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Demonstration of a New Smallsat Launch Vehicle: The Orbital/Suborbital Program (OSP) Space Launch Vehicle Inaugural Mission Results

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Abstract. The United States Air Force and Orbital Sciences Corporation (Orbital) completed development and demonstration of a new low cost space launch vehicle for launching small satellites using surplus Minuteman II rocket motors melded with commercial launch vehicle technology. The Orbital Suborbital Program Space Launch Vehicle (OSPSLV, aka OSP Minotaur) successfully achieved all mission objectives with the inaugural launch into a 405 nm circular, 100 deg inclination orbit on 26 January, 2000. This launch achieved "firsts" in several areas including being the first space launch utilizing Minuteman boosters. It was also the first launch from the California Spaceport (Spaceport Systems International Commercial Launch Facility) at Vandenberg AFB.

The OSP Minotaur accurately delivered a total of 11 satellites to orbit on its inaugural launch, involving complex maneuvering and multiple payload separations. Satellite sizes covered the range from minisatellite (JAWSAT Multiple Payload Adapter (MPA), 110 kg), microsatellite (USAFA's FalconSat, 50 kg, and OPAL, 20kg), nanosatellite (Arizona State University's ASUSat-1.5 kg), and picosatellites (ARPA/Aerospace, ARTEMIS, STENSAT, and MASAT, 0.5 kg each). ASUSat-1 was the first scientific nanosatellite and the picosats were the world's first active "pico" satellites. Additionally, an Optical Calibration Sphere was placed into orbit for the Air Force Research Laboratory (AFRL) Starfire Optical Range. The mission also demonstrated the Soft Ride for Small Satellites (SRSS) full-spacecraft isolation system developed by AFRL and CSA Engineering.

The OSP Minotaur is a four stage, ground launched solid propellant inertially guided spacelift vehicle. It is capable of putting up to 1400 lbm into LEO (100 nm, 28.5 deg) and over 700 lbm into a 400 nm, sun-synchronous orbit. The first two stages are from surplus Minuteman II ICBM's (M-55 and SR-19). They are combined with the upper two stages (Orion 50XL and Orion 38), structure, and fairing from Orbital's Pegasus XL air-launched space vehicle. However, new flight software, avionics, and telemetry components provide greater payload support capability relative to the Pegasus system.

Introduction

The path to the inaugural launch required creative thinking and coherent teamwork to achieve the ultimate goal of a successful demonstration launch. In the 28 months from contract award to launch, a new launch vehicle was designed, integrated, tested, and launched; a new spaceport launch site was completed and christened; and a demonstration payload was assembled after several configuration changes and a late start.

The launch vehicle developed under the Orbital Suborbital Program (OSP) awarded to Orbital Sciences Corporation (Orbital) in September 1997 by the Air Force. The goal of the OSP program is to develop and field suborbital and orbital Minuteman II derived launch vehicles in support of DoD activities. The program consists of two suborbital configurations, the capability to use Minuteman II stages to boost developmental upper stages into space for flight test, and an small spacelift vehicle, the successful demonstration of which is the primary focus of this paper. The Air Force contracted with Orbital Sciences

Corporation to integrate the surplus rocket motors with other system elements, integrate the launch vehicle with the payload and launch facilities, and execute the launch mission. This gives the Air Force flexibility to support a variety of sub-orbital missions as well as an efficient system to support small spacelift requirements.

The OSP Space Launch Vehicle (SLV), also known as OSP Minotaur, is a four stage, ground launched solid propellant inertially guided spacelift vehicle (Figure 1). It uses the first two stages from the Minuteman II ICBM combined with the upper two stages, structure, and fairing from the Pegasus XL air-launched space vehicle. The OSP Minotaur approach reduces the development and recurring launch costs by this utilization of the commercially developed, flight proven components and propulsion from the Pegasus vehicle. Moreover, adapting an austere site launch approach, including portable Ground Support Equipment (GSE) and the ability to launch from a stool over a flat pad or a duct, further reduces launch support costs.

Figure 1- Inaugural OSP Minotaur at SSI CLF

An additional significant challenge was met in the delivery of a viable payload. The candidate payload for the Demonstration mission of the OSP Minotaur underwent several configuration changes during the execution of the mission. The Air Force needed a payload to meet the primary launch requirement of demonstrating a satellite launcher capability by actually putting a satellite on orbit and wanted a satellite that supported important, but not critical, missions due to the inherent risks of a demonstration launch.

After the support the initial JAWSAT payload configuration was withdrawn 14 months prior to the planned launch date, a quest of a suitable payload configuration was undertaken. The final configuration for the Demonstration mission payload stabilized into a complex five-satellite and one experiment configuration. This payload configuration included the JAWSAT Multi Payload Adapter (MPA), FalconSat, Arizona State University Satellite (ASUSat), Stanford University's Orbiting Picosat Automated Launcher (OPAL) which carried six small pico satellites, the Air Force Research Laboratory (AFRL) Optical Calibration Spheres (OCS) balloon, and AFRL's Soft Ride for Small Satellites (SRSS) payload.

The initial launch – as well as the second – were designated to launch from the Spaceport Systems International (SSI) Commercial Launch Facility (CLF) on South Vandenberg AFB, CA near the mothballed west coast Space Shuttle launch complex (SLC-6). The Launch Control Room (LCR) and administrative support areas were actually located inside the SSI Integrated Processing Facility (IPF) which was originally built as the Shuttle Payload Processing Facility (PFF). The use of the SSI CLF allowed for the use of the existing flame duct constructed by SSI. SSI completed additional support structures and infrastructure, but an overhead gantry was not part of the baseline. This lack of a gantry structure required creative approaches for vehicle access and environmental control. In general, the vehicle needed to be accessible for pre-launch processing as well as being protected from the elements during that time. Moreover, the Minuteman motors must be maintained between 60-80 deg F since their original use kept them in an environmentally controlled silo. These requirements were addresses by a temporary, retractable scaffolding structure and an inflatable thermal blanket over the Minuteman boosters.

Vehicle Description

The JAWSAT mission was the first launch of the OSPSLV "Minotaur" vehicle. As such, it established the baseline for future modifications. . A photograph of the JAWSAT launch vehicle on the pad is shown in Figure 1.

The overall OSP Minotaur vehicle configuration is shown in Figure 2. It consists of two major subassemblies: 1) the Lower Stages Assembly (LSA) consisting of the Minuteman boosters and 2) the Upper Stages Assembly (USA) incorporating the Pegasus-derived front section and new interstage. The vehicle length is approximately 63 ft from Stage 1 nozzle exit planes to the top of the fairing. The launch weight of the OSP Minotaur is 80,100 lbm, not including the mass of the payload.

The Minotaur vehicle utilizes surplus Minuteman II M55A1 and SR19 solid rocket motors for Stages 1 and 2 respectively. These motors are refurbished by the USAF at Hill AFB and provided as GFE. Stages 3 and 4 consist of Orion 50XL and Orion 38 motors, respectively, manufacturer by Alliant TechSystems. These motors are virtually identical to the Pegasus XL Stage 2 and Stage 3 motors. The payload fairing utilized is the 50 in (OD) Pegasus design with some structural reinforcement to accommodate the loading differences between the Pegasus and OSPSLV applications. Although the overall integrated avionics system is a new configuration, the majority of the avionics components have previous flight history on Orbital's Pegasus, Taurus, or suborbital vehicles with no major changes for the OSP implementation. The same INS (Litton LN-100G), Flight computer (otto-reichler), and Reaction Control System (RCS), among other components, are common with Pegasus. Significant "first flight" items used on the JAWSAT mission were:

2/3 Interstage Structure. The interstage between the second and third stages was the only new structure required for the OSP Minotaur vehicle. It is the mechanical interface between the Minuteman boosters and the Orion 50XL. It is an aluminum monocoque structure and incorporates mounting for some electronics and a separation system.

