

Development and Transition of Low-Shock Spacecraft Release Devices for Small Satellites

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Abstract. Small satellites require a variety of release devices to accomplish mission-related functions such as separation from the launch vehicle, separation from each other, and deployment of instruments. The Air Force Research Laboratory (AFRL) has been working with several private companies to develop low shock, non-pyrotechnic spacecraft release devices to mitigate problems with traditional pyrotechnic release devices. Pyrotechnic devices produce high shock, contamination, and have costly handling requirements due to their hazardous nature. Small satellites are particularly susceptible to shock-related failure because of the close proximity of sensors and instruments to the shock source. In addition, small satellites deployed as constellations may experience multiple release shocks from adjoining satellites prior to their own deployment. AFRL has arranged two successful flights for low shock separation devices: the Shape Memory Alloy Release Device (SMARD) experiment on MightySat I in May 1999, and the deployment of the Air Force Academy FalconSat spacecraft from the Orbital Sub-Orbital Program Space Launch Vehicle (OSP-I) in January 00. Two on-going AFRL programs, EELV Secondary Payload Adapter (ESPA) and the University NanoSat Program, will employ low shock separation systems as well.

Introduction

Spacecraft require a variety of separation and release devices to accomplish mission-related functions such as separation from the launch vehicle and deployment of solar arrays and other appendages. The separation device has a dual purpose – to secure the payload against the launch loads and to release the payload on-orbit with low tip-off, at the appropriate time, while minimizing detrimental effects such as shock and contamination. In some cases, where more than one release device is used, the additional task of synchronous release becomes a factor in mission success.

Separation has typically been achieved through the use of pyrotechnic devices. Generally these devices meet many of the basic requirements for a separation device. They are able to secure the payload during launch, and if the device operates properly, can provide a timely, synchronized release on-orbit.

However, there are numerous drawbacks to the pyrotechnic devices. The first is the cost of handling the pyrotechnic devices safely. Launch vehicle manufacturers have extensive, costly, safety standards for storage, transportation, and handling of pyrotechnics during ground operations and integration. For shuttle payloads, incorporation of pyrotechnics further increases the burden of compliance with a manned space flight safety program. The second problem with pyrotechnics is their impact on the payload upon release. Pyrotechnic devices generate high shock, on the order of thousands of g's, which can physically damage the payload, and can produce contaminants that are detrimental to lenses and electronics. A 1985 study indicated that from 1963-1984, in 600 launches, 83 shock-related failures occurred, half of which resulted in loss of the mission.¹ Finally, from a reliability standpoint, the pyrotechnic charge is consumed during any testing that might take place; therefore, the separation device that flies with the payload is not the same as the one that was tested.

With the newest generation of nano and picosatellites, the issues of shock and contamination become even more critical. For satellites of this size, external and internal parts are physically closer to the source of shock and contamination than those on larger satellites of the past. In addition, multiple satellite or constellation launch schemes may subject an individual satellite to multiple release shocks prior to its own release. These new challenges, and the drawbacks mentioned above, are compelling motives for the investigation and development of new approaches to satellite separation.

Recognizing these issues, the Air Force Research Laboratory (AFRL) has taken steps to develop, test, and fly a new generation of low-shock, non-pyrotechnic separation devices. These steps have included funding several corporations to design and test separation devices and separation systems, and providing flight opportunities for both test and actual release applications. The following paragraphs will describe the history and operation of the devices, discuss test data, and describe future flights.

Design Goals for Low Shock Release Devices

Based on the positive and negative aspects of existing pyrotechnic release devices, several desirable features were identified and established as design goals for new low-shock devices.

Perhaps the most important goal is to develop non-pyrotechnic devices, both for shock mitigation, and to eliminate safety and handling issues. Shock criteria was determined by Lockheed Martin Astronautics (LMA) of Littleton, CO, who designed the first low-shock release devices funded by AFRL. For LMA launch programs, expensive payload qualification testing can be avoided if release devices produce shocks lower than certain limits. For preliminary and conceptual design, the guideline upper limit is 500 g shock at any frequency. For final design, a frequency dependent limit has been established. This empirical limit, in which the shock limit in g's is 80% of frequency in Hz, has been determined from years of vibration testing and has been the shock design goal for the devices designed thus far.

