ESPA Class Redefined

Joseph R. Maly
Moog Space and Defense, Mountain View, California
jmaly@moog.com 650-960-4226

Gregory E. Sanford
LoadPath LLC, Albuquerque, New Mexico
gsanford@loadpath.com 505-853-2422

Andy Williams
Air Force Research Laboratory/Space Vehicles Directorate
Kirtland Air Force Base, New Mexico
afrl.rvsv@us.af.mil

Lisa Berenberg
Aerospace Corp., Albuquerque, New Mexico
Lisa.A.Berenberg@aero.org 505-872-6263

ABSTRACT

ESPA is established launch infrastructure for small satellites on Atlas V, Falcon 9, and Delta IV. Satellites mount to ESPA in a cantilever mount with defined limits on spacecraft mass and center of gravity (CG). ESPA auxiliary payload (APL) capability was established by test in 2002 as 181 kg with CG at 51 cm (400 lb at 20 in). This mass/CG combination is a defining characteristic of the small satellite standard "ESPA class."

Increased APL capability for ESPA has been validated with Delta Qualification testing at the Space Vehicles Directorate of the Air Force Research Lab on Kirtland Air Force Base. New ESPA APL limits, including a new interface, "ESPA Heavy" (with Ø5/16" instead of Ø1/4" fasteners), are the following:

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: 322 kg at 51 cm (710 lb at 20 in), mass increase of 77%.

The paper reviews the test program including motivation and conclusions, and also discusses current and future developments for ESPA and ESPA Grande. An ESPA Mass-Acceleration Curve (MAC) is proposed that encompasses the range of APL mass available with the new capability.

BACKGROUND

ESPA, the EELV Secondary Payload Adapter, originated in the mid-90s to provide capability to the Air Force for launching small experimental payloads, utilizing the excess lift capacity anticipated for the new Evolved Expendable Launch Vehicles (EELV).[1] CSA Engineering (now Moog Space and Defense) designed the ring under a Small Business Innovation Research contract from the Air Force Research Laboratory/Space Vehicles Directorate with funding and technical requirements from the DoD Space Test Program. The prototype adapter was designed for Atlas V and Delta IV, the EELV Medium vehicles in development at the time by Lockheed Martin and Boeing. An ESPA flight unit is shown in Figure 1; the nomenclature ESPA 6-15-24 designates the number of ports (6), the port diameter in inches (15) and the ring height in inches (24).

Figure 1: ESPA 6-15-24

The ESPA structure was designed and qualified to mount a 6804-kg (15000-lb) primary payload (PPL) and six 181-kg (400-lb) APLs on an EELV. APL volume is nominally 61.0cm x 71.1cm x 96.5cm (24in x 28in x 38in). ESPA is installed at the EELV Standard Interface Plane, which is a 157.5-cm (62-inch) diameter bolt circle at the top of launch vehicle upper stage. The ESPA duplicates this bolt circle for the PPL, and the ring is designed to be stiff in all directions to provide minimal impact to the PPL. Six ports with Ø38.1-cm (Ø15-inch) bolt circles provide mount locations for the APLs. The standard ring is 61 cm (24 in) tall, so only a small amount of volume in the fairing is utilized from the PPL allowable volume.

2002 Qualification Test

Qualification testing subjected the ESPA structure to static loads representing the Maximum Predicted Environment (MPE) on EELV, with a qualification factor of 1.25.[2] MPE for the PPL was determined by enveloping published load factors for Delta IV and Atlas V. APL load factors were conservatively selected for 181-kg (400-lb) payloads, with concurrence from both Lockheed Martin and Boeing, based on the Boeing Secondary Load Factor Curve for secondary structure design: 10g in two directions simultaneously, i.e., 14.1g (vector sum). Testing was performed in the structural test facility at the AFRL Space Vehicles Directorate developed as part of the ESPA program. Moog CSA designed and built the reaction frame, shown in Figure 2, and designed and performed the qualification test. The facility has since been used for numerous aerospace structures testing, operated for the AFRL by LoadPath.

