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AIR UNIVERSITY

BUILDING A CADRE OF SPACE PROFESSIONALS WITH RESPONSIVE LIFT

by

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In Partial Fulfillment of the Graduation Requirements

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Preface

This paper investigates a new concept for launching small satellites to space. It first discusses small satellite capabilities, since many view them as being only applicable to special niche markets, current launch deficiencies for this market, development of the new launch system, and a conops for its application. My intention for writing this paper at ACSC is to show that there is a conops for affordable access to space. If low cost small space systems can be produced at the same cost as some of our other expendable assets (e.g. precision bombs ranging in price from $100 K - $1,000,000 each) the small space systems could provide a force enhancement function to our existing higher cost space systems. Some say that bigger, higher performance, longer lifetime space systems are the only way to move forward in space. I would say if we took this approach to the computer market, we would only have big mainframe computers and no personal computers today. However, I know proving that a low cost system can be developed and provide a useful capability is a challenge. Hopefully this paper is a start.

I would like to acknowledge Mr. Sexton and Mr. Marley of ACSC for their helpful hints on space system design, sound advice on how to write a good paper, and the many nice open door discussions in their office; Lt Col Jerry Sellers of USAFA for his help and liaison with DARPA; Major Vince Park for STK modeling of a nanosatellite constellation; Lt Col Mike "Chanz" Chandler, Major Mike "Beege" Farrell, and Major Dean Ward for helping me out with aircraft configuration; Dave and Kathy Almand for the many great meals and a nice boat trailer for me to drive and wreck; Sean Bishop for the many long drives down from Atlanta and helpful

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Abstract

The purpose of this paper is to produce a proof of concept conceptual design of a nanosatellite launcher. To date, several nanosatellites (< 10 kg) have flown, demonstrating remote sensing in space and on the ground, 3-axis control, and small bandwidth communications. However, as a system, they currently are not the best option due to the current market high launch costs. It is the purpose of my research to show that a low cost launch system could be developed. My approach is to use "off the shelf" technology and limit the dimensions and mass of the system to integrate onto existing USAF air platforms. I chose the GBU-28 due to its high volume and mass, and capabilities to horizontantly integrate with many air platforms. Taking its core shell, I will show that a system can fit into its dimensions and take a 6.5 kg satellite from 40,000 ft to a 430 km orbit. The paper will describe on-going small satellite programs, showing their capabilities; discuss current launch vehicle options, discuss my design, and conclude by showing a conops for this rapid system to provide a remote sensing constellation to the warfighter or educate young space professionals.

Chapter 1

Introduction

If I don't do it, you can kill me!

—Dr Wernher von Braun, after being asked by Vice President Johnson on the feasibility of his technical leadership of the manned mission to the Moon.

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, specifically for small satellites.

Commercial advances in electronic and micro-mechanical technologies have made it possible to develop 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 1, 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-board 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)[1]

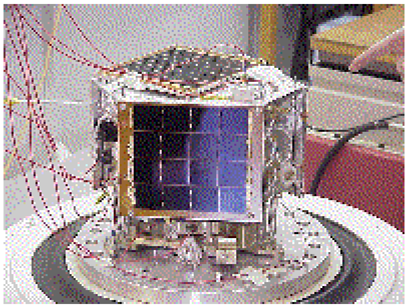


Figure 1. SNAP-1, a 6.5 kg nano-satellite[2]

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

- the first fully 3-axis attitude stabilized '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 maneuvering

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

Appendix A).

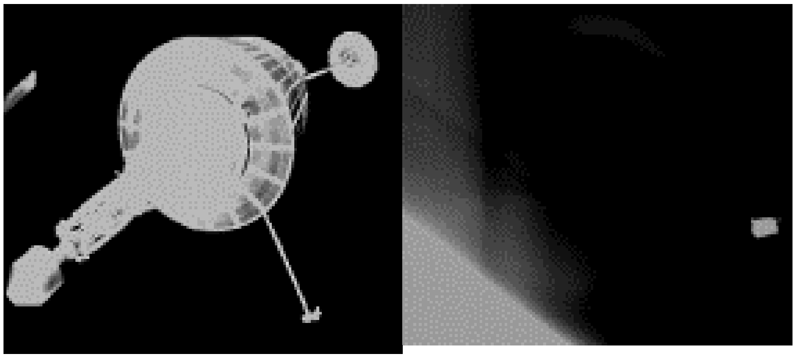


Figure 2. Russian NADEZHDA and Tsinghua-1 Satellites-Imaged by SNAP-1.[3]

The second element of a space program is ground operations systems. These too are now relatively cheap and easy to establish ($150 K). The US Air Force Academy Space Operations Center (SOC) for the FalconSAT-2 mission (see Appendix A) 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 in the SOC using an engineering model of the satellite as a hardware-in-the-loop simulator.

affordable access to space

Missions accomplished.

SSTL has built and launched 12 microsatellites into low Earth orbit and provided sub-systems and payloads for two more microsatellites in geostationary transfer orbit. We have an enviable 90% mission success rate.

With our independent Mission Operations Centre located in Surrey, England, SSTL has over 35 orbit-years experience in spacecraft control and operations.

