ESPA: EELV Secondary Payload Adapter with Whole-Spacecraft Isolation for Primary and Secondary Payloads

Joseph R. Maly, Paul S. Wilke, Emily C. Fowler
CSA Engineering
2565 Leghorn Street, Mountain View, California

Capt. S. A. Haskett
Space Test Program, USAF Space and Missile System Center
Kirtland Air Force Base, NM

Dino Sciulli
Space Vehicles Directorate, Air Force Research Laboratory
Kirtland Air Force Base, NM

T. E. Meink
Space Vehicles Directorate, Air Force Research Laboratory
Kirtland Air Force Base, NM

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ESPA: EELV Secondary Payload Adapter with whole-spacecraft isolation for primary and secondary payloads

J. R. Maly[a] Capt. S. A. Haskett[b] P. S. Wilke[a]
E. C. Fowler[a] D. Sciulli[c] T. E. Meink[c]

[a]CSA Engineering, 2565 Leghorn Street, Mountain View, California

[b] Space Test Program, U. S. Air Force Space and Missile System Center, Kirtland Air Force Base, New Mexico

[c] Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico

ABSTRACT

ESPA, the Secondary Payload Adapter for Evolved Expendable Launch Vehicles, addresses two of the major problems currently facing the launch industry: the vibration environment of launch vehicles, and the high cost of putting satellites into orbit. (1) During the 1990s, billions of dollars have been lost due to satellite malfunctions, resulting in total or partial mission failure, which can be directly attributed to vibration loads experienced by payloads during launch. Flight data from several recent launches have shown that whole-spacecraft launch isolation is an excellent solution to this problem. (2) Despite growing worldwide interest in small satellites, launch costs continue to hinder the full exploitation of small satellite technology. Many small satellite users are faced with shrinking budgets, limiting the scope of what can be considered an "affordable" launch opportunity.

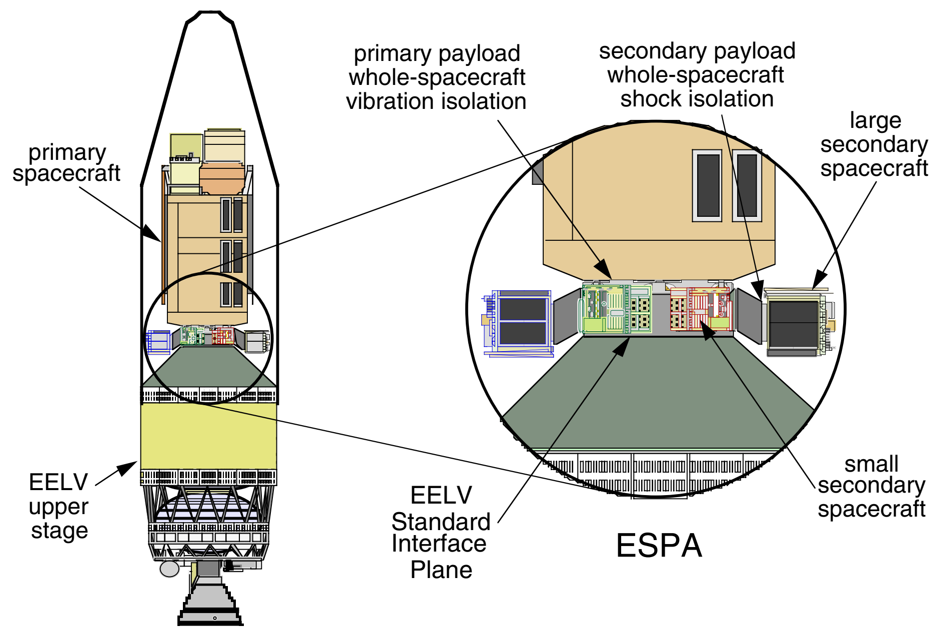

Figure 1. Schematic of ESPA mounted to EELV upper stage at Standard Interface Plane with one primary payload and six small satellites; all payloads have whole-spacecraft launch isolation

Further author information: (Send correspondence to CSA Engineering, Inc.)
CSA Engineering: E-mail: jmaly@csaengineering.com Phone: 650-210-9000
STP: E-mail: hasketsa@comanche.plk.af.mil
AFRL/VS: E-mail: sciullid@plk.af.mil

ESPA will be implemented on the new generation of expendable launch vehicles, the Evolved Expendable Launch Vehicle-Medium (EELV-M) boosters. ESPA will provide a cost-effective means for launching up to six small satellites, plus a large primary payload, on a single booster, while minimizing added impacts on the primary payload. In fact, ESPA can improve the dynamic environment seen by the primary payload through the use of whole-spacecraft, passive isolation systems. Vibration or shock isolation systems will be available for primary payloads; shock isolation will be offered for all secondary spacecraft. With whole-spacecraft isolation for all payloads, the addition of secondary payloads to the launch stack is expected to be transparent to the primary payload dynamic environment. ESPA is expected to reduce the launch dynamic environment for all payloads while shrinking the cost of launching a small satellite to less than 5% of the cost of a dedicated launch vehicle.