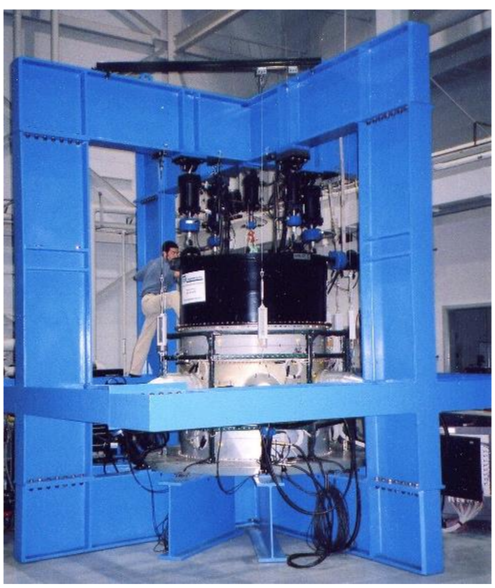

Figure 2. Static test facility at AFRL developed during ESPA program

ESPA Grande

ESPA was adopted by the launch vehicle and rideshare communities and it became a small satellite standard (400 lb, 24in x 28in x 38in, Ø15in interface), but frequent requests were received for "the next size up." A NASA engineering study for a proposed New Millennium mission sparked the concept for a ring with 106.7-cm (42-in) height for a large internal (co-manifested) payload. For increased cantilever carrying capability on the ring exterior, Moog CSA designed an alternate port to replace the 38.1-cm (15-inch) diameter ESPA interface. ESPA Grande features Ø61-cm (Ø24-in) diameter ports, shown in Figure 3, to enable APLs up to 318 kg at 51 cm (700 lb at 20 in); this bolt circle diameter was also selected to be consistent with other adapters.[3] ESPA Grande APL capacity with the Ø61-cm (Ø24-inch) port is shown in Figure 4, compared to the heritage ESPA class capacity. The ESPA Grande port is a "boss port" as opposed to "flanged port" of the original ESPA design that was determined difficult to support APL integration. The ESPA Grande port has not been tested and flight qualification to date has been performed with analysis per DoD-HDBK-343.[4] Other variants of ESPA and ESPA Grande to date have been analyzed in lieu of delta qualification testing.

Figure 3: ESPA 4-24-42

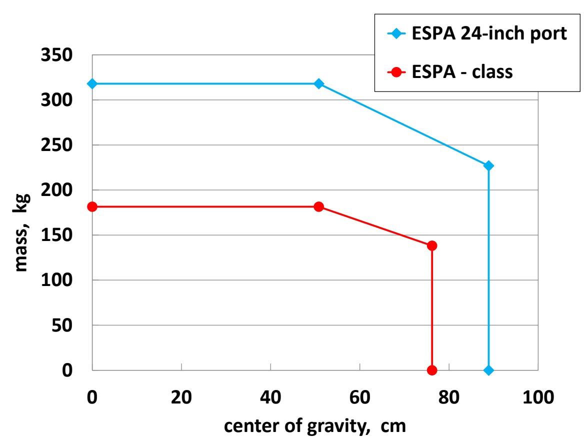

Figure 4: ESPA Grande and heritage ESPA-class payload capacity

Flight heritage

The first flight of the ESPA ring occurred in March 2007 on the Air Force's STP-1 Atlas V mission; the STP-1 launch stack is shown in Figure 5. The DSX ESPA was manufactured for AFRL in 2008 and it is now integrated (with avionics and payload modules from Sierra Nevada Corporation) as a free-flyer satellite and ready to go on the STP-2 Falcon Heavy Mission. In June 2009, ESPA was the hub of the Lunar Crater Observation and Sensing Satellite (LCROSS) as a secondary payload on the Lunar Reconnaissance Orbiter (LRO) launch on Atlas V; in October 2009, the LCROSS impacted the lunar surface producing evidence of liquid water at the lunar south pole. Air Force missions using ESPA include AFSPC-4 in July 2014, and AFSPC-6 in August 2016, both on Delta IV launch vehicles. The first commercial ESPA missions, and also the first use of ESPA Grande, were the ORBCOMM Generation 2 (OG2) launches[5] on Falcon 9; Mission 1 in July 2014 orbited 6 OG2 satellites on two ESPA rings followed by Mission 2 in December 2015 with 11 satellites on three ESPAs (Figure 6).

Figure 5: STP-1 Integrated Payload Stack

Figure 6: OG2 Integrated Payload Stack

RATIONALE FOR DELTA QUALIFICATION

The motivation for re-testing the ESPA structure was the desire to carry APLs that exceed the heritage definition of ESPA class in terms of mass and center of gravity (CG), i.e., 181 kg at 50.8 cm (400 lb at 20 in). A substantial increase was anticipated because high strength margins in the structure had been carried since the early days of ESPA. The margins were high for three reasons:

1. reduction in published flight loads since the original test,
2. re-design of the ESPA port following STP-1 to facilitate integration of large APLs, and
3. the ESPA design is stiffness driven.

