# XSS-10 Micro-Satellite Flight Demonstration

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## ABSTRACT

The Air Force Research Laboratory established the Micro-Satellite Technology Development Program (XSS series of flight demonstrations) to leverage micro-satellite technologies with the aim of providing solutions to Air Force future space mission capabilities. XSS-10 was the first in this series and was intended to demonstrate key operational concepts and technologies relating to close-in satellite inspection operations. The XSS-10 program began in December 1997 and launched from Cape Canaveral on 29 January 2003 attached to the second stage of a Delta II. Eleven orbits later the XSS-10 micro-sat ejected from the orbiting Delta second stage and successfully completed a brief series of semi-autonomous maneuver and inspection operations using the Delta second stage as the RSO. The mission objectives of XSS-10 were to demonstrate autonomous navigation, proximity operations, and inspection of a Resident Space Object (RSO). XSS-10, a 31 kilogram micro-satellite launched as a secondary on a Delta II expendable launch vehicle carrying a GPS satellite. 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. The XSS-10 micro satellite was released from the Delta II second stage after the GPS satellite was released. Operating autonomously, on a preplanned course, XSS-10 performed its mission of navigating around the Delta II second stage. Autonomously navigating around the second stage, at preplanned positions, the microsatellite took images of the second stage and sent them back in real time. During these demonstrations, XSS-10 demonstrated 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. This paper will discuss the results of the mission and post mission analysis of the XSS-10 space flight.

## 1.0 Introduction

This paper documents the results of the XSS-10 mission and post-flight review. It presents a summary of the program and mission objectives, accomplishments, achievements and lessons learned during the integration, test, and execution of the development program and flight experiment. The paper also addresses supplemental analysis performed by the post mission analysis review team to confirm XSS-10 mission results. The Air Force Research Laboratory established the Micro-Satellite Technology Development Program — the Experimental Small Satellite (XSS) flight series — to demonstrate the capabilities of microsatellite technologies emerging from the Laboratory that are potential solutions to meet Air Force Space Command space control mission deficiencies. XSS-10 was the first in this series and was intended to demonstrate key operational concepts and technologies applicable to proximity operations in space and autonomous navigation.

The XSS-10 program began in December 1997 as a re-directed successor to the cancelled Clementine II program. Through its preliminary and critical design reviews, XSS-10 baselined a shuttle mission using the Goddard Space Flight Center's Spartan carrier to deploy the Micro-Sat and serve as an RSO. In April 1999, NASA cancelled XSS-10 shuttle support and the program baselined the Delta II as its launch vehicle and RSO. This legacy imposed substantial hardware, funding, and mission constraints on the subsequent program. As a result AFRL formulated a compromise flight demonstration that did not include any power generation, data storage, or independent relative navigation performance capability. Consequently, battery life limited mission lifetime to approximately 24 hours, flight data transmission was limited to a real-time telemetry stream, and relative navigation evaluation was limited to inferring performance from telemetered imagery. Despite these constraints, the XSS-10 program laid the foundation for a whole new approach to space support missions.

The Air Force launched the Micro-Sat, from Cape Canaveral on 29 January 2003 attached to the second stage of a Delta II. Eleven orbits later, the Micro-Sat ejected from the orbiting Delta II second stage and successfully completed a brief series of semiautonomous maneuver and proximity operations using the Delta II second stage as the RSO. The XSS-10 mission objectives focused on a set of operations intended to demonstrate and evaluate the performance of semi-autonomous relative navigation, maneuver, RSO tracking and real-time communication technologies needed to successfully conduct proximity operations.

For each mission objective, the program set associated minimum and full success criteria in terms of quantitative performance metrics. A key component of the post-flight review was to verify and validate the experiment performance results. This included an independent re-interpretation of the guidance, navigation, and control telemetry to confirm the maneuver results. Since the XSS-10 Program did not collect precise Micro-Sat or Delta-II second stage relative position information, the post-flight review used an independent image analysis to infer the navigation distances as confirmation of the performance of the autonomous navigation algorithms. The analysis determined that XSS-10 fully met all objectives and success criteria with one possible exception.

The post-flight review could not confirm successful completion of operations at one of five primary navigation points due to a temporary loss of signal for the real-time telemetry, which included imagery from the tracking camera. XSS-10 had no on-board recording capability, so loss of the telemetry resulted in permanent loss of flight data for operations at that navigation point. However, flight data both before and after the loss of signal are consistent with the planned proximity operations at the fifth navigation point. The post-flight review determined that the available flight data provides strong circumstantial evidence that there is a high probability that the XSS-10 Micro-Sat met this last objective as well. The program also set and met important extra credit objectives.

During development the XSS-10 program instituted several processes and procedures the post flight review team determined to be best “practices”. Among these were the use of an AFRL-led integrated product team to manage and conduct integration and test activities, the use of a spiral development approach supported by test beds and auto-code generation tools to incrementally build and test flight software concurrently with hardware, and the use of a mission simulator to train the flight operations team and validate mission activity plans and commands.

Due to early hardware decisions and continuing funding constraints, XSS-10 was not able to include an onboard flight data storage unit or independent relative navigation performance evaluation system on the mission. This created difficulties in both acquiring and analyzing flight data. In general, the post-flight review team strongly recommends programs provide accurate and sufficient instrumentation to determine critical mission and technology performance, confirm successful completion of mission objectives, and assure this information is captured for later analysis.

# 2.0 XSS-10 Mission

The program mission was to “…develop, integrate, and deliver on orbit, a Micro-Sat which demonstrates typical satellite operational functions utilizing the Air Force Satellite Control Network (AFSCN) for Tracking, Telemetry and Commanding (TT&C) operations.” The specific mission was to demonstrate “…the proximity operations with a resident space object, employing a semi-autonomous, maneuverable space vehicle communicating with command and control sites via a space/ground link.” Beyond this, AFRL and AFSPC set some general goals for the program. These included “…space qualification of an integrated Micro-Sat system, space qualification of advanced and state-of-the-art subsystems, and demonstrated capability and agility of a Micro-Sat for rendezvous and inspection missions.” The subsystems to be space qualified included a miniature satellite to ground link system (SGLS) transponder, a light weight integrated star tracker and visible imager, and flight software for proximity operations.

## 2.1 Mission Objectives and Success Criteria

The XSS-10 mission objectives focused the proximity operations mission demonstration on a set of operations intended to evaluate the application of system and technology solutions to AFSPC space control mission deficiencies. The objectives are listed below:

- Execute free flight of a space system of approximately 25 kg, defined as a ‘Micro-Sat’.
- Communicate real-time with ground sites with two-way link.
- Maneuver around a resident space object based on visible imaging, relative position knowledge, and inertial position/attitude knowledge.
- Demonstrate station-keeping capability relative to a resident space object continuously.
- Demonstrate life extension (‘Sleep’) mode for a Micro-Sat.
- Obtain images of the microsatellite ejection and initial maneuvers about a resident space object.

