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Building a Cadre of Space Professionals: Hands-On Space Experience at the USAF Academy

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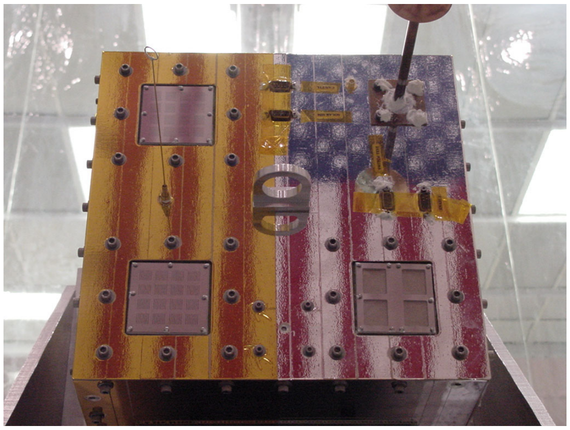

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ABSTRACT

The paper describes small satellite research at USAF Academy's Space Systems Research Center. The program's goals are to give students the opportunity to "learn space by doing space" while delivering useful science results to the US Department of Defense. Background on the programs is first presented followed by details of the current satellite and rocket projects. The paper concludes with a discussion of the challenges of finding reliable, timely launch opportunities to sustain rapid system development and educational opportunities. On-going efforts by USAFA to investigate a rapid, nanosatellite launch capability are then described.

INTRODUCTION

The capstone of the United States Air Force Academy Astronautics curriculum is the FalconSAT and FalconLAUNCH Programs. One goal of these programs, housed within the Academy's Space Systems Research Center, is to give undergraduate cadets the unique opportunity to "learn space by doing space." The programs facilitate cadet development of small satellite and sounding rocket mission design through instructor guidance and mentorship. It allows cadets to gain real-world experience with satellite or rocket system design, assembly, integration, testing, and operations within the context of a two-semester engineering course sequence.

A second goal of the programs is to provide useful platforms for Air Force and Department of Defense (DoD) space experiments. Through FalconSAT or FalconLAUNCH participation, cadets are given a hands-on opportunity to apply the tools developed in a classroom to a real program, ideally preparing them for the situations they may encounter as officers and as engineers after they graduate.

Background on the programs is first presented including previous and on-going missions. The long term vision for the program is then presented including the major challenges that face a sustainable, fully-integrated nanosatellite program to educate and train space professionals.

BACKGROUND

The USAF Academy's foray into small satellites began with a series of cadet-built prototypes that were "launched" on high altitude balloons. These projects gave the students immediate, hands-on experience and allowed the Astronautics Department to gradually evolve the curriculum to accommodate increasingly more ambitious space projects. This initial development culminated in the launch of FalconGold in October 1997. FalconGold was a fixed, secondary payload on an Atlas-Centaur launch vehicle. The mission of FalconGold was to determine whether GPS signals could be detected above the GPS constellation. FalconGold relayed GPS data for 15 days prior to battery depletion. Successful operations and data recovery from FalconGold concluded that GPS signals could be used for orbit determination, even beyond the altitude of the GPS constellation. [10]

The Academy's first "free flyer" satellite, FalconSAT-1 was launched on January 14, 2000 aboard the first Minotaur launch vehicle (a modified Minuteman II ICBM) along with several other university-built microsatellites. FalconSAT-1 flew the DoD-supported Charging Hazards and Wake Studies—Long Duration (CHAWS-LD) experiment which was designed to measure electric potential created by a spacecraft's wake to examine how charging varies throughout an orbit. The CHAWS-LD sensor was designed to assess the hazards for spacecraft operations in the wake of larger bodies. Unfortunately, a power system problem became apparent soon after deployment. Despite repeated attempts to recover the spacecraft by the cadet/faculty operations team, the mission was declared a loss after only one month.