Keywords: EELV, expendable launch vehicle, launch loads, launch environments, payload adapter, whole-spacecraft launch isolation, vibration isolation, shock isolation, secondary payload

1. INTRODUCTION AND MOTIVATION

The EELV Secondary Payload Adapter, referred to as "ESPA," was conceived to take advantage of anticipated excess launch capacity on many of the DoD and commercial launches of the new large expendable launch vehicles, currently being built by Lockheed Martin and the Boeing Company. The Air Force has seized this opportunity and is applying advanced structures technology both

- to reduce the high cost of putting small satellites into orbit, and
- to reduce the vibration environment during launch.

The Space Test Program (STP; office symbol SMC/TEL) has teamed with the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VSD) at Kirtland Air Force Base, Albuquerque, New Mexico, to produce ESPA.[1]

1.1. Launch Costs

Despite growing worldwide interest in small satellites, launch costs continue to hinder the full exploitation of small satellite technology. In the United States, the Department of Defense (DoD), NASA, other government agencies, commercial companies, and many universities use small satellites to perform space experiments, demonstrate new technology, and test operational prototype hardware. In addition, the DoD continues to study the role of small satellites in fulfilling operational mission requirements. However, US government agencies are restricted to the use of US launch vehicles, which eliminates many affordable launch opportunities. Additionally, many small satellite users are faced with shrinking budgets, limiting the scope of what can be considered an "affordable" launch opportunity. In order to increase the number of space experiments that can be flown with a small, fixed budget, the Space Test Program (STP) has teamed with the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VSD) to develop a low-cost solution for the small satellite launch problem. ESPA will be implemented on Evolved Expendable Launch Vehicle-Medium (EELV-M) boosters, and will potentially shrink the cost of launching a 180-kg (or smaller) satellite to under $700,000, less than 5% of the cost of most dedicated launch vehicles.

STP is one of many organizations using small satellites to accomplish their mission. However, small satellite launch costs are currently very high. For example, the least expensive expendable launch vehicle available to US government agencies is the Orbital/Suborbital Program (OSP, or "Minotaur") vehicle, which is a converted Minuteman II Intercontinental Ballistic Missile. Using a dual-payload adapter, the cost to launch a pair of small satellites on OSP is about $14M, or $7M per spacecraft. Other small launch vehicles are similarly expensive; Pegasus costs about $18M and both Taurus and Athena I/Athena II cost more than $20M. Arianespace offers inexpensive secondary payload flights on Ariane 4 and Ariane 5 boosters using an adapter called Ariane Structure for Auxiliary Payloads (ASAP), shown in Figure 2. Unfortunately, foreign launch systems are not currently available to DoD or other US government customers unless the White House grants a foreign launch waiver.

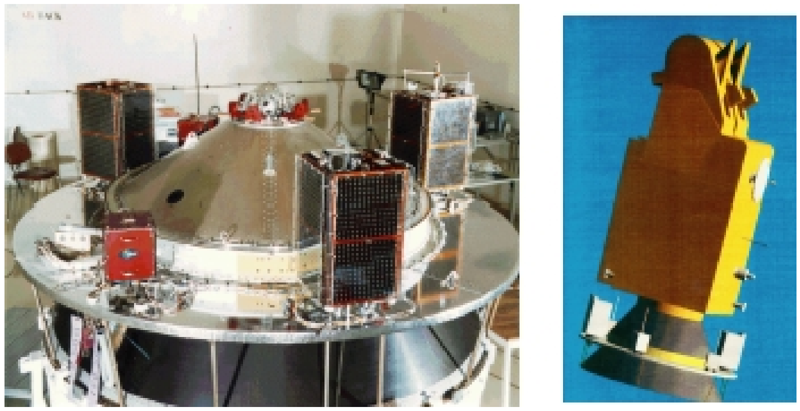

Figure 2. Secondary payloads and adapter on the Ariane 4 Launch Vehicle

1.2. Launch structural dynamics

In addition to cost, launch dynamics are a major design driver in structural design of spacecraft. Launch survival is often a more difficult design problem than is ensuring operational performance on orbit. Either the dynamic launch loads on the spacecraft must be reduced or the spacecraft must be stiffened. Stiffening the structure adds weight, but reducing the dynamic loads on the spacecraft by whole-spacecraft vibration isolation allows lighter-weight systems. Reduction of the launch loads greatly reduces risk that spacecraft and its sensitive components will be damaged from vibrations during ascent into orbit, and allows more sensitive equipment to be included in missions. As the severe launch environment also accounts for much of the expense of designing, qualifying, and testing spacecraft components, significant cost can also be saved if loads are reduced.