Object Oriented Software. New flight computer software was implemented as a object oriented design, including new guidance and control algorithms. It allows easy evolution for new vehicle design and elements and features.

Additionally, several new avionics components were implemented:

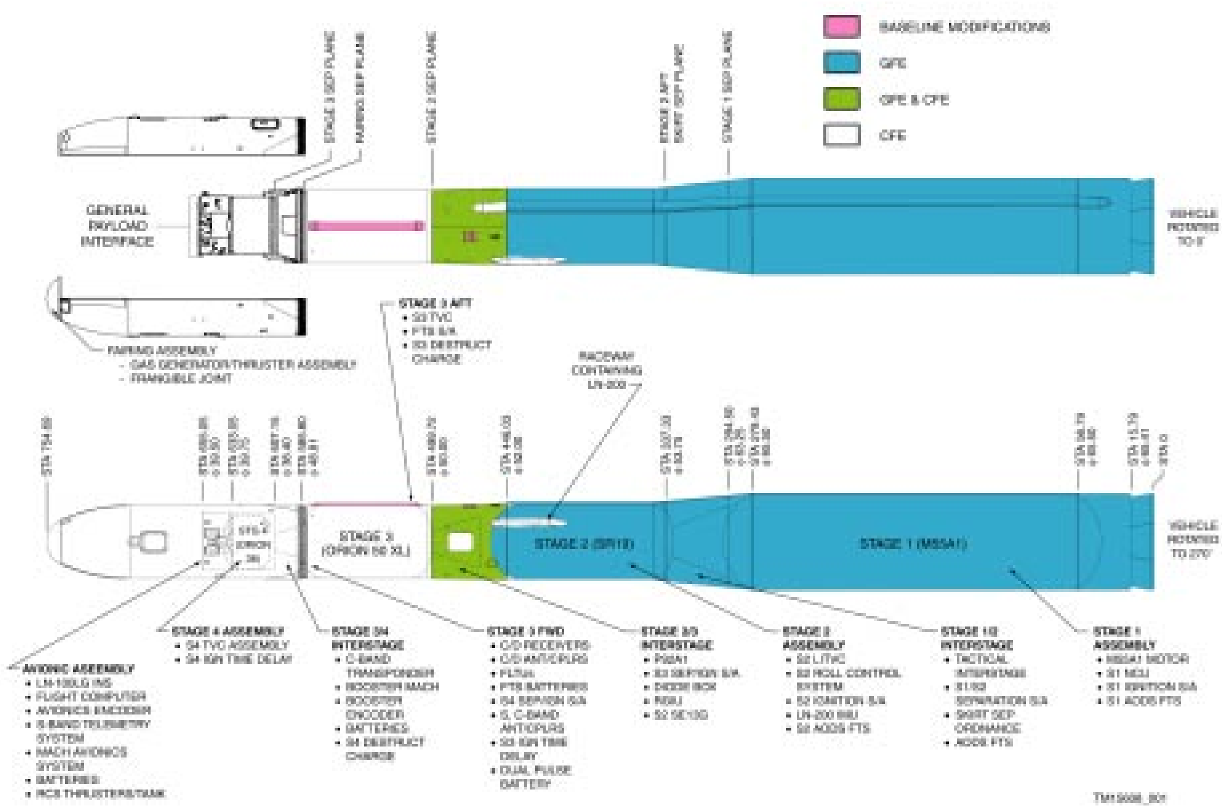


Figure 2 - OSP Minotaur Baseline Configuration

Diode Box. The diode box provides power routing and distribution for the downstage electrical components.

Dual Pulse Battery. Modification of an existing Orbital battery design (9300-1000) to provide two 14V ordnance batteries in a single housing.

Avionics/Remote Encoder. Implementation of a master/slave encoder system utilizing the L3 PCM600 encoder system.

The OSP contract is structured to provide a baseline vehicle configuration which can be augmented with enhanced options. For the JAWSAT, several enhanced options were implemented and demonstrated. These options consisted of:

Separation System. An option for a 23 inch separation system and adapter cone was exercised. This is one of the basic separation systems proven on Pegasus.

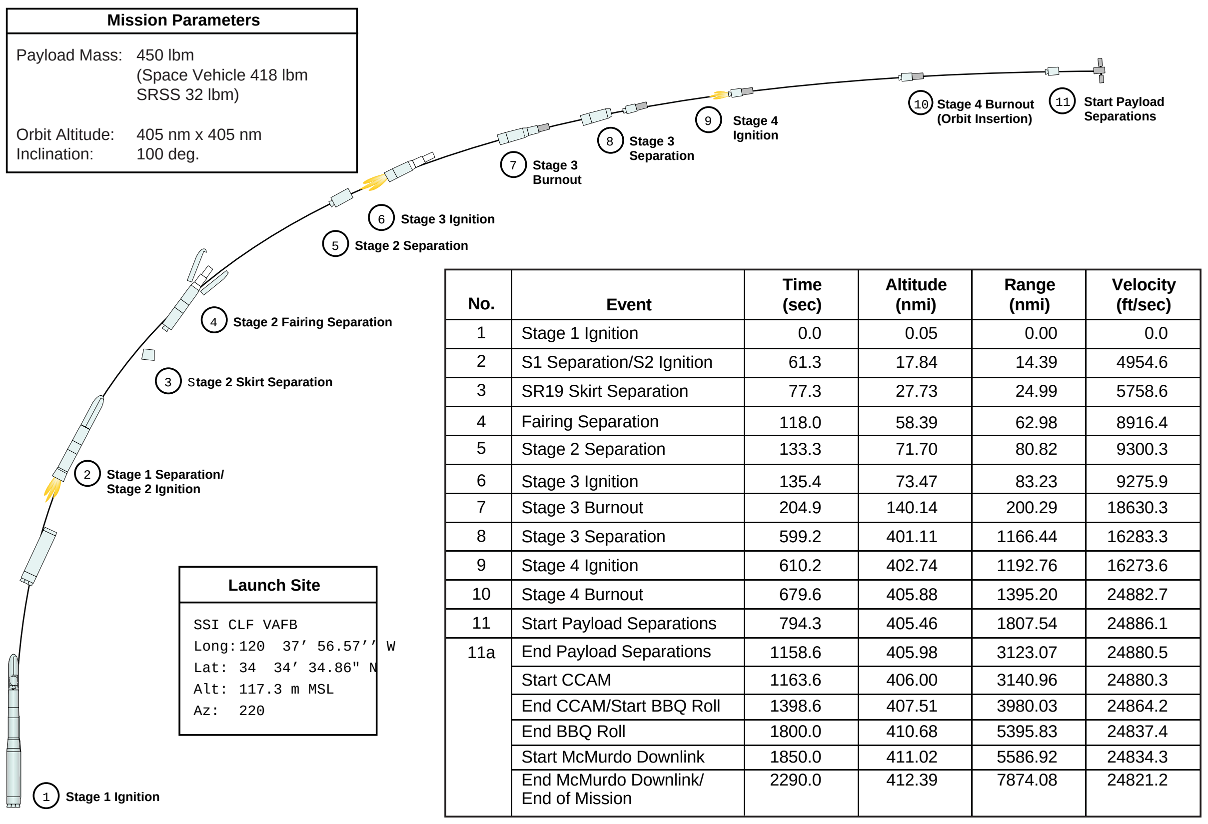
Softride System for Satellites (SRSS). A full-spacecraft isolation system was implemented between the avionics deck interface and the payload adapter cone. This was not an option under the launch vehicle contract. Instead, it was an isolation system developed and produced by CSA Engineering under contract to the Air Force Research Labs and provided as GFE to Orbital.

