XSS-10 Micro-Satellite Flight Demonstration Program

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ABSTRACT

The Air Force Research Laboratory (AFRL) is building and demonstrating a new class of low-cost satellites, referred to as "micro-satellites," weighing in at less than 100 kilograms. These new satellites are being flown under the Experimental Spacecraft System (XSS) program and will demonstrate the capabilities of micro-satellites for future Air Force missions. The XSS series demonstrates basic proximity operations capabilities on-orbit and will address both technical and operational risks before committing to micro-satellite system development programs.

The first mission, XSS-10, resulted in a 31-kilogram micro-satellite being launched as a secondary mission on a Boeing Delta II expendable launch vehicle along with a Global Position Satellite on January 29, 2003. The mission objectives were to demonstrate autonomous navigation, proximity operations, and inspection of another space object; a critical part of our overall strategic plan for space. The XSS-10 is a giant step in space support technologies and demonstrated capabilities needed on space support missions such as on-orbit servicing and health monitoring. The XSS-10 is a building block for future space operations.

Mission operations were conducted on January 30, 2003 when XSS-10 ejected from the Delta second stage and successfully demonstrated autonomous navigation and maneuvering in close proximity to the second stage using innovative guidance and control software. The XSS-10 featured a miniature communications system, a compact avionics, unibody propulsion, and a high-resolution integrated camera that facilitated close inspection. During the mission, XSS-10 traveled within 100 meters of the second-stage booster of the Delta II rocket, to take photographs and transmit the images back to ground from a low-Earth orbital position 800 kilometers above the equator. XSS-10 mission results were positive with all primary objectives achieved; lessons learned are being transitioned to other micro-satellite initiatives. This paper will review the development and flight qualification of the XSS-10 micro-satellite and discuss the results of the January 2003 flight experiment.

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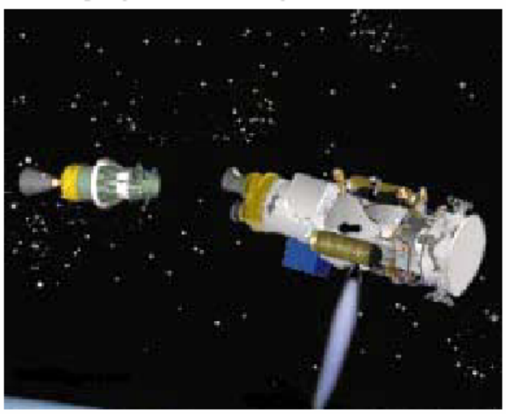
Introduction

The XSS-10 micro-satellite demonstration was the first in a series of micro-satellites to be used for important future Air Force space missions. The XSS-10 is a building block for future space operations and may lead to rapid, responsive space systems capable of enhancing space situational awareness. Micro-satellites bring affordable new capabilities that can potentially revolutionize space missions through reduced costs for development and launch.

XSS-10 was a technology program to demonstrate basic proximity operations capabilities on-orbit. XSS-10 addresses both technical and operational risks before committing to micro-satellite system development programs. Initiated in 1996, the program was realigned several times due to program and launch changes. In 1998, the program was renamed XSS-10 and restructured into a micro-satellite technology development program to support a range of space mission areas.



Simulation of XSS-10 and Delta II Remote Space Object

The program was originally planned for Shuttle launch, but NASA withdrew the ride in 1998 due to priorities for International Space Station. Vehicle alternatives assessed as options were the Taurus, Pegasus, Athena, Minotaur, and Delta II. The GPS/Delta II was accepted as the best fit for budgetary and technical reasons. An agreement was made with the Space and Missiles Center Launch Vehicle program office in October 2000 to attenuate and retrofit to a Delta II and be manifested on a future Delta II GPS mission. In July 2001, Major General Mitchell, Air Force Space Command Director of Operations, signed a letter manifesting it XSS-10 on GPS Mission IIR-8. The XSS-10 Delta II second stage "fit check" was completed at Pueblo, CO in May 2001; the custom second stage was shipped to Cape Canaveral Air Force Station in November 2001 for final testing and integration.

The XSS-10 spacecraft – compared in appearance to an automobile transmission -- launched from Cape Canaveral in late January 2003. It was a first-of-a-kind, low-cost "microsatellite" carried aloft via a second-stage, modified Boeing Delta II rocket. The 24-hour mission demonstrated autonomous operation with uniquely developed guidance and control software. The expedition also revealed some "lessons learned" that are being incorporated into a follow-on mission called XSS-11, a one-year test of the technology. The successful completion of the satellite's experimental mission January 2003 was an important first step in the development of a technology that promises to dramatically decrease launch costs and extend the capabilities of uninhabited space vehicles.

Description

XSS-10 was a 31-kilogram micro-satellite with a heritage to previous work accomplished by Boeing's interceptor programs. The XSS-10 was the first demonstration mission in the planned series and was mandated to develop, integrate, and deliver on-orbit a micro-satellite, which demonstrated nominal satellite operational functions. The mission objectives were to demonstrate autonomous navigation, proximity operations, and inspection of another space object. The XSS-10 micro-sat used the Air Force Satellite Control Network (AFSCN) for Telemetry, Tracking, and Commanding (TT&C) operations. The XSS-10 mission employed a semi-autonomous, maneuverable space vehicle communicating with command and control sites via space ground links. XSS-10 was equipped with a visible camera, a star sensor, GPS receiver and a mini SGLS system, all specially built for this program. In addition, a visible camera was also mounted on the second stage to observe the release of the microsatellite and observe its maneuvers.

XSS-10 also demonstrated several advanced micro-sat technology components. The "unibody" ultra lightweight structure eliminates 98% of the welds, reduces cost, and minimizes schedule risks. The Miniature Space to Ground Link System (SGLS) was the lightest device of its type ever built, incorporating an S-band transceiver, which weighs a factor 10 less than any comparable subsystem and consumes a factor of 10 less power than conventional SGLS links. It is compliant with NASA class B specifications and relatively

NRL developed Miniature Space to Ground Link System

inexpensive with reliability in excess of 90%.

Revolutionary Hardware-in-the-Loop simulation capabilities developed for XSS-10 will have a profound impact on future proximity operations capabilities. This provided a closed loop test environment for flight software with six-degree-of-freedom (6-DOF) simulation capability and uniquely combined the hardware components in the simulation along with the flight software. It also allowed the demonstration of mission elements on the ground and resulted in high confidence in flight. The autonomous proximity operations guidance and navigation and control software enabled the semi-autonomous on-orbit rendezvous, inspection assessment capabilities. It performed the relative position calculations based on imagery data - using LVLH reference frame.