UoSAT-1 *(Delta)* **1981**
The first experimental microsatellite from Surrey carried research, technology demonstration and educational payloads.
Re-entered in 1989

UoSAT-2 *(Delta)* **1984**
Built in only 6 months, UoSAT-2 carries the first modern digital S&F communications payload and a prototype CCD camera
Operational

UoSAT-3 *(Ariane)* **1990**
The first of SSTL's modular microsatellites launched on the ASAP carries an operational S&F communications payload for SateLife and Data Trax Inc. (USA)
Operational

UoSAT-4 *(Ariane)* **1990**
Launched alongside UoSAT-3, the microsatellite operated perfectly for 2 days before a failure occurred in the downlink.
Not operational

UoSAT-5 *(Ariane)* **1991**
Carries S&F communications and Earth Observation payloads, replacing those lost on UoSAT-4.
Operational

KITSat-1 *(Ariane)* **1992**
Korea's first satellite achieved via a technology transfer programme with SSTL - carries S&F communications DSP and Earth observation payloads.
Operational

S-80/T *(Ariane)* **1992**
An industrial research microsatellite built by SSTL for Matra and CNES (France) to carry out 'little LEO' communications service experiments.
Operational

PoSAT-1 *(Ariane)* **1993**
Portugal's first satellite achieved through a technology transfer programme with SSTL. Carries S&F, DSP communications, GPS and Earth observation payloads.
Operational

KITSat-2 *(Ariane)* **1993**
Korea's second satellite (built in Korea) via the technology transfer programme with SSTL. Carries S&F, DSP communications and Earth observation payloads.
Operational

HealthSat-2 *(Ariane)* **1993**
S&F communications satellite operating in the SateLife 'HealthNet' LEO satellite communications network for remote regions.
Operational

Cerise *(Ariane)* **1995**
A military research microsatellite built by SSTL for Alcatel and DME (France).

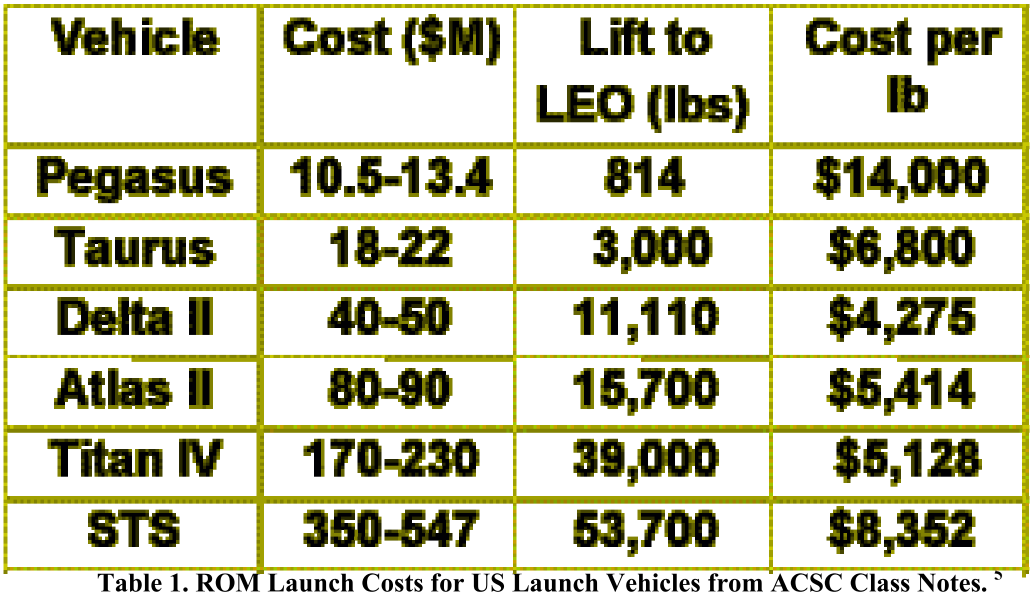
FASat-Alfa *(Tsyklon)* **1995**
Chile's first satellite achieved through a technology transfer programme with SSTL. Carries S&F, DSP communications, ozone monitoring and Earth observation payloads.

Figure 3. Satellites Flown at University of Surrey, UK as of 1995.[4]

The third element of a space program, integration systems, includes all of the software needed to tie together mission lifecycle. Integration systems include everything from 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. Unfortunately, this can cause difficulty in mission operations. For example, if a small satellite is tasked to provide more persistent coverage of a remote sensing area, the data must integrate into the other ground, space or airborne platforms and not have its own "stove pipe" operating system.

The fourth element of a space program, launch systems, is the focus of this research paper.

The success of small satellites 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. ROM Launch Costs for US Launch Vehicles from ACSC Class Notes. [5]

Since the target recurring cost for this new class of small 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, then 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 (see Appendix A). 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 nor Russian options are available to USAF-built satellites due to US foreign launch restrictions on DOD built payloads and spacecraft.

