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The Atlas V Aft Bulkhead Carrier Update – Past Missions, Upcoming Launches and Future Improvements

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ABSTRACT

The Aft Bulkhead Carrier has been the primary tool of the National Reconnaissance Office (NRO) to launch auxiliary payloads since 2012. There have been three successful launches to date putting 35 CubeSats on orbit and paving the way for three new missions. The success of these missions is due in large part to the disciplined approach by United Launch Alliance to meet mission requirements and reduce risk to the primary mission with the "do-no-harm" philosophy. There have also been many lessons learned from the previous missions which have led to improvements and enhancements to future missions and giving access to even more small satellites.

INTRODUCTION

The Aft Bulkhead Carrier (ABC), developed by the United Launch Alliance (ULA) and the National Reconnaissance Office (NRO), for use on the Atlas V launch vehicle, has been an important asset delivering NRO and National Aeronautics and Space Administration (NASA) sponsored auxiliary payloads (APs) to orbit since 2012. The NRO has now successfully put 35 CubeSats on orbit with three missions using the ABC system.

In this paper, ULA's ABC AP User's Guide will be covered in detail to give the community an idea of what it takes to use an ABC to launch an AP. An overview of the NRO's current and past missions using the ABC will also be covered and will include lessons learned from those missions.

ABC Overview

The ABC is a system to support and deploy an AP from the aft end of the Centaur. The baseline ABC design accommodates a single AP on a given Atlas V flight. The ABC's function is to provide the means to deliver an AP to its specified destination orbit without degrading the primary spacecraft delivery and on-orbit performance.

The ABC system consists of a plate and two struts. The design was meant to minimize design and component testing costs and this was done on both the struts and plate. The struts were based on the existing helium tank strut design and the plate uses a standard ULA aluminum honeycomb core/aluminum facesheet composite design found throughout the vehicle. Figure 1 illustrates the ABC design.

Figure 1: ABC Plate and Struts

The ABC is then mounted to the Centaur, directly to the aft bulkhead using existing mounting locations from a previous Centaur pressure system design. Figure 2 illustrates the location of the ABC in relation to the rest of the Atlas V launch vehicle and the primary spacecraft. Figure 3 then illustrates the location of the ABC plate and the AP volume available. The location and orientation of the ABC plate, maximizes available volume, minimizes loading on the ABC plate and struts, and avoids impingement from venting. The notch in the AP volume is to accommodate the separation dynamics of the Atlas/Centaur interstage adapter in the 4-meter fairing configuration as illustrated in figure 2.

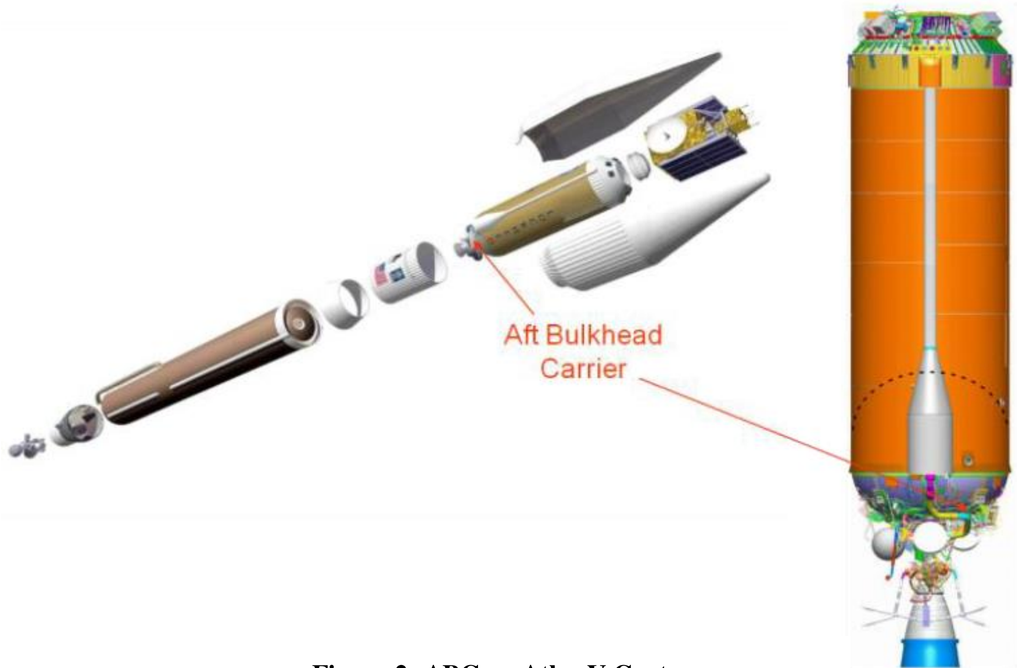


Figure 2: ABC on Atlas V Centaur

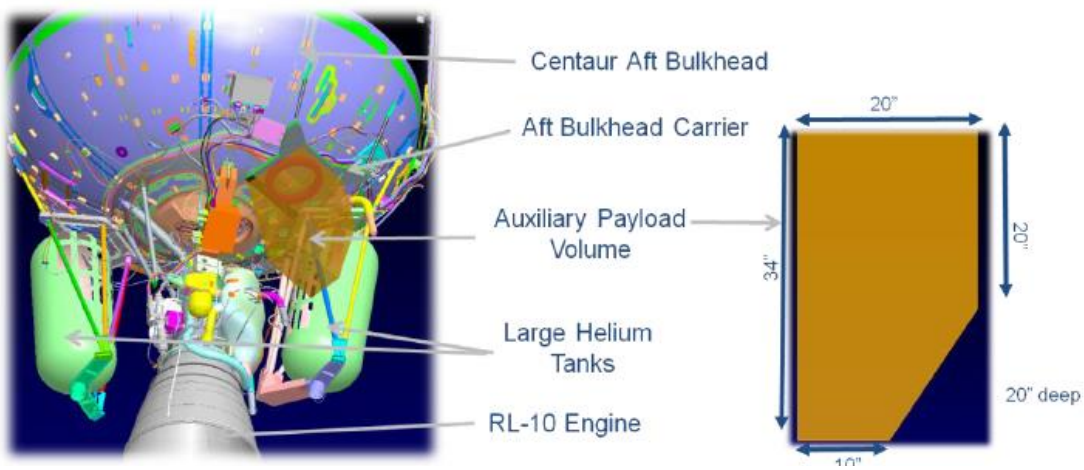


Figure 3: ABC Plate Mounted to Aft End of Centaur Showing Volume Available for AP

This design has proved over and over that it is robust and able to handle different configurations. To be able to ride on the ABC though, ULA requires that the payload must meet certain requirements and milestones. This is all detailed in the ABC AP User's guide which is summarized next.

ABC AP USER'S GUIDE

The ABC AP User's Guide is issued to the spacecraft user community to provide information about the ABC. The following is a summary-level look at the key AP requirements contained in the ABC AP Users guide. The User's guide may be found at www.ulalaunch.com.