Although it was considered a technical failure, FalconSAT-1 represented an academic success for the program as cadets participated from "cradle to grave" in a real-world mission with an all too real-world outcome. Cadets designed and built FalconSAT-1's payload and subsystems, and they were integral in the mission operations from devising operations plans to participating in the launch campaign. Cadets also manned the Academy's ground station during overhead passes of a satellite not operating under nominal conditions. Cadets involved with trouble-shooting the anomalies soon after deployment certainly gained deep insight into system functions and operations.

The lessons learned from FalconSat-1 motivated significant structural change to the Academy's long-term program, with the intention of building a program first and a satellite second. Thus, the new approach has been to focus on building up infrastructure, relying heavily on off-the-self hardware to provide a firm foundation to allow the design to evolve steadily over the course of several missions. When approached as a blank sheet of paper, the construction of an entire satellite is an entirely open ended problem with potentially thousands of considerations and interdependent design options. In a proto-type only satellite program, design changes in one basic component will cause many time consuming design iterations throughout the rest of the design. Eliminating options of the core components from the initial design process allows for continued engineering and analysis work while reducing the amount of follow on design iteration processes. This allows for a program to be designed in parallel from the standard sets of components rather than having subsystems designs relying on other designs in a design-string that is based on the initial program requirements.

However, even with the constraint of having standardized core subsystems in mission design there is still no limit to the available mission payload and peripheral design options. For these reasons, the USAF Academy has adopted new of-the-self hardware in the development of FalconSat-2. The FalconSat-2 design is based off of commercial hardware which can be readily adapted and enhanced to meet future payload requirements and secondary launch opportunities. Just as there has been a movement in the aviation industry towards modular sub-components, the idea of easy design, replacement and repair of modules is something the new FalconSAT-N program is evolving towards.

FalconSAT-2 is the first in this new series of modular microsatellites designed, built, tested, and operated by cadets at the USAF Academy. Due to difficulties and complications experienced with FalconSat-1, a major change in design philosophy was adopted for FalconSAT-2 and subsequent missions. This philosophy hinged on reducing the overall mission risk and time needed for design development. Rather than having students design the entire spacecraft "from scratch," we have attempted to significantly constrain the design problem by adopting the core subsystems available as commercial off-the-shelf (COTS) items.

The specific COTS solution we have turned to were developed by Surrey Satellite Technology Limited (SSTL), UK for their Surrey Nanosatellite Application Program (SNAP). FalconSAT-2 has experienced enormous success in the design process and has allowed students a multitude of engineering challenges to be resolved. With this COTS basis, three satellites will be developed to test and verify the system design before launch. However, these will be completed in nearly the same amount of time as the ground-up proto-flight method employed during FalconSat-1. This serves as proof of the fact that adopting commercial-off-the-shelf hardware can significantly reduce the time sink on a program while allowing for greater reliability measures to also be developed.

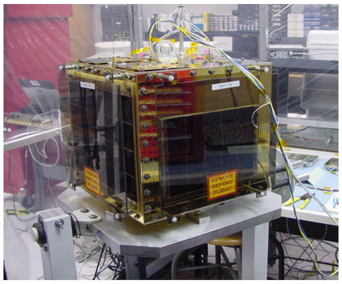

Figure 1: FalconSAT-2 is shown in the USAFA clean room awaiting launch.

As of this writing, FalconSAT-2 is complete and awaiting launch as shown in Figure 1. The spacecraft was designed for launch on the Space Shuttle via the Hitchhiker Pallet Ejection System and was originally manifested for launch in early 2003. The recent Shuttle disaster has put launch plans on indefinite hold. Undaunted by this setback, the program is steadily pressing on to the next project—FalconSAT-3.