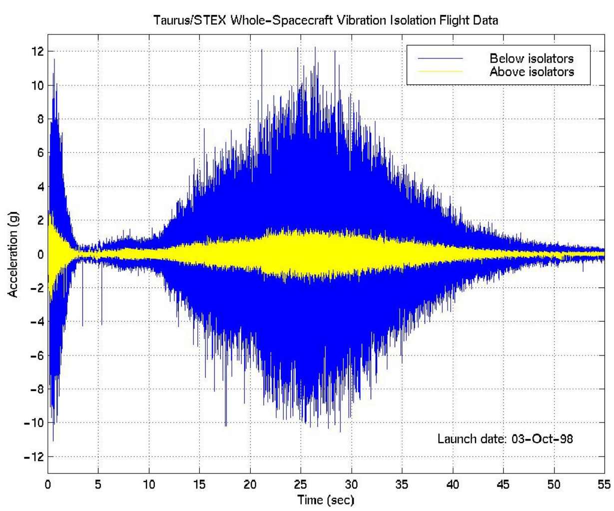

Figure 3. STEX payload transient acceleration measurements, above and below whole-spacecraft isolation system, during Taurus launch of October 1998

SoftRide whole-spacecraft isolation systems have flown since February 1998, and excellent results have been achieved.[2] Figure 3 shows transient acceleration measurements above and below the whole-spacecraft isolators for a payload that was placed into orbit on an OSC Taurus launch in 1998. Figure 4 shows the frequency content of these acceleration measurements as it varies with time after launch; this "waterfall" plot reveals the excellent high frequency attenuation also achieved with the isolation system. Because of the tremendous success of the the first series of whole-spacecraft-isolated launches, it follows that whole-spacecraft isolation should be considered for new launch vehicles, such as EELVs, during the initial design phase.

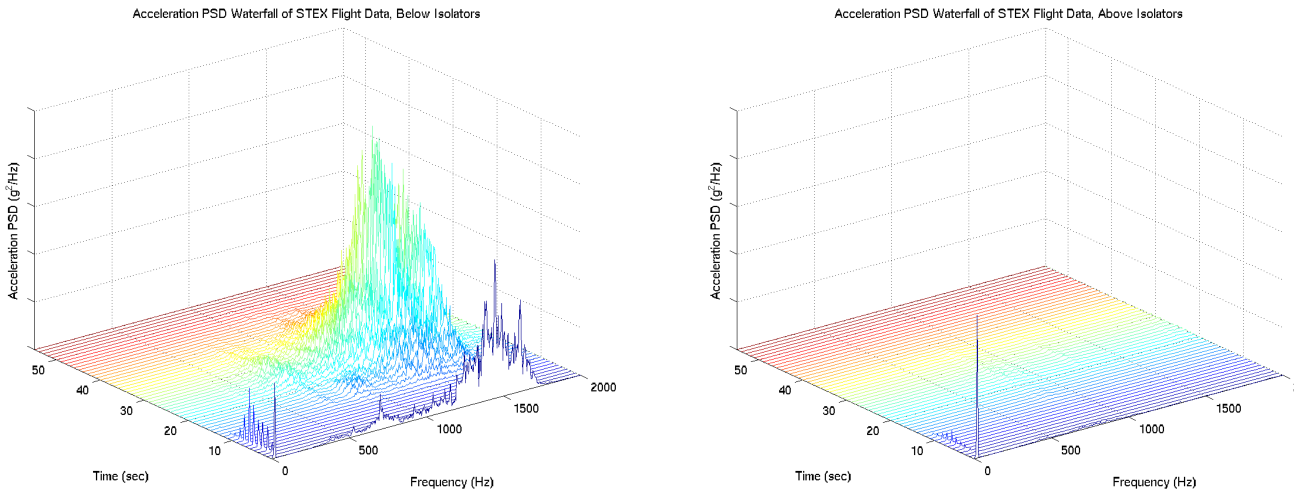

Figure 4. "Waterfall" plots showing frequency content of STEX payload acceleration measurements, above and below isolation system, at one-second intervals during first 55 seconds of launch

2. ADAPTER STRUCTURE DESIGN

ESPA consists of a 230-pound (estimated empty mass), 24-inch tall composite cylinder with a primary spacecraft isolation system, and accommodations for six secondary payloads with shock isolation. The secondary payloads are mounted at equal intervals around the cylinder, as depicted in Figure 5. This configuration allows the secondary payloads to be released before the primary payload, if necessary, a capability not offered with ASAP. As shown in Figure 1, ESPA is mounted to the EELV Standard Interface Plane (SIP). The SIP, a 62.01-inch bolt circle, is the mechanical interface defined for all military EELV-Medium payloads.[3] All primary payloaders must provide an adapter cone to attach their satellite to the Standard Interface Plane. The primary payload adapter cone is mounted to the top of ESPA. To eliminate primary payload mechanical interface concerns, the top of ESPA will replicate the Standard Interface Plane.