Enhanced Telemetry and Instrumentation. Added the capability to provide high bandwidth (2 Mbps) telemetry and instrumentation to characterize the performance of the SRSS.

GPS Position Beacon. An option was exercised to fly a GPS Position Beacon to demonstrate autonomous GPS tracking as a piggyback experiment. This option was added late in the program, after PDR and 13 months prior to the original launch date.

Additional Payload Access Panel. A option for a second payload access panel in the payload fairing was exercised for increased payload accesibility.

Most of the changes in the avionics from the Pegasus-baseline were made to provide greater payload accommodations, vehicle capability, and mission-to-mission flexibility required by the Air Force. For example, the baseline OSP Minotaur telemetry system is capable of up to 1.44 Mbps versus the 750 kbps system used on Pegasus. Additionally, for the JAWSAT mission, a separate telemetry link at 2.0



No.	Event	Time (sec)	Altitude (nmi)	Range (nmi)	Velocity (ft/sec)
1	Stage 1 Ignition	0.0	0.05	0.00	0.0
2	S1 Separation/S2 Ignition	61.3	17.84	14.39	4954.6
3	SR19 Skirt Separation	77.3	27.73	24.99	5758.6
4	Fairing Separation	118.0	58.39	62.98	8916.4
5	Stage 2 Separation	133.3	71.70	80.82	9300.3
6	Stage 3 Ignition	135.4	73.47	83.23	9275.9
7	Stage 3 Burnout	204.9	140.14	200.29	18630.3
8	Stage 3 Separation	599.2	401.11	1166.44	16283.3
9	Stage 4 Ignition	610.2	402.74	1192.76	16273.6
10	Stage 4 Burnout	679.6	405.88	1395.20	24882.7
11	Start Payload Separations	794.3	405.46	1807.54	24886.1
11a	End Payload Separations	1158.6	405.98	3123.07	24880.5
	Start CCAM	1163.6	406.00	3140.96	24880.3
	End CCAM/Start BBQ Roll	1398.6	407.51	3980.03	24864.2
	End BBQ Roll	1800.0	410.68	5395.83	24837.4
	Start McMurdo Downlink	1850.0	411.02	5586.92	24834.3
	End McMurdo Downlink/ End of Mission	2290.0	412.39	7874.08	24821.2

Figure 3 - JAWSAT Launch Scenario (Nominal)

Mbps was incorporated, utilizing a dedicated frequency, instrumentation, encoder, and transmitter to provided extensive data on the performance of the SRSS. No major changes to the baseline Demonstration mission design were required for future mission. The most significant improvement that has been implemented for follow-on missions is a larger raceway cover on Stage 3 (see Figure 2) to allow adequate cabling space to meet future payload pass-through requirements and downstage telemetry support.

Vehicle Performance

The launch vehicle performed very well for the JAWSAT mission, particularly given that it was a first launch. The JAWSAT payloads were successfully delivered to the desired orbit with no mission-critical anomalies. Orbit insertion values were within requirements, measured environmental levels matched-up favorably with preflight predictions, and overall vehicle performance was as expected. Unfortunately, telemetry transmission was lost at Stage 3 separation, so no useable telemetry was received during Stage 4. Very limited data was extracted from stored telemetry that was downlinked to the McMurdo ground station, but it was enough to indicate that the payloads had separated successfully and the Stage 4 appeared to operating nominal in the post-boost phase.

Mission Scenario

The nominal Launch Vehicle mission scenario is shown in Figure 3. The mission proceeded nominally through the Stage 3 coast period. All observed event timing was within pre-launch constraints. A delta of approximately 2.5 seconds early occurs relative to Stage 3 ignition and events thereafter. This was attributed to a faster than nominal burn of the Stage 2 SR19 motor. Similarly, a delta of about 14.5 seconds is observed relative to Stage 4 ignition. This a result of the real-time computation of Stage 4 ignition time and the higher than predicted performance of the Stage 3 motor. Continuous telemetry reception was lost coincident with the Stage 3 separation event. As such, detailed data on the Stage 4 burn or actual timing data for payload separation events are not available. However, the vehicle achieved the proper orbit and all payloads were separated and subsequently have indicated healthy status at one point or another. Additionally, all separation monitors showed nominal separation from limited data that was extracted from stored data downlinked to the McMurdo Ground Station (MGS). All evidence indicates the post-LOS mission events were executed as planned. The measured timing deltas from the JAWSAT mission appear nominal and are within the expected bounds given JAWSAT motor performance.

Table 1 - JAWSAT Separation Sequence

	Event/Maneuver	Time After S4 Burnout (sec)	Comment
1	Activate JAWSAT Imaging System	15.0	
2	Orient for ASUSat Separation	45.0	ASUSat sep vector along zenith; 11.9 lbm at 1.5 ft/s
3	Switch to Camera	58.0	
4	Start Payload Sep Sequence	60.0	Nose pointing along nominal yaw angle at Stage 4 burnout
5	Initiate ASUSat gravity gradient boom deployment	60.0	
6	Separate ASUSat	85.0	
7	Hold Attitude	85.0	
8	Switch to Camera 2	113.0	
9	Separate Opal	115.0	Note: OPAL had no attitude requirement; 41.8 lbm at 0.6 ft/s
10	Hold Attitude	125.0	
11	Reorient for OCS Sep	125.0	
12	Switch to Camera 3	143.0	
13	Separate OCS	145.0	Note: OCS had no attitude requirement; 39.6 lbm at 1.0 ft/s
14	Hold Attitude	145.0	Maintain Pointing to Image OCS Separation and Inflation
15	Reorient for FalconSat Separation	235.0	
16	Arm FalconSat Firing Box	260.25	
17	Switch to Camera 4	268.25	
18	Spin-up to >0.5 rpm (Nominal)	270.00	
19	Separate FalconSat - Pri	270.25	Sep along +x-axis; 99 lbm at 2 ft/s
20	Separate FalconSat - Sec	270.25	
21	De-Spin/Hold Attitude	272.50	
22	Orient in Pitch for JAWSAT Sep	282.50	Open loop command to nominally orient sep axis towards nadir
23	Orient in Roll for JAWSAT Sep	405.00	Open loop command to nominally orient tip off axis along velocity vector
24	Switch to Camera 5	443.00	
25	Send JAWSAT Turn-ON Signal	444.00	
26	Separate JAWSAT MPA	445.00	218 lbm at 2.7 ft/s
27	Separate JAWSAT MPA	445.10	
28	Hold Attitude	445.00	
29	End Separation Sequence	455.00	

The Stage 4 bus performed a complicated series of maneuvers to separate the five distinct payloads in a manner to mitigate recontact concerns, as well as command switching of an imaging system onboard the JAWSAT MPA. The overall timeline of post-boost, payload separation events is shown in Table 1, relative to Stage 4 burn-out.