In order to be a viable alternative, a new device should be capable of being released using the same amount of power as a pyrotechnic device. The power supplied by a launch vehicle for separation devices is not standardized; however, it is similar for a variety of different launch vehicles. A typical launch vehicle

pulse supplied to a separation system is about 5 amps for 20-40 ms, from a 28V launch vehicle power supply. This typical launch vehicle power supply has become known as a "pyro pulse" to reflect the fact that it has defined the electrical activation requirements of pyrotechnic devices. Therefore, pyro pulse compatibility has been emphasized as the ultimate design goal for device power requirements.

In addition to power compatibility, a high priority was placed on development of devices with a satellite attachment interface similar to that used with pyrotechnic devices. To this end, AFRL has supported discrete point bolt release devices, and "Marmon" or "v" band release devices. The first major developments and test flights involved discrete point devices, while current efforts include band type devices as well. The first generation of low-shock, discrete point release devices employs a ¼ - inch bolt for attachment of a satellite to a launch vehicle, a size considered to be typical of standard pyrotechnic devices used for satellite release. Pyrotechnic Marmon bands are manufactured in a wide range of sizes for varying loads. The first low-shock Marmon band release devices are being developed in sizes to accommodate small satellites and nanosatellites, which may benefit the most from the low-shock characteristics. The challenge is to design these types of release devices with size, mass, and preload capability comparable to the pyro devices.

A final consideration is that the device should be resettable. This last requirement provides several benefits, primarily, improved reliability, because the device tested is the same device that is flown. In addition, resettable allows multiple ground tests not only of the device but of the entire separation system as well. In most cases the separation device is actually part of a separation system, which as a whole supports the launch loads. Having a resettable device eliminates the need for consumable test devices and reduces the number of devices required for a mission to the number required on-orbit.

Shape Memory Alloy Release Devices

A major focus in the development of low-shock release devices has been the incorporation of Shape Memory Alloys (SMA) as release actuators. The general scheme is to take advantage of the ability of SMA's to recover a parent shape when heated by an electrical current. SMA materials, such as Nitinol, when heated, can recover a parent shape from a cold deformation involving up to 8% strain. Thus, an SMA actuator may be used to trigger a mechanism that releases a captive element such as a bolt.

The basic design requirements for space applications present a challenging problem. The mechanism must be

Table 1. Characteristics of 1/4" Bolt Spacecraft Separation Devices

	Pyrotechnic ¹	Low Force Nut ¹	Two Stage Nut ¹	9101 ²	QWKNUT ²
Preload, lb	8,800	2,860	5,500	2,500	3,000
Shock, g	7,200	400	<150	<50	<100
Mass, grams	120	250	300	80	200
Release Time, ms	15	62	22	25	35
Reset (Yes/No)	N	Y	Y	Refurbish	Y
Pyro Pulse³	-	N	N	Y	Y

Notes:

1. For Pyro, LFN, and TSN the shock and release times are from the SMARD Experiment. Other data is from Reference 2. Shocks are maximum values.
2. Shock and release time data are preliminary, pending test completion.
3. "Y" entry indicates compatibility with typical launch vehicle "pyro pulse".

capable of retaining a bolt that is preloaded as required by the launch loads. However, the device must also have sufficient mechanical advantage to allow release by an SMA actuator, which receives a pyrotechnic equivalent firing pulse. The release time from one device to another should be consistent enough to allow synchronous release in cases where multiple separation devices are used.

Table 1 contains the characteristics of the discrete point SMA devices that will be discussed in this section as compared to a pyrotechnic device. Also included is data on a non-SMA fuse link device discussed later in this paper. All devices are designed for a 1/4" bolt.

