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The JAWSAT Mission:
Final Report and Lessons Learned

by

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Abstract

One Stop Satellite Solutions and the Center for Aerospace Technology recently completed the JAWSAT mission. This was the first flight of the Minotaur launch vehicle and the first time eleven separate micro and pico satellites were placed into orbit with one launch. The JAWSAT project required both new technical designs as well as new programmatic ways of conducting a space mission. Main stream, large satellite, methods were not adequate.

Technical lessons learned on this project range from new techniques in versatile, low-cost, structural design to a reasonable method of qualifying commercial off-the-shelf electronic components. New methods of final integration and ride sharing were also invented.

In program management, new methods in documentation, technical exchange, design review and reporting were developed. Lessons related to schedule, goals, budget, team building, logistics of personnel and materials, and risk assessment and management were studied and implemented. The positive and negative lessons learned in this large small-satellite mission will be of interest to the small satellite community and give insight to those who plan future missions.

1. Introduction

The combined groups of One Stop Satellite Solutions (OSSS) and the Center for Aerospace Technology (CAST) have recently completed the Joint Air Force Academy Weber State University Satellite (JAWSAT) mission. After two years of planing, building and testing, a successful launch occurred on January 26, 2000. JAWSAT became the first orbital launch of the new millennium and the first payload to be placed into orbit using the Minotaur launch vehicle. Minotaur was also the first launch vehicle created from surplus Minuteman ICBM components. This project has many other firsts which include: deployment of 11 independent satellites from a single Multi-Payload Adapter (MPA), the first three-axis attitude controlled bus for under five million dollars, broad, cross-organization, teaming and web based documentation with distributed management techniques.

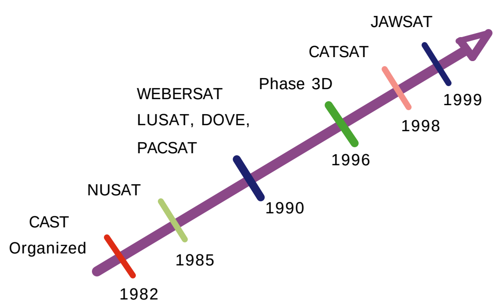

Figure 1 – OSSS/CAST Satellites

Early in the project it became apparent that if this most ambitious small-satellite mission were to be successful, the JAWSAT project would required both new technical designs as well as new programmatic ways of conducting a space mission. Main stream, large satellite, methods were not adequate.

Technical lessons learned on this project range from new techniques in versatile, low-cost, structural design to a reasonable method of qualifying commercial off-the-shelf electronic components. New methods of final integration and ride sharing were also invented.

In program management, new methods in documentation, technical exchange, design review and reporting were developed. Lessons related to schedule, goals, budget, team building, logistics of personnel and materials, and risk assessment and management were studied and implemented. The positive and negative lessons learned in this large small-satellite mission will be of interest to the small satellite community and give insight to those who plan future missions.

2. A Decade of Satellites at Weber

As shown in the time line of Figure 1, CAST and OSSS has been involved in building and flying satellites for over 18 years.

2.1 NUSAT I (Northern Utah Satellite)

CAST started with the Northern Utah Satellite. NUSAT I was constructed in the early 80's, launch in 1985 from the Challenger Space Shuttle and have the distinct honor of being the first satellite designed, built, and flown by an undergraduate school. The prototype is currently in the National Air and Space Museum at the Smithsonian Institute. NUSAT I, see Figure 2, was in orbit for 18 months and was designed to study high altitude radar field patterns for the Federal Aviation Agency.

Figure 2 - NUSAT I Satellite

2.2 NUSAT II

NUSAT II, a and b models, were designed and under construction when the Challenger disaster took place. As a consequence of the tragedy, NASA imposed a moratorium on shuttle flights. Without means to fly, the CAST program was in jeopardy.