The Air Force Research Laboratory's Space Vehicle Directorate managed the XSS-10 program. AFRL played a unique role as a government agency in that they assumed responsibility for systems integration. Associate contractors included Boeing Rocketdyne which designed and fabricated the micro-satellite, Octant Technologies which had responsibility for development of the autonomous guidance and control software, Jackson and Tull who provided qualification testing and launch integration support, and Swales Aerospace who designed the Sconce Payload Platform (SPP). SAIC provided the Integrated Camera System through a subcontract with Jackson and Tull. Boeing Launch Services provided launch support through a contract with the Space and Missiles Center Delta II program office. The 45th Space Wing, the 1st Space Launch Squadron, Space and Missile Center's Detachment 8, and Lockheed Martin provided support at the Cape Canaveral Air Force Station launch site. Mission operations were conducted with the assistance of Space and Missile Center's Detachment 12 RDT&E support center (RSC) at Kirtland AFB, NM.

The XSS-10 micro-satellite was launched as a secondary mission aboard a Delta II launch vehicle carrying a GPS satellite. After the GPS satellite was released, the Delta II circularized its orbit at 800 km and raised its inclination until its liquid fuel was depleted. With the remaining cold gas attitude control system (ACS) and electrical power, the second stage spun up around its thrust axis to approximately 6 RPM. From this state, the XSS-10 mission commenced and was completed with a high degree of success. XSS-10 performed its mission of navigating around the Delta II second stage. Navigating around the second stage, at preplanned positions, the microsatellite took images of the second stage and sent them back in real time. The mission demonstrated a responsive checkout of the microsatellite and all of its subsystems, autonomous navigation on a preplanned course and a variety of algorithms and mission operations that are critical for future mission operations.

Micro-Sat Design Details

The XSS-10 micro-satellite consisted of a visible sensor assembly, avionics module, telemetry subsystem and antennas, Guidance Navigation and Control (GN&C), power subsystem, propulsion subsystem, Global Positioning System (GPS) and antennas, and a structure subsystem. The visible sensor assembly consisted of two flight camera systems, one a visible star tracker and the other a visible imager. Overall dimensions of the XSS-10 were 32 inches in length by 15 inches in diameter. The XSS-10 avionics provided overall guidance navigation and control of the micro-satellite based on data from the onboard IMU, the visible tracking camera, the star tracker, health and status sensors, ground commands, and the programmed flight plan. The system was capable of autonomously maneuvering to rendezvous with and inspecting the second stage of the Delta II on orbit. The micro-satellite, including the avionics system, was unpowered during launch.

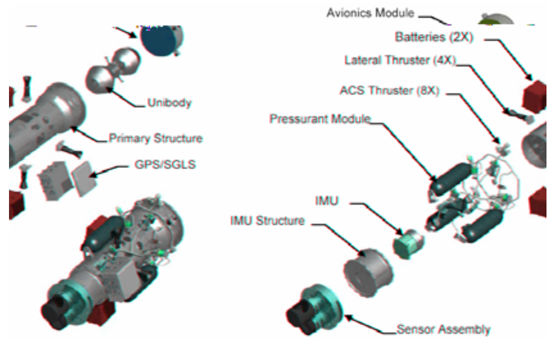
The primary micro-satellite communications link was an S-band, omni-directional uplink and downlink transceiver that communicates with ground stations via the Air Force Satellite Communications Network (AFSCN). These encrypted/decrypted communications include receipt of command functions and the transmission of mission data. The micro-satellite continuously transmitted to the ground where data was received and recorded for post-flight analysis. The XSS-10 Miniature Space Ground Link Subsystem (SGLS) Transponder was developed by Naval Research Laboratory (NRL) for XSS-10. The SGLS Transponder consisted of a receiver/demodulator transmitter/baseband. The transponder accommodated the standard uplink/downlink SGLS and is capable of receiving and retransmitting ranging signals, receiving, demodulating command signals, and transmitting telemetry signals. The SGLS Transponder included a Communications Security (COMSEC) unit. This unit consisted of an integrated equipment assembly capable of providing decryption and encryption security capabilities for satellite communications links.

The XSS-10 micro-satellite Visible Camera System (VCS) consisted of two charge-coupled device imagers each reading out through two-ten bit analog to digital converters producing a digital data stream representing the images taken. The optics on one charge-coupled device was sized to take pictures, specifically of the Delta II second stage.

SAIC developed Visual Camera System

The optics on the other charge-coupled device was sized to take pictures of stars. The star tracker looked through a folding mirror at the stars so its line-of sight was perpendicular to the imager line-of-sight. The sensor consisted of an aluminum housing that contained the printed circuit boards. The aluminum lens housings were attached to the main body aluminum housing.

The Litton LN-200 Inertial Measurement Unit (IMU) was a small lightweight strap-down unit that measures velocity and angle changes in a coordinate system fixed relative to its case. It provided digital output of incremental velocity and incremental angle. The IMU used a triad of fiber optic gyroscopes and three silicon accelerometers. The accuracy was better than one degree per hour and 300 micro-g.



XSS-10 Sub-Systems

The propulsion system provided divert and attitude control of the XSS-10 micro-satellite. The system used liquid bipropellants NTO and MMH for the divert thrusters. Gaseous nitrogen was used for propellant pressurization and attitude control. The propulsion system consisted of the propellant module (unibody), pressurant module; divert thrusters, and ACS thrusters. The one-piece unibody, which contained the propellant tanks and integral divert manifolds, was mounted internally to a cylindrical aluminum-beryllium primary structure. The unibody design combined many functions/components into a single piece, which results in high volumetric and weight efficiency. Components incorporated into the unibody included the propellant tanks, propellant and divert valve pilot gas feed manifolds, burst disks, filters, and service valves. Four orthogonal divert thruster mounting surfaces were provided on the unibody. The four divert thrusters were mounted on the unibody manifold at 90-degree intervals.

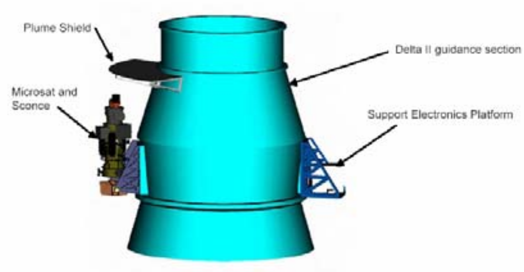
The micro-satellite spacecraft received its mission power from a lithium ion polymer rechargeable battery supplied by Alliant Tech Systems ATK. However, the battery used as a primary battery in the XSS-10 flight experiment and was not recharged on-orbit. The battery consisted of two series-connected battery module subassemblies. Each battery module subassembly contained four series connected cell elements operating from 3.0 to 4.1 volts with a total nameplate capacity of 12Ah. Battery charging was accomplished during preflight checkout by a fully automatic charger (GSE) supplied by ATK, which had "designed in" software and hardware maximum operating conditions. The battery cell element consisted of four 3Ah lithium-ion polymer cells in parallel with a 7.5A fuse on each battery cell negative terminal. The lithium-ion polymer cells, provided by Valence, obtained a high energy density because lightweight plasticized foil packaging was used instead of heavy metal cans required for liquid lithium ion cells.