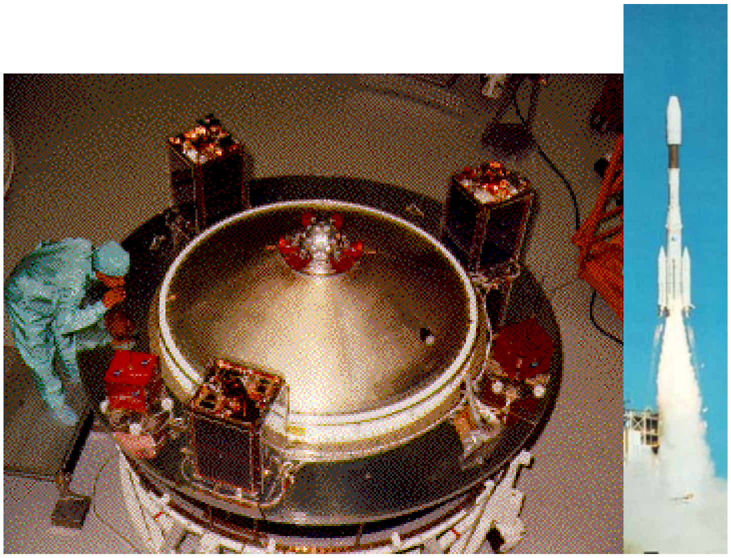


Figure 4. Ariane IV Launch Vehicle and ASAP Ring with 5microsatellites mounted on it. [6]

Unfortunately, in all of these options, two things stand in the way : (1) launch frequency, and (2) launch cost. For example, to provide USAFA cadets some space mission experience in their academic careers, 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.[7]

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 5 shows the technology required to produce such a system. If we stay with liquid chemical technology (Isp's from 400-470 sec—Isp is defined in detail later in the paper), the inert mass fraction (everything on the rocket accept the fuel) required means that most of the rocket (pump, tanks, combustion chamber, nozzle, etc) needs to be made out of composite materials. Even if most of the system components can be made out of composites to withstand the high pressures and temperatures of operation or re-entry, being able to survive over time and not have to be completely refurbished after each mission is still an issue. Two stage reusable systems are also being proposed; these systems are more reasonable for existing technology, but rapid maintenance turn around under the same severe environment must be demonstrated if these systems are going to be responsive.[8] High Isp systems like nuclear thermal propulsion are not being considered for this mission class.

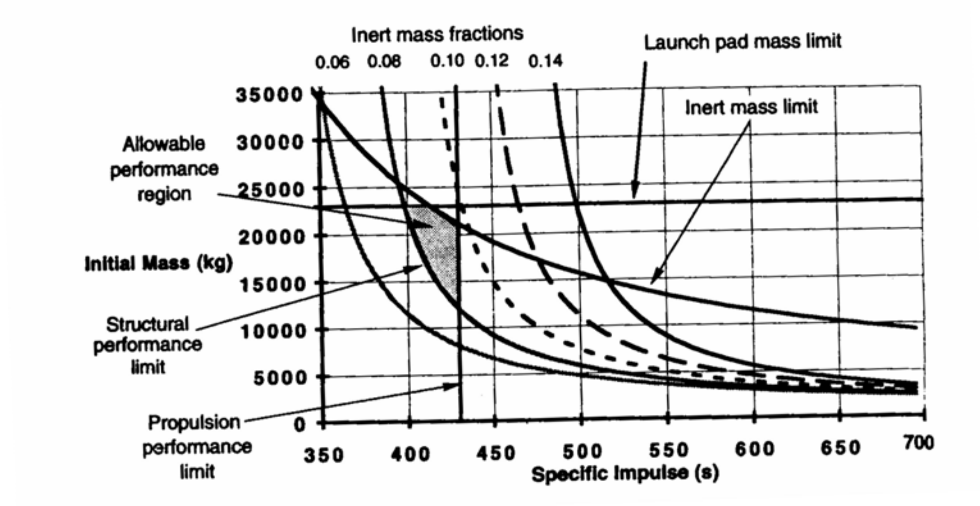


Figure 5. An analysis of Initial mass, Specific Impulse and Inert Mass fraction required for a single stage to orbit. The figure shows that if we use current and advanced chemical rocket technology, the inert mass fraction requires that most of the vehicle be made out of composite material [9].

Thus, there is a niche for a responsive nano-satellite launch capability in the United States. My approach is to design a vehicle using as much "COTS" technology as possible, similar to the approach taken in the University of Surrey and FalconSAT program (see Appendix A). 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 many 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.

Notes

[1] Underwood, C et al, "Flight-Proven Nano-satellite Architecture for Hands-on Academic Training at the US Air Force Academy", 16th AIAA/USU Small Satellite Conference, Logan, Utah, Aug 2002,4.

[2] Ibid.

[3] Ibid., 1.

[4] Ibid.

[5] Sexton, Allen, Air Command and Staff College Advanced Space Studies Course, Maxwell Air Force Base, AL, 2003, Launch Vehicle Power Point Presentation.

[6] Underwood, C et al, "Flight-Proven Nano-satellite Architecture for Hands-on Academic Training at the US Air Force Academy", 16th AIAA/USU Small Satellite Conference, Logan, Utah, Aug 2002,1.

[7] Personal Interview with Lt Col Jerry Sellers, USAFA, 20 March 2003, 4 April 2003.

[8] Henry, Gary, The Decision Maker's Guide to Robust, Reliable, and Inexpensive Access to Space, *Air War College Final Project*, Air War College, Maxwell AFB, AL, 2003,1.

[9] Humble, R.W., *Space Propulsion Analysis and Design*, McGraw Hill, 1995, 8.

Chapter 2

Discussion

> *A Single Stage to Orbit launch vehicle will never work.*
>
> — Dr Wernher von Braun

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 [1].

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.[2]

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 [3]. 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. USAF Air Launched ASAT ASM-135A. Photo taken at Edwards AFB CA Flight Test Center.