Orbital Insertion.

As shown in Table 2, the orbital altitude insertion parameters were well within the required limits. Inclination was at the limit of the ±0.2 deg accuracy. This was traced to greater than expected heading alignment error in the INS, as well as effects of the guidance algorithm in response to quick burning motors, roughly in equal parts. Improvements in both areas have been implemented for future missions to improve the accuracy of the delivered inclination.

Table 2 - JAWSAT Orbital Parameters

	Required	Pre-Flight (3-sigma)	INS (LN-100)	Actual* (NORAD)
Apogee	405±50 nm	405.5±0.7 nm (3-sigma)	406nm (+1 nm)	405 nm (+1 nm)
Perigee	405±50nm	406.3±44.2 nm	431nm (+26 nm)	435 nm (+30 nm)
Inclin-ation	100°± 0.2°	100°± 0.16°	100.1° (+0.1°)	100.2° (+0.2°)

* Mean data for all five separated objects from NASA GSFC Orbital Information Group, Satellite Situation Report, 31 Jan 00.

The OSP Minotaur launch vehicle had the performance capability to launch approximately 870 lbm to the JAWSAT orbit. Since the mass allocated to payload elements was about 480 lbm, there was 390 lbm of performance to be depleted. This was largely done by flying on a more westerly azimuth than would be done for a direct ascent into the 100 deg inclination orbit and then turning south during the burns of Stages 2 through 4, thereby scrubbing the excess energy. The resulting groundtrack can be seen in Figure 3. The altitude versus time history in shown in Figure 4.

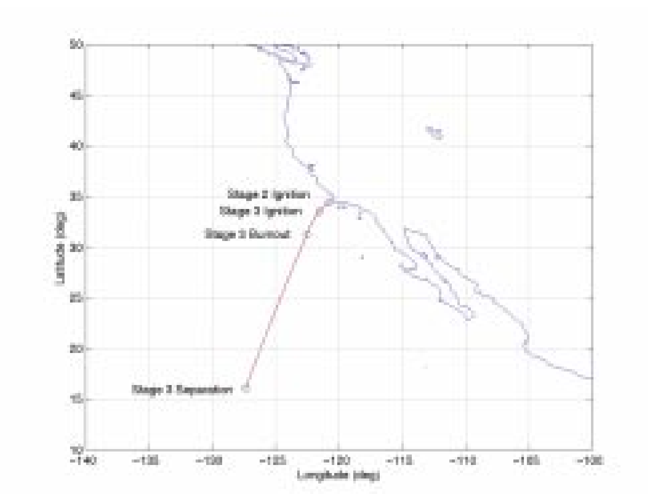


Figure 4 - Boost Phase Ground Track

Launch Environments

Overall, the measured launch environments matched up well with the prelaunch predictions. The loss of telemetry at Stage 3 separation resulted in no environmental data during Stage 4. However, since most peak levels were expected prior to that time minimal data was lost relative to verifying environments. Given the mission objective of demonstrating a new launch vehicle capability, particular emphasis was given to validating payload environments. That focus will be continued here at the expense of any additional discussion of overall launch vehicle environments. In general, there were no significant surprises in any of the environmental measurements.

The Launch Vehicle was well instrumented with 30 accelerometers and 1 microphone for dynamic measurements. Of the 30 accelerometers, 18 were placed to measure the performance of the Soft Ride System for Satellites (SRSS). Three sets of triaxial accelerometers were place above and below the SRSS interface. The 12 remaining accelerometers and the microphone were placed to measure vehicle responses.

In particular, the payload environments were shown to be within “spec” values. Given the first launch nature of the mission and the experimental status of the SRSS, a conservative approach was taken to defining payload design requirements (as documented in the JAWSAT-to-Launch Vehicle ICD). Shock, vibration, and acceleration environments were defined at the 38-in. avionics deck interface, below the SRSS, adapter cone, and separation system. The payloads were given these “hard mount” environments for design and test levels. The attenuation of the SRSS, plus the PAF and

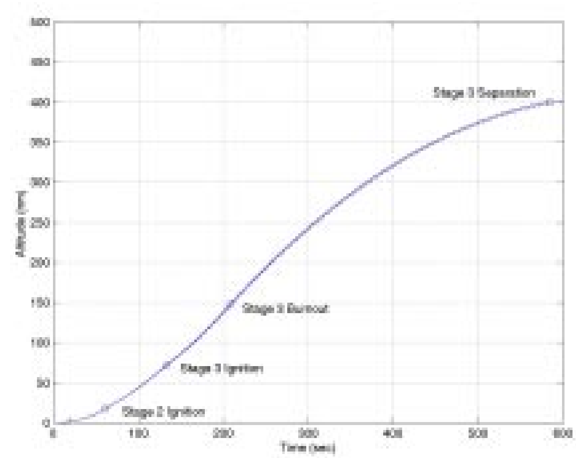


Figure 5 – Boost Phase Ascent Time History

separation system interface, was reserved as margin.

Accelerometer data indicated the vibration environments were within the predicted levels. Figures 6 and 7 shown the vibration levels for liftoff and powered flight. These levels were specified separately for liftoff and flight due to the significant difference in exposure time. Liftoff is a very short duration environment whereas the flight environment exists for a longer time.

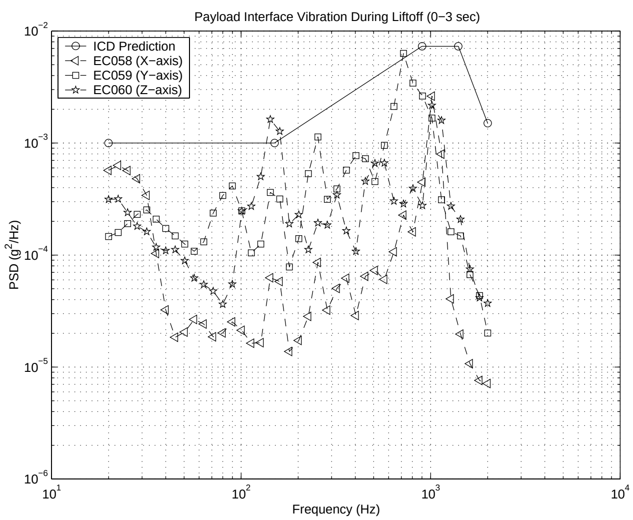


Figure 6 - Non-Isolated Payload Vibration Environment – Launch

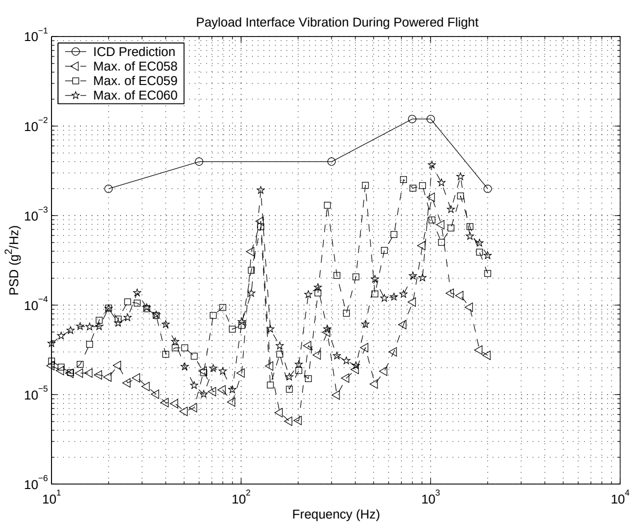


Figure 7 - Non-Isolated Payload Vibration Environment – Flight

One exception to added margin from the SRSS is the payload separation shock. These levels are driven by the separation system bolt cutters that are, by design, forward of the SRSS and adapter cone. However, because the other payloads were separated prior to the activation of the 23-in. separation system, only the JAWSAT MPA was exposed to this shock. For the other payloads, the Stage 3 separation event drove the shock levels, which were mitigated by the SRSS. However, measurement of shock levels was not attempted due to the bandwidth required and the ability to accurately measure them in test. Therefore, since the specified levels were well defined from ground-based testing there is high confidence in their accuracy.