Larger (50-kg, compared to 30 kg) and more complex than FalconSAT-2, FalconSAT-3 will carry three DoD SERB-approved payloads: (1) Micro Pulsed-Plasma Thrusters (MPACS), (2) Flat Plasma Spectrometer (FLAPS), and (3) Plasma Local Anomalous Noise Environment (PLANE). The MPACS experiment will provide flight heritage for this advanced electric propulsion technology. FLAPS will investigate ionospheric plasma depletions similar to the MESA experiment on FalconSAT-2 but with far greater range and accuracy. Finally, PLANE will investigate the localized plasma environment caused by the spacecraft's movement through the ionosphere. FalconSAT-3 is currently in critical design for a launch on the first Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter Mission (ESPA) in March 2006. A model of FalconSAT-3 is shown in Figure 2.

Figure 2: FalconSAT-3 carries 3 DoD payloads and is currently in critical design for a launch in 2006.

In addition to building and operating small satellites, USAFA has a parallel program to build and launch small sounding rockets. The goals of FalconLAUNCH are to first provide cadets another opportunity to "learn space by doing space," and second to one day provide a platform to launch DoD sounding rocket payloads. In April 2003, the program will launch a cadet-built rocket to approximately 35,000 feet. The eventual goal, over the course of several years, is to reach the edge of space at 100-km with a sounding rocket.

DISCUSSION

So far, the Academy's FalconSAT and FalconLAUNCH programs have been extremely successful at providing approximately 45 cadets each year the opportunity to learn at a gut level what it takes to carry out a space program. But the Academy graduates approximately 1000 cadets per year. Furthermore, the lifecycle of the FalconSAT missions, for example, is around 2-3 years, far too long for one class of cadets to experience the complete "cradle to grave" of a mission. Thus while our accomplishments have been laudatory, we have a long ways to go before we can fully meet the need laid out by Mr. Rumsfeld in the Space Commission Report of 2001 to "develop the space cadre the nation needs."[11]

The ultimate vision of the Academy's space program is "space for all," meaning that every graduate should be given the opportunity, some time during the four year cadet experience, to actively take part in some aspect of a space mission—design, build, test, launch or operations. While this vision may sound unrealistic given the current state of small space programs, it is useful to look back 20 years or so in the Academy's history. At that time, another vision was laid out: "soar for all," whereby every cadet would have the opportunity to solo in a sailplane sometime before they graduate. Today that vision is reality. Nearly 1000 cadet per year, either during the year or during summer training periods, participate in the soaring program, earning their cadet soaring wings. Those who participate early in their cadet careers, and who show a particular aptitude and interest, can go on to become cadet instructor pilots, teaching the underclassmen. In this way, the program is largely self-sustaining with older cadets mentoring younger ones and providing overall leadership in the program. Of course, to sustain a soaring program of this level requires an investment by the institution in manpower and infrastructure. However, the Academy's mission is to motivate young men and women to become career officers in the USAF. Most graduates go on to be career pilots, and most of the rest who do not fly themselves take on support roles for the flying mission. For the flyers, the cadet soaring experience helps to hone those important skills early and gives them an early taste of the flying mission. Even more important, for those cadets who do not go on to fly, their brief experience in sailplane cockpit gives them a visceral understanding of flying mission.

What would it take to make the "space for all" mission a reality? Any space program has four basic elements: (1) spacecraft systems, (2) ground operations systems, (3) integration systems, and (4) launch systems. Twenty years ago, putting in place any of these elements would have been viewed as a serious challenge. But today, things are different. The paper will examine each of these elements, focusing on the current most challenging: launch systems.