2.3 AmSat

The Amateur Satellite Corporation (AmSat) has a long history of building communications satellites to support amateur or 'Ham" radio needs. The North American branch of this international organization asked CAST to participate in the fabrication of four micro satellites. These satellites measure only 9 inches on a side and weigh less than 25 pounds. For their contribution, CAST received ownership of WEBERSAT, one of the four microsats. The four were launched January 22, 1990 as a piggyback payload on an 'Ariane IV' rocket of the European Space Agency. The microsats are spin stabilized and offer store and forward amateur packet communications around the globe.

2.4 WEBERSAT

The geometry of WEBERSAT is shown in Figure 3. Beyond the basic hardware common to the four microsats, WEBERSAT also contains additional experiments designed and constructed by student senior project groups. They include a particle impact detector, optical spectrometer, sun sensor, earth horizon detector, fluxgate magnetometer, and an on board color CCD camera experiment.

Over 300 students from Electronic Engineering Technology, Mechanical Engineering Technology, Manufacturing Engineering Technology, Computer Science, Mathematics, Physics and the local high schools have put in over 20,000 hours into the WEBERSAT project either in the initial design and construction phase or in interpreting the experimental results from the orbiting satellite.

2.5 Phase 3d

In 1997 CAST completed the fabrication and qualification of the spaceframe for a full-size communications satellite for the amateur radio society. The Phase 3d is a 1500 hundred pound satellite carrying 11 amateur radio transponders. This is an international project with a launch expected in 2000.

Figure 3 - WEBERSAT Satellite

Figure 4 - Phase 3D Satellite

3. One Stop Satellite Solutions

A major part of CAST's charter is to develop new technology that will spawn additional high-tech companies in the local community. In 1996 One Stop Satellite Solutions (OSSS) was formed with the purpose of marketing and manufacturing the technologies developed at CAST over the last two decades.

A grant from the State of Utah's Department of Economic Development, Center of Excellence program and sponsorship by Weber State University through their Technology Incubator program, gave OSSS an excellent beginning. The first few years saw team building, domestic and international patent filings, and fund raising from private investors.

To date, OSSS has partnered with or provided services for several departments of the U.S. Airforce (Air Force Academy, Space Test Program, Space Missile Command, Airforce Research Laboratory, Starfire Optical Range, Space Vehicle Directorate), NASA Marshal Space Flight Center, Stanford and Arizona State Universities, Orbital, TRW, Boeing, and Thiokol.

OSSS's international marketing efforts have been very positive with major accomplishment in Japan, Korea, France, Australia and Russia.

4. JAWSAT

JAWSAT, Joint Airforce Academy Weber University Satellite, was the first major project directed and managed by OSSS.

4.1 Initial Concepts

JAWSAT became an official Airforce mission when it was briefed to the Space Experiments Review Board in 1994. The mission at this time was purely academic being used as a student project involving cadets from the academy and students from Weber State. Launch was to be provided as a secondary 'piggy back' on a Delta launch vehicle. Structural mockups and prototypes of electronic hardware were developed but by 1995 it became clear that there would be a long delay before a Delta secondary would be available.

4.2 STP JAWSAT

In October of 1995 the JAWSAT mission was selected for the first ride on the OSP (Orbital-Suborbital Program) launch vehicle. This selection was by congressional mandate and read into the congressional record on September 6,1995.

Several STP experiments were selected and the mission proceeded through a successful Critical Design Review (CDR) in April of 1997.

On the day before the final contract was to be let to OSSS to complete the JAWSAT mission; the Secretary of State recalled all non-committed DoD funds to pay for Desert Storm military activities.

This created a unique situation in that the launch was still funded and scheduled but there was no budget for payloads or integration of payloads.

4.3 Resurrected Mission

Through extraordinary efforts of OSSS and SMC the JAWSAT mission was save. With only 18 month before the schedule launch date, JAWSAT was redefined in April of 1998 to support university, NASA and Air Force Research Laboratory payloads.

4.4 New Ground Rules

A new model for a multi-payload mission was needed. Each of the 15 different organizations furnishing major payload components would have to be responsible for their own mission success. OSSS as the mission integrator would only be tasked to insure that all components could structurally survive launch and not damage either another payload or the launch vehicle.