The XSS-10 mission consisted of a micro-satellite programmed to execute a series of attitude and position maneuvers in proximity to a Resident Space Object (RSO). The Attitude Control System (ACS) pointed the vehicle in the direction of the Delta II second stage while an imaging camera provided a digital image of the target to the DSP. The DSP tracked the object and provided to the GN&C line-of-sight errors. The GN&C nulled out the errors using the ACS cold-gas thrusters, thus performing a closed loop target track with the micro-sat. The four hot-gas or divert thrusters were used to position the vehicle to a different RSO viewing angle during the maneuver sequence. The ACS pointed the line-of-sight of a star camera to a star field when a vehicle attitude determination or attitude update was required.

The XSS-10 main electrical interface to the Delta II was through the Electronic Interface Unit (EIU). The purpose of the EIU was to provide driver electronics to be commanded for operation of the pyrotechnic pressurant valve and for ejection of the micro-satellite. The EIU also returned the health status information from the EIU electronics to the micro-satellite for safe ordnance enabling and ejection operations. It provided the electronics required for interfacing the electrical inhibits to micro-satellite hazardous functions.

With the change to the Delta II launch vehicle, it was necessary to develop an interface with the second stage. The XSS-10 launch vehicle interface consisted of two primary interface platforms including a micro-satellite and its support electronics. A primary interface platform, known as the Sconce Payload Platform (SPP), supported the micro-sat and its ejection system, and was integrated with the second stage guidance section of the Delta II. A witness camera was mounted on the SPP to witness the ejection of the micro-satellite. The other primary interface platform, known as the Sconce Electronics Platform (SEP), supported the micro-satellite support electronics (EIU) and an antenna, and mechanically interfaced with the Delta II guidance section at the opposite side of the SPP. The thermal analysis used the Boeing developed XSS-10 thermal model, which was correlated with the AFRL thermal balance test results. The correlated integrated thermal model consisted of the micro-satellite, SPP, SEP, and the Delta II Second Stage. Boeing Rocketdyne provided the micro-satellite model. Swales Aerospace generated the SEP, SPP and Delta II Second Stage thermal models with data supplied by Boeing Huntington Beach. Swales Aerospace incorporated all these individual models into one integrated XSS-10 thermal model.

The SEP functioned as a support platform for the microsat prior to its ejection. It provided power and telemetry routing between the microsat and the GSE as well as power routing from the Delta II to the microsat prior to microsat separation. The SEP also controlled all timing functions prior to micro-sat ejection including SPP tip out, ordnance arming and firing, microsat battery enable, microsat release, and witness camera enable. Lastly, the SEP provided a witness camera system to observe the separation of the microsat and telemeter the live



XXS-10 / Delta II Configuration

video to the ground. With the exception of the primary structure, this unit was designed, integrated and tested in-house at the AFRL Aerospace Engineering Facility (AEF) at Kirtland AFR and leveraged COTS as much as possible to reduce cost, improve reliability and shorten schedules. Swales Aerospace designed and fabricated the structure and the AFRL test team performed environmental testing to verify its flight worthiness. The team designed and built all blankets and cables for the SEP. They also designed and built all the brackets and fixtures for the antennas and harness supports.

The SPP provided a mechanical interface linking the Delta II second stage to the micro-sat. The microsat was attached to the large round table and stowed in the vertical position for launch. When the Delta II gave XSS-10 the "wake up" signal, the SPP responded by rotating the table 35 degrees and tipping out the microsat. The structure and rotation mechanism was designed by Swales and tested in the Kirtland AEF. In addition to holding the microsat during launch, the SPP provided mounting locations for the witness camera and a SGLS downlink antenna. Harnessing between a common bracket, the micro-sat, witness camera, and SGLS antenna was designed, fabricated and installed by Jackson and Tull engineers and technicians. Blankets were also designed by J&T and installed as part of the SPP build-up effort.

Flight Qualification Testing

Boeing conducted extensive performance evaluation of the micro-sat during acceptance testing at both the component and system level prior to shipment to AFRL's AEF for flight qualification. Additionally, Octant Technologies verified software performance through hardware-in-the-loop and processor-in-the-loop testing. Much of the activity in the early years of the program revolved around testing the individual components of the XSS-10 system. The integrated product team (IPT) consisting of engineers from Boeing, Octant, Jackson and Tull, and AFRL developed procedures to verify functioning and performance of many critical flight components. They ran environmental tests, mostly on vibration tables, to verify components' robustness to the expected environment of the Delta II. In some cases, the vibration or shock environment greatly exceeded the component's tolerance to it and as a result, the IPT launched itself into an investigative / development mode to create an attenuation approach that would preserve sensitive flight instruments from the harshness of the launch environment. Other testing focused on measurement and calibration, as in the case of the star tracker alignment testing. In all, the IPT accomplished dozens of tests ultimately resulting in a successful integration and test program and solid performance on orbit.

The XSS-10 software was verified through a series of several test efforts. These tests included development level test where the software was tested at a unit level and documented in a software development folder (SDF). The next level of software testing was to combine the units into software components. These were also tested informally and documented in the SDF. The final level for both the GN&C and DSP Computer Software Configuration Items (CSCI) was at the CSCI level in a Processor-in-loop (PIL) configuration. Additional tests were conducted to verify functionality at the system level. The two Air Bearing tests were conducted to verify GN&C performance. The purpose of Air Bearing testing was to provide comprehensive closed loop end to-end Attitude Control System and Seeker Algorithm performance evaluation of an Air Bearing Vehicle (ABV). The ABV contained as many intrinsic flight systems as practical, given the limitations of the test equipment/configuration and schedule. The ABV was a specially modified vehicle that floats on a thin layer of air. The vehicle was free to rotate in any direction within +8o. The timeline of the test was similar to an actual flight, except fewer modes are exercised. The power up and eject was similar to flight.

The first Air Bearing test verified GN&C performance closing the loop around the IMU. The second Air-bearing test verified both the GN&C and DSP CSCIs. The test used a vehicle that was a nearly complete flight vehicle. The bi-prop propulsion system and flight batteries were not a part of this configuration. The test used a Delta II second stage model placed in front of the imaging camera and a simulated star camera place in front of the star camera for a closed loop end-to-end (photons in to attitude control jet firing out) test. The last test conducted was an outdoor field test to verify star tracker performance. The star camera was mounted on a controlled gimbal to stabilize the camera on a star field. The DSP software used the star camera to collect star images and detect the seven brightest stars and report to the GN&C. The GN&C algorithms used the reported stars to compute the vehicle's attitude using an on-board star catalog.

Hardware-in-the-Loop (HIL) testing was conducted to verify interfaces and real-time operation of the embedded systems architecture of XSS-10. Most of these tests occurred at Boeing's avionics laboratory. Test configuration utilized many of the hardware components of the XSS-10 system. The VCS, actual avionics loaded with flight software, the IMU and environment simulators comprised the make-up of the test configuration. The test objectives were wide and varied. At the start, most of the testing revolved around verifying component-to-component and component-to-software interfaces were correctly implemented. Then, as the system matured, tests were run to determine optimal settings for image processing functions, which included auto-gain, target tracking, thresholding and false detection rejection. By the time the system had reached full maturity, nearly all testing proposed to verify performing mission rehearsals was accomplished with mission data load. Ultimately, Hardware-in-the-Loop testing was a successful endeavor for XSS-10. During these events, Boeing, Anaheim successfully tweaked their target tracking algorithms, which played a major role in the overall success of mission operations.