Associated with each requirement were corresponding minimum and full success criteria. The accomplishment of the minimum success criteria described as mandatory to a successful demonstration of system element functionality. So to be minimally successful XSS-10 needed to achieve the following:

- Deliver and release one Micro-Sat on-orbit.
- Establish real-time RF link between the Micro-Sat and the AFSCN.
- Perform maneuvers about a resident space object.
- Perform three points of an autonomous inspection about a resident space object.
- Acquire and track a resident- space object with the Micro-Sat visible sensor.
- Demonstrate station-keeping capability relative to a resident space object continuously.

XSS-10 successfully completed all minimum success criteria. The full success criteria extend the minimal criteria to validate specific technology performance. Consequently, to be fully successful XSS-10 needed to accomplish the following:

- Establish real-time RF link between the AFSCN and both the Micro-Sat and ELV-VAS simultaneously.
- Perform continuous track during maneuver between two inspection points.
- Perform 100% of an autonomous five-point inspection about a resident space object.
- Demonstrate Micro-Sat axial maneuvering while imaging capability.
- Demonstrate life extension ('Sleep') mode for a Micro-Sat.
- Obtain images of Micro-Sat ejection and initial maneuvers about a resident space object.

## 2.2 Systems Description

The XSS-10 system consisted of six major elements — the Micro-Sat, an expendable launch vehicle (ELV), the Sconce Payload Platform (SPP), the Sconce Electronics Platform (SEP), developmental test beds and training simulators, ground support equipment (GSE), and the mission operations architecture. The ELV for the XSS-10 mission was the Delta II. The primary payload for this flight was a Global Positioning System (GPS) satellite. The Micro-Sat, SPP, and SEP rode as a secondary payload on the Delta II second stage. Figure 1 shows the Micro-Sat/SPP and SEP mounted on the Delta second stage below the GPS primary payload. In figure 1 below the micro-sat systems and subsystems are depicted. The Delta II second stage also served as the RSO for the mission. The Micro-Sat was a fully functional spacecraft capable of semi-autonomous operations. Its dry weight (including ballast) was 26.98 kg. It carried 2.58 kg of monomethylhydrazine (MMH) and nitrogen tetroxide (NTO) propellant and 0.70 kg of nitrogen pressurant. Thus the total wet weight of the Micro-Sat was 30.25 kg. The XSS-10 was 81.28 cm in length by 38.1 cm in diameter. Four lateral divert thrusters used the MMT/NTO bi-propellant to maneuver the Micro-Sat through the mission sequence. Eight attitude control system (ACS) thrusters used the gaseous nitrogen propellant to ensure the Micro-Sat moved to the correct orientation

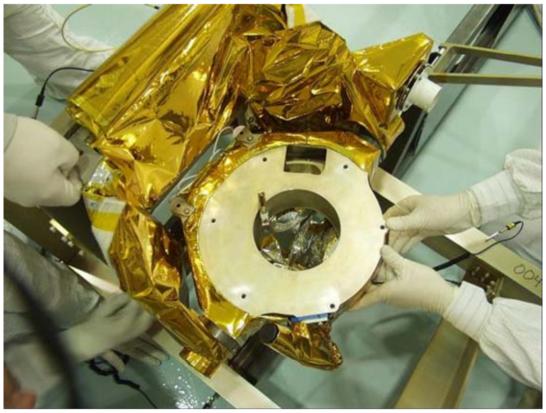

**Figure 1: Sconce Payload Platform**

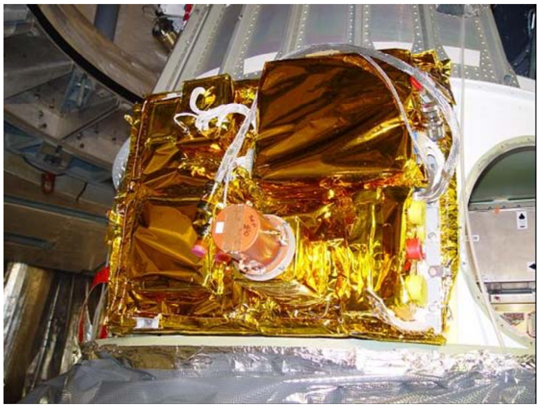

**Figure 2: Electronic Interface Unit**

for each mission event. The Micro-Sat visible camera system (VCS) mission sensor collected images of the RSO at designated inspection points. A star tracker integrated with the VCS provided attitude determination. GN&C and digital signal processing flight software resided on five digital signal processors (DSP).

The SPP served as the mechanical and electrical interface between the Micro-Sat and the ELV. It also provided a platform on which to mount the SEP witness camera. The SEP provided power and telemetry routing between the Micro-Sat and the GSE before launch and between the Micro-Sat and Delta II prior to Micro-Sat separation. In addition, it controlled all timing functions prior to Micro-Sat ejection. The SEP also provided a witness camera system mounted on the SPP to observe the separation and initial maneuvers of the Micro-Sat and telemeter the live video to the ground. A series of test beds simulated the Micro-Sat during software development and mission training. This included processor-in-the-loop (PIL) and hardware-in-the-loop (HIL) test beds used to test software builds and hardware-software integration. It also included a mission simulator (MSIM) built and used to validate commands and train the flight operations team. GSE provided command and control of the flight and test hardware and software during integration and test.

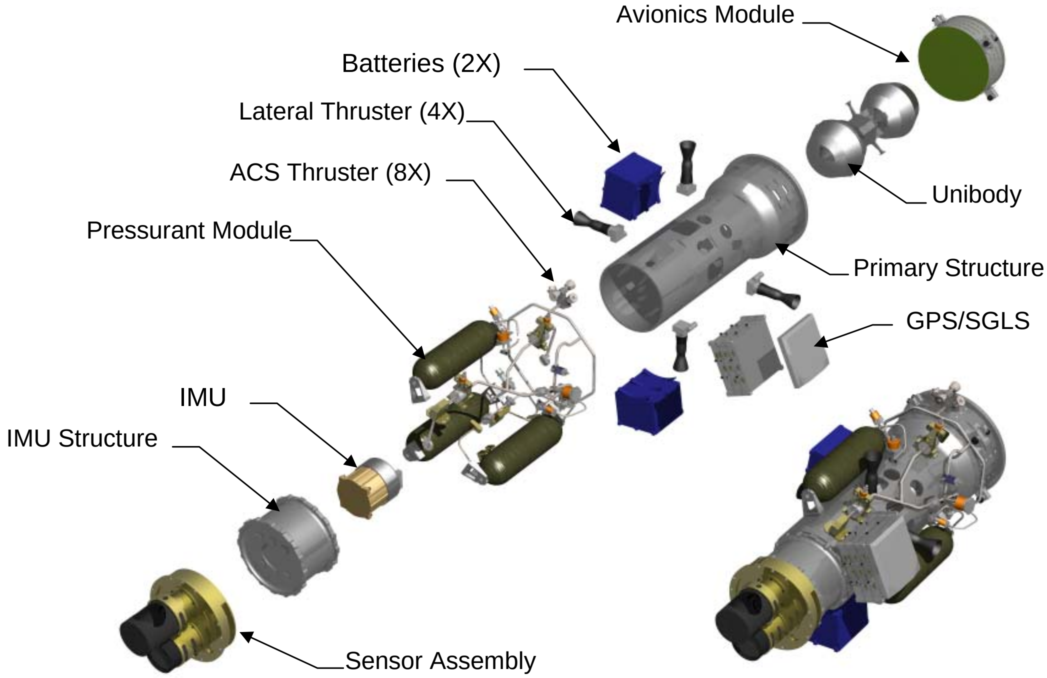


**Figure 3: Micro-Sat Systems Description**

The AFSCN provided ground stations for receiving Micro-Sat and witness camera telemetry and up-linking Micro-Sat commands. The SMC RDT&E Support Center (RSC) at Kirtland AFB served as the operations center for the mission. The AFRL Payload Test Center (PTC) housed the Micro-Sat flight engineers and was co-located with the RSC. Together the AFSCN, RSC, and PTC formed the XSS-10 mission operations architecture.