OSSS attended the CDR's for each payload and reviewed their structural design and qualification testing. A flyable mass dummy was require from each payloader three months before launch date. OSSS's multi payload adapter was first tested using software simulation then the mass models provided from each payloader were integrated into an engineering frame for complete qualification studies as per expected launch environment.

The understanding with all payload providers was that if their payloads did not satisfy OSSS expectation for structural integrity or if they were not delivered on time, their mass dummy would fly. The launch vehicle integrity and the launch schedule were the missions first priority.

5. JAWSAT Mission Participants

There were many participants in the JAWSAT mission. The major payload components were:

5.1 Falconsat

Falconsat is a U.S.A.F. Academy free flying satellite designed and built by cadets to support the CHOMS upper atmosphere experiment. Separation system design and hardware was furnished by STARSYS.

5.2 Opal

Stanford University's Opal satellite is DARPA sponsored and included a deployed constellation of 'hockey puck' sized free flyers from AMSAT, Aerospace Corp, and Santa Claira University.

5.3 ASUSAT

Arizona State University has been working on their satellite for a number of years. Their design incorporates new structures and sensor technology.

5.4 Optical Calibration-Sphere

The Star Fire test range of the Air Force Research Laboratory furnished this free flyer which deployed a four meter metalized balloon to act as a calibration source for ground-based optical systems.

5.5 Plasma Experiment Space Test

NASA Marshall Space Flight Center provided an upper atmosphere experiment, which will remain attached to the MPA frame. Electrical power, communications and attitude control for this experiment is being furnished from the CAST Attitude Controlled Platform.

5.6 The Multi Payload adapter

The main JAWSAT structure is an isogrid frame 28 by 28 by 30 inches. See Figure 7.

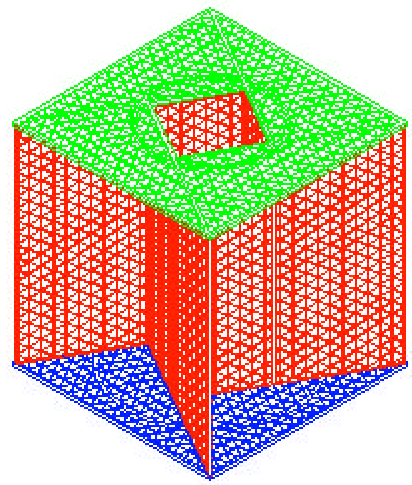

Figure 7 - JAWSAT Multi-Payload Adapter

This framework has been named the Multi-Payload Adapter (MPA) and deployed four independent main satellites and support two other experiments that will remain attached to the MPA frame.

5.7 CAST's Attitude Controlled Platform

The Attitude Controlled Platform (ACP) is an ensemble of hardware designed specifically for micro-satellite applications. As shown in Figure 8, the ACP includes four reaction wheels, fine and coarse sun angle sensors, three-axis magnetometer, flight computer, uhf/vhf communications, batteries, solar panels and a flight computer. The base plate is an inscribed hexagon with a radius of 17 inches. The height is 6 inches and the mass is 16 kg.

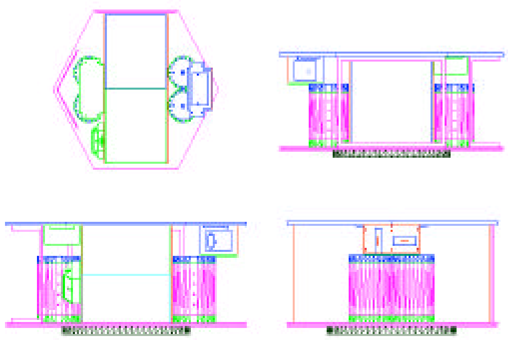

Figure 8 - Attitude Controlled Platform

The ACP can be used as a free flying satellite with all of the attributes needed to perform a true scientific mission. See Figure 9. In this configuration, the ACP can support up to a 150-pound experiment on its top surface and can be deployed from a get-a-way special canister.