AFRL/Lockheed Martin Devices: Low Force Nut and Two Stage Nut

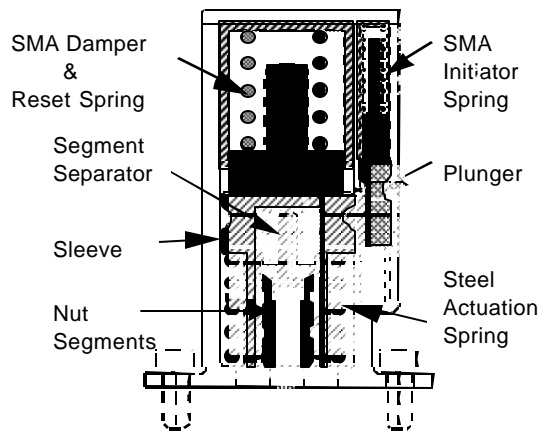
Beginning in 1993, AFRL provided funding to LMA for the design and test of two SMA based release devices, known as the Low Force Nut (LFN) and Two-Stage Nut (TSN). Prototypes of both devices have been built and tested extensively, both in the laboratory and on-orbit. The on-orbit testing was the Shape Memory Alloy Release Device Experiment (SMARD) on AFRL's MightySat I. The experiments, which will be discussed later in this paper, have shown that the devices have a shock output much lower than the required limits.

The LFN, shown in Figures 1a and 1b, is a resettable, discrete point device. The device contains a segmented nut into which a 1/4-inch bolt is threaded. The maximum allowable preload on the bolt is 2860 lb.

When the mechanism is triggered by the SMA actuator, it allows the pieces of the segmented nut to move away from the bolt radially, thus releasing the bolt. In an actual application, the head of the bolt is typically contained within a bolt retractor, which serves to pull the bolt out of the LFN and capture it. Three SMA springs are contained within the device. Two of the springs are identical, redundant initiator springs, which, when heated by an electrical current, extend from a compressed configuration and initiate the mechanical release sequence. Only one of the initiator springs has to work in order to actuate the device. The other SMA spring, which serves as both a damper and reset spring, is compressed when the device is actuated. When an external current is applied to the damper/reset spring it expands, resetting the mechanism and compressing the actuator springs to their original configuration. Because the reset function is electrical, the device does not have to be removed from its spacecraft mounting position to be reset.



1a. Low Force Nut (Lockheed Martin Astronautics)



1b. Low Force Nut, Cutaway View (Lockheed Martin Astronautics)

The TSN, shown in Figure 2, is also a discrete point hold-down device. It is designed to handle higher bolt preloads than the LFN, up to 5,500 lb, and it provides lower shock than the LFN. Release is accomplished through a two step process, which is the key to the low-shock characteristics. The TSN first removes the preload in the bolt, and then releases the bolt from the segmented nut. The segmented nut rides in a collet, which is free to travel axially and is supported by a bellville washer, which deforms under the preload of the bolt. When the firing pulse is applied, the SMA cylinder is heated, and the collet/segmented nut is translated, further deforming the bellville washer, and thus removing the preload from the bolt. At this point the SMA initiation springs, positioned tangentially between the nut segments, are actuated, separating the nut segments, and releasing the bolt. Redundancy is accomplished by having multiple heating circuits on the first stage cylinder and three SMA initiation springs, any two of which are capable of displacing the segmented nut. After actuation, cooling of the SMA components resets the device without applied power.

The LFN and TSN meet most of the requirements necessary for a replacement to the pyrotechnic devices. They are non-pyrotechnic, resettable, produce no contaminants, are comparable in size and mass to pyrotechnic devices, and provide a quick, synchronous release. The LFN can be released in as little as 62 ms and the TSN in 22 ms depending on the applied power.

The drawback of the LFN and TSN is that neither is pyro pulse compatible. In ground tests the LFN and TSN had an energy requirement of 90 watt-sec as

opposed to a pyrotechnic device which required 0.05 watt-sec.² The higher energy requirement results from the fact that the LFN and TSN draw a current significantly greater than the 5 amps typically supplied by a launch vehicle. The amount of current varies with the required release time, but in the on-orbit SMARD experiment discussed later, the LFN was supplied with over 100 amps.