Ccommercial advances in electronic and micro-mechanical technologies have made it possible to construct tiny (<10 kg) "nano-satellites" with significant capabilities, that can be constructed in very short periods of time and at extremely low cost, opening up many new possibilities for space exploration. A good example is the University of Surrey's (Guildford, UK) first nano-satellite: SNAP-1, shown in Figure 3, which was launched in June 2000 to a 700 km low earth orbit. It is a 6.5 kg spacecraft with advanced, UK-developed, GPS navigation, computing, propulsion, and attitude control technologies. Its primary payload is a machine vision system capable of inspecting other spacecraft. SNAP-1 had the following specifications:

- VHF up-link, 38.4 kbps packet-switched BPSK S-Band downlink;

- 32-bit Strong-Arm OBC; CAN-bus on-bard data handling network;
- UK GaAs solar cell technologies; advanced NiCd battery;
- 3-Axis control via miniature pitch axis momentum wheel and magnetorquer rods;
- Miniature 3-Axis flux-gate magnetometer;
- 3 m/s delta-V cold-gas propulsion system for orbit control;
- Precise orbit position via 12-channel GPS receiver system;
- 3 Wide angle and 1 narrow angle miniature CMOS APD cameras for remote inspection;
- UHF inter-satellite link receiver;
- VHF spread spectrum payload transmitter.
- Total mission cost (including development, salaries, $750 K)

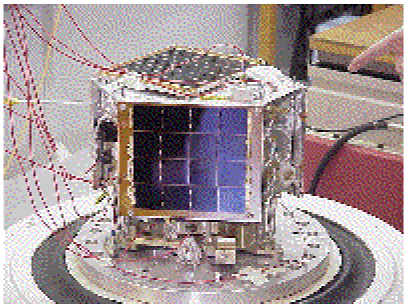

Figure 3. SNAP-1, a 6.5 kg nano-satellite

SNAP-1's flight test demonstrated the following capabilities:

- the first fully 3-axis attitude stabilised 'nano-satellite'
- the first nano-satellite with on-board propulsion demonstrating orbit control
- the first in-orbit images of another spacecraft from a nano-satellite
- the first successful use of GPS on-board a nano-satellite - used for orbit manoeuvring

In June 2000, SNAP-1 imaged the Russian NADEZHDA satellite and Chinese Tsinghua-1 micro-satellite – shown in Figure 4. Commercial-off-the-shelf (COTS) spacecraft bus hardware derived from SNAP-1 formed the basis for the Academy's FalconSAT-2 spacecraft.

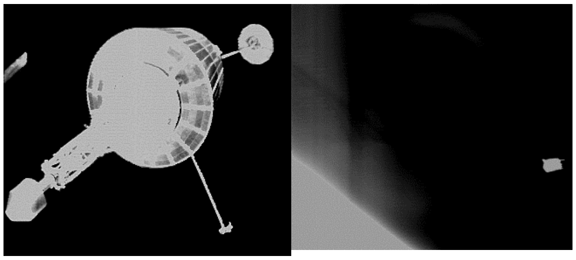

Figure 4. Russian NADEZHDA and Tsinghua-1 Satellites- Imaged by SNAP-1.

The second element of a space program is ground operations systems. These too are now relatively cheap and easy to establish ($150 K). The Academy Space Operations Center for the FalconSAT-2 mission consists of several PC's, a rack of RF communications gear and some antennas mounted on the roof. As of this writing, cadets are training the SOC using an engineering model of the satellite as a hardware-in-the-loop simulator.

The third element of a space program, integration systems, includes all of the software needed to tie together mission lifecycle. These include everything CAD and analysis tools to telemetry interpretation software. In the current state of the art, all of these tools exist in some form or another (either commercial or custom made) as separate packages most of which do not easily talk to each other. While this is not a show-stopper for the "space for all" vision, clearly an important, mission enabling area of research would be to develop an integrated suite of software that would allow students to easily move from design, to built, to test and to operations, without first having to learn new software tools.

The fourth element of space program, launch systems, is the focus of the remainder of this paper. The success of the "space for all" vision hinges on low-cost, responsive launch opportunities, opportunities that currently do not exist in the U.S. Table 1 shows the current US launch vehicles – payload capability and ROM launch costs.