Purpose

The User's Guide defines the Launch Vehicle (LV) to AP interfaces and worst case launch environments for the Centaur ABC AP component design. The AP that is attached to the ABC is required to conform to these constraints in order to fly on an Atlas V mission. The Centaur ABC design reflects the Atlas V current environments, loads, and envelopes, rather than meeting typical spacecraft standards.

Manifesting

Candidate APs must coordinate with ULA and the primary customer to ensure adequate performance and compatibility between primary and auxiliary payloads. APs must meet ABC AP User's Guide requirements. Further study may be required before an AP can be manifested.

ICD Process

An ICD will be jointly developed between the ULA and AP team. It will be controlled and maintained by ULA. Its purpose is to provide detailed technical requirements for interfaces in the areas of performance, physical, functional, environmental and ground operations. Requirements to be formally verified are identified in the ICD, assigned a Requirements Traceability Number (RTN), and tracked in a Verification Matrix that is part of the ICD. Participating parties are each responsible for tracking and verifying compliance for each requirement that applies to their respective side of the interface. To ensure requirements have been properly interpreted and implemented, verification evidence is made available to all other ICD signatory parties for approval. See figure 4 for timeline of verification closures.

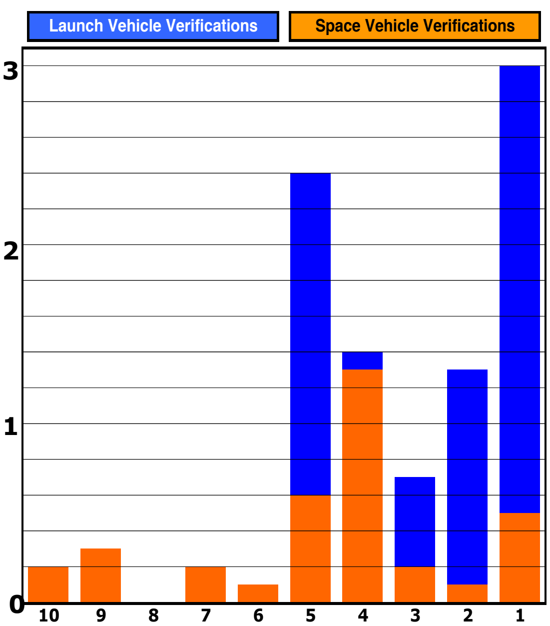


Figure 4: Typical Requirements Closure Plan (Months to Launch)

AP Mass Property Range

The Atlas V Centaur flight control systems can accommodate AP(s) that fall within the range 145 +/- 25 lbs. The AP mass properties include the AP(s), any AP adapters and/or separation system hardware that remains attached to the AP after the separation event, and associated 3-sigma uncertainties.

Collision and Contamination Avoidance Maneuvers (CCAM)

The Aux Payload will be released after the primary space vehicle has separated from the Centaur. The Centaur will perform a CCAM after release of the AP.

Processing and Pre-Launch Thermal

The ABC and the AP will be installed in the ASOC on the East Coast and Building 7525 on the West Coast. The ASOC is an air-conditioned space with a temperature range of approximately 50 to 95 °F. Building 7525 has heating capability only with a temperature varying anywhere between approximately 50 and 100 °F. Relative Humidity (RH) is not tightly controlled and reflects launch site ambient (0% to 100% RH). The AP must be capable of withstanding these environments while in these facilities.

Electromagnetic Compatibility

The integrated AP/SV/LV system design will provide EMC with a minimum of 20 dB Electromagnetic Interference Safety Margin (vs. dc no-fire thresholds) for ordnance circuits and a minimum of 6 dB EMISM for all other non-ordnance circuits (Category I and II) which are deemed safety or mission critical.

The AP will be compatible with the LV worst case intentional narrowband radiated emissions (E-Fields). Unintentional narrowband radiated emissions from Centaur equipment/avionics/RF transmitters and receivers will not exceed 114 dBμV/m in the frequency range from 14 kHz to 18 GHz, as displayed in Figure 3-3, at the AP static envelope. The flight configured AP/SV/LV integrated system will be compatible with the Eastern or Western Range RF sources located near VIF/LC-41 or SLC-3E, respectively. The AP will not activate transmitting antenna(s) (frequency range from 14 kHz to 18 GHz) having an EIRP equal to or less than 39 dBm (7.94 Watts), closer than 30.5 meters (100 feet) from the Atlas V Centaur or the Primary SV. The AP will not activate transmitting antenna(s) (frequencies □ 350 MHz and □ 18.0 GHz) having an EIRP greater than 39 dBm (7.94 Watts) and less than or equal to 43.8 dBm (24 Watts) closer than 2.7 meters (8.85 feet) from the Atlas V Centaur or the Primary SV.

AP Static Magnetic Field Limitations

Static magnetic fields due to intentional AP magnetic materials, if any, must be less than 0.5 gauss at the AP envelope.

Aft Bulkhead Contamination Environment

The Aft Bulkhead and attached hardware will be maintained at a Generally Clean (GC) level through launch. During Centaur hoist and mate with the booster, the aft end of the Centaur is exposed to the ambient environment without protection. At the launch pad, there is a potential for rain mist to enter the ISA compartment.

Aft Bulkhead Helium Environment

The Aft Bulkhead helium environment for the ABC configuration, assuming 4 launch attempts, is 3000 Torr-hours.

Acceleration limit load factors

The acceleration limit load factors are 7 g's in the ZAP direction and 5 g's in the XAP and YAP directions applied simultaneously (not including factors of safety).

Acoustics

The AP will be capable of withstanding the maximum predicted environment as shown in Figure 5.

Vibration

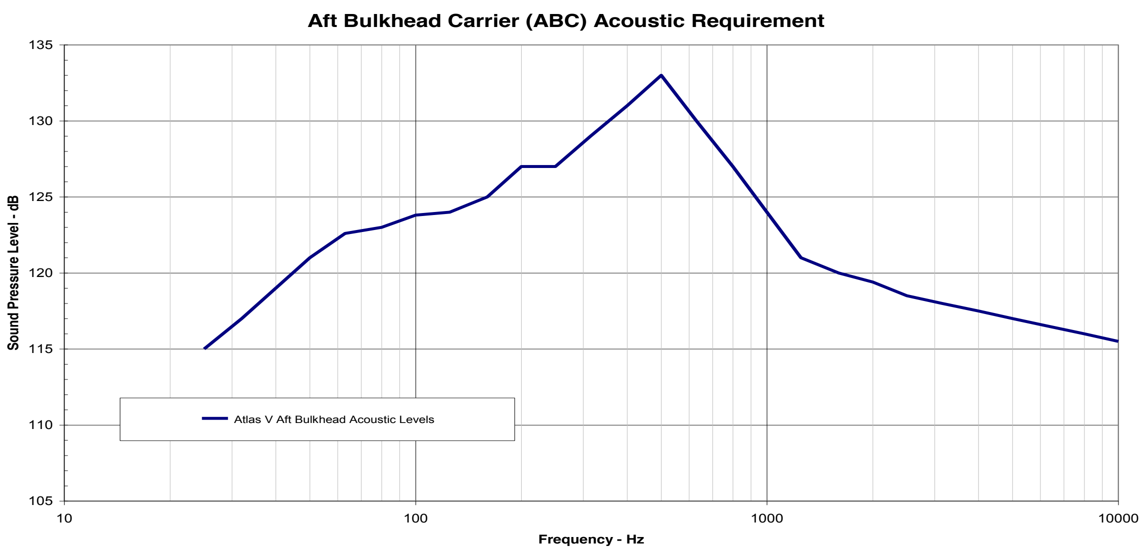
The AP will be capable of withstanding the maximum predicted environment as shown in Figure 6.