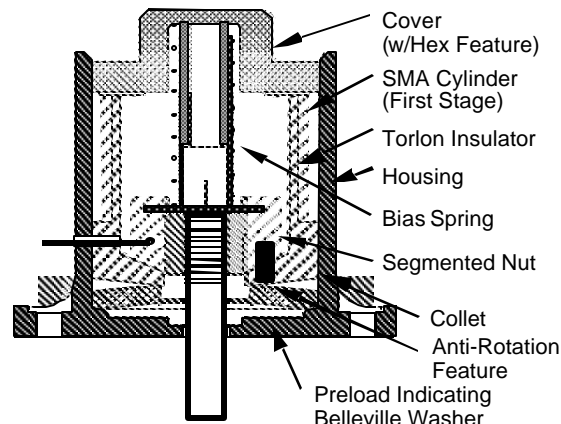


Figure 2. Two Stage Nut Cutaway (Lockheed Martin Astronautics)

Both devices succeed with regard to low-shock requirements. Ground testing revealed that the LFN and TSN provide a shock spectrum significantly lower than the maximum shock limits determined by LMA. Figure 3 shows the shock spectrum from ground tests on both devices as compared to the required limits, a pyrotechnic device, and a linkwire device. The linkwire device is an existing non-pyrotechnic, non-SMA device, which was included for comparison as well.

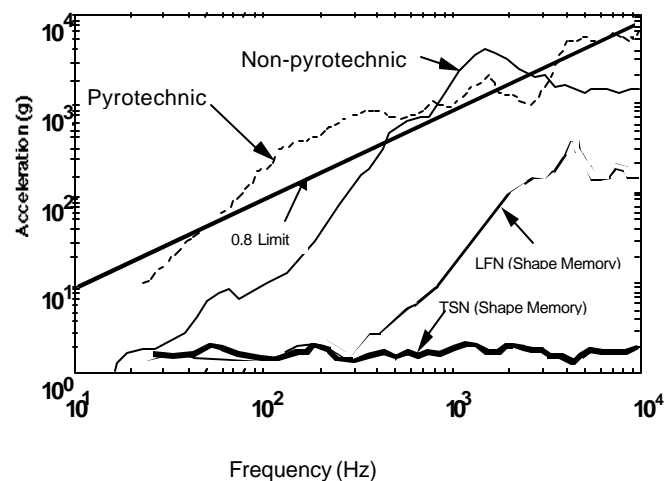


Figure 3. Comparison of Release Device Shock Output²

Shape Memory Alloy Release Device Experiment (SMARD)

AFRL provided an opportunity for on-orbit test firings of the LFN and TSN on AFRL satellite MightySat I, which was launched in December 1998. The purpose of the SMARD experiment, designed by LMA, was to demonstrate on-orbit operation of the TSN and LFN devices, and to compare shock and release times between SMA, pyrotechnic, and linkwire devices.

In the experiment, LFN, TSN, linkwire, and pyrotechnic devices were mounted on a common test fixture. The devices were preloaded, with load cells installed to monitor the preload and provide release time indication. Accelerometers were also installed to measure the shock induced by each device. In May 1999 each device was fired successfully on-orbit and release time and shock data was collected. Figure 4 shows the SMARD Experiment with all of the separation devices except the pyrotechnic installed. The shock and release time data in Table 1 are results from the SMARD experiment for SMA and pyrotechnic devices.

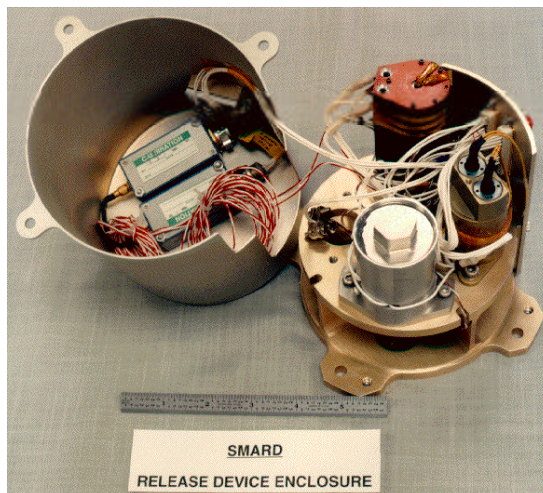


Figure 4. SMARD Experiment

The success of the SMARD experiment was the highlight of the LFN/TSN program. In all respects, other than power compatibility, the LFN and TSN were extremely successful in meeting all of the previously stated goals and proving that a non-pyrotechnic, low-shock device could operate successfully on-orbit.