Vehicle	Cost ($M)	Lift to LEO (lbs)	Cost per lb
Pegasus	10.5-13.4	814	$14,000
Taurus	18-22	3,000	$6,800
Delta II	40-50	11,110	$4,275
Atlas II	80-90	15,700	$5,414
Titan IV	170-230	39,000	$5,128
STS	350-547	53,700	$8,352

Table 1. U.S. Boosters Capacity * Assumes a third stage is used

Since the target recurring cost for this new class of Academy satellites would be in the $250K - $1M range, these launch prices make it difficult to justify a dedicated launch at the cost mentioned in Table 1. Thus, small satellites typically fly as hitchhikers along with another larger system that pays for most of the launch cost. This approach generally works well, and has been used by all USAFA satellites. It has been demonstrated repeatedly with the Ariane IV and Ariane V launch vehicles in Europe. The ASAP ring (Ariane Structure for Auxiliary Payloads) has the capability to launch 6 small satellites at once. If the ring is full, the cost to each satellite manufacturer is about $250,000. (If only one satellite is on the ring, than that satellite must pay the full costs for the ring). A similar concept will be employed for the EELV. The ESPA (EELV Secondary Payload Adapter) will allow up to 6 small satellites (up to 400 lb each) to be launched along with a primary payload. The first launch of ESPA is slated for March 2006 and will include the FalconSAT-3 spacecraft. As this is the maiden flight, recurring costs are still to be determined, but they are targeted to be in the same range as the ASAP. Launches are also available as secondary payloads on Russian vehicles at a cost of approximately $5,000 per kg. However, neither the ASAP or Russian options are available to USAF-built satellites due US foreign launch restrictions.

Unfortunately, in all of these options, two things stand in the way of achieving the “space for all” vision: (1) launch frequency, and (2) launch cost. To provide all cadets some space mission experience, we must achieve a launch frequency of at least 4 to 6 times per year. At this frequency, the cost needs to be in the range of $250k to $500k per launch. At roughly $250k per satellite and $250k per launch, at a rate of 6 per year, that gives a ballpark program cost (excluding operations) of $3M per year. This recurring cost is not out of line given that the Academy spends over $10M per year on its flying programs.

How can we achieve responsive and low cost lift? One possible solution that always comes up is a single stage to orbit concept. If a system can be developed that is completely reusable, and has minimal operational and maintenance costs, i.e. quick turn around, just add fuel—the argument goes—it would offer a low cost solution to launch, just based upon the frequency of use. Unfortunately, Figure 6 shows the technology required to produce such a system. If we stay with liquid chemical technology (Isp’s from 400-470 sec, the inert mass fraction required means that most of the rocket needs to be made out of composite materials (pump, tank, etc). Even if most of the system components can be made out of composites to withstand the high pressures and temperatures of operation, being able to survive over time and not have to be completely refurbished after each mission is still an issue. High Isp systems like nuclear thermal propulsion are not being considered for this mission class.

Thus, there is a niche for a responsive nano-satellite launch capability in the US. Our approach is to design a vehicle using as much “COTS” technology as possible, similar to the approach taken in the FalconSAT program. If a program requires “leaps” in technology, it is hard to justify that it will be responsive. We would also like the vehicle to be accessible enough to serve as an educational tool for cadets. One proposed design concept is to develop a standard vehicle that could be launched from all of the current USAF air platforms. This approach is possible by constraining the vehicle and payload to meet the volume and mass constraints of one of the bigger bombs in the inventory – the GBU-28.

The use of small missiles for use in space is not a new idea. After the Soviet Union had developed a "killer satellite" to disable other satellites in the 1970s, the U.S. Air Force decided to develop an anti-satellite weapon system. The ASAT (Anti-Satellite Missile) program began around 1977, and in 1979 Vought was awarded a contract to develop an air-launched missile for use against low-earth orbit satellites. The ASAT missile, also known as ALMV (Air-Launched Miniature Vehicle), was designed as a multi-stage rocket, which was to be launched by an F-15 Eagle interceptor in a zoom-climb. Captive flight tests with ASAT vehicles on a modified F-15A began in 1982, and the first launch aimed at a predefined point in space occurred in early 1984.