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 the nano-satellite launch vehicle concept, I 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 I decided to use for the conceptual baseline is the GBU-28. I chose it due to its flight heritage on the F-15, planned use for the F-22, and it can fly 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 (retired)

Table 3. Specifications of the GBU-28. Note that the unit cost is $145,600 [5].

Figure 7 Schematic of a GBU-28. It is an 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 the 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 their normal concept of operations for such missions. This will produce steering losses and require a slightly higher velocity requirement. For the fighter aircraft, I assumed a 60-degree angle of attack or pitch angle is feasible. When the ASM-135 was launched, the pilot had the aircraft at Mach 0.934 [6]. For the initial 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 Table 3. Off the shelf composite technology is required if a lower launch altitude is chosen. ΔV's took into account gravity and drag losses. Term definitions: ΔV is change in velocity needed to get to orbit, Payload mass is the mass of the satellite, Total mass is the mass of the launch vehicle that is deployed which includes the structure, satellite and propellant, Inert mass is the structural mass divided by the structural mass and total propellant mass, Launch and Final altitudes are the initial and final altitudes (400 km is high enough to be in orbit for weeks to months, depending on the solar conditions, and Isp is the rocket engine efficiency (defined as the Rocket Thrust/propellant mass flow rate x the gravitational constant).

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. Thus with these preliminary results, I decided to produce a conceptual design for this application.

Notes

[1] Puffer, Raymond, "Death of a Satellite", Air Force Flight Test Center Moments in Flight Test History, Edwards AFB, Ca, 1985,1.

[2] Parsch, A., *Directory of US Military Rockets and Missiles*, "ASM-135", 2002,1.

[3] Ibid., 3

[4] Ibid., 1.

[5] http://www.af.mil/news/efreedom/bombs.html.

[6] Puffer, Raymond, "Death of a Satellite", Air Force Flight Test Center Moments in Flight Test History, Edwards AFB, Ca, 1985,3.

Chapter 3

Concept of Operations

Champions don't make excuses!

—Alison Streeter MBE, Queen of the English Channel and world record holder with 40 successful crossings

In this Chapter, I will present a more detailed design of the launch concept and then propose two mission scenarios where it could be applied. Table 6 shows the specific design results of the launch system. The fantastic result of Table 6 is that everything required to build the launch vehicle is within the grasp of today's technology. The payload mass represents the 6.5 kg SNAP nanosatellite discussed earlier, and rocket engine technology is a chemical solid rocket motor. The sold rocket motor has a specific impulse of 282 sec. Specific impulse is the "miles per gallon" term used for rocket technology; it is the rocket's thrust (output energy) divided by the mass flow rate (input energy). Solid rockets are not as efficient as liquid chemical engines, but are storable (density is about the same as a pencil eraser) and simple (no pressurization system needed – just need an igniter and a case that is strong enough to handle the propellant loading and pressure while the rocket is firing).

For this scenario, I assumed launching at 40,000 ft out of a C-17 to an orbital height of 430 km. I chose 40,000 ft since that is the height that supports the current C-17 flight operations plan. The final orbital altitude is good for remote sensing and should allow operations on the order of months, before orbital perturbations and drag gradually cause the satellite to lose altitude and re-enter. The velocity requirement to reach a 430 km orbit is 8.07 km/s. At 430 km of altitude, the orbital speed required is 7.65 km/s. However, to reach this orbital height from 40,000 ft, we must overcome the force of gravity and drag, hence we need to add more velocity which increases our velocity requirement (500 m/s to overcome gravity and 3% of the final velocity required for drag, which gives 8.07 km/s). These numbers were derived from empirical studies of previous launches, so are good "ballpark" numbers for design[1]. The rocket equation is a way to look at the velocity required, and make sure the rocket has enough energy from the propellant to get the spacecraft to orbit.

$$\Delta V = Ispg \ln(Mi / Mf) \qquad \text{Equation (1)}$$

where:

ΔV = velocity required (m/s)

Isp = rocket efficiency (sec)

(g) = 9.81 m/s^2, gravity constant at sea level, remains the same throughout burn

$M_{initial}$ = total vehicle mass (rocket+ engine+propellant + payload)

M_{final}= final vehicle mass (no propellant)

Equation 1 predicts, based upon the mass and rocket performance from Table 6, that we have enough energy to get to orbit with one stage, with one 182 second burn. This is a nice feature; even though staging does increase performance, it also increases complexity and cost.

I also assumed since the deployment was from a C-17, that the initial rocket velocity would be zero since it would be dropped from the back end. Even though my calculations show that the concept can fit on the rail of an F-15 or other fighter (see Figure 8), the nice feature of keeping the system to the size of an existing missile, is that you have flexibility. I also looked at the added performance we could get by using the velocity of the aircraft. If we deploy at Mach 1, we get an additional 0.33 km/s of velocity, so we could decrease the total velocity required to ~ 7.8 km/s. We could use the same volume, and either increase the payload mass (up to ~ 16 kg from 6.5 kg) or increase the orbital height. However, deploying at Mach 1 could create some separation issues, which I will talk about later in this Chapter.