It was also desired to introduce a new ESPA interface, with larger fasteners, to further increase APL capacity.

Reduced Load Factors

During the original design, ESPA-class APL capability was determined by analysis and verified by test using design load factors recommended by the EELV manufacturers Boeing and Lockheed Martin, i.e., 10g in two directions simultaneously (vector sum of 14.1g). The first ESPA flight article was designed and then tested using these load factors, but soon afterward ESPA APL load factors were reduced to 8.5g in two directions simultaneously, a significant reduction (but still very conservative based on flight measurements). This reduction reduced the load factor vector sum from 14.1g to 12g.

Port Re-Design

Feedback from the STP-1 integration team prompted a design modification for the ESPA ports to facilitate mounting of APLs on the ports. Changing the configuration from a flanged port to a boss port (Figure 7) allowed fasteners to be inserted from inside the ring, eliminating access issues when integrating a large APL. This design change had the beneficial side effects of stiffening and strengthening the ESPA structure, and qualification for follow-on launches was achieved by analysis.

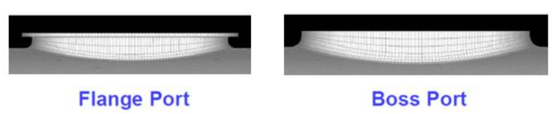

Figure 7: ESPA APL port configurations

ESPA Heavy Interface

In addition to the high margins that were carried for ESPA since the original test, a design option for the port using Ø5/16" fasteners was also introduced that further enhances ESPA port capability. ESPA mission stack analyses consistently show that APL fasteners are a weak link in the load path supporting the cantilevered ESPA APL, and a feature of the boss port is the capability to increase fastener diameter from 1/4" to 5/16" with negligible effect on adjacent (ESPA) structure. This configuration of ESPA has flight heritage on the ORBCOMM Generation-2 Falcon 9 missions, and will require new versions of existing ESPA separation systems. The new ESPA Heavy capability slightly exceeds the current advertised capacity of the Ø24-inch ESPA Grande port, which is 318 kg at 51 cm (700 lb at 20 in).

TEST APPROACH

The primary test objectives were to assess the maximum mass and center of gravity (CG) combinations for two ESPA APL configurations:

1. Standard ESPA APL, on port with Ø1/4" high-strength fasteners, and
2. ESPA Heavy APL with Ø5/16" high-strength fasteners.

A secondary objective was established to increase the primary payload (PPL) capability to 7,711 kg with a CG at 305 cm (17,000 lb at 120 in) forward of the launch vehicle standard interface.

Test load factors for the PPL used the "airplane curves" in the EELV Standard Interface Specification[6] to encompass existing and future EELV variants. Load factors for the APLs used the May 2010 ESPA Rideshare User's Guide,[7] with 8.5g applied in two directions simultaneously (12g vector sum), consisting of one axial load (launch vehicle thrust direction) and one lateral load.

The test was not intended to be a "test to failure." Rather, the maximum capabilities for the standard and heavy ports were determined in advance by analysis as the maximum payload masses achievable with positive strength margins.

The test used existing ESPA test hardware in the AFRL inventory, including the load frame and actuators, PPL and APL load heads, and interface adapters and rings. A new load head was fabricated for the Heavy APL with Ø5/16" fasteners.

PRE-TEST ANALYSIS

Preliminary analysis was performed to assess the appropriate load cases for the test, and to determine the maximum masses of the ESPA Heavy APL and the Standard ESPA APL, assuming a CG distance of 51 cm (20 in) so that existing test load heads could be used.

The test stack model, with one port modified to accommodate the Ø5/16" fasteners for the ESPA Heavy port, is shown in Figure 8. This model was first used to assess the location of the two test ports, adjacent to each other with the other four ports open. Analysis showed this to be the worst-case loading condition, and the maximum stresses do not change appreciably when the other ports are loaded.

