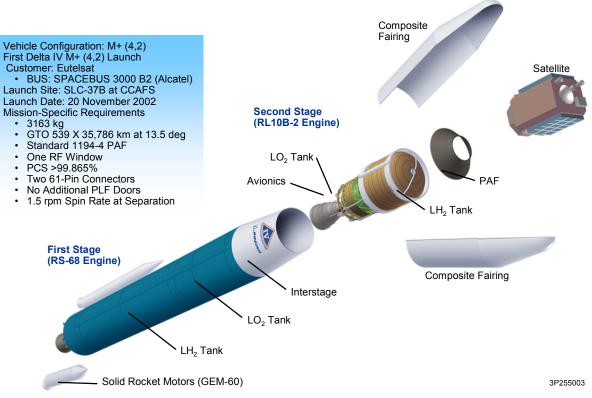


Figure 4. Eutelsat Delta IV Medium (4,2) Vehicle Configuration

composite fairing, 1194-1 payload attach fitting, tapered interstage, and a CBC first stage, with thrust augmentation provided by two Alliant Techsystems 60-in-diameter strap-on graphite-epoxy motors (GEM-60). The Pratt & Whitney RL10B-2 engine, with the extendible nozzle, provided the thrust to the second stage. The Boeing Rocketdyne RS-68 engine powered the first stage.

FLIGHT READINESS REVIEW PROCESS

In addition to propellant loading tests and the Flight Readiness Firing, the inaugural Delta IV launch vehicle was subjected to a rigorous review process to ensure mission success. The Delta IV flight readiness review process was derived from the flight-proven Delta II and Titan IV payload faring launch readiness review process.

Reviews are linked to key Delta IV launch milestones (Figure 5). The process progresses from production through post-launch data reviews and includes customers and independent assessment teams.

"Quick-Look" Data Review

A Quick-Look Data Review, also part of the launch vehicle readiness review process, was held approximately 4 hr following liftoff. In this review, the launch site team reviewed real-time data and reported general vehicle status and observations. All data at this time indicated a nominal flight and a flawless spacecraft delivery.

Post-Flight Data Review

A Post-Flight Data Critique was held on 9 December 2003. This review evaluated mission performance based on available flight telemetry data. Appropriate technologies provided an analysis of vehicle and payload performance to pre-defined performance criteria and attainment of mission objectives. A final Post-Flight Report was published subsequent to the Data Critique.

LAUNCH DAY

Terminal Countdown Activities – First Attempt

Following the LRR, the launch date was confirmed to be 19 November 2003. Terminal countdown began nominally with the main service tower (MST) rollback completion at 1240 UTC. The launch pad was cleared of personnel at 1415 UTC, with the Delta team tracking no constraints to proceeding. The countdown continued nominally through propellant loading, avionics turn-on, and vehicle slews. A slight delay occurred at the beginning of the launch window just prior to the release of the T-5 min built-in hold when the ground sequencer/timer was instructed not to release the hold. The issue was promptly corrected and the count continued.

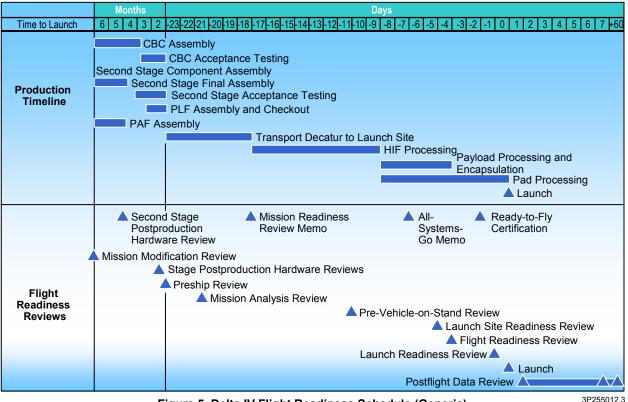


Figure 5. Delta IV Flight Readiness Schedule (Generic)

Into the T-5 min count, a 'hold' was called by the launch weather officer due to the ground winds velocity. The ground wind peaks at this point were high enough to violate liftoff constraints. Propellant tanks were recycled and the vehicle and ground systems were brought back to the T-5 min count configuration.