The design limit for secondary satellite mass is 400 pounds (∼180 kg). However, secondary payloads on ESPA will likely be limited more by usable volume rather than by weight. The precise total usable volumes for secondary payloads are being defined, based on inputs from both Lockheed Martin and Boeing. The ESPA secondary payload interfaces, both mechanical and electrical, are also being defined. Rather than define one particular mechanical interface for ESPA that all customers must use, an option for a "blank mounting plate" and user-provided interface are being incorporated.

The EELV program office has completed special studies with Boeing and Lockheed Martin to investigate the many technical and programmatic issues associated with ESPA. Among these are loading requirements for ESPA, as well as timelines for adding ESPA and secondary payloads to a given EELV launch. It is assumed ESPA can be loaded with any number of satellites, up to six, so long as mass balance is maintained. Figure 5 shows ESPA top and side views with a notional load of two large spacecraft and four small spacecraft.

Incorporating ESPA will obviously impact the primary payload. ESPA will raise the primary payload by 24 inches without isolation and 30.5 inches with isolation. This raises the payload center of gravity and reduces the usable volume inside the payload fairing. However, designing primary payload adapters with ESPA use in mind would minimize these effects.* Incorporating ESPA will actually have positive impact on the primary payload through the whole-spacecraft isolation system. The purpose is to minimize the dynamic interaction between the primary and secondary payloads and to reduce the dynamic response of the primary payload. To supplement the whole-spacecraft isolation systems, low-shock/non-pyrotechnic separation systems will be used for the secondary payloads. Low-shock separation systems will mitigate concerns associated with secondary payload separation prior to primary payload separation (on occasions when that option must be utilized) and non-pyrotechnic systems offer improved launch vehicle safety.

* "Payload adapters" here refer to the structural connection between the primary spacecraft and the Standard Interface Plane. As stated above, these adapters must be provided by each primary payload.

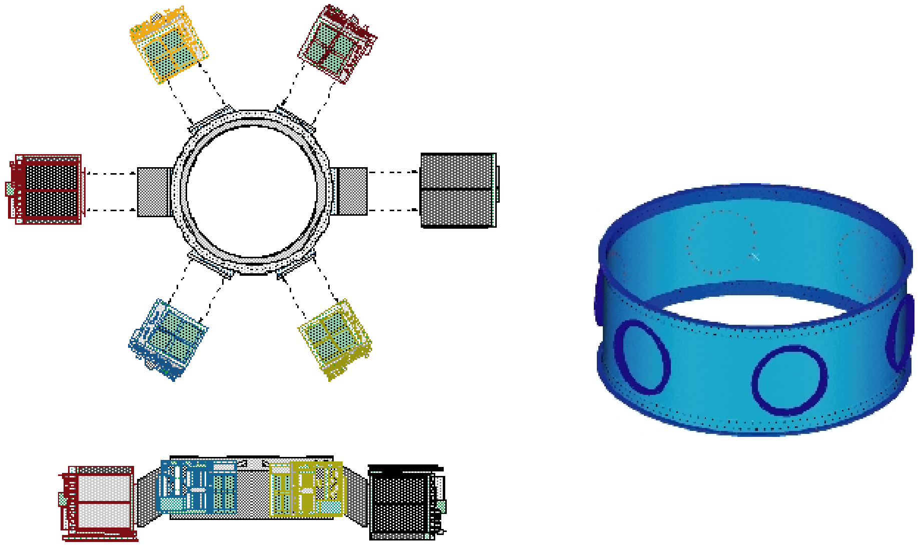

Figure 5. ESPA top/side views with notional satellite load, and solid model of ESPA cylinder with payload mounts

3. WHOLE-SPACECRAFT ISOLATION DESIGN

3.1. Isolation Design Methodology

The addition of a secondary payload adapter necessarily changes the environment for the primary payload, at the very least changing the height of attachment interface. One of the primary design drivers for ESPA is that impact on the primary payload must be minimized. Introduction of a primary isolation system can not only attenuate any adverse effects of the additional payloads, but can actually improve the launch environment seen by the primary payload. The safety of the smaller, secondary payloads is also of concern. Mounted below the primary in a horizontal, cantilevered configuration, the secondaries will be subjected to larger than usual lateral forces, as well as shock loads from primary payload separation, and will benefit from the protection offered by isolation.