Figure 5. USAF Air-launched ASAT ASM-135A. Photo Taken at the Edwards AFB Flight Test Center

The ASAT missile used the SR75-LP-1 solid-propellant rocket of the AGM-69 SRAM as the first stage and a Vought Altair III (the 4th stage of Vought's Scout B) with a Thiokol FW-4S motor as second stage. It was launched by an F-15 in a high-altitude supersonic climb. The F-15's computer was updated with special guidance algorithms, and the head-up display was also modified to provide additional steering cues to the pilot. This was necessary, because the zoom-climb and missile release had to be flown exactly as calculated to get the missile near the target satellite. The second stage of the ASAT pointed the MHV (Miniature Homing Vehicle) "warhead" in the target's direction, and destroyed the target by a direct hit at a speed of at least 24000 km/h. The maximum intercept altitude for the ASAT missile was at least 560 km, and possibly as high as 1000 km [4].

On 13 September 1985, the first and only destruction of a satellite by an American air-launched missile occurred, when an F-15A launched an ASAT against a retired communications satellite in a 555 km orbit. This was the only full-scale live test of the Vought ASAT missile. The program was terminated in 1988, mainly for political reasons [4]. Table 2 shows its specifications.

Length	5.42 m
Diameter	51 cm
Weight	1180 kg
Speed	> 24000 km/h
Ceiling	> 560 km
Propulsion	First stage: Lockheed Propulsion Co. SR75-LP-1 solid-fueled rocket Second stage: Vought *Altair III* solid-fueled rocket; 27.4 kN for 27 s
Warhead	Vought MHV "hit-to-kill" vehicle

Table 2. Technical Specifications of the ASM-135 [4].

Figure 6. **An analysis of Initial mass, Specific Impulse and Inert Mass fraction required for a single stage to orbit. The figure shows that if we use current and advanced chemical rocket technology, the inert mass fraction requires that most of the vehicle be made out of composite material [2].**

Thus there is precedent for using a smaller missile for space applications. In keeping with current Air Force doctrine of "transformation" and "horizontal integration," in developing the concept of operations for our concept nano-satellite launch vehicle concept, we decided to constrain the vehicle's mass and volume so it could be flown on many platforms. By making this decision, integration of this vehicle into the inventory would be minimized since crews would already have been trained to handle such a system – from maintenance handling on the ground to writing of flight plans and tech orders.

The missile that we have decided to use for our conceptual baseline is the GBU-28. We chose it due to its flight heritage on the F-15, planned use for the F-22, and is also able to be flown on bomber/cargo aircraft. A picture of the missile is shown in Figure 7 and its specifications are shown in Table 3.

GBU-28 Specifications	
Missions	Offensive counter air, close air support, interdiction
Targets	Fixed hard
Class	4,000 lb. Penetrator, Blast/Fragmentation
Service	Air Force
Contractor	Lockheed (BLU-113/B), National Forge (BLU-113A/B),
Status	In Production
First capability	1991
Weight (lbs.)	4,414
Length (in.)	153
Diameter (in.)	14.5
Explosive	6471bs. Tritonal
Fuse	FMU-143 Series
Stabilizer	Air Foil Group (Fins)
Guidance	Laser (man-in-the-loop)
Range	Greater than 5 nautical miles
Production cost	$18.2 million
Production unit cost	$145,600
Quantity	125 plus additional production
Platforms	F-15E, F-111F

Table 3. Specifications of the GBU-28. Note that the unit cost is $145,600 [4].

Figure 7. of GBU-28. It is a un-powered, hard target laser guided weapon.

The point of the analysis is not to propose using any of the existing components of this missile, just use its mass and volume as a footprint for the design of the system. Table 4 shows the aircraft in the inventory that were considered for the deployment of our system. Ones that were not mentioned are already taxed quite heavily as far as payload available – U-2, TR-1 or are not suited for the mission – F-16, A-10. However, many aircraft are capable as shown in Table 4.