Liftoff Altitude with C-17 deployment 40,000 ft	Final Altitude 430 km	Total Mass at Liftoff (Minitial) 2000 kg
Payload Mass (Mpayload) 6.5 kg	Mass of Propellant (Mpropellant) 1867 kg	Inert Mass (Minert) 126.5 kg
Rocket Specific Impulse (Average) 282 sec	Thrust (Average) 28,409 N	Mass flow rate 10.26 kg/s
Burn Time 182 seconds	Exit Velocity 2769 m/s	Thrust/Weight 14
Inert Mass Fraction 0.064 (composite)	ΔV = 8.07 km/s 7.65 km/s orbit velocity+500 m/s gravity losses + 3 % of total velocity for drag	Rocket Dimensions: Case diameter: 36.83 cm- 34 cm solid propellant + 1.3 cm insulator + 0.7 cm case (pressure vessel) by 286 cm length of propellant (propellant ρ=1800 kg/m^3) **103 cm length available for nozzle and payload, if expansion ratio = 40, nozzle length = 48 cm, payload length = 54 cm with 34 cm diameter**

Table 6: Conceptual Design Results, the system works! It can achieve space altitude for a nanosatellite class payload and use technology that exists today.

Figure 8: GBU-28 in flight on an F-111. Keeping the rocket dimensions the same as an existing system will ease its integration into the fleet.

Besides just using the rocket equation, I also used a rocket altitude prediction code[2]. This takes into account the aerodynamics of rocket flight, looking at the density of air as the rocket gains altitude and the vehicle drag characteristics. I chose conservative numbers for the prediction (high coefficient of drag-0.75, and that the density of air remained at 1000 kg/m^3 throughout the entire flight), and the code predicted that the 6.5 kg to 430 km of orbit is possible, using the design shown in Table 6. A more rigorous analysis will be required to look at the changes of the rocket performance with time (i.e., center of gravity will change due to expelling the propellant, thrust will change since the burn area in a solid changes over time and the thrust is proportional to the burn area, etc). It is good to note that a conservative approach showed that it is possible. Figure 9 shows the thrust profile for the vehicle, burn out time is 182 seconds, and the rocket coasts for 29 seconds before reaching its final altitude at 430 km.

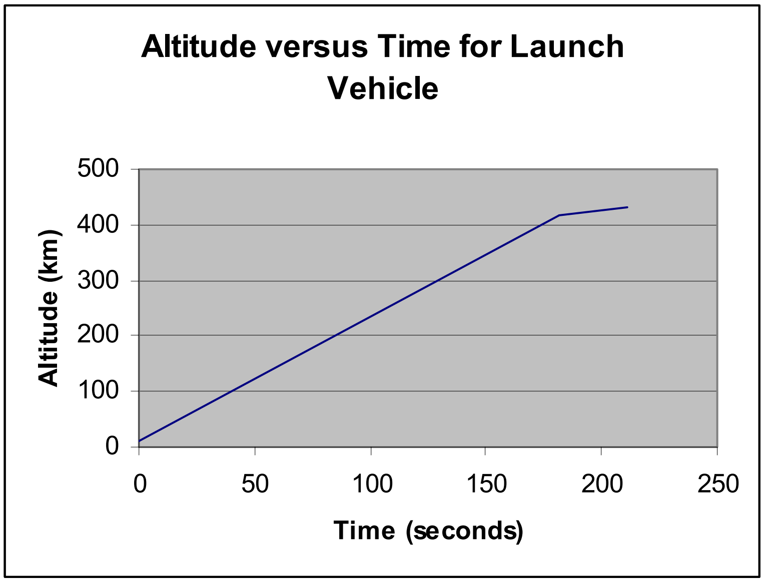


Figure 9. Altitude versus time for the launch vehicle using the AltSim software from my design data shown in Table 6. The rocket is deployed at 12 km, fires for 182 seconds, and then reaches its final altitude of 430 km after coasting for 28 seconds.

In April 2003, Aviation Week wrote an article on a similar concept under investigation at AFRL/VS. AFRL/VS presented a paper at the IEEE conference in Wyoming in March and described the use of a 10,000 lb rocket to launch 100 kg microsatellites into 760 km orbits from an F-15 traveling at Mach 1 [3]. Although I like the approach since it is similar to mine, their concept does have some issues. Since they required the rocket to weigh 10,000 lbs, they must put the rocket on the underbelly of the F-15 with only 1" clearance from the ground. This could create "interesting" issues as maintenance crews try to mount it to the underbelly. The other problem is that the aerodynamics of such a big rocket on the underbelly of the F-15 could create problems. The airflow under the F-15 has been unpredictable[4]. Different body stations on the platform have witnessed this effect. There tends to be air spill over from inlets on the smooth underbelly. This has created sometimes-unpredictable airflow under the belly, which sometimes causes bombs to drop and rise after deployment – usually just the non-aerodynamic dumb bombs. This has been worked out due to testing, but such a big system, flying supersonic, could create operational issues. According to Dr Preston Carter of DARPA, head of microsatellite launch concepts, he has lost interest in this concept due to the technical complications even though the article reported that the concept was being funded under his organization[5].

Figure 10 shows a drawing of my design. The more detailed calculations that support this drawing can be found in Appendix C. Besides verifying the volume fits for the velocity required to orbit, I also verified that the regression or burn rate also supports the burn time required of 182 seconds. However, a detailed trajectory simulation will also be needed to look at guidance and control for final orbit insertion, but as I have stated, my assumptions have allowed margin in the design. Finally, and most important, range support, basing and logistics support would need to fully explored. Since it is air launched, we have the flexibility of launching into many orbital inclinations since we can choose our launch window by just flying to the latitude of choice – but the range support must also be there. Recall, one of the goals is to have students participate in as many aspects of the launch operations as possible, so basing and safety considerations would be paramount.