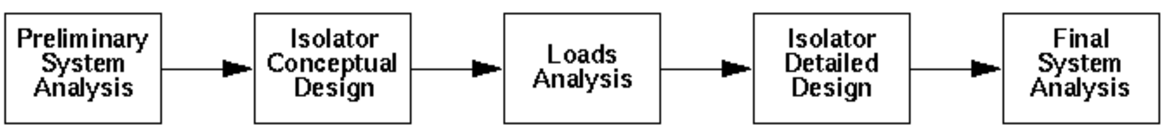

Figure 6. SoftRide design methodology for whole-spacecraft launch isolation

The goal of a vibration isolation system is to reduce the dynamic loads on a payload by reducing the transmission of dynamic loads present in a base structure to which the payload is attached. The design of classical vibration isolation systems assumes that the base is rigid and that the isolated payload has dynamics only well above the isolation frequency. However, in the launch industry, the primary and secondary satellites, as well as adapters and the launch vehicle itself, each have their own dynamic signatures to contribute to the combined system. This necessitates that system-level analysis be used in the design of any whole-spacecraft isolation system, specifically, full coupled loads analysis (CLA) using detailed models of launch vehicles, all payloads and adapters, and flight load events.[4]

The introduction of the isolation system itself changes the dynamics of a launch system. Along with the typical design constraints of weight, volume and strength, restrictions on the allowable system effects help dictate the design of the isolators. Two major constraints for whole-spacecraft isolation design are spacecraft-to-fairing relative displacement, and isolation modal parameters. Excessive relative displacements must be avoided, and isolation modes cannot be too low in frequency or too high in amplitude such that they interfere with the launch vehicle attitude control system. The interdependency of each structure dictates that the design process be a pairing of both coupled loads analysis and detailed design analysis. The basic procedure, shown in Figure 6 involves the following steps:

- Preliminary coupled loads analysis with worst load cases to optimize system-level isolator performance and get component-level requirements.
- Isolator concept design to meet component-level performance requirements.
- Isolator loads analysis to determine design loads for isolator strength design.
- Isolator detailed design to arrive at a design that meets all strength and performance requirements.
- Complete coupled loads analysis using final detailed isolator models in the system model to verify system-level performance.

The coupled loads analysis must be performed with actual launch vehicle and spacecraft models. The typical procedure at CSA Engineering is to obtain launch vehicle models and loads for worst case conditions from the launch vehicle manufacturer and perform coupled loads analysis with the latest model of the spacecraft supplied by its manufacturer. Once the detailed isolator design analysis is completed, then a model of the isolators is delivered to the launch vehicle manufacturer for a complete and final coupled loads analysis cycle.

For the design of the ESPA isolation systems, finite element models of the launch vehicles were obtained from the manufacturers. Lockheed Martin provided models of the Atlas V 401 and Atlas V 502 vehicles, along with load cases expected to be design drivers for the isolation system. The Boeing Company supplied models of the Delta IV-Medium launch vehicle and appropriate load cases.

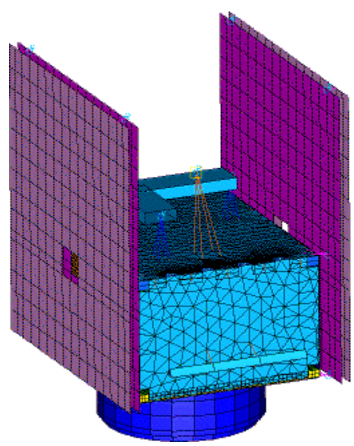

Figure 7. Finite element model of Air Force MightySat spacecraft

Detailed analytical models of payloads are also being used. For the primary payload, a finite element model has been provided by the manufacturer of a satellite expected to launch on one of the initial DoD EELV launches. This particular payload has sensitive equipment that will benefit from vibration isolation. The model includes its payload adapter structure, and response locations of interest have been specified by the payloader for the coupled loads analysis cycle. Since no specific secondary payloads have been identified for ESPA at this time, a model of typical Air Force small satellite is being used; the MightySat spacecraft finite element model is shown in Figure 7.

3.2. Primary Payload Vibration Isolation

The objective of the primary isolation design is to reduce the dynamic environment seen by the primary payload during selected "worst case" loadings, i.e., to improve the environment compared to predictions from "baseline" analyses. For evaluation of isolator performance, two baseline analyses are being used: launch vehicle and payload without ESPA, and vehicle and primary payload with ESPA (and secondary payloads) but without isolation. For design of specific flight isolation systems, configuration-specific coupled loads analyses will be performed so that the hardware can be tuned for the specific satellite(s) and launch vehicle.

For each of three "worst case" load cases originally under consideration, four types of isolation were studied: (1) axial only, (2) lateral only, (3) combination axial/lateral, and (4) shock isolation. Both axial and axial/lateral isolation systems have flight heritage through the Soft Ride for Small Satellites (SRSS or SoftRide) program. Critical response locations, selected by the payloader and CSA, were tracked to monitor the effectiveness of each isolation design. Low frequency vibrations were of concern for this particular primary payload, so the focus was on the design of a SoftRide isolation system, which acts to isolate payloads from the lower frequency vibrations, as well as from the damaging effects of shocks. (For payloads that do not have structures or carry equipment that are sensitive to low frequency vibrations, shock can still be a problem, in which case an isolator designed specifically for shock would be used.) From the coupled loads analyses it was found that a combination of lateral and axial isolation, with an "isolation frequency" of 25 Hz would provide the best attenuation of the launch loads. In the context of SoftRide isolators that have been flown previously, this type of isolator would be referred to as a 25-Hz MultiFlex design. The optimal system was configured with sixty individual isolator components equally spaced around the circumference of the 62.01-inch-diameter mount at the Standard Interface Plane.