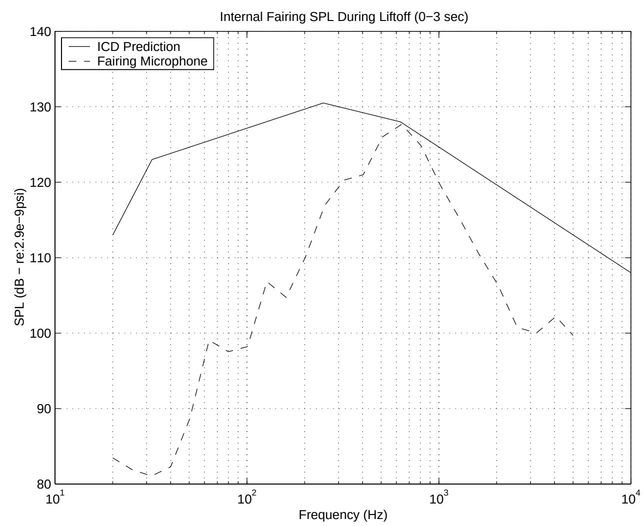


Figure 8 - Payload Acoustic Environment – Launch

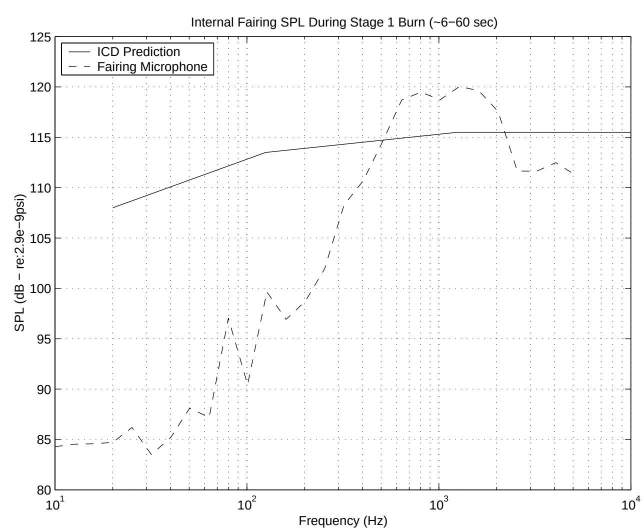


Figure 9 - Payload Acoustic Environment – Flight

Acoustic levels inside the fairing were measured with a microphone mounted within the fairing volume, approximately at the avionics deck payload interface.

As with the vibration data, levels were specified separately for launch and powered flight. These are shown in Figures 8 and 9. Only Stage 1 burn is shown in Figure 9 because the acoustic levels are insignificant after the Stage 1 separation. Notice that the liftoff prediction envelops the measured liftoff level, as well as the measured flight level. The flight prediction does not fully cover the measured flight level, with a minor exceedance centered around 1000 Hz. The reason for this exceedance has not been identified or verified. However, it is not considered to be of concern due to the bracketing of the levels by the launch environment and the relative insensitivity to acoustic environments by most payloads.

JAWSAT Payload

The candidate payload for the Demonstration mission of the OSP Minotaur underwent several configuration changes during the execution of the mission. The Air Force needed a payload to meet the primary launch requirement of demonstrating a satellite launcher capability by actually putting a satellite on orbit and wanted a satellite that supported important, but not critical, missions due to the inherent risks of a demonstration launch.

The initial direction was to launch a United States Air Force Academy cadet-built payload that would provide valuable experience in the design and construction of space systems as well as provide a "training aid" on orbit to support the development of new Air Force satellite operators. The Air Force Academy originated a joint program with Weber State University to build the Joint Academy Weber State Satellite (JAWSAT). This satellite was intended to be fully-capable including attitude control, full experiment support, and full communications capability and was to be a joint effort between the students at Weber State University and Air Force Academy cadets. The intent was to launch just the JAWSAT payload on the first Minuteman II-derived space launch. The Air Force Academy decided to produce their satellite in-house about a year before the OSP contract was let. This new satellite was called FalconSat and was to be an independent effort by the Academy.

During the summer of 1997, the Air Force Launch Test Program was actively developing the payload suite for the Demonstration launch as required prior to going on contract. The Launch Test Program, the Demonstration launch customer, had direction to launch the JAWSAT payload as well as support the Academy satellite program. The obvious solution was to launch the JAWSAT and FalconSat payloads as a dual-payload configuration. The Air Force decided to use the JAWSAT spacecraft to support three Space Test Program (STP) experiments. This plan was facilitated by the fact that the JAWSAT design allowed it to serve as a support structure for the FalconSat payload. This meant that the payload integration process for the combined JAWSAT/FalconSat payload stack would be essentially the same as that for a single payload.

The combined JAWSAT/FalconSat payload configuration was the payload that went on contract initially and remained the mission payload for about one year (about one-half of the two-year period of performance for the launch mission). However, Space Test Program officials elected to withdraw the STP JAWSAT from the mission.

The launch vehicle team immediately started a search for a new payload to fly with FalconSat. They settled on a continuation of the STP JAWSAT concept by converting the JAWSAT into a Multi-Payload Adapter (MPA) intended to carry other small payloads in addition to the FalconSat. This configuration for JAWSAT stabilized into the final integrated payload shown in Fig 9. The launch vehicle team took over the contractual and requirements process for the JAWSAT and started a process to populate the MPA with other appropriate mission payloads.

Figure 9 - Fully Integrated JAWSAT MPA

The Demonstration mission payload became a complex five-satellite and one experiment configuration (see Figure. 9). This payload configuration included the JAWSAT Multi Payload Adapter (MPA), FalconSat, Arizona State University Satellite (ASUSat), Stanford University's Orbiting Picosat Automated Launcher (OPAL) which carried six small pico satellites, the Air Force Research Laboratory (AFRL) Optical Calibration Spheres (OCS) balloon, and AFRL's Soft Ride for Small Satellites (SRSS) payload. Table 3 outlines the various characteristics of the Demonstration mission payload stack.

