This document, including all enclosed slides, consists of general capabilities information that is not defined as controlled technical data under ITAR Part 120.10 or EAR Part 772.
Outline

• EELV Secondary Payload Adapter (ESPA)
  – Background and Ø15-inch ESPA standard interface
  – ESPA Class capability defined in 2002 with qualification test
  – ESPA Grande Ø24-inch interface
  – Flight heritage

• Rationale for Delta Qualification
  – Realistic design load factors
  – ESPA port modification
  – New “ESPA Heavy” interface with Ø5/16-inch fasteners

• Test execution
  – New definition of ESPA Class

• Follow on activity
  – Mass acceleration curve
  – ESPA Grande test in 2018
Summary

• ESPA is launch infrastructure for small satellites on Atlas V, Falcon 9, Delta IV
  – Cantilever mounting for small sats with defined limits on spacecraft mass and center of gravity (CG)
  – Auxiliary payload (APL) capability established by test in 2002
    • Heritage ESPA class: 181 kg with CG at 51 cm (400 lb at 20 in) on Ø15” bolt circle

• Increased APL capability for ESPA has been validated with Delta Qualification testing
  – Test facility at Space Vehicles Directorate of Air Force Research Lab on Kirtland Air Force Base

• New ESPA APL limits
  1. ESPA class
     220 kg at 51 cm (485 lb at 20 in)
     increase of 21% compared to heritage ESPA class
  2. ESPA Heavy class (with Ø5/16” instead of Ø1/4” fasteners)
     322 kg at 51 cm (710 lb at 20 in)
     mass increase of 77%
ESPÁ Background

- ESPÁ originated at Space Test Program (STP) in 1990s
  - Provide AF capability for launching small experimental payloads
  - Utilize excess lift capacity anticipated for new Evolved Expendable Launch Vehicles (EELVs)
  - CSA Engineering (now Moog Space and Defense) designed ESPÁ ring under small business (SBIR) contract from AFRL/Space Vehicles Directorate with funding and requirements from STP

- ESPÁ structure was qualified for 6804-kg (15000-lb) primary payload (PPL) and six 181-kg (400-lb) APLs
  - Designed for minimal impact to PPL
2002 Qualification Test

- Test performed in structural test facility developed for ESPA at AFRL Space Vehicles Directorate
  - Static loads representing EELV Maximum Predicted Environment (MPE) with qualification factor of 1.25
    - MPE for PPL enveloped published load factors for Delta IV/Atlas V
    - APL load factors conservatively selected for 181-kg (400-lb) payloads based on Boeing Secondary Load Factor Curve for secondary structure design
      - 10g in two directions simultaneously, i.e., 14.1g (vector sum)
- Facility has been used for testing of numerous aerospace structures
  - Operated for AFRL by LoadPath
ESPA Grande

- Interest in larger secondary payloads drove development of 24-inch ESPA port
  - NASA New Millennium study sparked ESPA Grande concept for large internal payload
  - Alternate ESPA design with Ø61-cm (Ø24-in) diameter ports enabled APLs up to 318 kg at 51 cm (700 lb at 20 in)

- ESPA Grande port has not been tested – flight qualification to date has been performed with analysis per DoD-HDBK-343.4
  - Variants of ESPA and ESPA Grande have been analyzed in lieu of delta qualification testing
ESPA Flight Heritage

- March 2007 first flight of ESPA on Air Force STP-1 Atlas V mission
- DSX ESPA, manufactured for AFRL in 2008, is integrated with avionics and payload modules from Sierra Nevada Corporation for STP-2 Falcon Heavy Mission
- June 2009 ESPA was hub of Lunar Crater Observation and Sensing Satellite (LCROSS) as secondary payload on Lunar Reconnaissance Orbiter (LRO) launch on Atlas V
- Air Force missions AFSPC-4 in July 2014 and AFSPC-6 in August 2016, both on Delta IV
- First commercial ESPA missions, also first launch of ESPA Grande: two ORBCOMM Generation 2 (OG2) launches on Falcon 9, 2014/2015
Rationale for Delta Qual Test

• Motivation for re-testing ESPA was desire to carry APLs that exceed heritage definition of ESPA class
  – 181 kg at 50.8 cm (400 lb at 20 in)
• Substantial increase was anticipated because of high strength margins carried since early days of ESPA
  – Reduction in published flight loads since original test
  – Re-design of ESPA port (following STP-1) to facilitate integration of large APLs
  – ESPA design is stiffness driven
• Introduce new ESPA Heavy interface, with larger fasteners, to further increase APL capacity
  – Boss port design facilitates replacement of Ø1/4” with Ø5/16” fasteners
Test Objectives

• Primary objectives were to assess max mass/center of gravity (CG) combinations for two ESPA port configurations
  – Standard ESPA APL on port with Ø1/4" high-strength fasteners
  – ESPA Heavy APL with Ø5/16” high-strength fasteners.