AP Generated Shock

Any AP generated shock levels at the ASIP, based on a statistical significance of 95 percent probability and 50 percent confidence, will be less than or equal to the spectrum shown in Figure 7.

LV Generated Shock

The AP will be capable of withstanding the maximum predicted dynamic flight environment shown in Figure 8. The levels in Figure 8 are preliminary predictions for the Motorized Lightband (MLB) and have not been validated through Qualification testing.



1/3 OB Center Frequency (Hz)	Sound Pressure Level (dB)	1/3 OB Center Frequency (Hz)	Sound Pressure Level (dB)
32	117	630	130
40	119	800	127
50	121	1000	124
63	122.6	1250	121
80	123	1600	120
100	123.8	2000	119.4
125	124	2500	118.5
160	125	3150	118
200	127	4000	117.5
250	127	5000	117
315	129	6300	116.5
400	131	8000	116
500	133	10000	115.5
OASPL = 139.5 dB			

Figure 5: Atlas V Maximum Predicted Acoustic

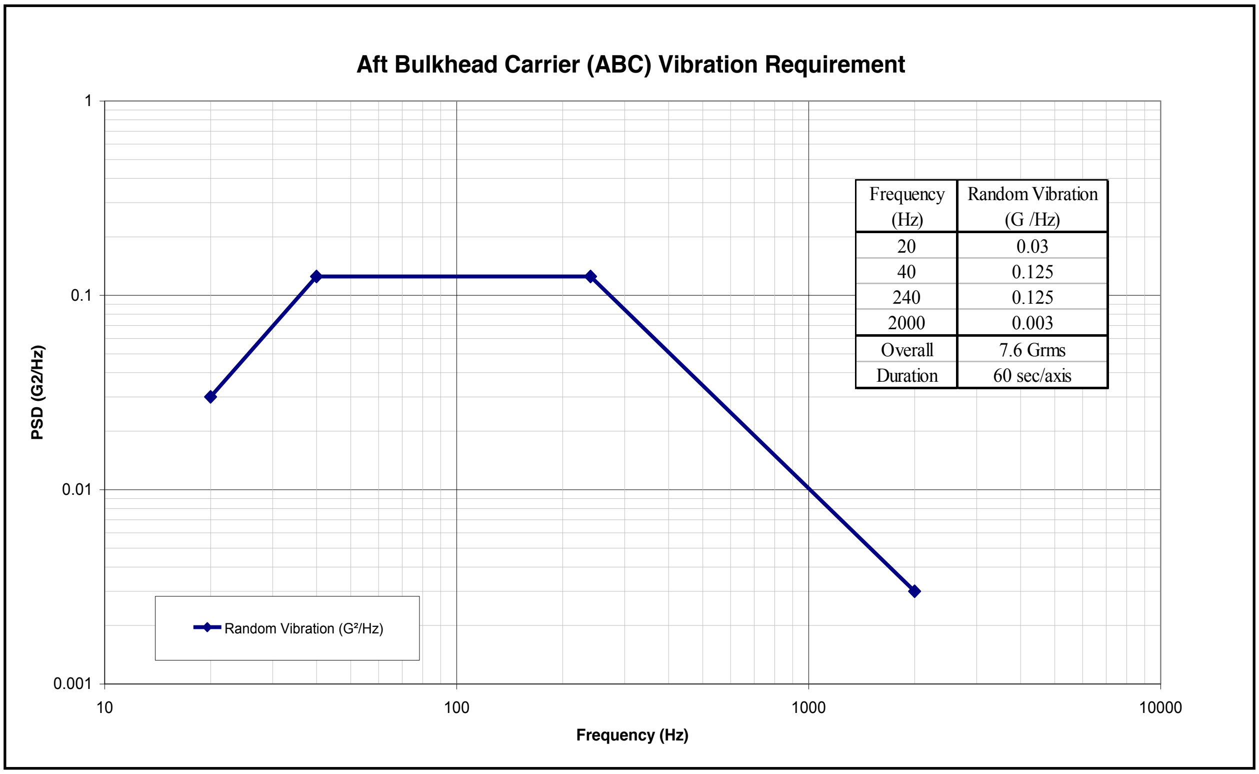


Figure 6: Maximum Random Vibration Environment at the ASIP

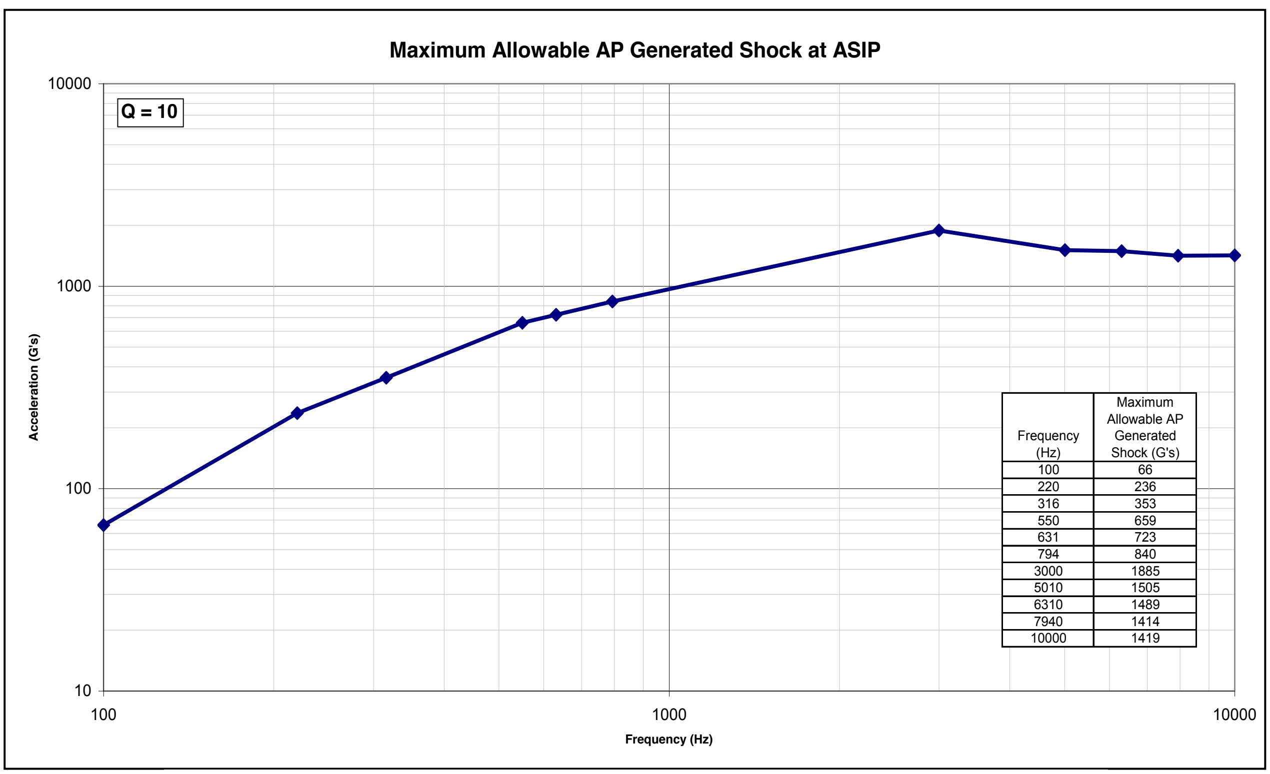


Figure 7: Maximum Allowable AP Generated Shock Levels at the ASIP

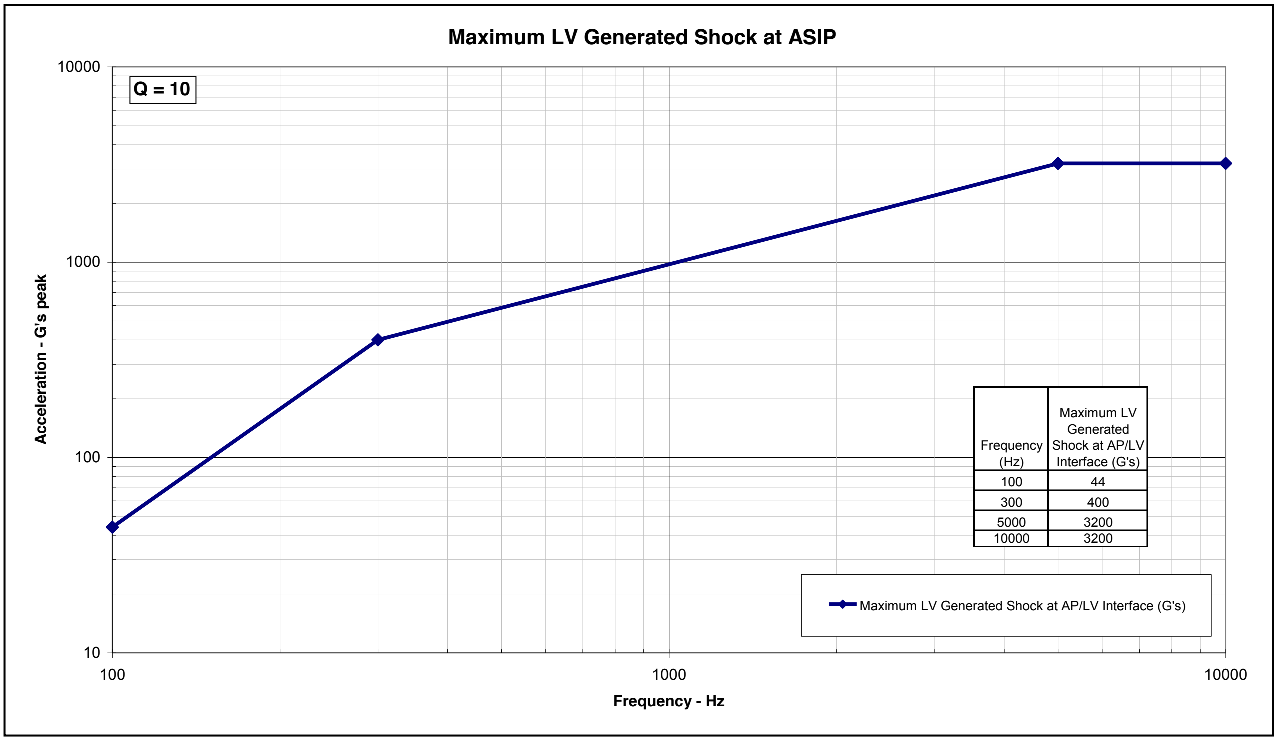


Figure 8: Maximum LV Generated Shock Levels at the ASIP

In-Flight Thermal

Consists of Ambient Temperature and Convection, Orbital heating, Plume Impingement, Centaur Component thermal Radiation. The AP will be compatible with values provided by the LV thermal analysis.

AP Dynamic Compatibility Test Requirements

The LVC requires that all APs be capable of experiencing maximum expected flight environments multiplied by appropriate margins to preclude impact to mission success. The AP structural designs and qualification programs will verify that the AP systems are compatible with all maximum expected flight environments. Compatibility is demonstrated by design margin, test, analysis, or a combination thereof. Particular attention should be paid to structure in the mid-frequency transition zone (50-100 Hz) between low frequency (CLA) and high frequency (acoustic) regions.

Coordination must take place with the LVC as early as possible in the planning stage to mitigate schedule, cost, and mission risk. A qualification plan must be supplied to the LVC which outlines the methods to be used to demonstrate AP compatibility to each of the above dynamic environments, in addition to plans for validation of the dynamic model used in the coupled loads analysis. A summary report must also be supplied at the end of the qualification program to summarize compliance to all dynamic environments.

Thermal Test Requirements

ULA suggests that the APC demonstrate the AP capability to withstand thermal environments from an AP mission success perspective. The APIC will demonstrate that the AP will not structurally fail or separate prematurely given the thermal environments.

EMI/EMC Test Requirements

ULA suggests that the APIC demonstrate the AP capability to withstand EMI/EMC environments (from an AP mission success perspective). The APIC will demonstrate that the AP will not inadvertently initiate AP functions or separate prematurely given the EMI/EMC environments.

Auxiliary Payload Volume

The separating AP envelope consists of 34 inches along the +ZAP, 20 inches along the XAP axis centered about the origin, and 20 inches along the YAP centered about the origin. The total envelope allocated to a separating AP is shown in Figure 9. This total envelope does not include the separation system. The total envelope allocated to a non-separating AP (Pre-CubeSat Separation) is also shown in Figure 9.