## 2.3 XSS-10 Team

An integrated Government-industry team conducted the XSS-10 program. Core Government team members consisted of AFRL, SMC, and AFSPC. Industry team members included the Rocketdyne and Launch Services Divisions of Boeing, Octant Technologies, Jackson and Tull Engineering, SPARTA, SAIC, Swales Aerospace, and Ingenium Spacecraft Engineering. These organizations worked very closely as an Integrated Product Team (IPT). Together they were able to design, develop, fabricate, integrate, and test the various system components as well as successfully carry the system through launch and mission operations. Government participation included management, development, and operations responsibilities. The AFSPC Requirements Directorate provided overall XSS-10 mission selection and direction. AFSPC also provide flight operations support through the AFSCN. The Space Vehicles Directorate of AFRL served as the XSS-10 program manager and led integration and test operations. SMC provided the primary mission control node at the RSC as well as Delta II launch vehicle procurement and integration services. The SMC GPS system program office was responsible for the primary Delta II payload and launch.

Boeing provided the spacecraft. They designed, fabricated, integrated and tested the flight and qualification vehicles, test equipment, and auxiliary support systems and launch vehicle electrical interface equipment. In addition, Boeing Launch Services, Huntington Beach, supported the launch vehicle trade studies and space vehicle to launch vehicle interface issues.

Octant developed the guidance, navigation and control algorithms and flight software. They also developed and tested the HIL test-bed systems for component integration and test, the PIL test-bed system for flight software build qualification, the MSIM dynamic vehicle simulation for mission exercises and rehearsals, and the command and telemetry displays for the PTC.

Jackson and Tull, together with AFRL, formed the systems engineering, integration, and test team based at Kirtland AFB, New Mexico. They also provided support to ground operations. Ingenium, under contract to Jackson and Tull, also supported systems integration and test, including ground support equipment development and test, and the mission operations development effort.

Swales Aerospace developed the SPP that ejected the Micro-Sat from the Delta II upper stage. They also performed the dynamic model analysis for the integrated system. SPARTA supported the program office with systems engineering, mission planning, and system safety. SAIC provided the VCS design and hardware.

## 2.4 Development and Mission Chronology

AFRL created the XSS-10 program after the President canceled the Clementine II asteroid rendezvous program via line-item veto in October 1997. Consequently, AFSPC and AFRL created XSS-10 to accomplish many of the Clementine II technology goals. Initially AFRL worked with National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) to manifest the XSS-10 flight for a Space Shuttle mission. By April 1999, the program passed both the preliminary and critical design review milestones and selected the Spartan 251 carrier as the host platform. Unfortunately in the same month, NASA announced that they could not manifest XSS-10 because of higher priority NASA missions. The program office immediately started exploring other launch options.

From May until October 1999, the program evaluated four different expendable launch vehicle options — Taurus, Pegasus, Minotaur, and Delta II — and determined that launch as a secondary payload on a scheduled Delta II GPS III replenishment mission offered the best overall opportunity. As a final step in this process, the program held a preliminary design review (PDR) for the spacecraft in October 1999 “to review and receive concurrence that the refined XSS-10 system and mission designs were compatible with Delta II". While generally compatible, shuttle era design decisions limited XSS-10 experiment operations in some important ways. Most notably, were the lack of an onboard flight data storage capability and the absence of instrumentation to independently measure relative navigation performance.

From October 1999 to November 2000, Boeing built the Micro-Sat and performed an initial pre-ship functional test. They delivered the Micro-Sat to the AFRL Aerospace Engineering Facility (AEF) in November 2000, where Jackson and Tull and AFRL members of the IPT prepared the Micro-Sat for system integration. Preparation included installing flight blankets, cleaning up Micro-Sat harness routing, and installing the ejector mechanism. The IPT then integrated the Micro-Sat with the SPP provided by Swales Aerospace and the SEP built by Jackson and Tull and AFRL. This culminated with an integrated functional test that served as a baseline for subsequent functional tests that the IPT performed after each system environmental test. Results of systems testing were very positive. The IPT observed consistent performance throughout the program and encountered no failures during vibration and shock. The IPT did discover and correct three failures in avionics' processing of image data.

The final system testing consisted of a series of functional tests, system verification, and alignments. The test sequence included: witness camera verification, plugs out testing, outdoor stellar acquisition verification, vehicle alignment verification, RF and self compatibility testing, factory compatibility tests, launch base compatibility tests, vibration and shock, thermal vacuum, thermal cycling, system center of gravity, and moment of inertia testing. The IPT successfully completed all tests and shipped the flight articles from Kirtland AFB to Cape Canaveral Air Force Base on 21 June 2002. Integration activities at the Cape included many functional tests, RF compatibility testing, fueling and pressurization, measuring center of gravity and moment of inertia of the fueled Micro-Sat, and integration with the Delta II. These were performed at three facilities — the NavStar Processing Facility (NPF), the DSCS Processing Facility (DPF), and Delta II launch pad B. Due to launch vehicle and primary payload delays, XSS-10 launch preparation and integration extended from June 2002 to January 2003. During this time the IPT deployed to the Cape on three different occasions to conduct extremely successful launch integration. The most difficult part was maintaining sufficient flexibility to accommodate changing launch vehicle and primary payload schedules. At 18:06 GMT on 29 January 2003, XSS-10 was successfully launched from Cape Canaveral AFB. The launch inserted the Delta II second stage into an approximate 800 km circular orbit inclined at 39.6°. The RSC/PTC flight operations team used the first 10 orbits to track the Delta II second stage, checkout the VCS, and prepare the Micro-Sat for mission operations. They ejected the Micro-Sat on schedule on rev 11.1 at 12:03:40 GMT on 30 January.