AFRL/Starsys Research Corporation Devices

Subsequent to development of the LFN and TSN with Lockheed Martin, AFRL provided funding for additional work on SMA release devices to Starsys Research Corporation (SRC) of Boulder, CO, through a Phase I Small Business Innovative Research (SBIR) contract. The SBIR included device development, but also had broader goals with regard to application. The device development research involved implementation of design improvements to two SMA devices: the LFN, and an SMA release device known as the QWKNUT, which had been developed solely by SRC. There were two application-oriented aspects of the SBIR. At the time AFRL had committed to providing low-shock release devices to the U.S. Air Force Academy for use with FalconSat I, to be flown in the fall of 1999 on the first launch of the Orbital Sub-Orbital Program Space Launch Vehicle (OSP-I). One of the devices was to be qualified and flown in that capacity. The contract also required conceptual development of a complete multiple nanosat separation system, which will be discussed in a later section.

The QWKNUT, shown in Figure 5, is a low-shock, discrete point device that, like the LFN, releases a ¼-inch bolt. The QWKNUT is similar to the LFN in that it uses SMA actuators to release a bolt from a segmented nut. A primary difference is that the QWKNUT incorporates design features, which mitigate internal friction, thus allowing the use of SMA actuators, which require less current than the LFN to achieve fast release times. In fact, at the time the SBIR was awarded, the QWKNUT incorporated most of the features desirable in low-shock release devices. The QWKNUT had “in-situ” manual reset capability, was pyro pulse compatible, and was capable of providing fast release times on the order of 50 ms. It was also designed for shock outputs less than 500 g, and was similar in size and mass to the LFN. The three design improvements targeted by the SBIR were 1) to increase the allowable preload to 3000 lb, similar to the LFN, 2) to incorporate a redundant shape memory alloy trigger for improved reliability, and, 3) to provide automatic cut-off switches in the device which will prevent damage to the SMA triggers from extended application of current during testing. These improvements were all successfully incorporated in the QWKNUT.



Figure 5. QWKNUT (Starsys Research Corporation)

Since the QWKNUT was farther along in the design cycle with regard to manufacturability than the LFN, the device was chosen for use with the U.S. Air Force Academy FalconSat. FalconSat was designed with a discrete point mounting system that required four release devices. In May of 1999, the QWKNUT successfully underwent qualification testing for OSP-I and was integrated into the launch configuration. In the launch configuration, FalconSat was mounted to a multiple satellite dispenser known as the Joint Air Force Academy-Weber State University Satellite (JAWSAT), using the four-point separation system. The JAWSAT, that carried several other small satellites, was attached to the OSP-I launch vehicle using its own separation system. OSP-I was launched on 27 January 00. FalconSat was successfully released from JAWSAT in the correct orbit, approximately 15 minutes after arrival on-orbit. No problems or anomalies involving the separation system were detected.

Fuse Link Release Devices

Concurrent with efforts to develop SMA devices, AFRL also funded NEA Electronics, of Los Angeles, CA to perform development testing of low-shock, fuse link devices through a Phase I SBIR. The fuse link devices designed by NEA employ a release technology similar to the linkwire device used in the SMARD experiment, except that NEA has used new design approaches to significantly decrease the shock output. The purpose of the SBIR was to perform a series of development tests on two NEA devices: a discrete point separation nut known as the 9101, and a Marmon band release device known as the VBRM.

Both NEA devices are pyro pulse compatible, contain redundant firing mechanisms and are comparable in size and mass to pyrotechnic and SMA devices. The devices are refurbishable rather than resettable because they contain a consumable part that must be replaced by the manufacturer after firing. Test results indicate that shock levels are less than 50 g, and release times less than 50 ms may be expected.

The 9101, shown in Figure 6, is a discrete point release mechanism that takes a 1/4-inch bolt and can handle a 2500 lb preload. In contrast to the devices discussed earlier, the 9101 captures the head of a bolt or rod, while the opposite end of the bolt is threaded into a suitable fixture on the payload. Because the bolt remains threaded into the satellite after release, no bolt catcher is required. This configuration results in a very simple payload interface which adds minimal, if any, deployed mass to the payload.

The VBRM, shown in Figure 7, is a mechanism specifically designed to release a standard Marmon band. It uses the same release technology as the 9101 and provides similar low shock release. The device employs redundant fuse link release mechanisms located at each end of the band, either of which will cause payload release if activated. Preload is applied to the band by tightening a turnbuckle style bolt between the two release mechanisms. The VBRM is designed to handle a 2000 lb preload.