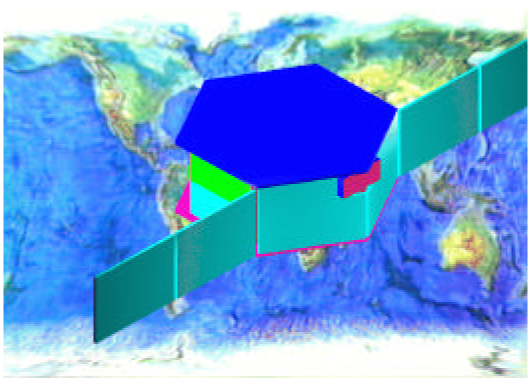

Figure 9 - ACP as a Free Flyer

The Attitude Determination and Control (AD&C) subsystem is an integral part of all phases of the JAWSAT mission. The AD&C hardware includes torque reaction wheels, magnetic torque coils, sun angle sensors, horizon angle sensors, and magnetometers. The attitude control software is state-of-the-art and includes algorithms for despin, Sun and Earth orientation and capture, state-sampled network control, reaction wheel desaturation, attitude recovery and intra-spacecraft communication.

During initial tip-off from the launch vehicle, spacecraft spin rate is determined and de-spin algorithms are employed as needed to reduce rotational velocity. After despin, the AD&C subsystem determines the orientation of the spacecraft relative to the Sun and Earth. A State-Sampled Control algorithm is then activated which uses torques produced by reaction wheels or magnetic torquing coils to turn the solar panel toward the Sun and the bottom of the spacecraft towards the Earth. Reaction wheel desaturation is accomplished by using magnetic torquing coils. This operation is accomplished in a method, which does not interrupt mission operations. Safing algorithms that identify anomalous spacecraft attitude scenarios and procedures for recovery of nominal mission operations are part of the AD&C software package.

5.8 Packaging and Integration

Figure 10 shows the packaging of these experiments and free flyers on the Multi-Payload Adapter frame. One Stop Satellite Solutions' Air Force contract was to act as the integrator for all of these experiments and provide interface between each payload and the launch vehicle.

5.9 Testing and Quality Assurance

As was detailed in an earlier section, four levels of review and testing were implemented. The first level was for OSSS's staff of engineers to review the design, quality control and testing preformed by each payload team on their own particular payload. The acceptance criteria were set by Orbital to a shake profile with 14 G peak acceleration in the flight axis and 8.5 G acceleration in the cross axes. Electrical and mechanical interfaces were documented and an abbreviated ICD (Interface Control Document) was created for each payload.

Figure 10 – JAWSAT Configuration

Flyable mass dummies were required from each payload team with a minimum second-order mass fidelity. That is, the same total mass, center of gravity and mass moments as the to-be-flown payload. OSSS received these mass dummies, inspected their construction. They were then shaken at launch loads and flight duration to test for flyability. There were a few design qualification issues uncovered at this time and some mass dummies were redesign and remanufactured.

These mass dummies were next integrated into an engineering model of the OSSS MPA (Multi Payload Adapter). A 100,000-pound Lange shaker with 32 channels of accelerometer data was use first in a swept sine test to determine assembly resonances. The first resonance was found to be at 28 Hertz. This assemble was then shaken to 100% of expected launch loads for 180 seconds with a random waveform in each of three axes based on Orbital's spectral profiles.

All of the payloads were delivered to OSSS by the required date of November 15, 1999. Each team was on site to uncrate and test their payloads. Mass properties of each payload were measured. A few of the payloads were over mass and/or had differing mass properties and some mechanical interfaces were not as documented in the ICD. The interface issues were not a serous problem. The MPA is similar to a 'peg board' construction in that there are mounting points every 1.5 inches. The open architecture of the MPA also allows for rapid changing of electrical cables.