Table 3 - JAWSAT Payload Characteristics

Payload	Description	Size (cm)	Mass (kg)	Mission
JAWSAT	Multi-Payload Adapter and Satellite	89 long 89 wide 107 tall	191	Secondary payload adapter and small satellite
FalconSat	Satellite	43 long 43 wide 43 tall	50	Cadet Training, Space Weather Experiment
OCS	Balloon	360 diameter	22.7	Optical Calibration
OPAL	Satellite	21 diameter 23.5 tall	25.5	Picosat deployment and Support
ASUSat	Satellite	32 diameter 24.5 tall	5.9	Demonstrate Minimum Mass Satellite
SRSS	Payload Isolation System	96.5 diameter	18.2	Demonstrate protection of payloads from launch vehicle loads

The final configuration of the Demonstration mission payload suite was determined about 14 months from the planned launch date and involved five satellites, one major experiment and fourteen separate design/manufacturing/management teams. The team structure is spelled out in Figure 10. It is obvious from the team diagram that the major challenge to ensuring that the Demonstration mission payload would be ready in time was getting all of the diverse independent teams to effectively work together to accomplish everything necessary on time.

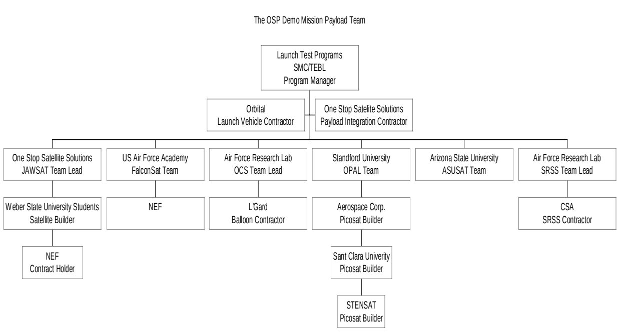


Figure 11 - JAWSAT Payload Organization

The Air Force elected to follow an authoritative approach to managing this integration effort. This approach was required due to the short timeline which left no room for the test delays, etc. that plague most payload schedules. The Air Force's management philosophy was to focus on the purpose of the launch, which was to "demonstrate that the OSP launch vehicle was viable by actually launching a satellite" while allowing the payload customers to take advantage of the launch opportunity. This approach was enabled by the fact that the payloads were simple and the customers were highly motivated by an opportunity to finally fly after years of searching for a ride to orbit.

All of the customers were also motivated by the opportunity to take advantage of the fact that the Launch Test Program had essentially paid for the launch effort and each was required to pay only the delta costs of adding their payload to the stack. This cost was typically under $50,000 for a ride opportunity worth at least $1 million.

The Air Force Payload Manager took three immediate steps to execute this integration program. The first was to enlist the Weber State University Center for Aerospace Technology (CAST) team and the spin-off commercial One Stop Satellite Solutions (OSSS) team as the integrating contractor for all payloads. This choice was the obvious one since the OSSS team was developing the JAWSAT MPA. The integrating contractor was made responsible for all aspects of payload integration including schedule, test processes, and launch campaign integration.

The second action that the Payload Manager took was to require that each payload deliver a mass model as their first delivery. This mass model was required to exactly match the payload mass properties when it was finally delivered. Failure to deliver a satellite that replicated the mass model would result in the mass model being flown in lieu of the payload. This rather draconian requirement was driven by the fact that the short timeline required that the team build a satellite that met planned mass characteristics since all integration testing needed to follow a parallel process rather than the normal serial process. The team followed this "define the payload integration factors then build a payload to meet those factors" approach throughout the payload development and integration effort. This integration plan was the only thing that allowed the building, testing, and integration of five satellites and one payload in the 14 months available to support the mission.

The final requirement levied on the payload customer by the Payload Manager was a delivery date for all payloads approximately four months prior to the planned launch date. The Payload Manager started an integration process which included empowering OSSS to work all details with the various payload teams, gathered all the payload customers at Payload Integration Working Groups (PIWGS) which were held monthly, and included weekly telephone conferences to work immediate issues.

The various payload teams responded well to this close control and served as active team members throughout the demanding process that led to the final integrated payload stack. The following lessons learned should prove helpful to others attempting to accomplish a similar payload integration task:

1. **Unity of Command**: Recognize that any complex teams with multiple objectives will sometimes encounter conflict. Place one person in command of all efforts that involve multiple payload teams. This Payload Manager should have complete authority to make final decisions that effect the integration effort but should serve as the arbiter or referee to drive solutions only after the integration team has failed to identify and execute a viable solution to the problem. Decisions should be based on an "everyone will fly" basis but the Payload Manager should be prepared to make the tough decision to not fly a customer if necessary.

2. **Build the integration team**: The job is too difficult for one person: The scope of any multi-satellite integration task is too great for one person to grasp and/or execute. Support the Payload Manager by an appropriately staffed agency or contractor, responsible for all day-to-day integration activities. This team should have the ability to identify issues and solve them in a way that keeps all payload teams satisfied that they are getting their requirements met. The establishment of a viable integration team is crucial for success.

3. **Be up-front**: Tell the various payload customers exactly what will be required before they sign up for the effort and ensure the Payload Manager sticks to the plan. Ensure that each payload team accepts the proposed plan before they are accepting as a launch candidate. Failure to establish a team that is composed only of motivated members is a guarantee of failure.

4. **"Cooperate and Graduate**": There is no room for payload teams that think only of their satellite requirements. Success comes with a "total mission" perspective. Ensure each satellite team is aware of the other satellite team's requirements and is committed to meeting them. Foster an environment where each payload teams sees all problems as "their problem" even if it doesn't directly involve their payload. Help each other as necessary.

5. **Communicate**: Communication between all team members is crucial to identifying and fixing all issues during the integration process. Meet face-to-face regularly. Foster discussion that synergistically surfaces issues. Fix those issues as a team concerned about "total mission success". Talk until you are tired of talking…then talk some more.

Launch Site Integration and Operations

In addition to developing a new launch vehicle and rapidly assembling a multifaceted payload, there was also the challenge of proving out field processing procedures and commissioning a new launch facility.

After testing and integration of the avionics and subassemblies at Orbital's chandler facility, they were shipped to Orbital's Vehicle Assembly Facility (VAB) at Vandenberg AFB where the Pegasus vehicle is assembled. The Minotaur vehicle underwent integration processing similar to Pegasus, albeit with revisions and increased scrutiny warranted by the first mission status. At the VAB, the avionics assembly, fairing, and interstage were integrated with the Orion 50XL and Orion 38 motors and, ultimately, the payload. The result of this integration is the Upper Stack Assembly (USA).

In parallel, the Minuteman boosters were thoroughly inspected and refurbished at Hill AFB, UT and shipped to Vandenberg AFB. At Vandenberg, they underwent processing similar to that applied to boosters prepared for Minuteman flight-testing. This includes system checkout and integration of the All Ordnance Destruct System (AODS) which is required by Range Safety to allow the commanded destruction of the vehicle if the flight goes awry. Additionally, a rate gyro was installed on the Stage 2 booster to provide more robust control of the vehicle to increase the ability to withstand upper level winds, thereby improving launch availability. This integration produces the Lower Stack Assembly (LSA). These two assemblies are ultimately mated at the launch pad, which discussed in further detail below.

Payload Integration

The JAWSAT payload was integrated to the launch vehicle in the same horizontal manner as all Pegasus payloads. The satellite was first mated to the 23 in. Payload Attachment Fitting (PAF) vertically by a crane operation as shown in Figure 12. This assembly was then “broken over” to a horizontal orientation using a two-crane operation. A three-point lifting fixture then supported the satellite horizontally to position it for attachment to the avionics assembly on Stage 4. This is shown in Figure 13.