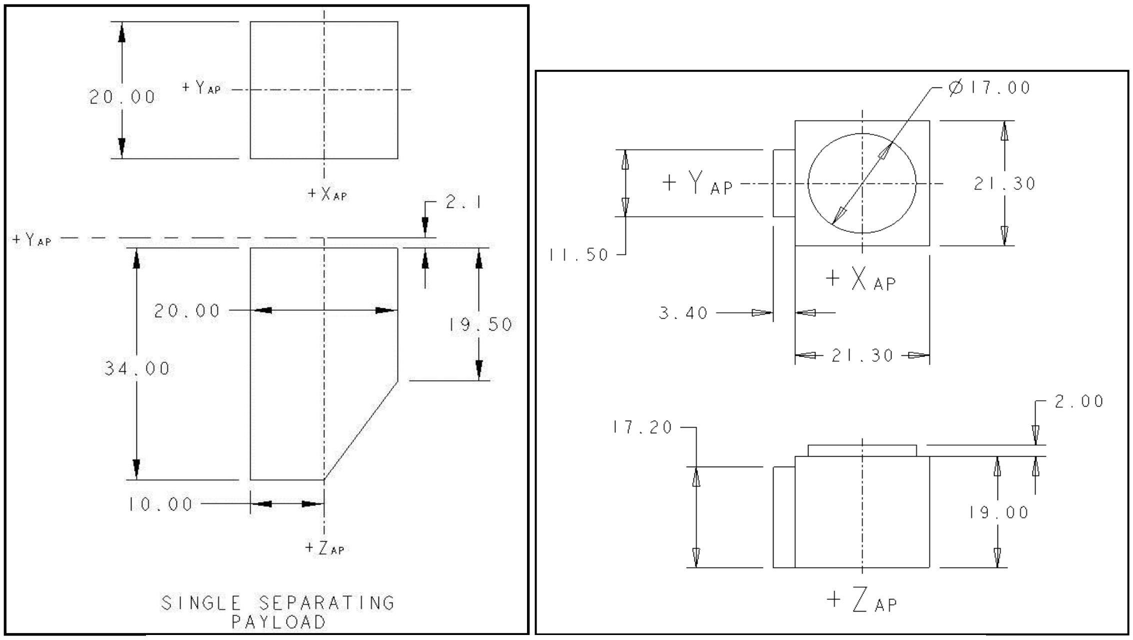


Figure 9: Separating and Non-Separating AP Envelope Definition

Mechanical Interface

Each AP must match the standard interface to the ABC, either directly or through an AP provided adapter. The insert pattern has a diameter of 15 inches between bolt-hole centers. The bolt pattern consists of (24) .2500-28UNJF inserts and are spaced every 15 degrees around the ring. The zero degree point of the ring lies along the +YAP direction in the AP coordinate system. Figure 10 illustrates the bolt pattern.

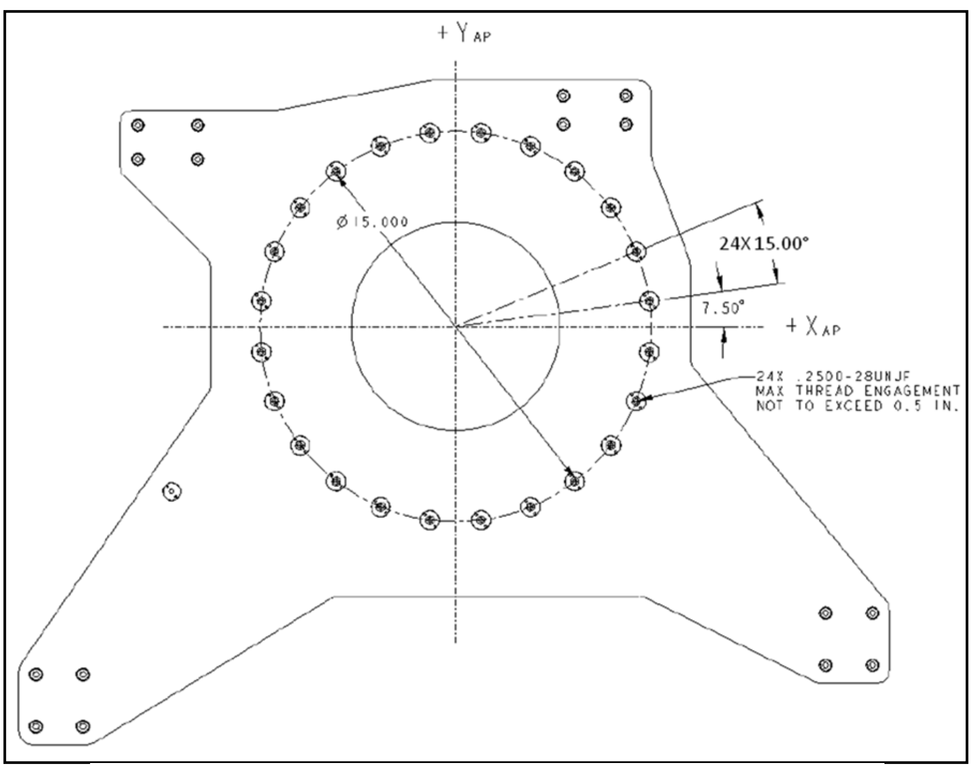


Figure 10: ABC Auxiliary Standard Interface Plane

AP Mechanical Interface Requirements

AP stiffness/fundamental frequency will be greater than 35 Hz when mounted to a rigid interface. Electrical bonding across the AP/LV separation plane will not exceed 2.5 milli-ohms. For Separating APs, the AP structure surface adjoining the Lightband Separation System will be flat to 0.0040 inches, peak to peak. For Non-Separating APs, the AP structure interfacing the ABC Structure will be flat to 0.010 inches, peak to peak.

Avionics Interfaces for Non-separating APs

The LV provides an airborne electrical interconnection from the time of LV power on until mission completion. All payload provided signals and power are handled as unclassified data. For Non-separating APs with CubeSats, the AP will provide separation indications from the P-POD door switches that go to the RDU. These are for use by the LV to indicate the opening of each P-POD door. The LVC will provide separation indication monitoring circuits to monitor the AP P-POD door switches. For Non-separating APs with CubeSats, the LV will transmit telemetry verification of each AP P-POD door opening event

Range and System Safety Interfaces

ABC APs will comply with the applicable programmatic, design and operating/operational requirements of Air Force Space Command Manual (AFSPCMAN) 91–710, Volumes 1, 3, and 6, as a minimum. An appropriate ABC AP-sponsoring organization will demonstrate compliance with the aforementioned applicable requirements by the generation and submittal to Range Safety and ULA of an acceptable Missile System Prelaunch Safety Package (MSPSP) consistent with the requirements of AFSPCMAN 91–710, Volume 3, Attachment 1, as a minimum.

An adequate MSPSP:

a. Identifies the hazards inherent in the ABC APs hardware and operations,

b. Identifies and describes the ABC AP design features and procedural precautions that preclude, prevent, control, mitigate, or ameliorate these hazards not only during nominal/planned operating/operational conditions but also during credible fault/failure conditions,

c. Summarizes how the effectiveness of the hazard controls or procedural precautions will be verified (by test, analysis, inspection, or some combination thereof), and

d. Provides the applicable data required by AFSPCMAN 91–710, Volume 3, Attachment 1.

AP Deliverables

Table 1 provides a list of typical/standard AP inputs required for the integration process, the approximate need date, and a brief description of the contents.