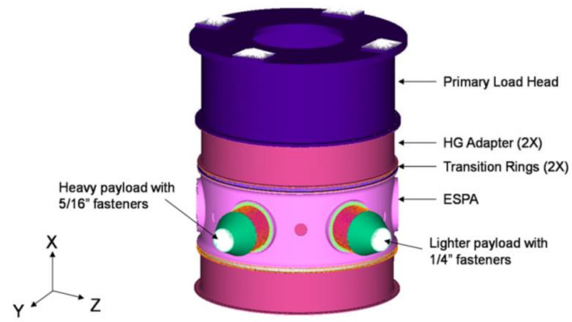

Figure 8: Test stack finite element model

Sizing for the target port masses, for both ESPA Heavy and Standard ESPA APLs, was set at the payload mass at which the predicted tested margins were zero (with 51-cm/20-inch CG offset). A PPL of 7,711 kg (17,000 lb) was included in the analysis with its CG offset at 304.8 cm (120 in). The ESPA Heavy APL was determined to be 322 kg at 51 cm (710 lb at 20 in) from the ESPA port. The Standard ESPA APL was 220 kg at 51 cm (485 lb at 20 in) from the ESPA port.

The pre-test analysis showed that six combinations of axial and lateral loads envelope the flight load profiles as summarized in Table 1.

Table 1: Axial and lateral load factors for qualification test cases

Load	PPL Load Factor, g's*			APL Load Factor, g's*		
Case	Axial	Lat +Y	Lat +Z	Axial	Lat +Y	Lat +Z
1	-6.5	0	0.5	-8.5	0	8.5
2	-4	0	1.5	-8.5	0	8.5
3	-3.3	0	2	-8.5	0	8.5
4	2	0	-0.6	8.5	0	-8.5
5	0.2	0	-2	8.5	0	-8.5
6	1	0	-1.5	8.5	0	-8.5

***Load factors at each payload CG**

TEST OPERATIONS

The test stack hardware is shown in Figure 9. Strain gages were installed at high-stress locations in the ESPA test article, including Rosette gages adjacent to the 4-inch-diameter access holes and uniaxial gages adjacent to the upper and lower primary flanges. All load lines featured a dual-bridge load cell having two independently calibrated and conditioned bridges; this redundant reading served to verify the applied load in lieu of an actuator hydraulic pressure reading. The first bridge (bridge 'A') was used as the load control feedback signal, and the second bridge (bridge 'B') was continuously monitored and compared to the feedback signal; if the error between the two bridges ever exceeded ±1%, hydraulic pressure would be removed and the test would be aborted. Both bridge A and bridge B were within ±1% error throughout all testing.

Figure 9: ESPA Delta-Qual Test Stack at AFRL test facility

All instrumentation and load cell channels were recorded continuously during test operations. Data was displayed in tabular and graphical format and high-strain channels were monitored in real time. All test data was downloaded with compatibility for both Matlab and Microsoft Excel formats. Data files included columns indicating the percent of flight load at which each sample was recorded.

All test cases were performed with a series of increasing loads, and all loads were applied simultaneously. All loads and critical strains were compared, real time, to predicted values between load increments to prevent overloading and unpredicted failures or yielding. Each load case had hold points that allowed sufficient time to review data.

POST-TEST REVIEW

Strain data from all load cases was exported for processing in Matlab and Microsoft Excel. Strain results were reviewed in three groups: (1) high-stress regions near ports, (2) adjacent to access holes, and (3) at upper and lower primary flanges. The stress profile in ESPA due to the cantilevered loading is dominated by localized high stress regions near the ports. Excellent agreement was seen at the port high-stress locations. Access hole and primary flange gages were in lower stress but high gradient regions, so they were more difficult to match with analysis. Nonlinearity was observed in the test data for several of the gages in these lower stress/higher gradient regions, especially near the primary flanges, while the port gages which recorded the highest strains were quite linear.

All success criteria for the test were achieved:

(1) Verification that all loads were applied at the qualification level (125% of MPE). The range of maximum applied loads was between 125.0% and 125.7%

(2) The ESPA structure did not exhibit detrimental elastic deformation, permanent set, or failure under flight acceptance level (110% of MPE) loads. Review of post-test data analysis showed minimal hysteresis in the 110% acceptance runs for all load cases. Strain data for the 110% runs and the 125% runs matched well and showed no anomalous data, indicating there was no structural damage.

(3) The test article exhibited no catastrophic failure at or below the qualification level. This criterion was met for all qualification load cases—there was no indication of structural failure. Strain and load data was continuous without sudden peaks or steps common to

structural failure. The ESPA maintained its ability to support the applied loads throughout all qualification load cases, and good agreement was seen between 110% runs and the proceeding 125% runs. There was no evidence of damage noted from post-test visual inspections.