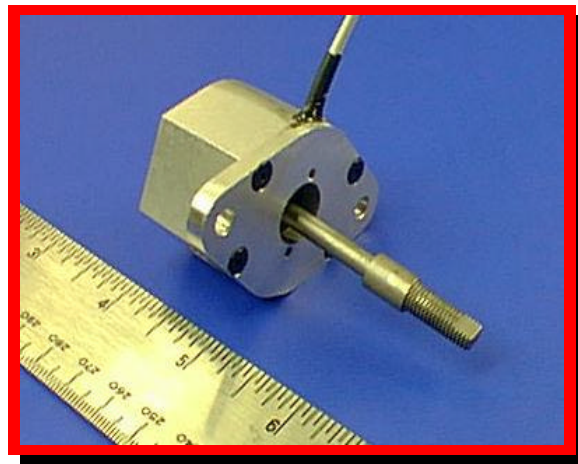


Figure 6. 9101 Release Mechanism (NEA Electronics)



Figure 7. VBRM V-band Release Mechanism (NEA Electronics)

Current Development Efforts

The most recent new development efforts involve two non-discrete point devices. AFRL has provided additional funding to SRC for development of a SMA clamp band (marmon band) release device, and to Planetary Systems Corporation for a new type of separation device known as the Lightband.

The Starsys clamp band is under development and is slated for use in two upcoming AFRL programs. Although the basic principle of operation for the band will be similar to traditional designs, a SMA mechanism will replace the pyrotechnic bolt cutter that has typically been used. The mechanism will be resettable, pyro pulse compatible, and low shock.

The Planetary Systems Corporation Lightband is also a low-shock, lightweight, resettable, non-pyrotechnic device. Similar to the other new technology, the Lightband produces no contaminants or debris. The design is currently proprietary so no details can be provided herein. AFRL is providing funding for development and test of the device and it is slated for use in the University Nanosat Program described in the next section.

Launch Opportunities for Low Shock Separation Devices

The completion of device development under the SBIRs and the success of the SMARD experiment represent a significant amount of testing and

experimentation. In order to develop flight heritage for the devices, AFRL has made commitments to provide low-shock separation devices for two small satellite programs, in addition to the Air Force Academy FalconSat application. The two programs, EELV Secondary Payload Adapter (ESPA) and the University NanoSat Program, will provide flight opportunities on an expendable launch vehicle and on the space shuttle. The projects also are a step forward from separation device design to separation system design. In each case, the release devices will be provided as part of a complete separation system consisting of interface adapters between the launch vehicle and payload, push off springs, microswitches, and low force electrical connectors. The separation systems will be designed to provide an interface between the launch vehicle and payload that meets structural and safety requirements while having minimal impact on the payload with regard to shock, tip-off, deployed mass, and surface area coverage.

University Nanosat Program

The University Nanosat Program consists of the design of an integrating structure and associated separation systems to deploy approximately 10 university constructed nanosatellites from the space shuttle. Figure 8 shows the nanosatellites mounted on the Shuttle SHELS deployment structure.

The satellites are being launched as part of an Air Force effort to explore formation flying, communication and control, sensing, and other issues of interest for military nanosatellite applications. The nanosats will be connected to each other and to the integrating structure using low-shock separation systems. The Starsys SMA clamp band will be used to separate stacks of nanosatellites from the integrating structure. The Planetary Systems Lightband will be used for intersatellite separation, i.e. separation of nanosats from each other. The entire structure containing the nanosats and separation systems will be ejected from the shuttle on-orbit, and the nanosats will subsequently be released from the structure and each other. The average satellite in this program has a mass of 15 kg, is 18" in diameter and is 10" high. Because of the close proximity of the satellites to separation devices, and the potential for each satellite to experience the shock from multiple device firings, this scenario is a perfect example of a need for low-shock separation systems in the nanosat community. The small size of the satellites also provides challenges with regard to separation system mass and surface area impacts. The program is currently working toward a January 2002 launch date.