## 3.0 Mission Performance

After ejection, the Micro-Sat stepped through a pre-planned mission sequence that included maneuvering the Micro-Sat to four primary navigation points and then to an extra credit station. Figure 4 shows the primary mission sequence and geometry. The Micro-Sat completed all mission operations in two contiguous ground site passes – BOSS and LION – lasting a total of about 23.5 minutes. At the first three primary mission stations the Micro-Sat maintained an approximate 100 meters separation with the RSO. At the third navigation point the Micro-Sat performed a move and stare operation. At the fourth, it planned to, and apparently did, perform a "v-bar" maneuver to close its separation with the RSO to about 50 meters. A telemetry dropout occurred at 12:14:25 GMT when the ground station (BOSS) lost signal. The dropout lasted for three minutes, fifty-three seconds, causing the loss of video and health and status data from the Micro-Sat for the fourth inspection operation. The cause of telemetry dropout is not known. The AFSCN (LION) reestablished contact with the Micro-Sat at 12:18:18 GMT when it was 800 meters from the Delta on its way to the extra credit navigation point.

When the Micro-Sat reached 1 kilometer, it stopped and slept for 10 seconds. It then woke and turned to look for the Delta II in its last known location. The RSC/PTC then transmitted the extra credit block command and the Micro-Sat maneuvered toward the Delta. About two minutes later, the RSC/PTC transmitted commands to abort the extra credit rendezvous because they could not determine if the Micro-Sat VCS had acquired the Delta. The RSC/PTC then transmitted the commands to perform the orbit-lowering maneuver per the plan, and mission operations were terminated at 12:26:57 GMT. The After this maneuver, Lincoln Laboratory measured the Micro-Sat final orbit to be 815 by 531 kilometers with an inclination of 39.8°.

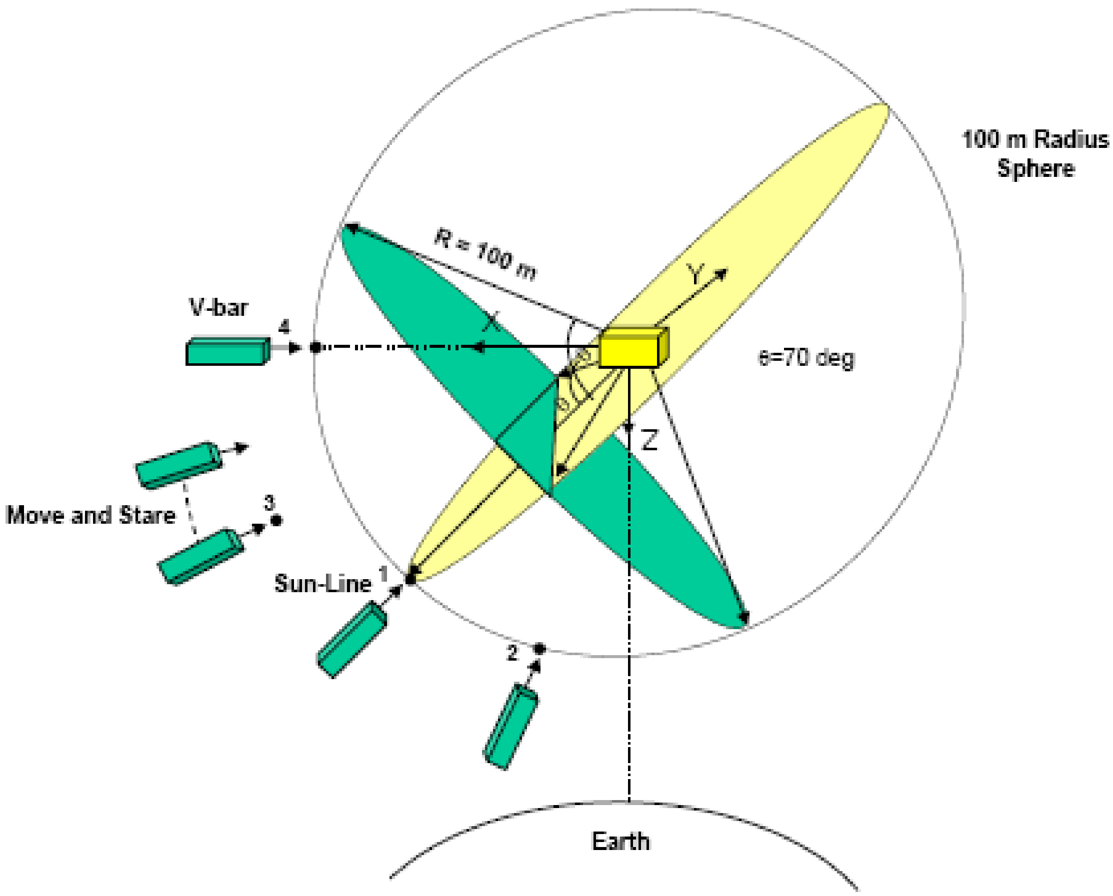


**Figure 4: Mission Design Diagram**

## 3.1 Relative State Navigation

The XSS-10 Micro-Sat used relative state navigation to guide it through the mission sequence. The GN&C software defined relative state in a Local-Vertical-Local-Horizontal (LVLH) reference frame with the Delta second stage RSO at the center. The flight software propagated the navigation state using the Clohessy-Wiltshire formulation for the relative motion of two closely located spacecraft. The relative orbit propagator started with initial vehicle position (meters) and velocity (meters/second) and then integrated accelerometer readings from the inertial measurement unit (IMU) to generate new relative vehicle position and velocity estimates in meters and meters/second respectively. The GN&C software updated the relative state by combining RSO image data from the VCS and DSP with the on-board relative state propagator while tracking the RSO at navigation points. (FOV) for point 0 plus the first three inspection points. A perfect inter point maneuver would put the RSO centroid in the center of the VCS FOV. Off-sets from the center represent error in the relative state estimate. The GN&C software used this centroid location information to update the relative state at each point except point 0. Since relative navigation errors continue to propagate beyond point 0, the relative state estimate error at IP-1 is larger than at P-0. A temporary loss of signal during IP-4 operations prevented ground station receipt of telemetry. Consequently, the relative navigation state at this point is unknown.

### 3.2 Proximity Operations

XSS-10 proximity operations consisted of relative velocity adjustment maneuvers to transition between the four primary navigation points as well as attitude adjustment and tracking maneuvers at the navigation points to center and track the RSO in the VCS imager FOV and update relative navigator. Operations at IP-3 combined velocity adjustment and tracking to perform a "move and stare" maneuver. Operations at IP-4 included a "vbar" maneuver that closed on the RSO along a radial path to within 35 meters and then radially out to the extra credit point located one kilometer from the RSO. Planned operations at the extra credit included a sleep, wake, and RSO re-acquisition sequence using the VCS star camera followed by a closing maneuver to bring the Micro-Sat within 200 meters of the RSO. To perform the proximity operations the Micro-Sat ejected from the Delta second stage about 35 degrees from the orbit normal. The exact direction is not known because the Delta was rotating about 1 rpm and coning. After moving about 100 meters the Micro-Sat divert engines fired to null the separation velocity, the ACS zeroed out rotational rates, and the Micro-Sat began initialization operations. This initialization point is designated P-0, but is not indicated on the mission diagram in figure 4. At P-0 the Micro-Sat initialized proximity operations by transitioning to stellar acquisition mode and performing a full field search to determine its attitude. This initial attempt to obtain an attitude solution was unsuccessful. Post-flight analysis by Octant indicates that this was caused by bright objects – sun, earth, moon, or Delta second stage — within the star camera exclusion angle after the first three slews and insufficient time to find a "lost-in space" solution after the fourth. Analysis of witness camera video, also suggests that ejection debris may have prevented the star camera from finding a star pattern with which to determine an attitude solution. The Micro-Sat then transitioned to the RSO track mode where it