(4) Critical load and strain data were recorded. All load and strain data were recorded as specified in the Test Plan and was provided by LoadPath as a deliverable for the Test Program.

Delta Qualification Objectives Met

The primary and secondary test objectives were met. Increased ESPA APL capability has been demonstrated for the Standard ESPA interface, and a new ESPA Heavy interface is available which provides a significant increase in ESPA APL capability. The test acquired sufficient load and strain data to document ESPA qualification and correlation with the ESPA finite element model. The ESPA PPL tested capability has been increased to 7,711 kg with a center of gravity (CG) at 305 cm (17,000 lb at 120 in) forward of the launch vehicle standard interface.

ESPA CLASS REDEFINED

Standard ESPA

The heritage ESPA-class mass and CG of 181 kg at 51 cm (400 lb at 20 in) was test qualified in 2002. The new Standard ESPA capability, based on the results of this test, increases the ESPA-class mass from 181 kg to 220 kg (400 lb to 485 lb), with a CG at 51 cm (20 in) from the ESPA port surface, a 21% increase.

ESPA Heavy

A new ESPA-class interface, "ESPA Heavy," has been introduced, replacing traditional Ø1/4" fasteners with Ø5/16" fasteners. The ESPA Heavy capability, with a CG at 51 cm (20 in) from the ESPA port interface, is 322 kg (710 lb), a 77% increase compared to heritage ESPA class. It is important to note that design of an ESPA mission with a cantilevered payload mass of this magnitude affects the entire APL load path, including fasteners, separation system, isolation system (if included), and satellite bus structure. When initial mission planning is being accomplished for these larger payloads, attention must be paid to the qualification status of all the systems and subsystems in the launch vehicle interface chain to ensure that the increased mass is analyzed and sufficient margins exist.

ESPA class capability based on the results of the delta qualification testing is summarized in Table 2.

Table 2: New ESPA class capability

	mass		CG		
	kg	lb	**cm**	in	**% increase**
Heritage ESPA Class	**181**	400	**51**	20	**--**
Standard ESPA (redefined)	**220**	485	**51**	20	**21%**
ESPA Heavy	**322**	710	**51**	20	**77%**

FUTURE ESPA WORK

ESPA has become an established element of small satellite rideshare infrastructure since its development and flight qualification in 2002. Moog offers a family of adapters based on ESPA and development work is continuing with internal funding. Increasing interest in propulsive ESPA missions has re-focused attention on reducing the mass of the ESPA ring structure while maintaining satellite mass capacity; reduced infrastructure weight is needed for high energy mission profiles where mass is critical, and generally it is desired whenever the ESPA separates from the launch vehicle during a mission. Research is underway on several fronts including additive manufacturing considering both aluminum and titanium, alternate materials including carbon fiber composites, and optimized aluminum structure. A specific target for optimization of the aluminum ESPA (now qualified to 322 kg) is a lightweighted design for APLs not to exceed heritage ESPA-class, i.e., 181 kg at 51 cm, essentially creating a lightweight ESPA APL class with respect to the new capability.

ESPA Grande Qualification

A qualification test for ESPA Grande is being planned for late 2017 to maximize the capability of the 24-inch port.

ESPA Mass-Acceleration Curve (Proposed)

Small satellites, in the range of 100 to 1000 kg, cannot use load factors published in the EELV User's Guides[8,9,10] which are sized for primary payloads (typically 3000 kg or more), because resonant vibration (dynamics) couples with the acceleration loading due to launch events enveloped by the published EELV load factors; this effect increases in magnitude as payload mass decreases. During ESPA development in 2000, design load factors for APLs were suggested by Boeing and Lockheed Martin, the EELV builders at the time, based on engineering judgment and the Boeing Secondary Load Factor Curve for secondary structure design. Because dynamics is predominant in load factor determination for small satellites, the lateral direction is usually the same magnitude as the axial (launch vehicle thrust) direction. This is the case for ESPA with 8.5g axial applied simultaneously with 8.5g lateral; for the non-technical reader, 8.5g applied in two directions at the same time is the same as applying 12.0g at 45° to the original vector orientations (see Figure 10).