Once the ground winds died down as the evening progressed, the count was resumed; however, shortly thereafter MAPS aborted the launch attempt. A T-5 min script inadvertantly remained active after the first launch attempt.

The propellant tanks were again recycled. However, the launch window expired as the Delta team assessed the MAPS abort. Subsequently, the vehicle was detanked, the launch attempt scrubbed, and a new launch date set for 20 November, the following day.

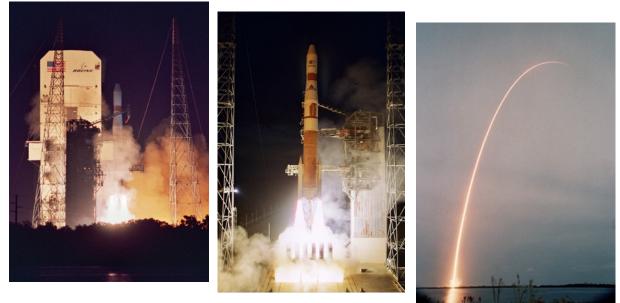
Terminal Countdown Activities – Day of Launch

On 20 November 2003, the launch attempt of the W5 mission began with the MST rollback completion at 1500 UTC. At 1539 UTC, the countdown entered a 60-min built-in hold at launch minus 7 hr, 0 min (L-7H 0M). During the hold, personnel were dispatched to the pad to re-route a special instrumentation umbilical cable

that had lodged against one of the vehicle interstage vent doors. Countdown activities resumed at 1639 UTC at L-6H with nonhazardous items only, which included avionics turn-on and propellant loading preparations. Following securing and re-routing of the special instrumentation cable, the launch pad area was cleared by L-5H 34M, at which time vehicle pressurizations and propellant loading commenced and continued nominally for the next 4 hr. At L-1H 38M, all vehicle propellant tanks were in stable replenish mode awaiting final securing and pressurization for flight.

Due to a range instrumentation issue with the portable wideband instrumentation system (WIS) equipment, vehicle-to-ground radio frequency (RF) link checks were delayed at L-3H 45M, with final completion at L-3H 30M. Vehicle engine slews were completed by L-00:59 M. At L-00:20 M, vehicle load relief data were loaded and the countdown entered a planned 15-min built-in hold at 2219 UTC.

Following final status checks and countdown team polls, the countdown resumed at T-5 min at 2234 UTC. Liftoff occurred at 22:39:00.278 UTC (Figure 6). A standard terminal countdown is shown in Figure 7.



3P255014

Figure 6. Delta IV Inaugural Launch Success, 20 November 2002

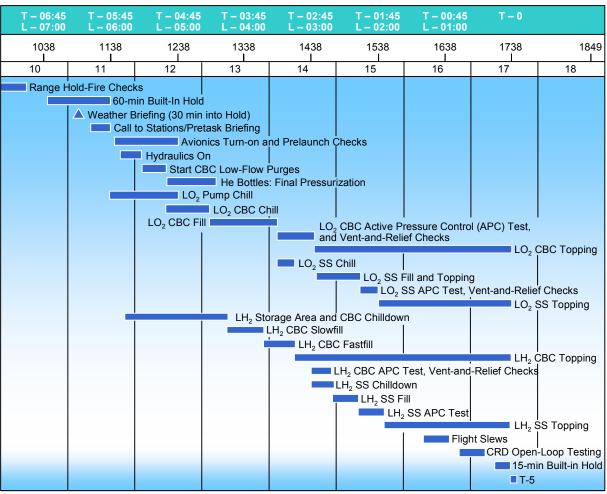


Figure 7. Standard Terminal Countdown

3P255007.4

5 American Institute of Aeronautics and Astronautics

Inaugural Flight Profile and Results

To evaluate the performance of the Delta IV inaugural flight, vehicle and ground systems were outfitted with the standard suite of instrumentation (found on all vehicles of similar configuration), and additional "special flight" and "drag-on" instrumentation. drag-on The instrumentation functioned until liftoff, while the special flight instrumentation functioned through flight. For example, Figures 8 shows all instruments used on the ground and vehicle to measure the dynamic environments; Figure 9 shows the instrumentation specifically located on the second stage.