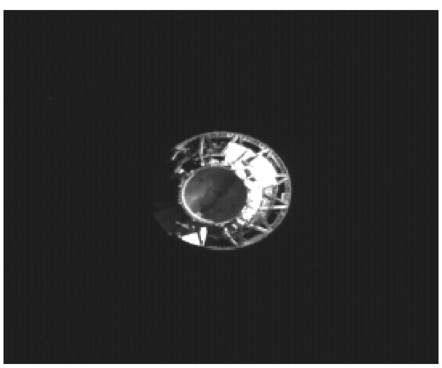

**Figure 5: Image from P-0**

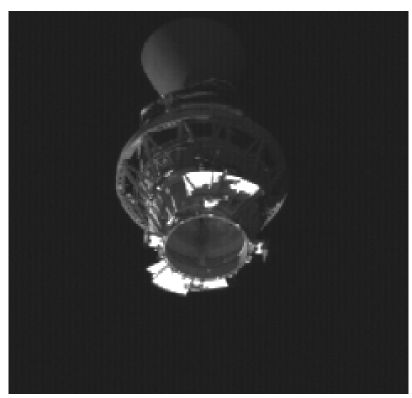

**Figure 6: Image from IP-2**

successfully captured the RSO in the camera FOV. Figure 5 is one of several images taken from P-0 and shows that the Micro-Sat is looking at the nose of the RSO as planned. The initial failure to obtain an attitude solution triggered an attitude acquisition contingency which initiated entry into a second stellar acquisition mode upon exiting the RSO track mode. In this attempt the Micro-Sat successfully acquired star measurements and determined an attitude solution. The ground then commanded the Micro-Sat to resume mission queue execution and at this point the proximity operations began. The XSS-10 Micro-Sat then maneuvered to its first inspection position (IP-1). IP-1 was located approximately 100 meters from the RSO — about the same separation distance as P-0 — along the Sun-line. Distance from the RSO means distance from the estimated center of mass. The total maneuver time was 22 seconds. The maneuver time is defined to be the time from the start of the rotation of the satellite to align the divert thruster until acquisition of the next RSO. After an attitude update, the satellite entered the RSO track mode, acquired the RSO, centered it in the camera field of view and tracked for 11 seconds. Figure 7 shows one of the images from IP-1. It is evident that there are no shadows, indicating the position is along the sun vector.

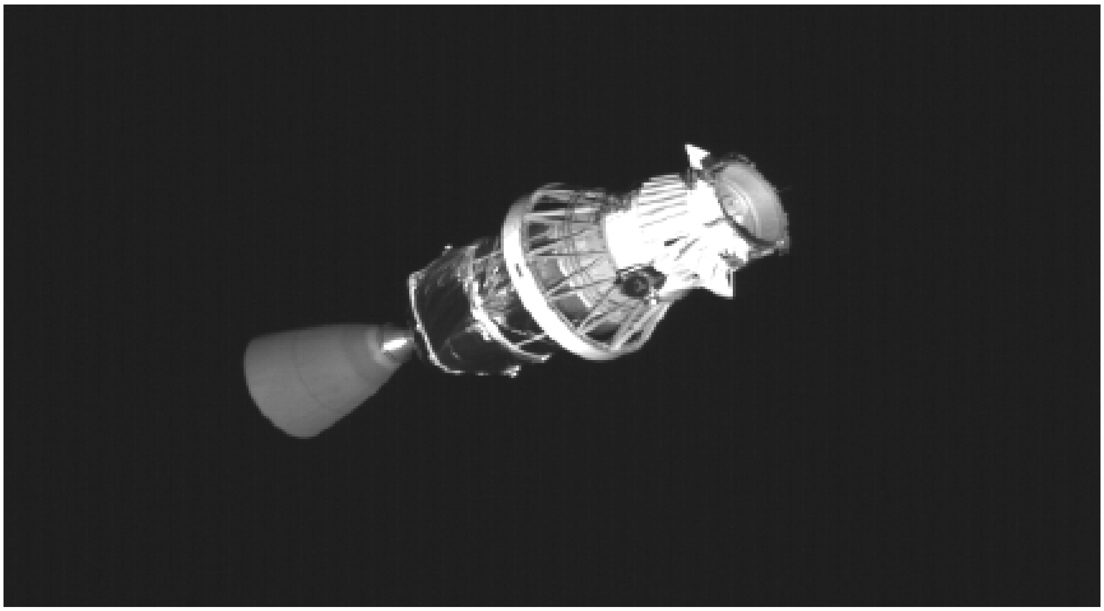

**Figure 7: Image from IP-1**

The Micro-Sat then exited the RSO track mode and maneuvered to IP-2, which was separated from IP-1 by about 78 meters. The Micro-Sat detected the RSO, centered it in the FOV and tracked for 14 seconds. IP-2 is about the same distance from the RSO as IP-0 and IP-1 but has moved below and to the right as shown in Figure 6. Since it moved about 78 meters, this would mean a rotation of about 45 degrees from the RSO nose. The Micro-Sat then maneuvered approximately 90 meters to IP-3, which was located about 119 meters from the RSO. After acquiring the RSO, the Micro-Sat began a velocity adjust maneuver and stared at the RSO while moving. This mode was performed for 74 seconds. IP-3 was back near the sun-line and the translation here was about 90 meters. Figure 8 shows the launch vehicle from IP-3. A comparison of imagery indicates that the separation between the Micro-Sat and the RSO increased during the staring maneuver.

The Micro-Sat then zeroed out the relative translational motion and started the maneuver to IP-4, which was located about 100 meters along the RSO velocity vector. As it was approaching IP-4 the ground station (BOSS) lost telemetry. The planned maneuver was to acquire IP-4 then move to within 35 meters of the RSO, and then back off to a distance of one kilometer. When the next ground station (LION) regained contact after approximately four minutes, the Micro-Sat had moved to about 800 meters from the RSO and was heading to a planned extra credit standoff position of one kilometer. Thruster firing data in the telemetry received indicated that a maneuver had occurred, and the data was consistent with the end-state expected for the planned maneuver. However, no direct confirmation of IP-4 operations is possible since the XSS-10 Micro-Sat could not store images on-board during the loss of signal. Also, while the witness camera mounted on the SPP provided useful independent information regarding Micro-Sat ejection, it could not, and was not intended to, provide independent measurement of proximity operations.