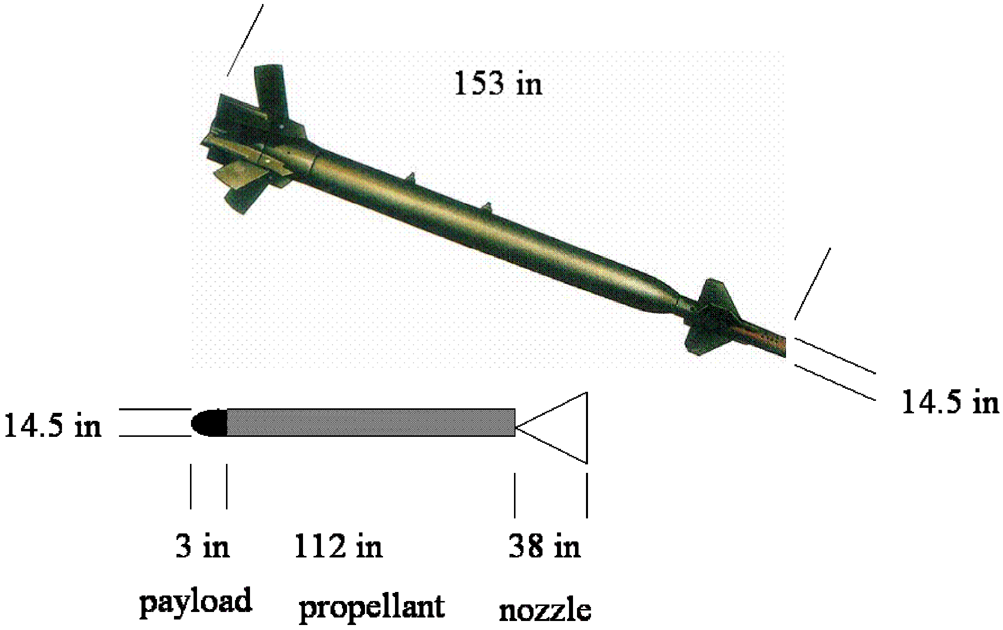


Figure 10: Conceptual Design. My calculations from Appendix C show that the design can meet the volume requirements of the GBU-28. The payload area supports the SNAP dimensions.

As far as applications, such a concept could support nanosatellite remote sensing constellations for the warfighter or serve as a test platform for research/training. Assuming that a 2" inch camera is put on the 6.5 kg nanosatellite, I calculate that a black and white ground image resolution of 10 m can be achieved from 430 km (see Appendix B). Looking at the orbital mechanics from 430 km, 1 satellite could image the location of choice (swath width of 361 km, Field of View of 88 degrees) every other day, and a constellation of 4 launched in the same plane could image the same swath width every day at 0800 every 20 minutes until 1100, and again at 1900 every 20 minutes until 2241. If a 5th satellite is added, the imaging starts at 0730, and repeats every 17 minutes until 1113, and starts again at 1850 and goes every 17 minutes until 2230.[6] Each of these simulations assumed a repeat period of one week. I calculated the first order number of satellites in the constellation by looking at the orbital period, swath width, and circumference of the earth. Looking at available bandwidth, the satellite could take one image per orbit and transmit it to the ground station.

Such a system could give persistent remote sensing at 10 m resolution, which could provide data that could be integrated/compared with other remote sensing assets with higher resolution. The key is that the small satellite operating system must be the same as the other assets so data can be readily transferred and not go through some type of "translator" for integration. Communications could also be an application, with data transmitted at the kByte level – possibly upgraded as technology improves. The concept of operations would be that the system would be launched from an air asset, and control would then be given to the theater commander, even though the assets will only be in theater at certain times. The estimated orbital lifetime at 430 km will be worst-case 6 months, up to 1 year, all depending on the drag parameters of the orbit. The small satellite could also have a propulsion system for stationkeeping, or to keep the satellites in the right phase (separation from other satellites to maintain persistence--one leaves the theater, the next one arrives, etc). Since these assets are "expendable", total cost should be limited to the current expendable assets used in the theater – missiles and bombs. With SNAP costing $750 K starting from scratch (complete cost), ground stations at $100 K each, and a target launch cost of the new system to be $250K (all existing technology), this should be feasible. In order to provide affordable access to space, I propose that the launcher be initially constructed at the Air Force Academy with a team of engineers, faculty, and cadets.

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 must 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. For example, an even simpler 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 imagine other applications, such as attitude control demonstration, and formation flying.

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 affects 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 11. 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.