Figure 12 - JAWSAT-to-PAF Integration

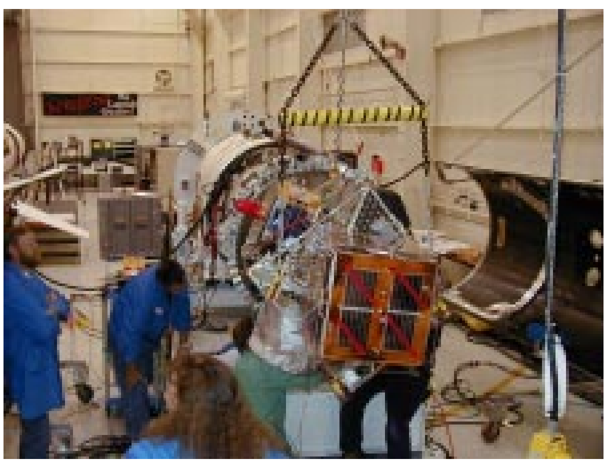


Figure 13 - Mating JAWSAT to Minotaur

Also integrated, as part of the payload mating process was the Softride System for Small Satellites (SRSS). The SRSS was designed by CSA engineering, having a proprietary isolator unit at each of the 58 boltholes of the avionics deck-to-PAF attachment. This can be seen in Figure 12 prior to attachment to the avionics deck and in Figure 14 following final integration. The SRSS substantially reduces dynamic transmission of vibration and loads on the payload. In particular, the SRSS developed for Minotaur helps to mitigate loads imparted by an acceleration impulse that is sometimes imparted at the ignition of the Stage 2 (SR-19 motor).

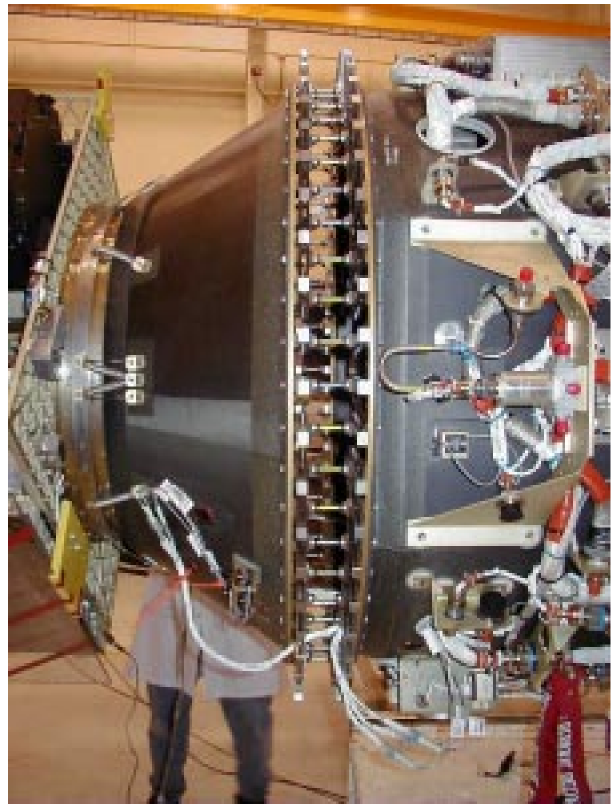


Figure 2 - SRSS Full-Spacecraft Isolation System Integrated

After payload installation, the fairing was integrated. Integration of the fairing was done using procedures nearly identical to Pegasus. Once the clamshell was closed, the separation bands were tensioned using computer-aided methods to ensure proper retention and separation during flight. The JAWSAT payloads were inert following encapsulation with no electrical interfaces passing through the launch vehicle. The next test of the satellites would be in LEO.

Stacking Operations

The LSA is nominally emplaced on the launch stand approximately two weeks prior to the emplacement of the USA. Using the Rocket Systems Launch Programs (RSLP) modified Transporter/Erector (TE), the LSA was emplaced over the exhaust duct (Figure 14). The RSLP TE was modified to allow extraction the rocket motors out of the top of the erected TE with an overhead crane or a mobile crane, whereas the standard MM TE is used to lower entire Minuteman ICBMs into silos through the rear doors.

For the JAWSAT Mission, the LSA and USA were emplaced with no major problems. A large contributor to this success was due to a Pathfinder emplacement, using inert boosters, conducted several months prior to the actual emplacement. Moreover, the USA had to be destacked and emplaced a second time, again with no problems, due to the need to replace a C-band tracking transponder that failed during pre-mission testing. As a result, the vehicle stacking operations were well proven during the JAWSAT operations that should pay dividends for future mission operations.

Figure 14 - Lower Stack Assembly Emplacement

Environmental Protection and Access System

Due to lack of a permanent gantry structure at the new SSI CLF, a temporary method of access to the vehicle after stacking and environmental control was required. Although the exposed Orion 50XL booster in the Upper Stack was designed for adverse weather conditions (i.e. air launch at 38,000 ft), the Minuteman boosters in the Lower Stack were designed to be launch from a climate controlled silo with virtually no outside weather effects until launch. Therefore, continuous temperature control was required. Moreover, since typical weather conditions at Vandenberg AFB can be harsh to both personnel and equipment, a system to protect the erected Launch Vehicle and mission personnel was necessary.

The access system was designed using simple commercial scaffolding (Figure 15). Levels for the scaffolding were placed along the rocket at key points, such as at 2/3 interstage and at fairing access panel. For the JAWSAT mission, there were six access levels. One of the keys to the design of the access system is the levels can easily be changed if requirements dictate. Also because it is built on rails, the access system can be rolled away from the rocket for launch operations using a tug vehicle. For JAWSAT operations, a commercial Caterpillar farming tractor was used to move the access system. However, any vehicle capable of overcoming the maximum wind loads on the scaffolding could be employed.

Figure 15 - Environmental Protection and Access System with Tug

To protect personnel from wind and rain during operations, the inner part of the access system was enclosed with a plastic covering or “scrim”. The material used is also used for protecting aircraft during ground transport and storage. The covering was installed by unrolling it onto the scaffold and then using a heat gun, it was melted to itself to provide a good seal. While it is not a perfectly sealed environment, it did keep personnel comfortable during operations. This plastic protective cover used to enclose the rocket work areas was the second attempt to solve the problem of protecting personnel. The first attempt used a material that was not as tightly secured. As a result, the high winds at the launch site destroyed the material and could have been a danger to personnel and equipment. While the sides of the revised protective cover for the work area worked well, the team never found an adequate workable cover for the roof. Fortunately, the launch pad encountered very few days where rain was a problem. An alternate approach to a roof is being tested on the second Minotaur mission.

Although the scrim was adequate to keep the wind and rain off of personnel and launch vehicle, it was apparent that during typical weather at the launch site the tight booster temperature constraints could easily be broken. It was decided that whatever system was used it had to be quickly removable - to ensure the availability of the full launch window - and quickly replaced - in case of launch abort. After trading off various options, the approach finally implemented was an inflated, insulated thermal blanket. The blanket can be seen in Figure 16 as the yellow cover over the lower portion of the Launch Vehicle.

The blanket is comprised of four 50-lb pieces that are joined length-wise together with Velcro that was thoroughly coated with staticide. To put the four pieces on the rocket, each piece was pulled up the rocket using a pulley system inside the scaffold. Once in place, the

Figure 16 - Minotaur with Thermal Blanket and Retracted Scaffold

Velcro strips are rolled down the rocket and secured. Each piece of the blanket has two bladders. One bladder is inflated so the blanket remained firm against the rocket and allowed free airflow for the second bladder. Conditioned air is pumped inside the second bladder to maintain adequate constrains on the rocket.