• Secondary objective was to increase PPL capability to 7,711 kg (17,000 lb)
  – With CG at 305 cm (120 in) forward of launch vehicle standard interface
Test Approach

• Load factors (g)
  – PPL load factors from “airplane curves” in EELV Standard Interface Specification (SIS) to encompass existing and future EELV variants
  – APL load factors from May 2010 ESPA Rideshare User’s Guide
    • 8.5g applied in two directions simultaneously (12g vector sum)
    • One axial load (launch vehicle thrust direction) and one lateral load

• Use existing ESPA test hardware in AFRL inventory
  – Load frame and actuators
  – PPL and APL load heads, except new load head fabricated for Heavy APL
  – Interface adapters and rings

• Not a “test to failure” → Maximum capabilities for standard and heavy ports were determined in advance by analysis
Pre-Test Analysis

- Analysis was performed to define load cases and establish maximum masses for ESPA Heavy and Standard ESPA APLs
  - Assumed CG distance of 51 cm (20 in)
- Test stack model used to assess test port locations, i.e., adjacent to each other with other four ports open
  - Worst-case loading condition, and maximum stresses do not change appreciably when all ports are loaded
- Payload masses for predicted zero test margins
  - ESPA Heavy APL 322 kg (710 lb)
  - Standard ESPA APL 220 kg (485 lb)
- Six load cases were found to envelope the flight load profiles

<table>
<thead>
<tr>
<th>Load Case</th>
<th>PPL Load Factor, g’s*</th>
<th>APL Load Factor, g’s*</th>
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<tbody>
<tr>
<td></td>
<td>Axial</td>
<td>Lat +Y</td>
</tr>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
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<tr>
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<tr>
<td>6</td>
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</table>

*Load factors at each payload CG
Test Operations

• Strain gages at all high-stress locations

• Load lines had dual-bridge load cell with two independently calibrated/conditioned bridges
  – Redundant readings verified applied loads; error between bridges exceeds ±1% → hydraulic pressure removed and test aborted

• Loads and critical strains were compared real-time to predicted values
  – Each case had three load cycles with hold points for data review
    • 40% Set Run: to check instrumentation and relieve any inherent set
    • 110% Acceptance Run: engineering data
    • 125% Qualification Run
Test Success Criteria Achieved

1. Verification that all loads were applied at qualification level
   - Range of max applied loads was between 125.0% and 125.7%
2. Structure did not exhibit detrimental elastic deformation, permanent set, or failure under flight acceptance level loads
   - Review showed minimal hysteresis in 110% runs for all cases
   - Strain data for 110% and 125% runs matched well; no anomalous behavior
3. Test article exhibited no catastrophic failure at or below qual level
   - Met for all qual load cases—no indication of structural failure
   - Strain and load data was continuous
   - ESPA maintained ability to support applied loads throughout all qual load cases; good agreement between 110% and 125% runs
   - No evidence of damage from post-test visual inspections
4. Critical load and strain data were recorded
   - Provided as Test Program deliverable
New ESPA-Class Capability

• Heritage ESPA-class, 181 kg at 51 cm (400 lb at 20 in), was test qualified in 2002
  – New Standard ESPA capability increases ESPA-class mass from 181 kg to 220 kg (400 lb to 485 lb)
• New ESPA-class interface, “ESPA Heavy,” is introduced, replacing traditional Ø1/4” fasteners with Ø5/16” fasteners
  – ESPA Heavy capability is 322 kg (710 lb)
ESPA Heavy Interface

• Introduction of Heavy port configuration was motivated by ESPA payload analyses
  – Analyses consistently have shown APL fasteners to be weak link in cantilevered payload load path

• Only change from Standard ESPA port to ESPA Heavy port configuration is Ø5/16” fasteners instead of Ø1/4”
  – Feature of boss port is capability to change fastener size with negligible effect on adjacent (ESPA) structure
    • No change to port geometry or fastener count, i.e., 24x equally spaced fasteners
  – Fastener configuration has flight heritage on F9 OG2 missions

• Designing for ESPA Heavy must address the entire APL load path, including fasteners, separation system, isolation system (if included), and satellite bus structure
Future ESPA Work

- Moog offers family of payload adapters based on ESPA
  - Development work is continuing with internal funding

- Reduced mass ESPA rings
  - Increasing interest in propulsive ESPA missions has re-focused attention on reducing ESPA structure mass
  - Research is underway on several fronts
    - Additive manufacturing (aluminum and titanium)
    - Alternate materials including carbon fiber composites
    - Optimized aluminum structure

- ESPA Grande qualification test program is underway
  - ESPA currently in fabrication
  - Test planned for early 2018 at AFRL/Space Vehicles Directorate
  - Mass acceleration curve has been introduced for test load factors
ESPA Mass Acceleration Curve

• Since 2002, ESPA Auxiliary Payloads (APLs) have been designed with load factors that were:
  – Specified before EELVs were flying
  – Sized for 181.4 kg (400 lb) maximum APL mass

• Mass Acceleration Curve (MAC) for design of secondary structure is accepted practice across aerospace industry
  – Developed at Jet Propulsion Laboratory (JPL) in 1980s
  – During ESPA development, original APL load factors were taken from Boeing Load Factor Curve for secondary structure

• Proposed ESPA MAC
  – Following Delta Qual test, and anticipating Grande Qualification test, more realistic load factors are needed for the range of APL masses that can be accommodated on ESPA
ESPA MAC

JPL curve scaled to intersect heritage ESPA class at (181.4 kg, 8.5g)

<table>
<thead>
<tr>
<th>APL weight</th>
<th>acceleration, g</th>
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<tbody>
<tr>
<td>kg</td>
<td>lb</td>
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<tr>
<td>45.4</td>
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Conclusion

- ESPA Delta Qualification test program was performed at the Air Force Research Lab/Space Vehicles Directorate in New Mexico
  - Increased ESPA capability has been validated, and new ESPA payload limits documented

<table>
<thead>
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<th>mass</th>
<th>CG</th>
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</thead>
<tbody>
<tr>
<td>kg</td>
<td>lb</td>
</tr>
<tr>
<td>Heritage ESPA Class</td>
<td>181</td>
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<tr>
<td>Standard ESPA (redefined)</td>
<td>220</td>
</tr>
<tr>
<td>ESPA Heavy</td>
<td>322</td>
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</tbody>
</table>

- ESPA Grande Qualification program is underway to quantify capability of 24-inch port
  - Test is planned for early 2018
  - ESPA Mass-Acceleration Curve (MAC) adopted in lieu of conservative heritage ESPA load factors