Table 1: AP Inputs to Integration Process

AP Data Input	Approximate Need Date
Program Kickoff Meeting	L - 23 months
Initial Target Specification	Program Kickoff Meeting
Interface Requirements Document	Program Kickoff Meeting
Intact Impact Breakup Data	Program Kickoff Meeting
Inflight Breakup Data	Program Kickoff Meeting
Preliminary Coupled Loads Model*	Program Kickoff Meeting
Preliminary CAD Model*	Program Kickoff Meeting + 1 month
Range Safety Mission Orientation Briefing Input	Program Kickoff Meeting + 4 months
Final CAD Model*	Program Kickoff Meeting + 6 months
Final Coupled Loads Model*	Program Kickoff Meeting + 7 months
Procedures Used at PPF	AP Arrival - 2 months
Preliminary AP MSPSP*	L - 12 months

Thermal Models	L - 12 months
AP EMI/EMC Analysis	L - 7 months
AP EED Analysis	L - 7 months
Final AP MSPSP*	L - 5 months
AP Environment Qualification Test Reports*	L - 5 months
Procedures Used at Launch Site	First Use - 2 months
Final Target Specification	L - 90 days

THE SYSTEM WORKS!

NROL-36/OUTSat

The ABC has delivered three payloads to orbit to date with a total of 35 Cubesats deployed. The first mission, the Operationally Unique Technologies Satellite, or OUTSat, launched on NROL-36 from Vandenberg Air Force Base (VAFB) in September, 2012.

Shortly after contract go-ahead, a kick-off meeting was held to establish the process for which the teams would demonstrate the "do-no-harm" objective was being met. In addition to the two planned OUTSat design reviews, ULA implemented three "Gate Reviews" to status the progress not only of OUTSat, but also that of the Atlas effort. These reviews were timed to coincide with key primary mission milestones. Success criteria was established for each of the reviews, with over 20 criteria established for the reviews for this first mission. These reviews were presented to the primary mission management team and members of the ULA Chief Engineer's office.

In addition to the Gate criteria, ULA led the effort to establish a list of "do-no-harm" requirements that needed to be fulfilled prior to the flight. This set of requirements has subsequently been reviewed and updated, and now is a baseline set of requirements for any rideshare mission, ABC or other configuration, that is manifested on a ULA launch vehicle.

As with any first-time process, there were numerous lessons learned, refinements to the original plan, and "gotcha's" along the way. However, the integrated team worked extremely well together with everyone's goal to make this first time EELV rideshare mission a success. Some of the lessons learned are addressed later in this paper.

The team necessary to bring the mission to fruition included: ULA, the Auxiliary Payload Integrating Contractor (APIC), Naval Postgraduate School (NPS), the Range Safety office at Vandenberg AFB (VAFB), the Launch Systems Directorate (LR) and the Air Force Space and Missile System Center, Mission Integration Directorate (MID) at the NRO, NASA Launch Services Program (LSP), and the OSL.

ULA not only provided the launch service for OUTSat, but also was the entity that the primary satellite customer looked to for assurance "do no harm" requirements were met – by both OUTSat and ULA - and provide them confidence they'd experience no impact to the mission. For completeness, do-no-harm includes schedule as well as technical/mission success.

The APIC was led by the California State Polytechnic University (Cal Poly) in San Luis Obispo. Cal Poly subcontracted with SRI International in Menlo Park, CA to provide additional technical expertise and backup integration and test facilities. A competent APIC is critical to a mission that consists of multiple entities, but must "herd the cats" and manage the integration of up to 20 different satellites. The APIC was responsible for integrating OUTSat, ensuring a fully tested satellite is delivered to the launch site, integrating the AP with the launch vehicle, making sure all Range Safety, launch base, transportation, operations, and other documentation is completed and delivered on-time. In addition, the APIC is responsible for compiling all do-no-harm evidence to be presented to the primary spacecraft customer and the launch vehicle provider.

At the time the decision was made to proceed with the OUTSat mission, OSL did not have a contract with an entity to perform these functions. To ensure a competent APIC was chosen in a timely fashion, OSL teamed with NASA's LSP to leverage their experience in manifesting CubeSats and their existing contract with Cal Poly to provide such services. Using the NASA contract as a baseline and detailing the myriad of other requirements required to complete the integration effort, OSL was able to obtain Cal Poly's services in time to support the OUTSat mission.

The APIC oversaw the development and build of the manifested CubeSats, ensured requirements satellite development specification and ICD requirements were met, and conducted integration of the CubeSats with their P-POD's at their Cal Poly facility.

NPS was instrumental in the success of the program. Once the CubeSats were integrated with the P-PODS, they were delivered to Monterey for integration with the NPS-developed and built NPS Cubesat Launcher (NPSCuL) and readied for final system-level vibration testing. NPS staff oversaw the integration process and electrical checkouts of the system. NPS engineers conducted final testing of OUTSat, implementing the Force Limited Vibration Testing technique to avoid over-testing the individual components. NPS also characterized the vibration levels at CubeSat positions to ensure the developers had the proper levels to test to ensure confidence of surviving system acceptance testing and flight.

The 30th Space Wing Range Safety Office at VAFB provided safety oversight and approval of the OUTSat system. Their efforts ensure the safety of personnel working with the system and protect the general public. The Safety individual assigned to OUTSat was extremely proactive and engaged throughout the entire process. His support ensured no disruptions, last minute surprises, or an auxiliary payload system that was not compatible with range requirements.

The Air Force's Launch System Directorate (LR) is responsible for certifying the launch vehicle readiness to the NRO's Mission Director. As such, they evaluated the technical readiness of the ABC system and its interfaces with OUTSat. LR participated in all OUTSat design and Gate reviews to maintain a current understanding of the entire mission design. LR completed its evaluation of all hardware and interface requirements and reported a positive "ready" to the Mission Director.

In addition to the early discussion of NASA LSP's critical role in the APIC contractual relationship, LSP also provided programmatic oversight of the NASA-sponsored CubeSats to ensure that not only OUTSat requirements were met, but any NASA-specific items were fulfilled as well. LSP, in coordination with the APIC conducted a Mission Readiness Review for each CubeSat to ensure requirements were fulfilled.

The NRO's Mission Integration Directorate (MID) was responsible for manifesting and programmatic oversight for all NRO-sponsored CubeSats. These included not only NRO procured CubeSats, but those from our partners to include the Army and Department of Homeland Security to name just a couple. Like LSP, MID completed Mission Readiness Reviews for each of their satellites.

And finally, OSL provided overall program management for the mission. A small, three-person team oversaw the integration process.

After multiple CubeSats fell off the manifest, just enough remained to completely fill the eight P-PODS. Table 1 lists the OUTSat manifest. The CubeSats were delivered on-time, integrated, tested, and delivered to VAFB with significant margin to the need date. Integration activities went smoothly and Atlas V and Centaur upper stage processing proceeded as planned.