Based on these preliminary analyses, a detailed model of a 25-Hz MultiFlex isolator component was created. This model was sized and configured for the desired stiffness and damping, and it was optimized for strength. The detailed model had over 180,000 degrees of freedom, and, based on test/analysis correlation of previous flight hardware, it was quite adequate for both dynamics and stress analysis. For system analyses, this model was reduced with a static condensation to 12 degrees of freedom, replicated sixty times for the system model (720 degrees of freedom for the complete isolation system), and the coupled loads analyses were repeated. This level of detailed analysis will provide the primary payloader and the launch vehicle manufacturer with very accurate predictions of isolation performance and overall system dynamics.

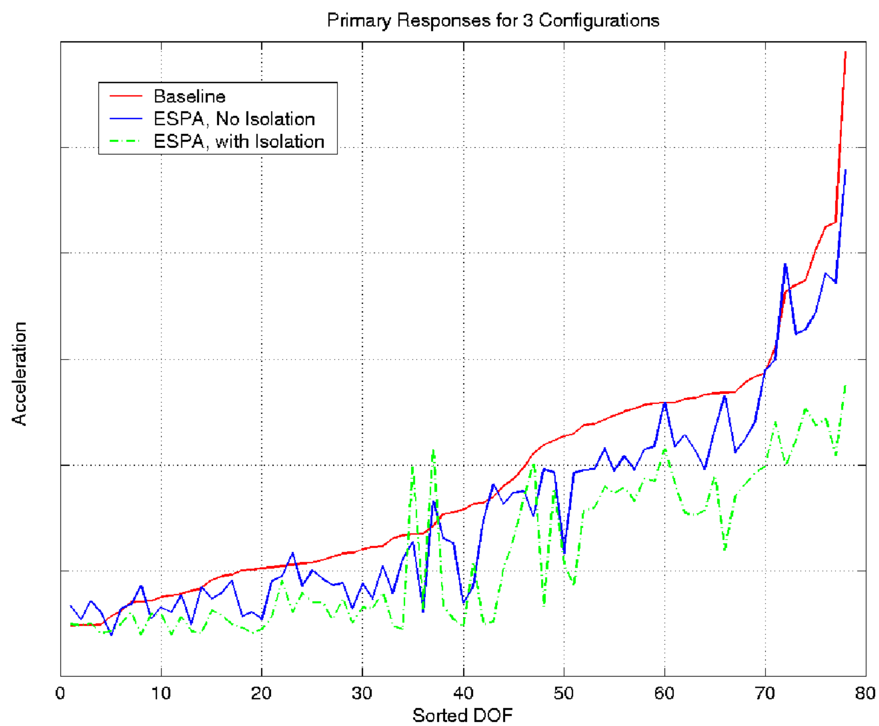

Figure 8. Peak acceleration responses at key locations on primary payload sorted in order of increasing response for baseline case

Results from these coupled loads analyses are studied in the format of sorted peak response plots, which show all peak responses for the baseline case plotted versus response location in order of increasing response; isolated configurations are overplotted with the baseline for comparison, with the same plotting order as used for the baseline. Figure 8 shows sorted peak response plots for one of the load cases analyzed. Acceleration responses of 26 key locations on the primary payload (three directions each, or 78 total degrees of freedom) are plotted in the Figure. The plot shows comparison responses on the primary payload for (1) the baseline case of the launch vehicle without ESPA, (2) the launch vehicle with ESPA but no isolation, and (3) the launch vehicle with ESPA and isolation. For this load case, some of the responses are very high in the baseline configuration. When ESPA without isolation is added, most of these responses are reduced somewhat, but some locations still see very high response levels. When ESPA is added with the isolation system, all the high responses are reduced substantially, and the highest overall response is less than 50% of the corresponding baseline response.

Primary Payload Shock Isolation

Shock isolation systems will also be available for the primary satellite on ESPA. Figures 9 and 10 show the excellent high-frequency benefit (ground test data) and the associated reduction in transient response provided by the SoftRide isolation system. Similar results are expected from the ESPA shock isolation system. These shock isolation systems will be very stiff mounts that will attenuate vibration above 100 Hz. Detailed finite element analysis will be performed for each system, as for the vibration isolation systems, to optimize performance and verify that stress margins are met. Shock isolation systems are not expected to require any additional coupled loads analyses. Testing will be performed on the isolation system for both performance and strength.