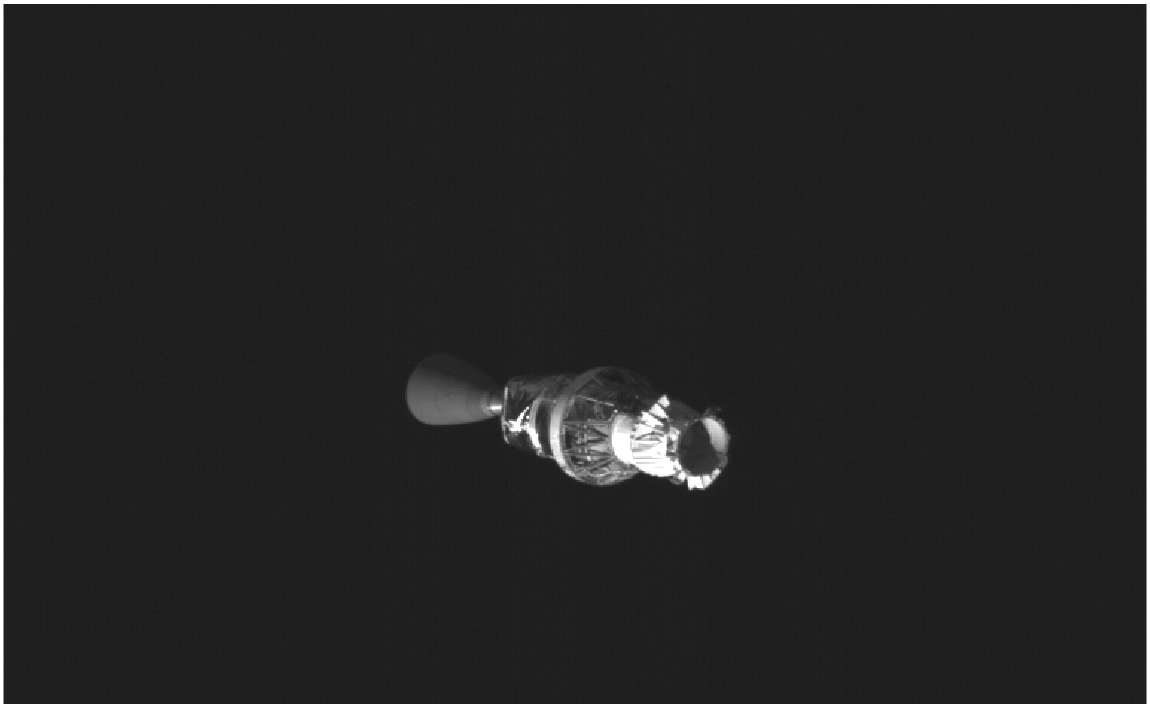

**Figure 8: Image from IP-3**

Upon reaching the extra credit point, the Micro-Sat went into sleep mode for 10 seconds as planned. When it awoke, it tried to re-acquire the RSO using the VCS star camera. (The Micro-Sat used the VCS imager to acquire the RSO at primary inspection points.) However, the star camera did not successfully acquire the RSO because the background intensity was high and the auto exposure function did not correctly adjust the RSO intensity adequately for tracking. Figure 9 shows the image of the Delta II second stage as seen by the VCS star camera at the extra redit point. The small extended object in the center of the image is the Delta second stage as seen from approximately one kilometer. The bright vertical line in the image is charge coupled device (CCD) vertical saturation caused by setting the star camera integration time too long. The review team did not analyze the extra credit image to confirm separation distance. The Micro-Sat then started a closing maneuver on the RSO, but the RSC/PTC flight operations team aborted this extra credit maneuver when they could not determine that the Micro-Sat had acquired the Delta II second stage. The RSC/PTC team then terminated the mission by commanding the Micro-Sat to "de-orbit". The de-orbit maneuver lowered the Micro-Sat's perigee to about 531 kilometers.

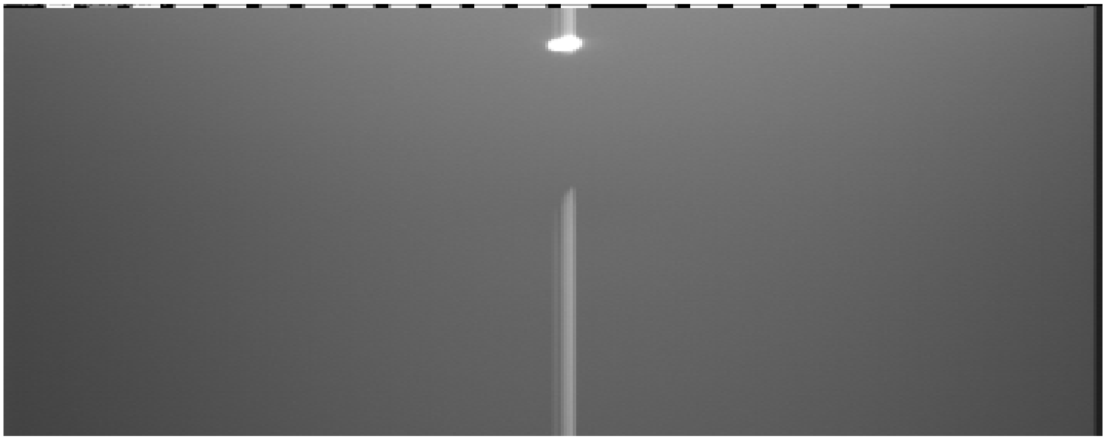

**Figure 9: Image at Extra Credit Point**

## 3.3 GN&C Performance Evaluations

Since XSS-10 did not have instrumentation to provide truth data for independent validation of relative navigation performance, the PFR study team used flight telemetry as well as RSO size and orientation in VCS imagery to analyze performance at the three navigation points. Due to a temporary loss of signal, there are no estimates for inspection point four. The XSS-10 team planned to operate with an approximate Micro-Sat to RSO centroid separation of 100 meters for these inspection points. An independent post-flight analysis performed by the review team using flight telemetry and the Clohessy-Wiltshire equations of relative motion. The PFR maneuver analysis started with the flight software solution at P-0 used essentially the same data and methods. The results track the flight software very closely and confirm that the flight software generated the intended velocity adjustment maneuver solutions. With the exception of P-0, the image analysis results show reasonable agreement with the GN&C software. The P-0 results exhibit a slightly larger difference between the GN&C flight software separation estimate and the image analysis. Despite this difference, the image analysis confirms the GN&C software maintained the desired approximate 100 meter separation between the Micro-Sat and RSO.

## 3.4 Mission Success Evaluation Summary

XSS-10 meets all minimum, and conditionally met all primary mission success criteria. The PFR team verified that the Micro-Sat successfully completed operations at navigation points 0 through 3. However, the team could not verify successful completion of the v-bar operation at navigation point 4 due to a temporary loss of signal and, therefore, permanent loss of telemetry and images at that point. Neither the XSS-10 nor the post mission analysis team performed an in-depth investigation of the cause or consequences of the temporary loss of signal; however, all information before and after the loss of signal is consistent with successful completion of the inspection objective at point 4. In particular, command history and propellant telemetry downloaded after the loss of signal indirectly corroborates this conclusion.