All parties arrived at VAFB in August for the planned launch and all systems were "go" until shortly before launch, the Western Range experienced a problem that resulted in a launch scrub. The Atlas V configuration was maintained while the Range worked to understand the problem, make repairs, and retest to ensure a robust capability. The team returned to VAFB in September for a successful launch that placed the primary spacecraft and all 11 CubeSats, listed in table 2, in orbits right on target with preflight predictions. Deployment of all CubeSats was successful.

Table 2: OUTSat CubeSat Final Manifest

Sponsor	Developer	CubeSat	Size & Qty
NRO	Aerospace Corp	AeroCube 4	1U x2
NRO	Aerospace Corp	AeroCube 4.5	1U x 1
NRO	Army SMDC	SMDC-One	3U x 2
NRO	Univ of Southern California - ISI	AENEAS	3U x1
NRO	Lawrence Livermore National Laboratory	Re	3U x 1
NASA	Univ of Cal-Berkeley	Cinema	3U x 1
NASA	Univ of Colorado	CSSWE	3U x1
NASA	CP5		1U x 1
	CXBN		2U x 1

NROL-39/GEMSat

Prior to the launch of OUTSat, OSL manifested another "NPSCuL-type" auxiliary payload using the ABC system on NROL-39. "L-39" was scheduled for launch in December of 2013, also from VAFB. This timing allowed OSL to keep the ULA, APIC, and NPS teams intact, a distinct plus when attempting to further refine processes, reduce the time required to integrate such a mission, and drive down costs. OSL once again teamed with NASA LSP to use their contract mechanism for the APIC effort.

The teams remained basically the same, with Cal Poly adding Tyvak, along with SRI, to the APIC.

A process change for GEMSat was the elimination of one of the Gate reviews, leaving two meetings to present status to the primary customer mission management team and the ULA Chief Engineers. It was determined after OUTSat this change could be made with no decrease in management awareness or risk to the program. One less review meant less travel and less time required for the team to prepare presentation material.

The Government Experimental Multi-Satellite, or GEMSat, deployed 12 NRO- and NASA-sponsored CubeSats on this second mission. Table 3 provides the list GEMSat CubeSats, after starting out with just over 20 candidates. Although GEMSat had many similarities to OUTSat, there were some new challenges along the way.

Table 3: GEMSat CubeSat Final Manifest

Sponsor	Developer	CubeSat	Size & Qty
NRO	Aerospace Corp	AeroCube 5	1.5U x 2
NRO	Army SMDC	TacSat VI	3U x 1
NRO	Army SMDC	SMDC-One	3U x 2
NRO	Army SMDC	SNaP	3U x1
NRO	AFIT	ALICE	3U x 1
NASA	Montana State Univ	Firebird	1.5U x 2
NASA	JPL/Cal Poly	IPEX	1U x1
NASA	Univ of Michigan	MCubed-2	1U x 1
NASA	Medger Evans College, City Univ of New York	CUNYSat	1U x 1

Updated ULA thermal predictions required Cal Poly to re-evaluate the thermal tape configuration of the various GEMSat components. As a result of this evaluation, the taping scheme for GEMSat differed from OUTSat and there was no tape applied to the P-POD's.

GEMSat was the first time our auxiliary payload contained a propulsion system. Based on the propellant used and system pressures through launch, the system was on the "low end" of a propulsion system posing little safety concerns. However, it did prove a very good exercise for Range Safety, ULA, and the entire auxiliary payload community, including OSL, on the documentation, testing, and discipline required to get such a system approved. Due to the diligence of the entire community, SNaP was approved by Range Safety and flew on GEMSat.

Although there were some significant challenges for a number of the CubeSat developers, enough CubeSats were delivered on scheduled to completely fill the eight P-POD's. Integration went smoothly and again, OSL's auxiliary payload was delivered to the launch site on-time ensuring no impact to the overall mission schedule.

NROL-39 launched on the first attempt and again the Atlas V hit a perfect bulls-eye, delivering the primary payload and the 12 CubeSats to the prelaunch predicted orbits.

AFSPC-5/ULTRASat

Again, OSL was successful manifesting not just one, but two ABC auxiliary payload missions prior to the GEMSat launch in late 2013. The first was the Ultra Lightweight Technology and Research Auxiliary Satellite (ULTRASat). This again is an NPSCuL-configured satellite with eight P-POD's.

However, this time, OSL manifested the payload on an Air Force launch rather than an in-house NRO mission. Thanks to collaboration with the Air Force Space Test Program, LR, and the primary customer, we were able to demonstrate the benefits on maintaining close relationships with our mission partners. As a result, we were able to take advantage of an otherwise unused available volume and performance on the Air Force's AFSPC-5 launch.

For this launch, the Mission Director ultimately responsible for the flight readiness of the launch stack, including the auxiliary payload, was LR instead of OSL. Roles and responsibilities as well as required briefings to management were outlined early in the program and the process worked flawlessly with senior management kept apprised of project status throughout the mission.

Also, by this time, OSL had established our own APIC contract with Cal Poly eliminating the need to use the NASA LSP contract. In the spirit of collaboration, we continued to offer LSP two P-POD slots on the mission. Our agreement with LSP is for "like" opportunities for NRO smallsats on future NASA launches and at least one of those is currently in-work.

Another significant difference for this mission was the number of separation signals available from the Centaur to the auxiliary payload. For the first two missions, eight redundant signals were available providing a one-to-one direct path for each P-POD separation signal. For AFSPC-5 only six signals were available. Engineers at NPS came up with a design to implement relays in their Splitter Auxiliary Device (SAD) that passes the signals from the Centaur to the P-POD's. This design provides signals to all eight P-POD's using only five Centaur signals. An outstanding effort on the part of NPS, ULA, APIC, and Range Safety to coordinate the design, testing, and implementation of this redesigned SAD resulted in its use for ULTRASat and the successful deployment of CubeSats from all eight P-POD's.

And finally, AFSPC-5 was launched from Cape Canaveral AFS (CCAFS), FL; this introduced a new player to the team – the 45th Space Wing Range Safety Office. Leveraging the work that had been completed at VAFB, the 45th personnel worked hand-in-hand with the APIC, NPS, and ULA to ensure all aspects of the program were consistent with Range Safety requirements at CCAFS.

The launch from CCAFS also presented a new challenge for transporting ULTRASat from NPS in Monterey, CA to the launch site. The first two missions were an easy three-hour drive from NPS to VAFB. NPS personnel drove the truck with an APIC and OSL escort. A cross-country drive for the team was deemed unreasonable due to the cost, time, and liability involved with such a trip. After investigating various government options, we contacted the FedEx Space Solutions group. After discussions with them, it was decided to use the FedEx Custom Critical option that delivered ULTRASat overnight door-to-door from NPS to ULA at CCAFS. ULTRASat was picked up at NPS on Monday, March 2 and delivered Tuesday morning to ULA/CCAFS prior to 10AM. Another success story!