3.3. Secondary Payload Shock Isolation

For the secondary payload isolation system, initial trade studies consisted of setting the primary isolation system to a 25-Hz MultiFlex system and running the coupled loads analyses with various secondary isolation configurations. Because of the horizontal, cantilevered mounting orientation, the highest loads are applied to the satellite laterally rather than axially. For secondary isolation systems below 35 Hz, some responses increased due to low-frequency rocking modes of the secondaries with excessive displacements. Because of these effects, it was decided to develop "high frequency" shock isolation systems for the secondary payloads. A preliminary hardware design was configured for a shock isolation system, tuned to approximately 90 Hz, and based on shock isolator technology developed previously. A shock isolator of this nature will be low-risk, and will not deflect substantially under the high lateral loads on the secondary payloads. A detailed finite element model was built with sufficient detail to perform stress analysis.

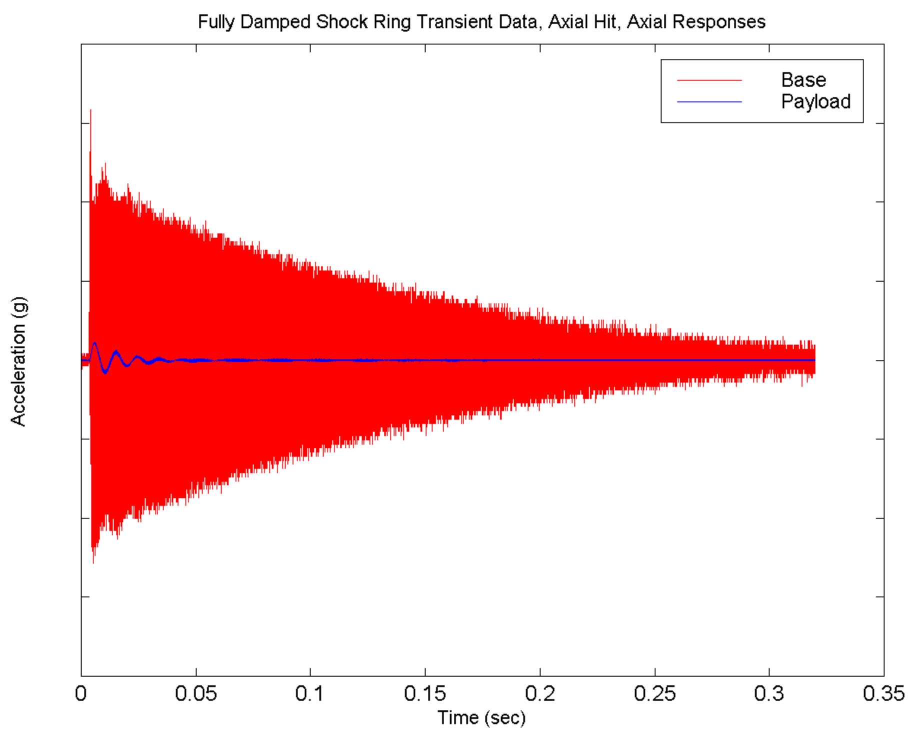

Figure 9. Test results on shock isolation system showing transient acceleration responses above and below isolator

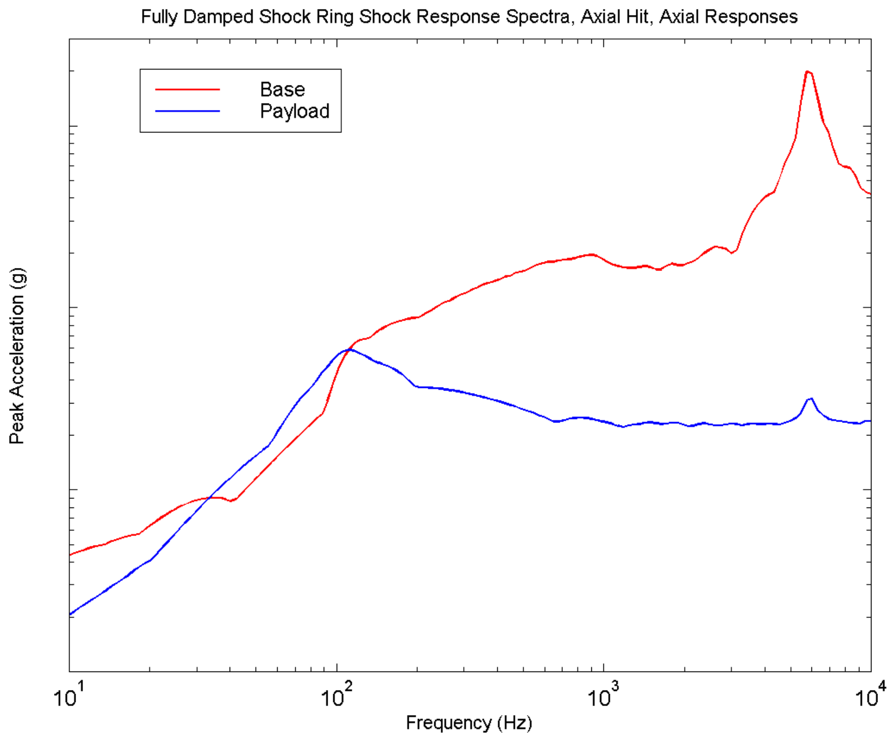

Figure 10. Test results on shock isolation system showing shock response spectra of acceleration responses above and below isolator