Two methods were devised for launch operations removal. If the final weather forecast, call for good weather during the launch window, at T-10 min the thermal cover is removed by pulling off the Velcro strips and allowing the cover to fall. It is then collected and stowed for future launches. However, if the weather forecast call for adverse weather, the thermal cover is rigged at T-10 min to fall away at lift-off. Rigging is the least desirable because the asset could not be saved for future flights and the rigging hardware could impact the launch vehicle during initial accent. A remotely controlled release approach has been conceived but not yet implemented or tested.

Spaceport Facilities and Launch Support

The JAWSAT mission was the first launch from Spaceport Systems International's (SSI's) Commercial Launch Facility (CLF). The spaceport, intended to ultimately be capable of supporting several different launch vehicles, is located just south of Space Launch Complex-6 (SLC-6) on Vandenberg AFB. A launch duct previously constructed by SSI was used for the Minotaur launch. Additional infrastructure, including equipment buildings, electrical and fiber optic cabling, paving, and support for the retractable scaffolding and RSLP TE was completed to support the JAWSAT mission. The launch site is shown in Figure 17 during stacking operations for the Upper Stack.

The Launch Control Room (LCR) was located inside the SSI Integrated Processing Facility (IPF) originally built to the processing of Space Shuttle payloads for West Coast launches. The mission team operated the launch vehicle via fiber and copper lines from the LCR to the Support Equipment Building (SEB). Approximately 150 ft from the launch pad, the SEB is where the vehicle interface consoles that directly controlled the launch vehicle were located. It can be seen at the left of top center in Figure 17. Also in close proximity to the launch pad is the Launch Equipment Vault (LEV) (small building adjacent to the flame duct in Figure 17). Less than 65 ft from the centerline of the vehicle, the LEV primarily protected the Ground Support Equipment (GSE) near the pad from dangerous launch environments.

Figure 17 - Spaceport Systems International Commercial Launch Facility

The Vandenberg AFB 30th Space Wing Western Range (WR) operated for this launch in a similar capacity as previous launches. WR provided safety oversight, security, space operations expertise, and range coordination in addition to providing facilities and pre-launch test and launch day support. Close Range coordination was essential for this mission due to the new vehicle nature and Strategic Arms Reduction Treaty requirements to record all ICBM telemetry. To record the delayed transmission of stored telemetry data, NASA's McMurdo Ground Station (MGS) on Antarctica was also part of the launch operations.

Launch Operations

Finally, in early January 2000, after many years of work, launch of the Minotaur was imminent. After failing to get to launch day in December due to the transponder failure, the team began the final launch countdown on 14 January. The countdown, however, was filled with a multitude of anomalies involving Range assets, the Launch Vehicle, and other support elements. Some of the problems encountered during the countdown included, failure of primary range assets, commercially operated trains operating in the hazard zone, and injuries on off-coast oilrigs. The Range personnel – who have participated in many launch operations - were amazed at the number of issues that arose and were successfully dealt with. And although the launch team was able to overcome all of these issues, at T-2min the flight computer auto-sequencer failed to begin its internal countdown and the mission was aborted. After due consideration, the launch team decided recycle and try again that evening. On second attempt, it was decided to manually initiate the flight computer to circumvent the auto-sequencer issue. However, the second launch attempt was ultimately aborted, also at near T-2min, when avionics battery voltages dropped below limits. When the decision to recycle was made, battery margins had been calculated indicating there was just enough margins to sustain the second attempt. However, the calculations had not accounted for reduced capacity of the NiCad battery packs because they hadn't been deep cycled for several recharge cycles.

One of the determining factors leading to the recycle decision was the fact that the Minuteman Premature Stage Separation (PSS) system batteries had already been activated during the first attempt. The PSS batteries are initiated at T- 6min and once initiated are useable for only three hours. Due to Lot Acceptance issues with the manufacturer, PSS batteries have been in very short supply for all Minuteman applications. In order to acquire a replacement set, the OSP program negotiated to take the batteries from an upcoming Minuteman mission. Once the new PSS batteries were installed, the team moved back to launch operations.

Figure 18 – Inaugural Launch of the OSP Minotaur

For the second launch attempt, it was decided again to use the manual initialization of the flight computer for the launch attempt because it was not possible absolutely exonerate all possible causes of the auto-sequencer failure. Also, prior to this launch attempt, the avionics batteries were deep-cycled. On this attempt, no major issues were encountered during the countdown. At 26 January 2000, 1903 PST, the Minotaur, the first space launch vehicle to use Minuteman ICBM rocket motors, successfully lifted-off and approximately 19 minutes later, all payloads were successfully released into the proper orbit. The Stage 4 burn and the near twilight launch produced a dramatic, comet-like effect that was visible from Southern California, as captured by amateur astronomer Brian Webb in Figure 19. The launch was also reported visible as far away as Phoenix, AZ. Approximately, 38 minutes into the mission the Stage 4 ceased transmitting telemetry to McMurdo, as planned, as completed the first Minotaur mission.

Photo by Brian Webb

Figure 19 – JAWSAT Stage 4 Burn from Thousand Oaks, CA

Future Missions and Opportunities

The successful launch of JAWSAT demonstrated a new small launch vehicle for the US Air Force. Proving this system has allowed the Air Force to fill a gap in small launch vehicle availability created by the expiration of the Pegasus and Taurus Air Force contracts. There are several hundred Minuteman II motor sets in storage and available for future Minotaur missions. The Office of the Secretary of the Defense (OSD) has currently given the Air Force permission to use five of these sets for space launch – two of which have been used (JAWSAT and MightySat II.1). There are also two other missions in the planning stages. Now that the Minotaur has been proven a viable system, it is anticipated that additional motor sets will be released for space launch missions.

The JAWSAT launch also demonstrated the capability available to launch multiple payloads on one vehicle. This allows several small payloads to come together to split the cost of the ride to orbit – a concept that is being pursued for future Minotaur missions. An, as demonstrated on the MightySat mission, single payloads can also be readily accommodate. The "baseline-plus-options" structure to the contract allows payload customers to tailor the mission to their needs, from basic to complex.

One critical criteria necessary to contracting for a Minotaur is having US government sponsorship. Before, each launch, the OSD must specifically approve the use of these assets. This approval is worked in parallel to the launch services contract. Working with the Air Force, the customer prepares a Mission Requirements Document (MRD), which spells out the specifics technical requirements for their mission. The Rocket Systems Launch Program (RSLP) provides the MRD to Orbital who responds with a NTE cost for the vehicle. RSLP will then roll this cost into the total cost of the launch service, including other line items such as technical support from TRW, spaceport/launch site services, and Minuteman booster refurbishment. After the option on the contract is exercised, Orbital executes the mission on an 18-month schedule.

The OSP contract allows for launch from any of four commercial spaceports: California, Florida, Alaska, and Virginia. Additionally, launches can occur from government facilities at Vandenberg AFB or Kennedy Space Center. Depending on the orbital requirements and other customer requirements, the spaceport contract will be awarded through a task order selection process within six months of the option award to Orbital.

For further information on mission availability and launch services, contact the Air Force at:

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3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776
(505) 846-8957 FAX: (505) 846-1349

For additional information specifically on Minotaur launch vehicle capabilities and technical details, contact Orbital Sciences at:

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