The Sconce Payload Platform (SPP) came to the AEF as an integrated unit, ready to receive and attach to other flight hardware such as the microsat and ejector, the connector bracket, the witness camera, etc. Swales Aerospace made two units, one for flight and an engineering model designed to the same standards as the flight. The engineering unit became the test unit, where it underwent exposure to environments 3dB greater than expected flight environments as well as suffering multiple exposures to those environments. It also became the pathfinder for functional tests like the tip out test and fit checks with other XSS-10 components as well as with the Delta II second stage.

The creation of a test that would verify the tip-out action of the SPP was absolutely critical to mission success, if the tip-out mechanism failed to function properly, the micro-sat would impact the Delta II upon ejection resulting in a myriad of unpredictable effects, all with negative impact to mission success. The challenge was to create a realistic test, where the SPP could rotate in the presence of gravity, but function as if the unit was located in space under a micro-G environment. Working with Swales Aerospace, AFRL developed an approach to negate the gravity using tension lines to lift up on the cantilevered portion of the SPP. The SPP was rotated on its side so that the hinge axis was aligned with gravity. The tip-out test was conducted several times, each time to verify performance as the integration of the SPP matured. Most of the testing was successful. However, after the flight harness was installed, the SPP would not reliably actuate. Inspection revealed that the wire harness exerted a counter torque to the rotation springs. When added to the counter torque of the motion dampeners, the unit seldom would function properly. After considering all the options, the IPT decided to remove the dampener and allow the cable to provide the dampening. The solution worked great and was further supported by demonstrating flawless operation on orbit.

XSS-10 mounted with Sconce Payload Platform

The SPP underwent several vibration tests to prove its robustness to the Delta II environment. These tests occurred using both the flight and the engineering units. After each event, the actuation performance was verified by running a tip-out test. During some of the initial tests, engineers learned that localized G-loading exceeded flight hardware specifications. Note engineering hardware was installed for these tests. As a result of this discovery, the test team began investigative vibration testing to determine a method whereby attenuation could be introduced and flight hardware insulated from high vibrational inputs. Several months of testing ensued. In the end, engineers solved the problem by adding a one-half inch, hard foam pad on the interface of the affected components, namely on the microsat ejector and the witness camera. Sconce Electronics Platform (SEP) testing closely mirrored the testing done on the SPP with the exception that the SEP did not require tip-out testing. The SEP did, however, undergo extensive vibration testing, some of which included development of an attenuation system for several components that were experiencing localized G accelerations in excess of their specifications. The same material used on the SPP was used on the SEP to meet the attenuation requirements.

The visual camera system (VCS) was tested extensively in preparation for flight. Functional tests, performance tests, alignments, and environmental tests were performed to certify the VCS for space. Outdoor testing occurred several times during the course of the program. At first, the engineering unit was brought to Edwards AFB. Star data was gathered and used to determine lens aberrations and settings to optimize sensitivity. Other similar tests occurred to validate the two flight units that SAIC built. Initially, this test leveraged the custom Ground Support Equipment (GSE) supplied by SAIC. This GSE directly interfaced with the VCS, but this configuration could not support any higher functions like target tracking or pointing determination. Follow-on testing did accomplish these higher-level tasks. By integrating the VCS with flight avionics and software, flight software was verified. These tests also occurred at Edwards AFB.

Component level testing was accomplished on all of the critical subsystems. Power Converter Unit (PCU) testing was completely successful. No anomalies were encountered during any of the testing. It was run through a series of functional and environmental tests to verify its suitability for flight on a Delta II. Video Compression Unit (VCU) testing was completely successful. No anomalies were encountered during any of the testing. It was run through a series of functional and environmental tests to verify its suitability for flight on a Delta II.

The SGLS transponder was one of the key components in the chain to downlink witness camera video was the transmitter. Developed by NRL, it closely matched the specifications for the microsat transponder, but without the receiver and COMSEC sections. Functional and environmental testing was initiated in the summer of 2001. The unit passed initial functional testing, but after exposure to vibration, the unit would not transmit on the proper frequency. The IPT shipped the unit back to NRL for their evaluation. Upon receipt, NRL discovered the primary oscillator had fallen off its mechanical support, thereby breaking electrical connections with the rest of the circuit. They also announced that the part they had chosen for the oscillator was not a space flight part and not robust to vibration environments. They had chosen the part to meet delivery / schedule requirements. A more robust part was identified and the transmitter returned with a space rated oscillator and passed all functional and environmental tests. The IPT successfully integrated the unit into the flight system just, in time for system thermal vacuum testing to begin. The Electronics Interface Unit (EIU) contained all the logic, power relays, and signal routing required to execute the pre-ejection sequence. It directly interfaced with the microsat and provided all the range safety controls for the microsat inhibits and was provided by Boeing Rocketdyne in addition to the micro-sat.

Three major efforts formed the basis of system integration for XSS-10. They were (1) micro-sat buildup, (2) SPP buildup and integration of SPP to microsat, and (3) SEP buildup and integration of SEP with SPP / microsat. Most of the microsat buildup occurred at Boeing Canoga Park. Boeing engineers and technicians assembled the microsat, installed software and performed a short functional test before shipping it to the AEF. They did not install flight blankets at that time, nor did they perform any integration work with the ejector, the mechanical interface between the microsat and the SPP. Jackson and Tull performed the other integration tasks including installation of flight blankets and cleanup of micro-sat harness routing. The IPT conducted systems testing at the AEF on all flight hardware, which included the integrated SEP, SPP, and Microsat. This effort focused on proving system robustness within space environments – vibration, shock and thermal vacuum. Some effort was expended on verifying software as well. The IPT verified all software to hardware interfaces, commanding and telemetry, and basic software functioning. Lastly, they gathered performance / parametric data and system responses, which couldn’t be achieved until after integration was complete. Data items like vibration responses, thermal parameters, misalignment data, and stellar acquisition performance were included in this arena.

The IPT followed an approach proven to work on other fast paced, low cost programs. Immediately following system integration, the plan called for an end-to-end functional test. This test then formed the baseline and it was repeated after exposure to each environment. Results of each test were compared and differences triggered anomaly resolution efforts. This process worked well in highlighting subtle differences in performance over exposures to environments including temperature and pressure variations, and post vibration / shock exposures. Most of the functional testing was automated and results were archived according to the date of test. In this way, human error was virtually removed from the process.