Shock isolation is offered as an option for secondary payloads. As for the primary isolation systems, the hardware will be configured for the specific satellite(s) and launch vehicle. The isolation system will be designed based on the mass and inertia properties of the secondary payload. These isolation systems will be stiff mounts that will attenuate vibration above 100 Hz. Detailed finite element analysis will be performed for each system to optimize performance and to verify that stress margins are maintained. Testing will be performed for both performance and strength. The shock isolation system for the secondary satellites will provide excellent high-frequency benefit to the satellites for a small weight, volume, and cost. Figures 9 and 10 show typical transient results and the associated shock response spectra from testing of a similar shock isolation system. Secondary spacecraft will experience significant attenuation of dynamic loads above 100 Hz, thereby increasing the launch reliability. The secondary shock isolation system will provide the same interface as would be used for a secondary payload without isolation.

4. THE ESPA PROGRAM

STP and AFRL/VSD are working together to design ESPA and build two ESPA units. The first unit will be used for EELV qualification testing and the second will be a flight model. Preliminary Design Review was held in March 2000, and Critical Design Review is scheduled for September 2000. Both ESPA units will be finished in FY02, and STP hopes to demonstrate ESPA on a DoD EELV-M launch in FY03 (only one DoD EELV mission is scheduled in FY02).

STP would like to fly ESPA with either the Defense Meteorological Satellite Program (DMSP), the Defense Satellite Communications System (DSCS), or the Global Positioning System (GPS). These launches have suitable weight margin for ESPA. Currently, STP is planning to pay ESPA hardware and mission integration costs for the first flight. However, it should be noted STP is unlikely to fill all six secondary payload slots. We currently project one to four ESPA slots filled by Space Experiment Review Board (SERB) payloads. STP hopes to fill any remaining slots with non-STP payloads, particularly for organizations that can pay their portion of the flight integration costs. Priorities for filling any open slots on the demonstration mission are as follows: 1) DoD Payloads; 2) Other US Government Payloads; 3) University, commercial, and foreign payloads. Due to EELV processing timelines, the ESPA payload manifest should be decided two years prior to the launch date. STP will manage the secondary payload manifest for the first ESPA mission, so interested payloaders should contact STP for information regarding the demonstration launch. STP and AFRL may provide low-shock separation systems for payloads on the first ESPA mission as part of the overall system demonstration, but later missions will likely require each payloader to provide their own qualified (preferably low-shock/non-pyrotechnic) separation system.

After the demonstration mission, STP hopes to "commercialize" ESPA. The goal is to authorize commercial use of the ESPA design in return for integration and mission management services for DoD. Presently, it is unclear what organization will take responsibility for ESPA.

The cost goal for ESPA, assuming a fully loaded ring, is less than \$0.5M per satellite. The recurring cost for the ESPA units is estimated at \$600,000 plus \$50,000 for each secondary payload isolation system, if needed. The EELV integration costs for ESPA are estimated at \$1M, although a more refined figure should come from the special studies recently completed with Boeing and Lockheed-Martin. Assuming no EELV launch-cost-sharing with the primary payload (a reasonable assumption for DoD launches), the total ESPA mission cost could be as low as \$1.9M for six small satellites, or about \$320,000 per satellite. Thus, by using ESPA, the cost to launch a single small satellite drops from \$7-10M to about \$0.3-0.5M.

5. CONCLUSION

We expect ESPA to have a tremendous impact on future military and commercial spacecraft programs by providing a fast and inexpensive way of launching small payloads. Whole-spacecraft launch isolation will reduce the dynamic environment for all the payloads, and it will help motivate primary payloads to include auxiliary spacecraft on their launch vehicle. ESPA will provide a cost-effective means for launching up to six small satellites, plus a large primary payload, on a single EELV-Medium booster. ESPA causes minimal impact to the primary payload and provides the primary payload with an improved flight environment through the use of a passive whole-spacecraft isolation system. For improved safety and ease of integration, ESPA will incorporate low-shock/non-pyrotechnic secondary payload separation systems. ESPA will reduce the cost of access to space for small satellites to less than 5% of the cost of a dedicated launch vehicle, with a reduced dynamic environment through the use of SoftRide isolation systems.

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