Aircraft	Deployment Altitude
B-1, B-52, B-2, F-117	30,000 ft
F-15, F-22	40,000 – 50,000 ft
C-130	25,000 ft
C-17	45,000 ft
USMC Harrier	40,000 ft

Table 4. Aircraft and launch vehicle deployment altitudes.

The analysis also assumes that the cargo/bomber aircraft would deploy the rocket at a low angle of attack since this is there normal concept of operations for such missions. This will produce steering losses and require a slightly higher velocity requirement. For the fighter aircraft, we assumed a 60-degree angle of attack is feasible. When the ASM-135 was launched, the pilot had the aircraft at Mach 0.934 (Puffer, 1985). For this analysis, the rocket is assumed to start at rest. This assumption would allow the fighter aircraft to hold a high angle attack at a higher launch altitude, since higher speeds would possibly take them out of their performance regime if they were at high Mach and high altitude at the time of deployment. For the lower flying aircraft a zero take off velocity is reasonable, since at this point we are just producing a baseline concept for feasibility, it is better to have more design margin.

Launch Altitude (ft)	ΔV (km/s)	Payload Mass (kg)	Total Mass (kg)	Inert Mass Fraction	Final Alt. (km)	Isp (sec)
40,000	7.6	10	986	0.08	400	295
40,000	7.6	6.5	571	0.08	400	295
40,000	7.9	6.5	1168	0.06	400	295
40,000	8.4	6.5	2239	0.06	400	295
25,000	9.4	2.7	2574	0.06	400	300

Table 5. Conceptual Design Results for a nano-satellite launcher. Total volume must be at or under the current GBU-28 dimensions shown in Table3. Off the shelf composite technology is required if a lower launch altitude is chosen. ΔV's took into account gravity and drag losses.

The results shown in Table 5 indicate that all current off the shelf technologies are feasible for a single stage system. The inert mass fraction of 0.06 represents composite material technology (available today) for the structure, and 0.08 is stainless steel. The Isp's of 295-300 sec represent current high end chemical solid rocket motor technology performance. Since we want the concept to integrate with existing aircraft, moving to a liquid or hybrid program will not justify the added development cost. Staging could also be considered, but would also make the system more complex.

The purpose of this top-level analysis was to show basic system feasibility. These represent preliminary results only, a more detailed conceptual design would be needed to analyze thrust/weight, thrust profile, regression rate to determine web thickness and outer casing dimensions to see if a single stage with multiple firings could be configured to the GBU-28 dimensions. A detailed trajectory simulation would also be needed to look at guidance and control. Finally, and most important, range support, basing and logistics support would need to fully explored. Recall, the ultimate goal is to have students participate in as many aspects of the launch operations as possible, so basing and safety considerations would be paramount.

How could this vehicle be used as part of the "space for all" program? Current Academy missions are much larger than the 6.5-10-kg missions used in the above analysis. Infrequent launch opportunities dictate that maximum utility be gained from every launch. This drives the program to include more payloads, requiring more power, data, etc., driving size up.

However, there are no technical reasons why a 10-kg spacecraft size could not become a new standard. As the primary mission for these launches would be cadet education and training, these "TrainingSATs" could be launched several times per year, providing a continuous constellation for cadets to practice operations on. For example, a simple 30-m resolution camera onboard would give cadets practice in tasking "reconnaissance" satellites and downloading and interpreting the data. Beyond this rudimentary capability, it is easy to image other applications.