Results of systems testing were very positive. Consistent performance was observed throughout the program. No failures were encountered during vibration and shock. By the end of systems testing, high confidence existed in vehicle robustness to environmental exposure. To provide guidance and a plan for systems testing, the test team leader prepared a system test index. This document captured a list of test objectives / requirements and matched them to test procedures. The system test index, while providing a summarized test plan, also doubled as a test verification matrix. Multiple procedures were written to verify functionality and performance in each of these areas. Once the first test was completed, all the testing was combined/integrated-automated test that would effectively verify performance compared with the baseline run. This effort resulted in generation of two sets of automated procedures. The first procedure was a comprehensive test requiring multiple configuration changes and several hours to complete. It was executed between major testing events – between vibration and thermal vacuum testing for example. The second procedure required one simple configuration and could be run within 2 hours. This second test was used during thermal vacuum and between axes during vibration testing. The biggest difference between the two tests was that the more comprehensive test actually recorded many performance values, while the second test only verified system functionality. This relied on the implication that the system was meeting performance requirements by functioning correctly.

Witness camera verification showed consistent performance in witness camera video quality was observed, but that quality was not perfect. Discovered during system integration, close inspection of witness camera video revealed that a diagonal pattern of alternating dark and light lines was superimposed across the camera field of view. The lines possessed a very thin geometry and only caused a minor impact to image quality. Testers also noted that when the micro-sat was unpowered or detached from the SPP, the noise on the witness camera video disappeared. After considering that the witness camera video was really only needed immediately after micro-sat separation, test directors decided to accept the performance and fly "as-is". A short engineering investigation ensued after anomaly discovery to determine cost and schedule impacts to completely correct the noise problem. First, troubleshooting efforts resulted in showing the noise was sourced by the micro-sat. It appeared the micro-sat DC-DC converter frequencies were showing up on the primary structure and feeding back through the 12 V power supply feeding the witness camera. It quickly became apparent the only solution left was to add an EMI filter on the either the microsat (preferred) or on the witness camera power supply. After looking at the cost and schedule impacts, it was decided to fly "as is". Witness camera verification occurred as part of the baseline functional testing effort.

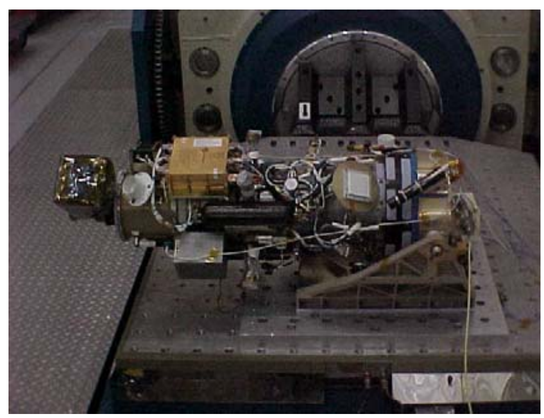
Plugs out testing first required setting up the flight hardware in a way that was electrically identical to the flight configuration prior to launch. Then, the spacecraft, following its flight profile, executed its timeline through vehicle power up; inhibit removal, ejection and mission start. Batteries were used for power supplies, just as expected during flight. Additionally, pyro simulators were removed and real pyros were installed so that real currents were passed along the wire harness. No anomalies were encountered.

A procedure was developed where testing increased in complexity, adding one component at a time until the whole system was integrated prior to firing the pyros. First, pyro simulators were installed and power supplies replaced the batteries. The mission start sequence executed without flaw. Then incrementally, power supplies were replaced by fused batteries and then by unfused batteries. Next, battery-arming plugs were installed, but pyro simulators were still in place. Once again, the mission start sequence commenced without anomaly. For the last run, real pyros were installed and the system was electrically configured identically to the flight hardware. The mission sequence executed perfectly. Some effort was expended to configure the setup mechanically in the same fashion as the flight hardware, especially with regard to how the ejector and pin release mechanism functioned. The ejector was installed upside down on a homemade support fixture. A mass model of the microsat was installed on the ejector and left to hang from it over a box filled with foam padding to catch it after release. Flight-like pin pullers were installed and the ejector release mechanism was configured as per pre-launch requirements. When the 'eject' discrete fired, the mass model successfully released and softly landed in the box.

After completing system integration but prior to environmental testing, the micro-sat underwent a nighttime, outdoor test to verify system capability to acquire attitude from the stars. Normally this test is conducted at the component or subsystem level, but due to the complex nature of the teaming arrangement between Octant (software developers), Boeing Anaheim (avionics and image processing) and Boeing Canoga Park (systems engineering and vehicle integration), there was a risk that perhaps vehicle phasing might have been adversely impacted. Hence the basis for conducting an outdoor stellar acquisition test was to verify system capability to correctly acquire stars, track them and calculate a vehicle quaternion. For this to work, the VCS sensitivity, focus, and electrical ICD must work, the microsat avionics must correctly receive VCS digital data, and the image processing software must correctly track stars and correctly report their physical parameters. Then lastly, the vehicle software must correctly identify the stellar pattern and determine where the vehicle is pointed. This was a very good test at verifying a huge portion of vehicle functioning. Flight hardware and software had to work and correct vehicle parameters had to be uploaded (sensor misalignments, vehicle axes definition and VCS focal length). Test plans and computer scripts were developed to capture the vehicle attitude determination performance. These scripts relied upon IMU sensed accelerations and rotations, time of day, and location upon the Earth to build an independent vehicle quaternion to be compared with the one generated by the system using star tracker data. A success criterion was set to be from calculated truth using IMU only data. Vehicle / flight hardware safety drove process and configuration requirements during the test. The test personnel, following procedures, monitored relative humidity, temperature, and other weather conditions for the purposes of avoiding condensation on the vehicle. They monitored wind and air quality in order to minimize accumulation of dust and other contaminates on the vehicle and they followed strict ESD procedures resulting in the avoidance of incidental static discharge.

RF compatibility testing was performed to verify that the system was immune to its own RF emissions as well as to verify that the ground systems could successfully communicate with the flight systems. Verification of this was conducted at several points in the integration and test flow and was structured to verify the command and telemetry data base, RF communications, COMSEC and telemetry display. Self-compatibility testing was conducted at the AEF. The purposes of the test were to verify vehicle could receive all commands in the CTL and that all the telemetry brought across the umbilical cable could be decoded and displayed properly, verify that the RF system working with the crypto gear functioned properly, and verify that vehicle was robust to potential interferences from its own RF sources. The vehicle successfully underwent this test. No degradation was noted as a result of free radiation. Some commands and some telemetry appeared to be anomalous. Further investigation revealed that flight software maturity had not reached a level where the command and telemetry database were set in stone. It was shown that Octant (flight software developers) was aware of problems and was on course to make another revision change. The good news was the vehicle could be commanded through the RF link reliably and telemetry could be received with no dropouts over the RF link as well.

Factory compatibility test continued where the self-compatibility test left off. Whereas the self-compatibility verified the spacecraft to be functional, the Factory Compatibility test verified the vehicle could be commanded and telemetry could be received and displayed by the ground system. Factory compatibility required the use of the SMC Detachment 12's telemetry test van. This van simulated the digital and RF functions of a standard remote ground sight. By successfully sending commands and receiving telemetry, the RSC verified "compatibility" between mission control and the flight vehicle. System vibration and shock were conducted without incident on the SEP and the SPP / micro-sat assemblies. No anomalies were encountered. The flight hardware was exposed to 3 different environments: Random vibration, Shock, and Sine Sweep. Two kinds of sine sweeps were conducted. First, low level sine sweeps (0.25G) were performed before and after each of the main tests. Differences in responses would indicate failure or breakage in the structure.