# 4.0 XSS-10 Accomplishments

The major accomplishment of the XSS-10 program was the development and demonstration of microsatellite hardware, software, and operations procedures for the autonomous inspection of resident space objects. In so doing the program demonstrated a degree of autonomy that is a step beyond anything the Air Force has flown in space before. Proximity inspections require agile spacecraft, precision flight software, autonomous operations, and effective ground support. The XSS-10 spacecraft was built using legacy hardware from the Lightweight Exo-Atmospheric Projectile (LEAP) program. The developments in hardware included a unibody propulsion system, a miniaturized SGLS transponder, high capacity lithium-ion batteries, and a low cost VCS. The flight software executed closed-loop GN&C algorithms that performed scripted top-level commands sent from the ground. The script told the satellite what to do (i.e., move to inspection point 2) and the satellite determined its configuration, location and attitude, the actions it had to accomplish to perform the task, and then executed that set of actions. The XSS-10 program accomplished several important "firsts". These included:

- Demonstration of a unibody propulsion system on-orbit;
- Demonstration of GN&C software mode sequence control to move from one mission phase to the next;
- Demonstration of a relative navigation scheme based on centroid information from a tracking camera;
- Demonstration of a RSO track function that locked on to the Delta II second stage RSO at every primary navigation point where telemetry data exists; and
- Demonstration of avionics that transitioned into and out of "sleep" mode to conserve battery power during the mission.

While several individual functions have been demonstrated on other spacecraft for other applications, this is the first time they have been successfully implemented on a microsatellite performing proximity operations around an RSO. In demonstrating these capabilities, the XSS-10 flight addressed two sets of AFSPC mission needs — space access/mobility and counterspace — and three AFRL/VS technology interests

- proximity operations,
- autonomous control, and
- responsiveness.

The XSS-10 flight was a strong first step in demonstrating technology that will enable micro satellites to maneuver and service on-orbit satellites and opens the door to a number of new missions in using micro-satellites for space situation awareness.

# 5.0 XSS-10 Lessons Learned

The lessons learned during the XSS-10 program can be best understood in the context of program development (teaming, organization, and concept development), system integration (the tools, components, and testing), operations (training and mission operations), and post-flight analysis and reporting (documentation and data analysis).

## 5.1 Program Development

***A Government/contractor integrated product team provided an effective approach to integration and test.*** The IPT structure flowed from a logical breakout of skills brought by each participating organization. The IPT included contractors, Government employees, and military working seamlessly as a single team. This small-motivated team resulted in excellent communications, tighter system engineering, smoother working relationships, and fewer "dropped balls". In addition, the IPT approach builds core internal capability and infrastructure that strengthens AFRL/VS position as the Laboratory's space system demonstration lead. The AFRL-led IPT approach is in marked contrast to the typical Air Force prime contractor approach and requires the dedication of sufficient in-house resources to effectively manage and conduct the program.

***Stable program management was essential to maintaining team focus***. Turnover of program managers early in the program caused gaps in continuity, loss of momentum, changes in direction, and frustration among both contractor and Government members of the team. These problems were alleviated when AFRL/VS selected a full-time program manager assigned for the duration of the program.

***Explicitly identifying total system performance responsibility was essential to effective management***. Each contractor was responsible for making sure their particular component or system worked, but until the Government took on the total system performance responsibility to ensure the integrated system functioned, no one organization had end-to-end responsibility for the system.

***The launch vehicle was not "locked in" as part of the initial acquisition strategy.*** The XSS-10 program lost valuable time and substantial resources due to launch vehicle uncertainty and changes. Specifying the launch vehicle early would have substantially reduced the need for mission requirement changes and system redesign. The ultimate impact of the loss of the Space Shuttle as a launch vehicle can be counted in millions of dollars and a two to three year delay in launch.

***Selecting hardware prior to specifying mission requirements and top-level vehicle specifications resulted in reduced mission capability and increased costs.*** A "hardware is life" philosophy was allowed to drive mission requirements instead of mission requirements driving the hardware design. This resulted in unforeseen design limitations, and ultimately, increased costs. While legacy hardware designs are used to control risk, creating a new program around existing leftover hardware may cost more (in actual cost or in mission capability) than developing new hardware to meet the program requirements and specifications.

## 5.2 System Integration

***The processor-in-the-loop test bed provided a valuable closed loop test capability of the GN&C software***. The PIL provided a means to incrementally build and test flight software. It was also invaluable during qualification testing and simulation of test cases that were executed during the air bearing test. It allowed the ground support equipment to be introduced into the mission simulation and internal system qualification. It also provided a closed loop scene ejection capability for the Visual Camera System emulation.

***The hardware-in-the-loop test bed reduced program risk by validating flight hardware and software during integration and the outdoor star sensor test.*** The purpose of the outdoor star sensor test was to integrate hardware and software testing of the attitude determination and attitude update functions of the GN&C and DSP system. A secondary objective of the test was to further test the inertial measurement unit processing function within the GN&C software.

***The mission simulator provided a great training and simulation capability***. The MSIM added fidelity to the training scenarios and allowed new personnel to learn the mission and Micro-Sat capabilities quickly. In this way the MSIM ultimately reduced the mission risk introduced by personnel changes caused by the launch delays. Although the XSS-10 team did not need to, the MSIM could have validated real-time commands prior to upload during flight operations. The PFR team recommends that future flight demonstrations use mission simulators to improve operations team training and validate mission plans and commands.

***The use of the Satellite Toolkit/Visualization tool provided a realistic view of the mission and an increased sense of the Micro-Sat geometries and situational awareness***. It helped personnel visualize the complex Sun/Earth/Moon/RSO/ Micro-Sat geometries involved in the inspection scenarios.

***The lack of good document configuration control resulted in extra development costs.*** The command and telemetry list created by the flight software developer became a key tool used by the RSC developers. Unfortunately, there was a lack of configuration control of the list and that created inconsistencies leading to corrupted software interfaces between the spacecraft and the RSC. This ultimately had cost and schedule impacts.

***Prescreening electronics interface unit relays prior to testing and integration into the Electronic Interface Unit (EIU) would have saved time and money***. These units were not screened and failed during vibration testing. The relays were up-screened, cleaned, the magnets strengthened, and an attenuator added. Had they been properly screened, these steps would not have been necessary.

***An accurate pixel map determined prior to the start of operations would have permitted the GN&C system to ignore bad pixels***. There were bad pixels on the Star Camera focal plane array that did not show up in testing. The bad pixels in the camera could cause the GN&C system to misidentify them as stars – increasing the time to determine spacecraft attitude and could have caused mission failure on a longer mission.

***On orbit, the image display system (IDS) in the GSE began overwriting visible camera system images***. This problem never occurred on the ground during testing. Poor quality of the telemetry from the spacecraft may have caused the IDS to start numbering images with a lower value. No definite cause was determined, but this should be investigated in depth and fixed prior to follow-on missions.

***Better thermal load analysis would have provided more accurate thermal loads and battery sizing requirements***. The Delta II second stage battery consumption prior to ejection was less than expected, due in part to a higher temperature, reducing the need to power component heaters.