Unfortunately, CubeSat delivery wasn't quite as successful. For the first time, enough candidate satellites did not complete build and test to meet the required delivery date. When the dust settled, there were enough CubeSats to populate five P-PODS. The backup plan for all missions has been to launch optical tracking CubeSats or "OptiCubes" at the request of the NASA Orbital Debris Program Office and the Air Force's Starfire Optical Range. The OptiCubes have specialized coated and polished surfaces that provide the ground assets an opportunity to enhance tracking capabilities, orbit prediction techniques, and assess material properties in space. Three 3U OptiCubes were completed by Cal Poly in short order once it was clear that enough CubeSats would not be delivered to fill the P-PODS. Orbital lifetime of the OptiCubes is expected to be approximately six years.

The final ULTRASat manifest is listed in Table 4.

Table 4: ULTRASat CubeSat Final Manifest

Sponsor	Developer	CubeSat	Size & Qty
NRO	Aerospace Corp	AeroCube 8	1.5U x 2
NRO	AFRL	GEARRS	3U x 1
NRO	Cal Poly	OptiCube	3U x 3
NRO	US Naval Academy	BRICSat	1.5 x1
NRO	US Naval Academy	PSat	1.5 x 1
NRO	US Naval Academy	USS Langley	3U x 1
NASA	Planetary Society	LightSail A	1.5U x 2

The ten CubeSats, including the three OptiCubes, were delivered to CCAFS with schedule margin to meet the ULA processing flow. The team arrived at CCAFS this past May and once again the Atlas launched on the first attempt. The primary satellite and all 10 CubeSats were placed in orbit exactly according to pre-flight predictions.

NROL-55/GRACE

The other auxiliary payload contracted in late 2013 was the Government Rideshare Advanced Concepts Experiment (GRACE). GRACE is flying on the NROL-55 mission from VAFB. At the outset, UTLRASat and GRACE were required to meet the early "protect" launch dates for the two missions. At the time these were within one month of each other at the end of 2014. With the slightly different Atlas processing schedules at the two launch sites, our original delivery dates for the two auxiliary payloads were right on top of each other. As the primary missions progressed, the ULTRASat and GRACE launch dates were refined to May and August 2015 respectively – giving the team some breathing room between the two missions.

Fortunately, GRACE presented minimal new challenges. With the same team in place from the first two missions, the APIC, NPS, ULA, LR, and 30th Space Wing Range Safety worked well together to make the GRACE integration the "easiest" to date.

The well-seasoned team worked the two missions simultaneously, with final delivery, integration, and test taking place for the two missions almost none-stop from Jan 4 through April 10 of this year. In addition, the team had to support numerous readiness reviews, Gate reviews, launch prep activities, early on-orbit preps, and public affairs requests. The team divided and conquered as necessary, and each activity was supported and successfully completed on time and to the satisfaction of all customers.

This time there were more than enough CubeSats to fill the eight P-POD's. Final manifest decisions were made and Cubesats were delivered in late February. The GRACE manifest is shown in Table 5.

Table 5: GRACE CubeSat Final Manifest

Sponsor	Developer	CubeSat	Size & Qty
NRO	Aerospace Corp	AeroCube-7	1.5U x 1
NRO	Aerospace Corp	AeroCube-5	1.5U x 1
NRO	SRI	SINOD	2U x 2
NRO	SRI	PropCube	1U x 2
NRO	Army SMDC	SNaP	3U x 3
NASA	LMRST	JPL	3U x1
NASA	AMSAT	Fox-1	1U x 1
NASA	Salish Kootenai College	BisonSat	1U x 1
NASA	Univ of Alaska – Fairbanks	ARC-1	1U x 1

Integration and test went smoothly and the payload was placed into its shipping container on April 10 readied for delivery to VAFB. Due to a one month delay in the NROL-55 launch date, GRACE has remained at NPS in secure storage and is presently scheduled to be delivered to VAFB on 30 June 2015 for a September launch.

LESSONS LEARNED

There have been many important lessons learned from the past three missions that the NRO has launched. The following are a few that should be highlighted.

Establishing End Date for Future Candidates

It is important to establish an end date, at which point you will stop accepting new candidates. With the fluidity of CubeSats, more candidates are better one would think. There is a point though, when the extra work out-weighs the benefit to a full manifest.

Identify Interdependencies Early

When you are the AP, you must identify interdependencies with the primary mission early. For example, it is critical that you deliver the AP to the launch base so that there is no impact to the launch vehicle and primary payload ground processing at the launch base.

CubeSat Inhibits

A CubeSat with three inhibits and dual fault tolerance for system power up limits EMI/EMC interference concerns and provides flexibility. On OUTSat there were very few CubeSats with more than one inhibit. The lack of quality inhibits created quite a bit of work for the CubeSat developers, APIC, ULA, and Range Safety. This greatly improved with GEMSat, ULTRASat and GRACE but there is still improvement needed in this area.

Early Coordination with Range

The range is extremely busy with all the launches that happen on the east and west coast each year. This means early coordination with regard to MSPSPs and LV integration is important. This will allow time for questions and clarifications and will keep your program on schedule.

Central Location for All Documents

With all the players involved, to include CubeSat developers, APIC, ULA, and NRO, there are a lot of documents floating around and coordination needed. A central location for documents, that everyone involved with the AP has access to, is extremely helpful and keeps email inboxes from filling up.

After going through all the lessons learned and talking with the community on future needs the NRO started to work with ULA and Cal Poly on future improvements. These future improvements will be discussed next.

FUTURE ABC IMPROVEMENTS

The following future improvements are ones that are on contract and in work. These directly support CubeSat requirements on future missions.

6U Deployer Qualification

The NRO has begun work with Cal Poly and ULA on the qualification of two 6U Deployers for ABC environments. The plan is to run the Planetary Systems Corporation 6U Canisterized Satellite Dispenser and the Tyvak 6U Dispenser through a full flight qualification to ensure the NRO can launch CubeSats designed to either Dispenser system. This work is scheduled to be complete by the end of September 2015. This will open many opportunities for larger u-class payloads on the ABC than in the past.

Vibration Reduction

The User's Guide defines the current maximum vibration requirement, see figure 6, which is a very conservative predicted environment and when proto-qualification levels are 3dB and qualification levels are 6dB higher than this, there is a high probability of over-testing CubeSats. These testing levels have prevented CubeSats from riding on the ABC in the past. ULA has an analysis tool that they have been using to better predict the vibration environment for their new avionics boxes and the NRO asked ULA to do the same thing for the ABC location on the aft bulkhead of the Centaur. This work is ongoing and is planned to be complete with updated vibration requirements in the ICD by the end of 2015.

CONCLUSION

The ABC system is a proven technology with flight heritage and is extremely useful when putting small satellites on orbit aboard the Atlas V. The amazing collaboration between the NRO, STP, LR, NPS, Cal Poly, Tyvak, SRI and ranges on both coasts have been critical to the success of the ABC. The NRO continues to look for more missions to add this technology to and open up even more access to space.