XSS-10 Vibration Testing in Kirtland AEF

Thermal vacuum testing occurred at the system level to verify system thermal design, to correlate system thermal model parameters, to verify functioning of thermostats and heaters, and to verify system functions at hot and cold temperature extremes. The test had elements of thermal cycling, thermal balance, and "day in the life" testing. The plan called to begin with thermal balance testing. Test execution progressed as follows. First the test article was raised to warm condition, typical for pre-launch. The vacuum chamber walls were cooled to a known cold, steady state temperature. The power was removed from the vehicle and thermal couples were monitored and recorded, revealing the temperature decay rates as the vehicle cooled, trying to match the surrounding wall temperature. The test was repeated several times at different starting and terminating temperatures. From these data, Swales Aerospace was able to successfully tune the thermal model for the XSS-10 system.

The plan for thermal cycle testing was for the microsat to complete the planned set of 8 thermal cycles. The first cycle went well and so did the second, but the third cycle (which would have been the eighth overall) an anomaly with the avionics was detected, which required RAM replacement on the CCIM-A board. It had undergone RAM replacement, signal termination correction, and solder re-flow. Following the avionics repairs, the micro-satellite successfully completed the thermal cycle test at the AEF with solid performance. The final phase of thermal vacuum testing was to conduct "day in the life" testing. This test was set up to simulate actual on orbit conditions and was conducted from a pre-ejection and post-ejection configuration. No anomalies were encountered. At this point, the thermal vacuum testing was completed. The effort brought the micro-sat once again outdoors to repeat the star tracker attitude determination test. This time, the test was a success due to the CCIM-A board rework.

Launch Integration

A Ground Operations Working Groups (GOWG) was established in December 2000 at Cape Canaveral Air Force Station to coordinate launch integration activities. The members included Boeing Launch Services; the Lockheed Martin GPS program office, the 1st Space Launch Squadron, Eastern Test Range, and AFRL. The GOWG helped identify facilities for XSS-10 launch vehicle integrations activities, established processing flow, coordinated fueling activities, and developed an integrated launch pad processing schedule for XSS-10, the GPS satellite, and the Delta II launch vehicle. The 45th Space Wing Safety Office assisted in the preparation and approval of the XSS-10 Missile System Pre-launch Safety Package (MSPSP). A number of mission readiness reviews were conducted with the 45th Space Wing, the SMC Delta II program office, and Aerospace Corporation with the primary objective assuring XSS-10 did not pose a threat to the GPS primary mission.

Launch integration was accomplished at Cape Canaveral Air Force Base at three different facilities; the NavStar Processing Facility (NPF), the DSCS Processing Facility (DPF), and the Delta II launch pad 17B. Planned activities extended for nearly six weeks, but due to multiple delays caused by both technical problems with the launch vehicle, launch integration was actually spread out over three separate deployments, the first in June / July 2002, the second in October 2002, and the final in January 2003. As a result of these delays, total time on the road exceeded nine weeks. Launch integration was exceptionally successful. There were no surprises. All testing yielded expected results and all integration activities occurred without incident. The most difficult part of launch integration was maintaining the flexibility required of a secondary payload to meet the ever-changing schedules of the rocket and primary payload. The integration activities reserved for the Cape included many functional tests, RF compatibility testing, fueling and pressurization, measuring CG/MOI and integration with the Delta II.

Functional testing occurred between each major integration step and after each time the vehicle was transported. Procedures developed and proven at the AEF were used at the Cape so that performance could be compared to a validated baseline. After the propulsion valves were mated, procedures were reduced to insure against inadvertent dry cycling of thrusters. The integration team setup and accomplished flight hardware integration in the NPF. The setup mimicked the mechanical and electrical configuration as expected on the Delta II second stage. In this configuration, the flight hardware successfully passed the functional checkout procedure. Part of the functional testing included performing a pressure verification test. During this test, fueling experts from Edwards AFB joined the IPT and verified

Launch Pad 17B at Cape Canaveral Air Force Station integrity of the 10 KPSI bottles and all the lines leading up to the cold gas ACS thrusters. Additionally, they supported functional testing of each valve using low pressure, ultra-pure nitrogen as the pressurant and then monitoring nozzles for flow.

XSS-10 fueling operations were supported by a crew from the AFRL Propulsion Directorate (Edwards AFB) and successfully accomplished in the DPF in October 2002. Since fueling was considered a hazardous operation, the building was cleared of non-essential personnel. To minimize impact to other activities at the DPF, the XSS-10 activities were schedule during night shift over the weekend. Both Friday and Saturday nights were required - the first night to load fuel (MMH) and the second night to load the oxidizer (NTO). No anomalies were encountered during operations.

All launch vehicle integration activities occurred at launch pad 17B on level 9A, at the top of the Delta II second stage. Work began as the sun was rising and continued for approximately 15 hours. Immediately following integration and checkout, pressurization commenced and was concluded at approximately 2:00 am the next morning. This series of activities make a fine example of the flexibility that the XSS-10 crew maintained. Originally, these activities were to occur over two days on the weekend and happen on day shifts. Instead, the integration activities happened on day shift and pressurization occurred the following night shift. The first steps to attaching XSS-10 to the launch vehicle included attaching lifting fixtures to XSS-10, tipping the stand to the vertical position and moving the "Iron Maiden" into position so it can be bolted onto the lifting fixture. Then the Iron Maiden was bolted to the XSS-10 lifting fixture and the lifting fixture was disconnected from the vertical mount of the transporter. Finally, XSS-10 held by the lifting fixture, which was held by the Iron Maiden was moved away from the vertical mount of the transporter.

After successfully completing functional testing and battery charging, the microsat was readied for flight pressurization. Pressurization occurred immediately following final flight configuration of the microsat. The activity was expected to require 8 to 12 hours to complete in anticipation of worst case constraints placed on the team by range safety. Instead of the eight hours baselined, pressurization actually was accomplished in about four hours. The Edwards AFB crew was allowed to pressurize their GSE earlier in the day since their system exhibited better than 3 to 1 margin at 10 KPSI. Additionally, they ran their GSE from the facility nitrogen supply. These two elements enabled the faster schedule. Final launch preparations included witnessing fairing installation, running a post fairing functional test, and arming the system for flight. All these activities were accomplished without incident.