## 5.3 Operations

***Training was the key to success for XSS-10 mission operations***. Significant launch delays and the need for real-time flight operations made training and rehearsals essential to mission success. Train early, train often, and avoid "cowboy" operations by developing procedures, and sticking to them was a philosophy that served the program well. Training days immediately prior to rehearsals increased operational focus during rehearsals.

***Rehearsals provided opportunities to coordinate with external outside agency support.*** There were three exercise/rehearsals with the external agencies providing orbit data. The focus of the exercises was coordination of external agency support. Timing and data formats were established during these exercises. They were invaluable in focusing the team, and getting feedback on technical approaches in real-time. One problem was that during operations development, technical advisors introduced unnecessary alternative procedures to what turned out to be well thought out and satisfactory initial procedures. As a result the operations team lost valuable training.

***A close working relationship with the launch vehicle program office, launch site, and launch preparation team, enabled the program to react to, and avoid, delays.*** The ground operations working group provided an effective forum for timely coordination of launch preparation activities. A close working relationship with the launch vehicle program office allowed the XSS-10 program to work critical launch vehicle integration and potential demanifesting issues before they became major problems.

***Strong senior leadership advocacy greatly facilitated launch preparation resource availability and support effectiveness***: The XSS-10 program office was very effective in communicating the military value of the program to senior Air Force leadership. As a result the program secured strong advocacy from SMC/CC, 14th AF/CC, and others.

***Mnemonics on the RSC displays would have expedited real-time commanding.*** The RSC displays did not contain command verification mnemonics for the Micro-Sat telemetry.

***The lack of Delta II second stage attitude information prior to Micro-Sat ejection resulted in some inefficient use of mission time***. The Micro-Sat constructed its ejection profile in a temporary frame of reference until it could determine its attitude. Initial attitude determination was critical to accurately constructing the RSO LVLH reference frame and inspection positions. Valuable mission time was used in obtaining an attitude reference after ejection.

***The decision to use the star camera rather than the imager resulted in the loss of some extra credit objectives***. XSS-10 used the VCS imager to acquire and track the RSO at the primary inspection points, but at the extra credit point used the VCS star camera for this purpose instead because of its wider FOV. During the extra credit acquisition attempt the star camera focal plane saturated and was unable to acquire and track the RSO. In retrospect, the VCS imager would have been able to adequately adjust to the scene lighting conditions, and, given the short “sleep” time and associated drift, the VCS would have been a better choice. Alternatively, a more thorough extra credit scene analysis and effective star camera RSO acquisition algorithm would also have permitted successful completion of all extra credit objectives.

### 5.4 Post Mission Analysis

***The lack of attitude and relative position truth data hampered post mission analysis***. Due to early design decisions, the XSS-10 program did not provide instrumentation to collect in-flight relative navigation truth data to evaluate mission performance and confirm successful completion of maneuver and inspection objectives. For the same reason, the program did not provide on-board storage of images or other flight data to prevent loss of data if the real-time telemetry signal was interrupted. Where telemetry was available, the XSS-10 and PFR teams were able to partially reconstruct and infer mission performance and success for maneuver and inspection operations. Where flight data was not available, during the v-bar maneuver around IP-4, the XSS-10 and post mission analysis teams were only able to compare the Micro-Sat state before and after loss of signal and examine the command queue to confirm consistency with planned operations.

### 5.5 Best Practices

Three of the XSS-10 lessons learned rise to the level of space research and development community best practices. Where applicable, AFRL incorporate these practices in future programs.

***The use of an integrated product team brought the requisite skills, resources, and motivation to accomplish the mission.*** AFRL accepted total system performance responsibility for the integrated system. The team worked seamlessly between contractor, civilian Government employees, and military. The AFRL-led integration and test process found and corrected more than 50 anomalies, many that the contractor teams did not recognize as problems.

***Spiral development together with the extensive use of test beds and auto-code generation tools allowed the team to find and correct software and hardware problems early and quickly***. Early resolution of interfaces problems is a particular benefit of this incremental development approach.

***The use of the MSIM provided a well-trained cadre of personnel for the operations team***. The fact that training started early, provided the experienced personnel necessary for the short mission timeline and quick decisions required for mission success.

## 6.0 Conclusions and Recommendations

The XSS-10 program culminated with an exceptionally successful mission that demonstrated that it is possible to use microsatellite technologies to conduct semiautonomous proximity operations about, and close-in inspection of, resident space objects. The program also demonstrated the ability to quickly checkout spacecraft systems on-orbit and to provide real-time supervision of mission operations from the ground. In doing this XSS-10 has laid the foundation for a whole new approach to the space control and space support mission areas. Post mission evaluation of mission performance determined the program fully met all minimum and primary mission objectives with one possible exception. Successful completion of operations at one of five primary inspection points can not be confirmed due to a temporary loss of signal and a resulting loss of flight data at that point. However, since flight data both before and after the loss of signal was consistent with the planned operation at the fifth inspection point, post mission analysis determined that XSS-10 probably met this objective as well. The program also met important extra credit objectives. In retrospect, XSS-10's greatest accomplishment was that the mission flew at all. With the launch vehicle changes, system re-design, changes in program management, and all the other perturbations that rocked the program, the mission exceeded all expectations. This is truly a testament to the creativity and perseverance of the entire XSS-10 team. Beyond this, however, XSS-10's greatest accomplishment was the development and demonstration of microsatellite hardware, software, and operations procedures for the autonomous inspection of resident space objects. This included a number of firsts. Perhaps the most noteworthy of the operational firsts was demonstration of a relative navigation scheme for close-in inspection based on camera-derived RSO centroid information. Several XSS-10 activities are considered to be best “practices”. These included the use of an AFRL-led integrated product team to manage and conduct integration and test activities, the use of a spiral development approach that extensively used test beds and auto-code generation tools to incrementally build flight software and test it with engineering model and flight hardware, and the use of a mission simulator to train the flight operations team and validate mission activity plans and commands.

From a post-flight mission analysis perspective, the most significant XSS-10 lesson that future programs can benefit from is that providing on-board flight data storage and an independent means of measuring system performance is essential to verifying successful completion of mission objectives. Due to early hardware decisions and continuing funding constraints, XSS-10 was not able to include these capabilities on the mission. This resulted in a loss of data when the real-time telemetry signal was lost as well as difficulties in completely analyzing the flight data that was transmitted. With onboard data storage and either an on-board or remote means of independently measuring the relative navigation states of the XSS-10 Micro-Sat and the Delta II second stage RSO, post-flight analysis would have accurately determined navigation errors at each inspection point and unambiguously assessed operations during the temporary loss of signal. Objectives and criteria that can not be measured and adequately assessed lose their value. It is recommended that future demonstration programs provide sufficient instrumentation to determine critical mission and technology performance to the accuracy needed to confirm the successful completion of mission objectives and success criteria.

XSS-10 gained national recognition for the multiple mission successes receiving the Rotary National Award for Space Achievement and the AIAA 2003 Space Systems award. In conclusion, the XSS-10 program overcame significant obstacles to deliver an extremely successful flight demonstration of technologies and operational concepts critical to the successful development of microsatellite enabled, Air Force space control and servicing capabilities.

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