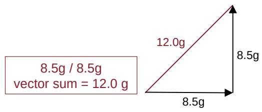

Figure 10: Vector summation of 8.5g in two orthogonal directions is 12g

The use of the Mass Acceleration Curve (MAC) for lightweight secondary structure has been adopted and used across the aerospace industry since its development at Jet Propulsion Laboratory (JPL) in the 1980s.[11] The MAC envelopes numerous responses on representative structure models as a function of physical structure mass (an alternate version uses modal mass). Figure 11 shows MACs developed at JPL for the Titan 4 and Space Shuttle Inertial Upper Stages (IUS). We are proposing to specify ESPA load factors with the MAC approach, and replace the one-size-fits-all ESPA factors used since 2002, sized for 181 kg at 51 cm (400 lb at 20 in).

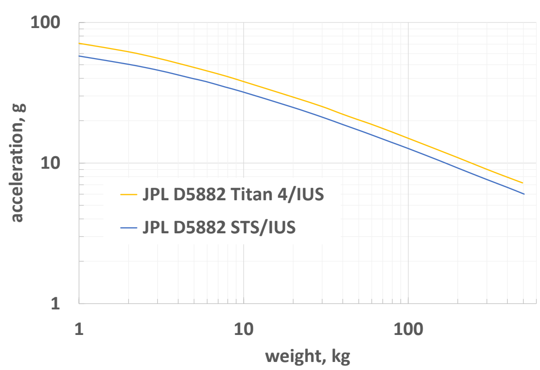

Figure 11: JPL Mass Acceleration Curves

Following the recent test program, it is clear that the range of APL masses that can be accommodated on ESPA merits a more refined method for defining APL load factors. Figure 12 shows the JPL mass acceleration curves scaled to intersect the heritage ESPA class load factor specification of 8.5g for 181-kg payload. This scaled MAC provides load factor values for a range of APLs compatible with ESPA. Table 3 lists the (single-axis) load factors, to be applied in two directions simultaneously, for the range of possible ESPA payloads; a second column lists the vector sum of the two applied loads

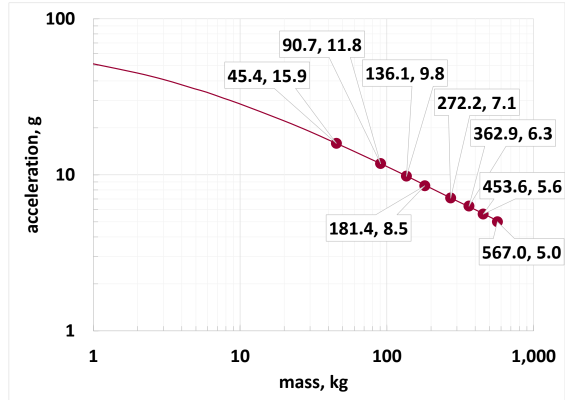

Figure 12: JPL MACs scaled to intersect heritage ESPA load factor (181.4 kg, 8.5g)

Table 3: Proposed load factors for range of ESPA APLs

APL mass		acceleration, g		
kg	lb	single axis	two axes	
45.4	100	15.9	22.5	
90.7	200	11.8	16.7	
136.1	300	9.8	13.9	
181.4	400	8.5	12.0	heritage ESPA class
272.2	600	7.1	10.0	
362.9	800	6.3	8.9	
453.6	1000	5.6	7.9	
567.0	1250	5.0	7.1	

It's a very big deal when designing a satellite (or a qualification test) for, say, a 454-kg ESPA Grande APL whether the 1-g load is multiplied by 12.0 or by 7.9. Implementation of the ESPA MAC will reduce load factors for large APLs, and refine the conservative approach that has been used for ESPA payload design since its inception.

This proposed new methodology to apply different acceleration factors to different payload masses is an industry standard. It should be noted that the proposed curve is anchored by the original 8.5 g acceleration for 181 kg mass, which has proven to be a conservative value on the ESPA missions that have flown, and therefore creates an overall conservative curve. The recommendation is, that by designing to the conservative curve, the APL should be robustly designed to have positive margins to the results of the mission unique coupled loads analyses that are accomplished for every mission, and determine the final mission Maximum Predicted Environments.

CONCLUSION

This paper reviews the recent ESPA Delta Qualification test program that was performed at the Air Force Research Lab/Space Vehicles Directorate at Kirtland Air Force Base, New Mexico. Increased ESPA capability has been validated, and new ESPA payload limits are documented. Additional research on ways to reduce the mass of an ESPA is underway. An ESPA Mass-Acceleration Curve is proposed that encompasses the range of APL mass available with the new tested capability, anticipating as well increased capability for the ESPA Grande 24-inch port.

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