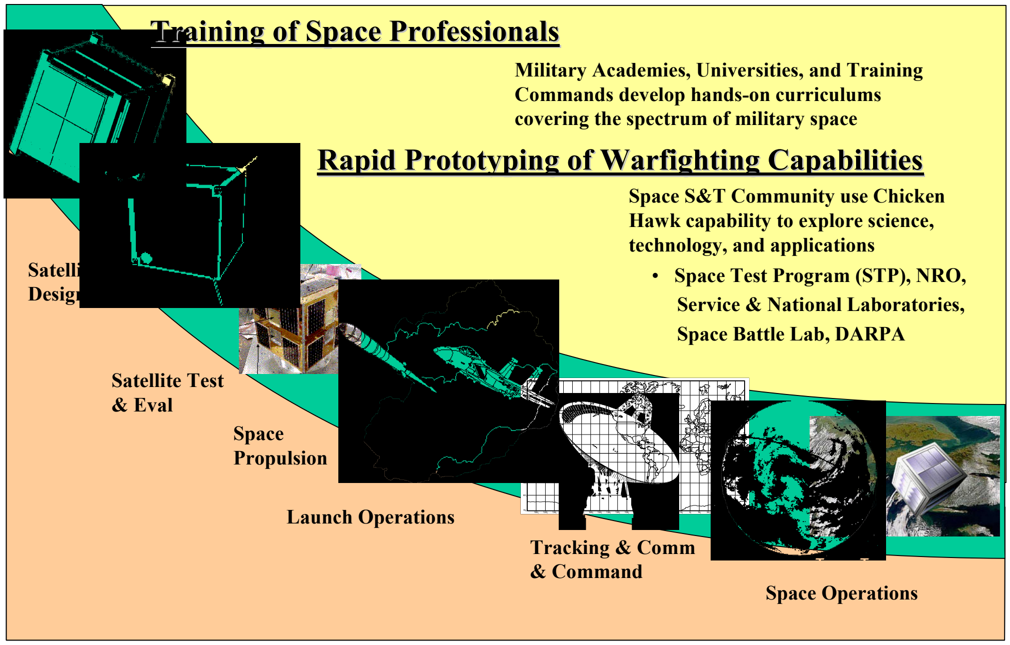

Figure 8. "Space for All" Program Concept of Operations.[12]

The first of these would be a constellation of "weather buoys" taking simple but continuous measurement of the little understood ionospheric plasma environment that greatly effects military communications capability. Finally, these nano-satellites could serve as platforms to gain flight heritage for new technologies. With satellites, an operations center, integration systems and a responsive nano-satellite launch platform, a fully integrated space program would provide a continuum of education and training opportunities while providing an infrastructure to support R&D for the warfighter. This concept is illustrated in Figure 8. And as a reminder, the University of Surrey did fly a 3 axis controlled imaging satellite with propulsion capability, with a total mass of 6.5 kg.

CONCLUSIONS

The current space program at the Academy provides cadets with a unique opportunity for hands-on experience with real satellite and sounding rocket missions. In its current form, the program could continue to evolve steadily, building and launching a 50-kg satellite every 2-3 years and a sounding rocket every year or so with roughly 50 cadets per year benefiting from the experience. But to achieve the vision of "space for all," a transformation is needed. Leveraging existing COTS nano-satellite technology, constellations of 10-kg class TrainingSATs, space buoys and other types of missions could be readily developed at low cost.

But the key element of this program is a low-cost, regular access to low Earth Orbit. This paper presented first order analysis indicating that an air-launched vehicle using existing propulsion technology could be developed and based from a variety of platforms in the AF inventory. The question remains whether sufficient commitment within government and industry can be found to invest in the necessary development costs of such a vehicle. The Ariane ASAP platform revolutionized the small satellite industry in the 1980's, taking micro-satellites from simple toys to powerful work horses, and allowing satellite builders to push the state of the art to the point where, today, we can easily image a new class of 10-kg satellites pushing the state of the art even further. Using education and training of future space learders at USAFA as the initial mission driver, this capability could quickly be expanded for education and training throughout DoD, industry and universities. Further down the road, an responsive, low-cost nano-satellite operational system could also offer transformational capabilities to future Combatant Commanders.

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