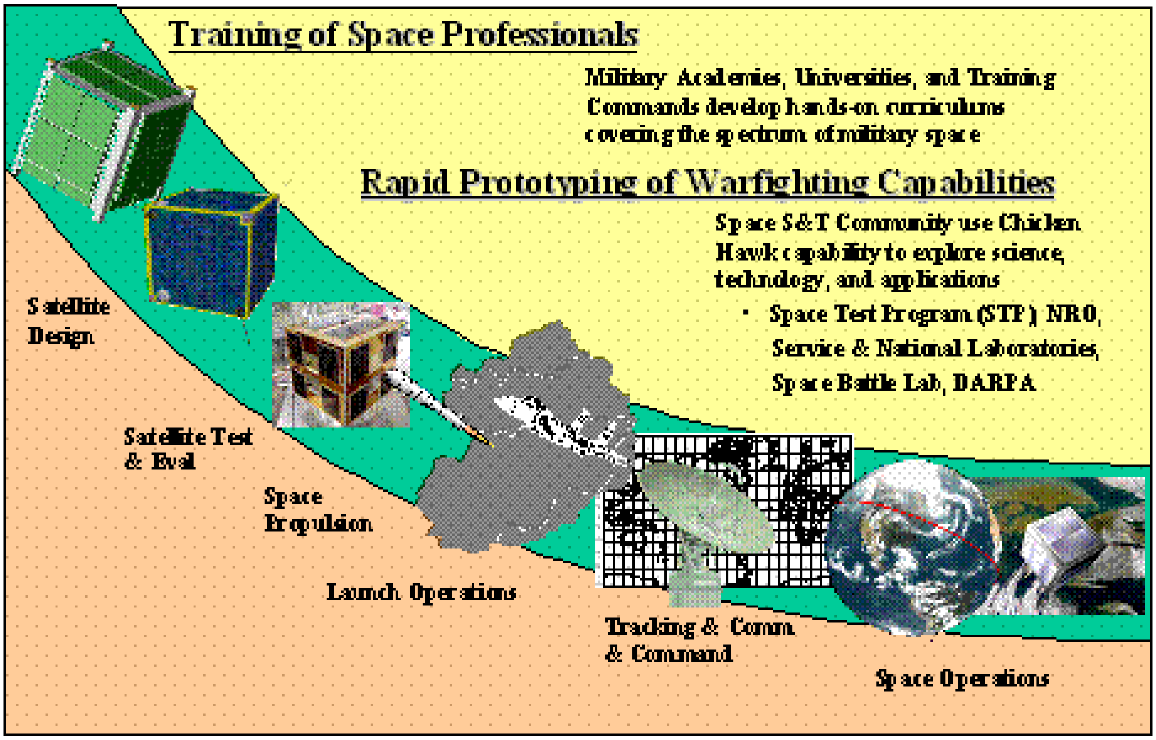


Figure 11 Space for All Concept of Operations. Such a concept could create a UPT for Space as well for new 2Lt's.[7]

Notes

[1] Wertz, J., Larson, W., *Space Mission Analysis and Design*, Kluwer Academic Publishing, 1992, 408.

[2] Forge Village Software, Rocket Altitude Perdition, (ALTPRED),Westford, MA, 1995.

[3] Aviation Weekly, "Special Report: MILSPACE Fighters as Spacelift", 7 April 2003, 21.

[4] Personal Interview with Major Mike "Beege" Farrell, ACSC, 11 April 2003.

[5] Personal Interview with Lt Col Jerry Sellers, USAFA, 20 March 2003, 4 April 2003.

[6] Personal Interview with Major Vince Parks, ACSC, based upon his STK simulations, 13 April 2003.

[7] Carter, Preston, Chicken Hawk Program Briefing, October 2002.

Chapter 4

Conclusion

Sometimes doing the impossible is fun.

—Walt Disney

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 workhorses, and allowing satellite builders to push the state of the art to the point where, today, we can easily imagine a new class of 10-kg satellites pushing the state of the art even further. Using education and training of future space leaders 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, a responsive, low-cost nano-satellite operational system could also offer transformational capabilities to future combatant commanders.

Appendix A

US Air Force Academy Small Satellite Program

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.

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 (mounted on Centaur with no deployment), 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. [1]

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 prototype 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 off-the-self hardware in the development of FalconSat-2. The FalconSat-2 design is based on 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 was 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.

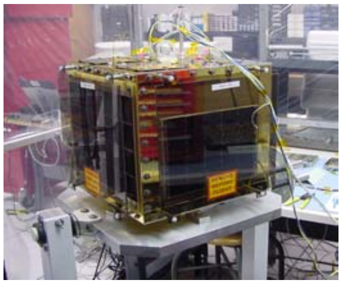


Figure 12: FalconSAT-2 is shown in the USAFA clean room awaiting launch.

As of this writing, FalconSAT-2 is complete and awaiting launch as shown in Figure 12. 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 (Scientific Evaluation Review Board) 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 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 (ESPA) Mission in March 2006. A model of FalconSAT-3 is shown in Figure 13.

Figure 13: 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 May 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. Results of this research can be applied to the design of a new launch system.

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 the 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."[2]

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 cadets 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 the flying mission.

Notes

[1] "FalconGold Program Mission Overview," this information is available on the web at www.usafa.af.mil/dfas/research/falcongold/falcongold.html.

[2] Report of the Commission to Assess United States National Security Space Management and Organization, January 11, 2001.

Appendix B

Remote Sensing and Orbit Mechanics Calculations

Imaging:

Number of orbits @ 430 km

Nanosat stuff 15.418

40053.84 Earth circumference

= Earth Circumference/#orbits 2600.899 for 430 km orbit

Resolution=$2.44\lambda H/D$ 10.492 resolution

Resolution = $2\phi H$ 0.0122 theta in rads

0.699363 theta in degees

tan theta = y/x

x and theta known

0.8412

swath width based on trig 361.7161

= D16*2 for swath width 723.4321 swath width

= D8/D18 3.595221 Equals 4 satellites needed @430 km, 10.4 m resolution

5 sats @ 430 10.4 m resolution

spare

STK sims for 4 and 5 sats 4 @ 8:00 a.m. every 20 minutes until 11:00 a.m.