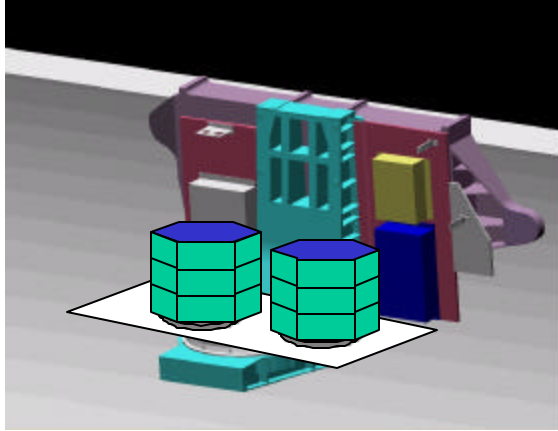


Figure 8. University Nanosat Concept

ESPA Program

The ESPA program will provide secondary payload facilities on an EELV launch vehicle to deploy up to six small satellites. ESPA is essentially an adapter ring with an integral vibration isolation system that will be installed between the EELV final stage rocket engine and the primary payload.

Figure 9 shows the general ESPA concept. The small secondary satellites will be mounted radially on the adapter by means of the Starsys SMA clamp band. Each clamp band system will be capable of holding and releasing a payload up to 400 lb. The clamp band will be the standard separation system for all secondary payloads.

The ESPA and University Nanosat programs are expected to provide a wealth of experience in qualification and design of low-shock separation systems and will pave the way for future efforts.

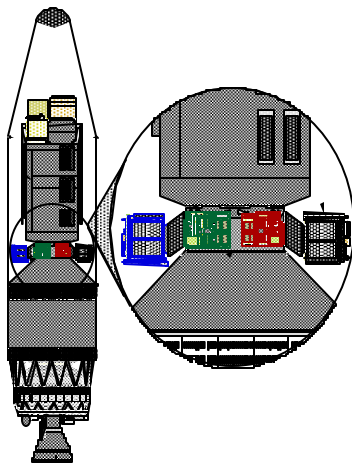


Figure 9. ESPA Adapter Concept

Future Developments

AFRL has several goals regarding further development of low-shock separation systems. One goal that has already been discussed with regard to future projects is to design and qualify complete low-shock separation systems of both the band and discrete point types. AFRL has launch opportunities to demonstrate both of these technologies for expendable vehicles and the shuttle. The shuttle will provide an opportunity to qualify a system to meet the rigorous manned space flight safety environment. EELV represents an opportunity to develop a standardized system to be used repeatedly for many different payloads if successful.

Another goal is to develop smaller devices that will be compatible with tiny satellites such as picosats with masses of 1 kg and less. Although the existing devices discussed herein are small enough to be reasonable options for nanosats, such as the ones in the University Nanosat Program, there are already picosats existing and under development upon which the existing release devices would have too high an impact. In addition to shock, the key issues are minimizing the deployed mass and minimizing the amount of satellite surface area taken up by separation system components. If designed with preload capabilities similar to the existing devices, smaller devices could also be beneficial for nanosat size payloads.

Conversely, although many of the efforts have been to accommodate small satellites, the existing technology could be scaled to accommodate larger loads. Larger payloads such as those launched from expendable vehicles are typically released using large diameter pyrotechnic Marmon bands. The Space Shuttle also employs pyrotechnic Marmon bands for its Hitchhiker program. Any or all of these may someday be candidates for replacement with low-shock Marmon bands.

Finally, although the focus has been on release of satellites, it is possible that the technology herein could eventually be modified to suit many other applications where pyrotechnics are used, such as fairing and rocket stage separation.

Summary

The first generation of new low-shock release devices has been successfully designed and developed. Of these, the SMA devices have undergone rigorous testing both on the ground and on-orbit, and have demonstrated that low-shock devices meeting all satellite release requirements are within the reach of near term launch endeavors. In fact, improved devices are currently undergoing testing

and are slated to fly in actual satellite release applications. These flights represent the near term challenge, which is to perform reliably on-orbit as part of a complete separation system. Soon, however, smaller release devices will be required as the size of satellites further decreases. Not only will low-shock be an issue but minimal intrusion in the satellite design will become even more critical because of extremely limited surface area and volume. The success of low-shock devices in these applications may very well be the driver for incorporation of the devices in more traditional large-scale separation systems, such as those commonly used for large satellites and fairings.

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