The mass being over budget was a serious issue. We were 20 pounds too high in total payload assembly weight. As per OSSS agreements payloads not meeting their specifications would not be allowed to fly. Payload teams that were over mass budget were asked to trim additional mass from their payloads. These payload teams informed OSSS that the only way to reduce their masses would be to eliminate major portions of their missions. In the end, and in a grand sprit of cooperation, some altruistic compromises were found. The Optical Calibration Sphere was under mass but had originally planed to ballast up to help their ballistic coefficient and extend their orbital life. They donated the ballast mass to the greater good. This was about three pounds. The Attitude Controlled Platform from CAST was at its proper mass but had a 12-pound secondary battery, which was not totally necessary. The Air Force Academy's deployment mechanism uses a battery pack just for powering the separation system. Since it would stay attached to the MPA it could be used for a backup battery for OSSS. With these gestures of team cooperation the Air Force directed their vender furnishing one of the large separation rings to be manufactured in aluminum alloy rather than of steel. This cost the mission $40,000 extra for the interface but reduced the total payload mass to 430 pounds which met specifications.

After integration of all payloads, the complete stack was shaken to acceptance levels which were define as 80% of launch loads for 60 seconds. Each payload was examined by its team and functionally tested as far as possible through ground test ports.

5.10 Launch Operations

Launch operation was at Vandenberg Airforce Base on the West Coast. Each payload team had an opportunity to inspect their payload and top-off batteries before encapsulation. Each payload team also had one member setting on console during countdown and launch.

The first three countdowns, which spanned December 1999, and the first part of January of 2000, were aborted due to range and launch vehicle considerations. The forth attempt on January 26Th, 2000 was successful with JAWSAT being placed in it proper polar orbit.

All free-flying satellites were deployed exactly on schedule. Each satellite was in communications with the ground for at least several orbits. This completed the OSSS contract with Space Missile Command. Although several individual experiments failed on-orbit, the Air Force mission of proving a new launch vehicle, deploying multiple satellites from a Multi Payload Adapter was completely successful.

6. Lessons Learned

There have been many lessons learned from the JAWSAT project. Some of these lessons were new but most were repeats from the past.

6.1 The first lesson learned is that small satellites are not defined by the size of the satellite. The program organization makes it a small satellite project.

6.2 Teams must be kept small for it to be a small satellite mission. Small means everyone associated with the project must be able to sit down in the same meeting to collectively address issues and design strategies. As soon as the team becomes too large for complete individual representation on all levels, communication begins to require paper trails and signoff procedures. Managers start to worry more about 'whose fault it is' rather that focusing on the mission goal. Each department starts to form their own agendas and non-productive egos start to drain the project.

6.3 Projects are usually small due to budget constraints. If we had a bigger budget we could do things the normal aerospace community way of doing them. In most cases, budget over-runs are program killers. There usually are not additional funding sources.

6.4 The biggest budget killer is schedule. Small satellite programs are very labor intensive. As much as 90% of the total budget is in labor costs. A 10% slip in schedule leads to a directly proportional increase in budget.

6.5 Small teams usually have one expert in any particular field. This is a potential dangerous situation in that if a key person is lost, and in a small team they are all key employees, the project may be fatally damaged. Cross training between personnel and good record keeping minimizes this risk but it always a major concern.

6.6 A well establish rule of design is that products are always designed to minimize the production cost while meeting the design objectives. If the production cost could be made lower by a design change, it should have been implemented as soon as the benefit is recognized. This means that taking an exiting design and miniaturizing it for a small satellite application is more expensive that to start with a new design using small satellite requirements.

7. Conclusion

In 1996 an STTR grant from the Air Force Research Laboratory was awarded to One Stop Satellite Solutions, to determine the future viability of small satellites. The results of this study concluded that regardless of satellite size, satellite missions were only useful if the attitude of the satellite could be determined and in most cases controlled. Virtually every DoD and/or commercial mission manifest for the foreseeable future needed better than one degree of attitude knowledge and better than two degrees of attitude control. Without AD&C (attitude determination and control) micro-satellites have no future!

On the other hand, small satellites with modern, state-of-the art capabilities have a bright future.