Mission Operations

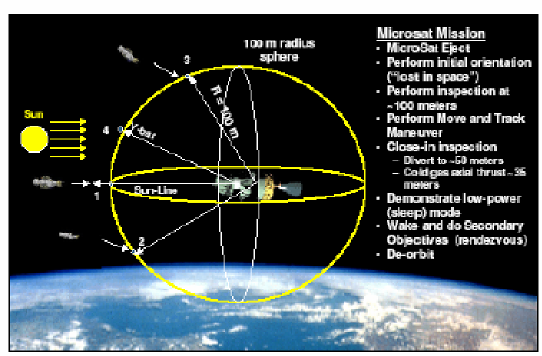
The XSS-10 mission was the first demonstration of an autonomous inspection of another resident space object using a highly maneuverable micro-satellite. The change to the Delta II launch vehicle resulted in a significant restructuring of the XSS-10 mission concept. Restricted to a 24 hour mission because of limited battery power, the mission objectives were planned around a sequence in which the micro-satellite was ejected from the Delta II second stage and performed a series of autonomous maneuvers starting with an initial orientation ("lost in space"), then an inspection of the second stage using the propulsion systems' cold gas axial thrust, demonstration of low-power (sleep) mode, and a wake and do "extra credit" (rendezvous). The XSS-10 free flight mission required the micro-satellite to have continuous ground station coverage for telemetry and appropriate lighting conditions. As a result the micro-satellite remained attached to the Delta II second stage booster after orbit circularization at 800 kilometer by 800 kilometer. Multiple passes were available for checking the health and status of the micro-satellite as well as characterizing the orbit for ephemeris uploads to the micro-satellite. A nominal 24-hour board showed the nominal passes and pass objectives. This pass plan was followed during the mission with only minor modifications. It is important to note that there were multiple potential eject sequence (free flight) passes. This was to mitigate the risk of having some anomaly on the optimal mission pass.

Mission operations were conducted at the Space and Missile Center's Detachment 12 RDT&E support center (RSC) at Kirtland AFB, NM. In preparation for the XSS-10 mission operations, twenty-nine Mission Operations Working Group (MOWG) meetings were held; additionally, six rehearsals, and a dress rehearsal were completed prior to launch. The MOWG meetings were conducted to manage mission operations planning and execution. In particular sixteen contingency procedures were defined for ground intervention and recovery from on-orbit problems. On launch day, XSS-10 orbit operations began immediately after the Delta second stage completed its activities and became inactive. The rehearsals were designed to emulate the actual operations time line. The rehearsals and operations were very challenging because the operations lasted approximately 20 hours and budget constraints dictated only one operations team could be developed. The rehearsals were an excellent tool to evaluate the operations teams' performance under high stress and fatigued conditions. The rehearsals also allowed practicing the contingencies procedures under varying conditions. This mission required that decisions be made quickly and swiftly executed. The XSS-10 operation/control architecture required repeating the same directions 3 to 4 times. The XSS-10 team practiced implementing contingency procedures that assumed the worst-case scenario and tried to fix it as compared to absorbing all the data and making small and fairly safe alterations to the configuration. Although all operations went as planned, the team was well prepared to address anomalies had they occurred.

The primary mission had one significant known deviation. During step 2 (attitude acquisition), the vehicle had to capture star images in four different orientations until a clean image (no sun, earth or target in FOV or exclusion angles) was obtained. The GN&C could not complete the attitude determination in time. As a result, steps 3 and 4 were executed and then an automated contingency was performed to repeat the lost in space attitude acquisition. This again required four star shots. The 4th star shot resulted in a successful attitude acquisition. The mission then proceeded through step 8. Unfortunately during the transition to the V-bar, the ground station lost lock on the micro-satellite and the witness camera telemetry. When telemetry was restored at the next ground station, the micro-satellite was nearing the 1 kilometer standoff point. It is highly probable that steps 9 & 10 were executed because the commands were executed were verified in the history buffer, there was good relative position knowledge, the axial cold gas thrusters were actuate (verified in telemetry) and the vehicle executed step 11. Thus it is asserted that all mission objectives were completed. A detailed analysis of all mission data will provide additional verification of mission results and will be published at a later date.

The XSS-10 operations team spent considerable time developing contingency procedures. This was a very long process. The team started by brainstorming a list of all possible problems with options on response, and actually writing the procedures during MOWGs with everyone giving input. It was then essential to revisit assumptions over and over again. Some anomalies were expected but did not impact nearly as bad as anticipated. Because XSS-10 was attached to the Delta II second stage, one of the SGLS antennas was obscured. Additionally, the Delta was rotating at 1 rpm and the micro-sat was actually canted out 35 degrees. The team planned for the worst case of 30 seconds with link, 30 seconds without. There was discussion that the signal would not be off and on but more likely oscillate between strong and weak. No auto track was planned and limited command time anyway. Reality was far better than expected. The sites were able to maintain auto track on the micro-sat downlink even though the telemetry lock was lost for 1-6 seconds every minute. Additionally, the team was able to auto track the Delta beacon through Rev 9. This signal was not as strong or consistent as expected but lasted 14 times longer than expected. Finally, during integration and test activities the SGLS receiver frequently locked on a sideband. The team planned and practiced for this but didn't see any occurrences during the actual mission.

On the spacecraft side there were only two problems that caused a response. The first was after the micro-sat ejected and began to perform its position determination. The micro-sat had trouble distinguishing the stars and actually executed an on-board contingency to get more time to try. The team opened the "Attitude Acquisition Failure"



contingency procedure but did not have to execute it. After the mission, the Witness Camera data was reviewed and saw the debris after the micro-sat ejected. The debris probably appeared as “stars” to the star camera, which was not anticipated. Finally, a late change to the extra credit sequence was to use the star camera instead of the main camera to acquire the second stage at one kilometer out since the star camera had a wider field of view. Unfortunately, the second stage was not clearly distinguishable (looked like a large star) so the PTC decided to halt the rendezvous. The halt command was added after the dress rehearsal.

There was one other problem for which the cause is still undetermined. During the mission pass, the micro-sat telemetry was lost just prior to the axial maneuver. However, the receiver at the site showed good lock on the witness camera downlink. Since this downlink was only being recorded it could not verified at the time. The witness camera data was later received from the BOSS ground station and there were no dropouts in the data. Additionally, both BOSS and LION ground stations had problems tracking the micro-sat downlink but not the witness camera downlink. Telemetry was lost twice for 20 seconds. The initial assessment is the tracking site did not have a malfunction that resulted in the loss of micro-sat telemetry nor any problems that may have occurred with tracking. The preliminary conclusion is the loss of the micro-sat telemetry was related to the micro-sat’s position (possibly several antenna nulls or were obscured by the 2nd stage) or there was something on-board the micro-sat that caused the loss of downlink (transmitter malfunction/ power drain, etc). A detailed review of mission results is currently underway at AFRL.

Several external agencies provided support to the XSS-10 mission operations team. The standard operating message (SOPM) was produced by Boeing, the booster manufacture. Prior to launch the team received a pre-launch nominal SOPM, which gave final orbit information based on modeling only. On launch day, the team received SOPM 4, which included actual data for the orbit circularization burns and modeled data for the final depletion burn. It agreed with the pre-launch nominal and what was expected based on the launch commentary. The team then received SOPM 5 after the depletion burn, which was actual data with no modeling. The team noticed right away the inclination was higher than expected based on pre-launch nominal, SOPM 4, and launch commentary. A call to the originator of the SOPM resulted in a revised SOPM 5 was received with the expected inclination.