4 @7:00 p.m. every 25 minutes until 10:41 p.m.

5 @ 7:30 17 minutes, 11:13 a.m.

5 @ 6:50 p.m. to 10:30 p.m. same frequency

If we just had one nanosatellite, we would see the same swath width every other day

Maj Park's data from STK
32 , 8 in 4 planes, evenly spaced
8-10 am, 2-4 p.m., 8-10 pm, 2-4 am directly nadir
sunsync, 430 km
7 day repeating

Appendix C

Rocket Altitude and Solid Rocket Design Calculations

Rocket Calculations:

0.666667 If plane is traveling Mach2, we can subtract this from delta V If traveling Mach1, subtract 0.33
8.07 is from 7.65 km veloctiy at altitude + 500 m/s gravity loss + 3 % drag loss
8.07 numbers come from SMAD, based upon empirical studies, assumed no start up velocity

Delta V calculation 8012.565 6.5 kg SNAP, 303 sec Isp (from SPAD), mass of system below
Using ALTPRED C17
Code: Rocket prediction:
Liftoff altitude:
40,000 ft 12.192 12.192 km Initial orbit units conversion
final =
= assumes Cd = 0.75 and density = 1 atm continuous for burn
428.674 km Final orbit from ALT Pred
Rocket specifics:
Minitial = 2000 kg
Mfinal = 133 kg
Mpayload=6.5 kg
Minert=126.5 kg
Burn time = 182 sec Mprop = 1867
Average 28409.06 N thrust Thrust/Weight = 14
Mdot 10.25824 Mdot Inert mass = 0.063504 for SNAP
2769.389 Ve
Average 282.3027 Average Isp

Volume Calculations:

```
Density of solid prop = 1800       P = m/v
Mass of prop = 1867                  1.037222  m^3
                                   14.5 x 153  total GBU 28 dimensions in inches
diagram in cm             0.3683   m                    36.83  cm         need  0.635cm for insulator,
                        Volume = pir^2 h                       .348 cm for case, so say - 2 cm from outer diameter
                          2.857487 length of propellant        in meters
                            3.8862 volume available!           1 m for nozzle, exit diameter = 80 % of case diameter
Throat diameter           0.079367  7.936684
length of nozzle        Lnozzle =   97.29085  nozzle length = 97.29 cm
from empirical results      0.9729
SPAD Chapter 6              1.0292 m available!!!!
                        Regression rate calcs:
           r              0.715323 cm/s       burn rate in cm/s
                          130.1888            total cm's burned
                          1.301888 m burned according to regression
                        so have margin for regression rate, could change Chamber pressure (thrust)
           dimensions:
                        propellant
                          112.4995 in
                        nozzle
                          38.30315 in
                        rest is for payload, SNAP was 12in in length!
```

Bibliography

Aviation Weekly, "Special Report: MILSPACE Fighters as Spacelift", 7 April 2003.

Carter, Preston, Chicken Hawk Program Briefing, October 2002.

Dean, E., Unal, R., "Designing for Cost," Transactions of the American Association of Cost Engineers, pp. D.4.1 - D.4.6, Seattle, Washington, 23- 26 June, 1991.

FalconGold Program Mission Overview," this information is available on the web at www.usafa.af.mil/dfas/research/falcongold/falcongold.html.

Forge Village Software, Rocket Altitude Perdition, (ALTPRED),Westford, MA, 1995.

http://www.af.mil/news/efreedom/bombs.html.

Henry, Gary, The Decision Maker's Guide to Robust, Reliable, and Inexpensive Access to Space, *Air War College Final Project*, Air War College, Maxwell AFB, AL, 2003.

Humble, R.W., *Space Propulsion Analysis and Design,* McGraw-Hill, 1995.

Parsch, A., *Directory of US Military Rockets and Missiles*, "ASM-135", 2002.

Personal Interview with Lt Col Mike "Chanz" Chandler, February 2003.

Personal Interview with Major Mike "Beege" Farrell, ACSC, 11 April 2003.

Personal Interview with Major Vince Parks, ACSC, based upon his STK simulations, 13 April 2003.

Personal Interview with Lt Col Jerry Sellers, USAFA, 20 March 2003, 4 April 2003.

Puffer, Raymond, "Death of a Satellite", Air Force Flight Test Center Moments in Flight Test History, Edwards AFB, Ca, 1985.

Report of the Commission to Assess United States National Security Space Management and Organization, January 11, 2001.

Sellers, J.J., *Understanding Space*, McGraw-Hill, 2000.

Sexton, Allen, Air Command and Staff College Advanced Space Studies Course, Maxwell Air Force Base, AL, 2003.

Underwood, C et al, "Flight-Proven Nano-satellite Architecture for Hands-on Academic Training at the US Air Force Academy", 16th AIAA/USU Small Satellite Conference, Logan, Utah, Aug 2002.

Wertz, J., Larson, W., *Space Mission Analysis and Design*, Kluwer Academic Publishing, 1992.