All technologies evaluated the data and reported a nominal flight with no anomalies, and all observations were noted and closed out in the Post-Flight Report previously mentioned.

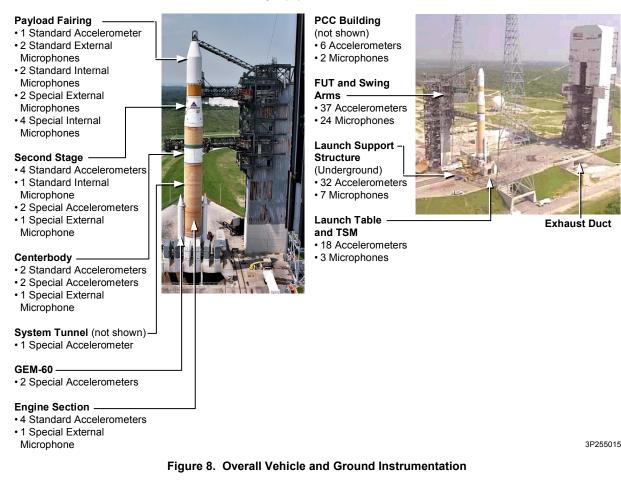
The Delta team used the data gathered to reconstruct the inaugural flight. Being the first flight, comparisons could not be made to past mission performance. However, the Delta team compared the actual flight data to predictions, Delta II performance where applicable, and test data including component and system qualification testing, the Static Fire test series performed at Stennis, Mississippi (first-stage firing), the tanking tests, and the Flight Readiness Firing.

Using this methodology, payload environments were verified. Figure 10 illustrates the dynamic instrumentation used on the fairing and payload attach fitting (PAF). During first-stage burn, flight acoustic, vibration, and shock environments behaved as predicted. Fairing external acoustics followed expectations, while fairing internal acoustics were measured below customer requirements. Fairing separation shock also exceeded customer requirements.

During second-stage burn, the RL10B-2-induced environments were very low at the spacecraft interface, as expected. Spacecraft separation time history indicated no spacecraft re-contact.

The PAF and spacecraft interface environments measured within predictions during the following flight events:

• RS-68 and SRM ignition and start-up shock transient.



Key Equipment Zones

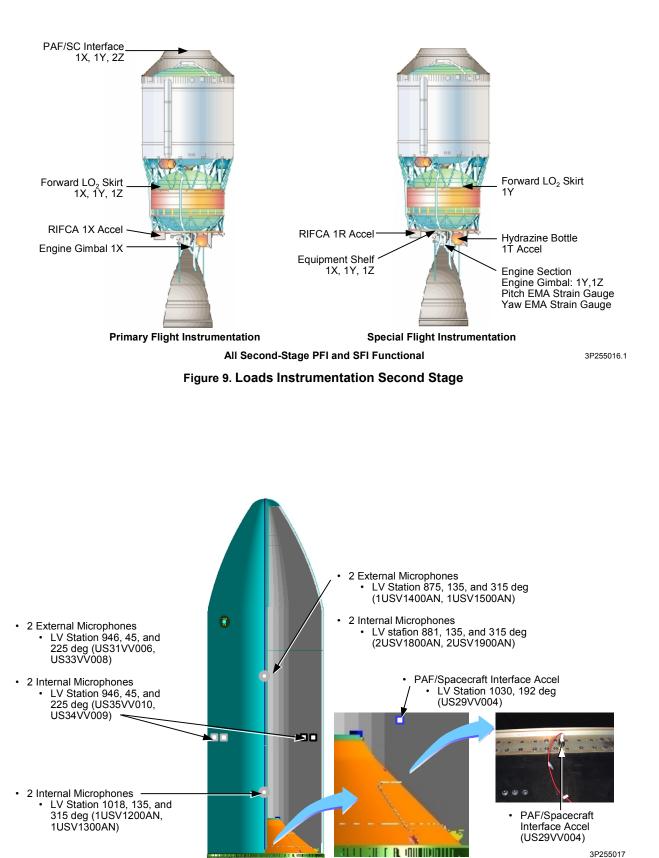


Figure 10. High-Frequency Dynamic Instrumentation

- Liftoff.
- Transonic and Max Q.
- Main engine cutoff (MECO).
- Stage I/II separation.