The Space Surveillance Center (SSC) coordinated the tasking of the Space Surveillance Network (SSN) sites. They also sent the observations to MIT/Lincoln Labs (LL) and used the observations to produce a state vector for the RSC. The SSC state vectors turned out to be as accurate as the LL state vectors. The SSC was very helpful in producing and sending the state vectors as soon as possible. Additionally, they faxed to the RSC the voice reports from the SSN sites, which contained TEAR (time, elevation, azimuth, range) data. The LL team was extremely helpful for this mission. They worked with the RSC to understand the requirements and challenges of the XSS-10 mission and produced high quality state vectors quickly during the mission. Additionally, they proactively contacted SSN sites to ensure their support of this mission.

The table below summarizes XSS-10 mission objectives and preliminary results:

Primary Mission Objectives	
Execute free flight of a space system of ~25Kg, defined as a 'Micro-satellite'	MET
Communicate real-time with ground sites with two-way link	MET
Maneuver around a resident-target based on visible imaging, relative position knowledge, and inertial position/attitude knowledge	MET
Demonstrate station-keeping capability relative to a resident-target continuously	MET
Demonstrate life extension ('Sleep') mode for a µSat.	MET
Obtain images of µSat ejection and initial maneuvers about a resident-target.	MET

Minimum success criteria were those mandatory to demonstrate system elements functionality:

Minimum Mission Success Objectives	
Deliver and release one µSat on-orbit	MET
Establish real-time RF link between the µSat and the AFSCN	MET
Perform maneuvers about a resident-target	MET
Perform three points of an autonomous inspection about a resident-target	MET
Acquire and track a resident-target with the µSat visible sensor	MET
Demonstrate station-keeping capability relative to a resident-target continuously	MET

Full success criteria were the minimum success criteria plus additional technical objectives that verify applicable technical parameters. The complete set of success criteria were:

Full Mission Success Objectives	
Establish real-time RF link between the AFSCN and both the µSat and the expendable launch vehicle video acquisition system (VAS) simultaneously	MET
Perform continuous track during maneuver between two inspection points	MET
Perform 100% of an autonomous 5-point inspection about a resident target	MET
Demonstrate µSat axial maneuvering while imaging capability	MET
Demonstrate life extension ('Sleep') mode for a µSat	MET
Obtain images of µSat ejection and initial maneuvers about a resident-target	MET

Extra Credit: Once the minimum success criteria were met there were sufficient consumables for additional objectives referred to as "extra credit". in priority order were:

Extra Credit Success Criteria	
Reacquire resident-target after µSat has been in sleep mode	NOT MET
Rendezvous with resident-target after µSat sleep mode to within 200m	NOT MET
Demonstrate real-time commanding through the Payload Test Center	MET
Perform orbit-lowering maneuver to reduce µSat life on-orbit	MET

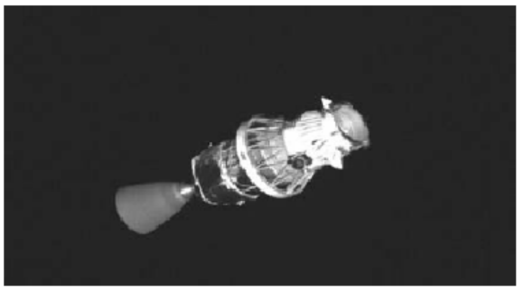
Since the star tracker was used to reacquire the Delta II second stage after sleep mode, it could not be determined conclusively that the "large star-like image" was the second stage. The initial assessment was the image seen was the second stage. In that case criteria A was met. Additionally, the micro-sat maneuvered for the rendezvous but a ground command was sent to stop it prior to coming within 200m. All indications were the micro-sat would have met criteria B as well.

Conclusions

All micro-satellite and support systems performed as expected during the flight. The micro-satellite software and hardware worked on every pass that the vehicle was contacted. The loss of telemetry did not allow the observation of the close in images of the target but the images collected up to the loss were exceptional. The failure to reliably track the second stage at long range was a small disappointment but the vehicle did turn and see the second stage and was able to report a few track points before the Delta II second stage was lost. Most extra credit objectives were also met. The re-acquisition of the Delta II second stage was not achieved likely because the background in a large area surrounding the target had a very high mean intensity and the auto-exposure settings were not selected properly to drive down to a level to enhance the target. Reacquisition could have been achieved if the Imager Camera was used instead of the Star Camera. The original concept was to use the Imager Camera as the primary on the extra credit sequence unless there was a failure to track or the Imager sensor failed outright. Then an on-board contingency would have switched to the backup Star Camera. The Star Camera was based lined as the camera to use on extra credit because most scenarios that were analyzed usually showed the extra credit portion occurring a full orbit after the primary Mission pass. But because of the January 29, 2003 date and launch time, the mission pass was selected as Rev 11.1 and extra-credit as Rev 11.3 with a 10 second sleep time in between the passes. Because of the short sleep time, the relative state between the Delta II and the micro-satellite did not drift very far from the truth and the Imager could have been used to track the Delta II at the 1000 m range.

Lessons learned from this mission will be carried forward to future space missions. The XSS-10 flight test verified the ability to navigate and station keep autonomously near a remote space object, the ability to provide real-time visual information on a space asset, the ability to maneuver in close proximity to remote space object, and the functional viability of micro-satellite class spacecraft for other Air Force. The XSS-10 demonstration verified critical station keeping and maneuvers control logic guidance and control software necessary to accomplish autonomous navigation. The successful results clear the way for more complex maneuvers on future micro-satellite missions. The visible camera and star tracker provided brilliant images of the near by rocket body. The ground control capability innovatively developed for XSS-10 enabled a small team to successfully interpret the real time data and control the spacecraft during its short mission. Future missions will build on this by both further reductions in ground staff and extension to orbit changes and complex maneuvers.

Operations on the XSS-10 demonstration were extremely successful; all primary mission objectives fulfilled. The flight experiment validated the design and operations of the micro-satellite autonomous



Delta II Launch Vehicle as seen from XSS-10 at 800KM

operations algorithms and the integrated visible camera and star sensor design. Equally important, XSS-10 demonstrated the capability for responsive micro-satellite operations through quick activation and systems checkout. XSS-10 positive results are a building block for other future micro-satellite demonstrations.

References

Barnhart, D.A., Hunter, R.C., Weston, A.R., and Chioma, V.J., "XSS-10 Micro-Satellite Demonstration." Proceedings of the AIAA Space 1998, Albuquerque, NM, September 1998

Davis, T.M. and Singaraju, B., "XSS-10 Mission Results." Proceedings of the 2003 MIT/Lincoln Laboratories 2003 Space Control Conference, Boston, MA, April 2003

Sanders, J.M., "The Little Engine that Could," Georgia Tech Research Horizons, Summer 2003