Flight measurements were compared to the coupledloads analysis (CLA) inputs and response predictions. Evaluation of the flight data at the spacecraft interface indicated that the interface response was within CLA predictions and spacecraft qualification when comparing envelopes over all flight events.

Event-specific comparisons of flight data measurements to CLA predicted responses were completed. The results suggested that small updates to the CLA were needed for subsequent flights to address flight-event-specific response underpredictions.

The major sequence of events is shown in Figure 11. Upon first-stage and solid rocket motor ignition, the vehicle was released from the launch pad and lifted off. After liftoff, the launch vehicle experienced transonic and maximum dynamic pressure environments; vehicle load responses during these aerodynamic events were as predicted.

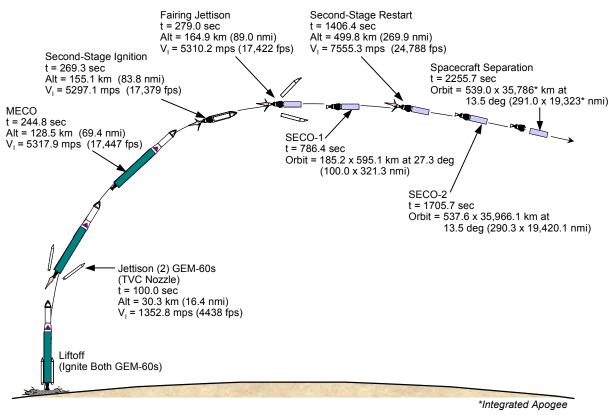
The solid rocket motors then burned out and separated. The first stage continued to burn at full power level until it throttled down to MECO. The vehicle load responses at MECO showed the presence of a "chug," or oscillation, as expected.

The first and second stages then separated. The second-stage nozzle extended, the engine ignited and, shortly thereafter, the payload fairing jettisoned. During this event, the low-frequency load responses were nominal and within predictions. Second-stage engine cutoff (SECO-1) occurred and the stage coasted until the second and final ignition. The two hydrazine settling thrusters operated during the coast period as well as the continuous vent system (CVS).

Following SECO-2, the vehicle oriented itself to the required spacecraft separation attitude. The maneuver was performed under zero thrust condition to allow the propellants to float freely and quench the hot tank walls.

Before vehicle separation, a rotation was achieved, using a sequence of two roll rate steps (-4.3 deg/sec and -9.0 deg/sec).

At 2261.5 sec following liftoff, the spacecraft was separated and inserted into orbit: apogee altitude 19,315 nautical miles (nmi)*, perigee 291.8 nmi*, inclination 13.49 deg, and argument of perigee 179.96 deg. As Figures 12 and 13 illustrate, Delta IV delivered its first payload flawlessly, well within the mission required accuracy.



3P255018



	3P2550				
Orbit Parameter ¹	Actual ²	Targeted ³	Error	Three- Sigma Accuracy	Mission Required Accuracy
Apogee Altitude (nmi)⁴	19,315	19,323	-8	±73	±158
Perigee Altitude (nmi)⁵	291.8	291.0	+0.8	+1.8/-1.7	±2.4
Inclination (deg)	13.49	13.50	-0.01	±0.02	±0.117
Arg. of Perigee (deg)	179.96	180.00	-0.04	±0.29	±0.37

1. Parameters Are Defined at Spacecraft Separation Unless Otherwise Noted

2. Based on 9.5 hr Tracking Data From GSOC/DLR, Dated 22 November 2002; Liftoff Time = 22:39:00.278 UTC, 20 November 2002

3. Final Mission Analysis

4. Integrated, at First Apogee; Based on 3443.92-nmi Earth Radius

5. Based on 3443.92-nmi Earth Radius

Figure 12. W5 Orbital Accuracy

Orbital Parameter	Target	Actual Orbit	Proximity to Target
Apogee Altitude (km) Perigee Altitude (km) Inclination (deg)	35,786 539 13.50	35,771 540.4 13.49	-15 +1.4 -0.01
-			3P25502

Figure 13. Delta IV Delivers Eutelsat W5 on Target