ENABLING AFFORDABLE, DEDICATED ACCESS to SPACE THROUGH AGGRESSIVE TECHNOLOGY MATURATION

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Abstract— A launch vehicle at the scale and price point which allows developers to take reasonable risks with high payoff propulsion and avionics hardware solutions does not exist today. Establishing this service provides a ride through the proverbial technology "valley of death" that lies between demonstration in laboratory and flight environments. NASA's NanoLaunch effort will provide the framework to mature both earth-to-orbit and on-orbit propulsion and avionics technologies while also providing affordable, dedicated access to low earth orbit for cubesat class payloads.

***Index Terms*—cubesat, propulsion, technology maturation, nanolaunch, launch vehicle**

I. INTRODUCTION

Many small launch vehicles have been proposed. A few proposed vehicles have initiated development and a relatively small number have been fielded. Many current efforts are underway ranging from balloon and air-launch architectures to traditional range and pad launched configurations. A review of these efforts is detailed by Zapata [1].

The Solid Controlled Orbital Utility Test system (SCOUT) was one of the earliest and most successful small launch vehicles. The concept was proposed in 1957 at the NACA Langley Center. The first successful SCOUT vehicle was launched within three years on July 1, 1960. The rapid fielding of the SCOUT vehicle was enabled by taking advantage of existing missile assets. The first and second stages were derived directly from the Navy Polaris and the Army MGM-29 Sergeant, respectively. The third and fourth stages were adapted versions of the Vanguard solid upperstage [2]. The SCOUT vehicle was operational from 1963 through 1994. The first payload weighed only 7 kg while the final payload was 163 kg [3].

The SCOUT program successfully sustained and/or increased capability for over thirty years. While the longevity of the program points to an affordable architecture, there is no clear evidence of any initiatives focused on reducing cost. A 1972 study focused on the most economical approach to reach the increased performance goals of the Advanced Small Launch Vehicle (ASVL), but it did not suggest a path for maintaining performance while reducing the price/cost of each launch. When faced with increasing performance or lowering costs, managers and programs almost always choose to follow the path of increased performance.

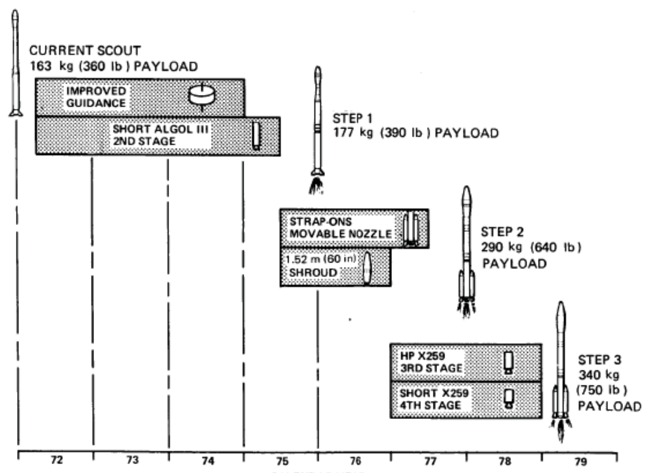

Figure 1. NASA Langley's 1972 recommendation on "the most economical (lowest cost/launch) approach for development of an Advanced Small Launch Vehicle (ASVL) for use over the next decade." [4]

MSFC's NanoLaunch Program seeks to duplicate the success of the SCOUT launch vehicle while applying two significant changes in focus. First, affordability not performance will drive design decisions. Second, maturing launch propulsion technologies will take precedence over delivering payloads to orbit. Performance and reliability will be maintained while novel technologies, approaches, operational paradigms, and manufacturing techniques are identified and developed to reduce the price point for orbital access.

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II. Objectives

The NanoLaunch Program seeks to establish an affordable orbital launch vehicle program that continually matures new technologies and implements new approaches to reduce the price point for orbital access. The program is not a launch service provider, although it will place cubesat class payloads in orbit with each successful launch. Technology and approaches will be sought from government, academic, and commercial sources. The qualification, by flying on Nanolaunch, of these technologies and approaches will raise the competitive bar and increase the available alternatives enabling launch service providers to create and maintain an affordable launch service without having to take on the full development cost and risk. Within this paradigm a new stage can be tested in flight within the scope and budget of a Phase II SBIR.

A goal of the NanoLaunch Program is to determine the payload and reliability target which minimizes the cost of a single successful launch. In general, the cost of a launch decreases with the size of the payload. At some point the cost of miniaturization will cause an increase in the launch cost even though the vehicle is smaller. Increasing reliability is always desirable; however, a point will be reached where the cost of increasing the reliability of a launch vehicle is more than the cost of flying a second launch vehicle.

For example, given a launch vehicle that has eliminated correlated failures with 90% reliability, two launch attempts with the same payload will yield 99% reliability for mission success. One launch vehicle and payload may be lost but you have a 99% chance of successfully placing one payload in orbit. The desire is to determine the reliability target for which it is cheaper to build and launch a second vehicle rather than pay to increase the reliability of a single vehicle to insure mission success.

The uniqueness of this approach is not the baseline vehicle (Figure 1) or the additively manufactured stages that enable orbital access rather it is the open "plug and play" architecture that allows for the entry of new technologies. Three primary objectives are outlined below to reach this goal: rides for high payoff technologies, orbital access for cubesat class payloads, and training for the next generation.

A. *Provide "Rides" for High Payoff Technologies*

The cost of entry into the launch market today is very steep. Novell technologies and approaches are often demonstrated in a laboratory environment but lack sufficient evidence to be placed in the critical path of existing launch vehicles. No one is willing, justifiably, to risk \$30M-\$1B (cost of existing vehicles) to mature these technologies. This often eliminates many high payoff options because there is no flight data to qualify and certify the new technology for flight.

The end result is that there are no available rides for the demonstration of new propulsion systems. This has contributed to a slow evolution in the development of propulsion systems and critical launch vehicles components such as avionics, guidance and contrand flight termination systems. An affordable launch vehicle which allows high payoff technologies in the critical path is needed. This launch vehicle should have clearly defined interfaces that allow for "plug and play" component and stage testing.

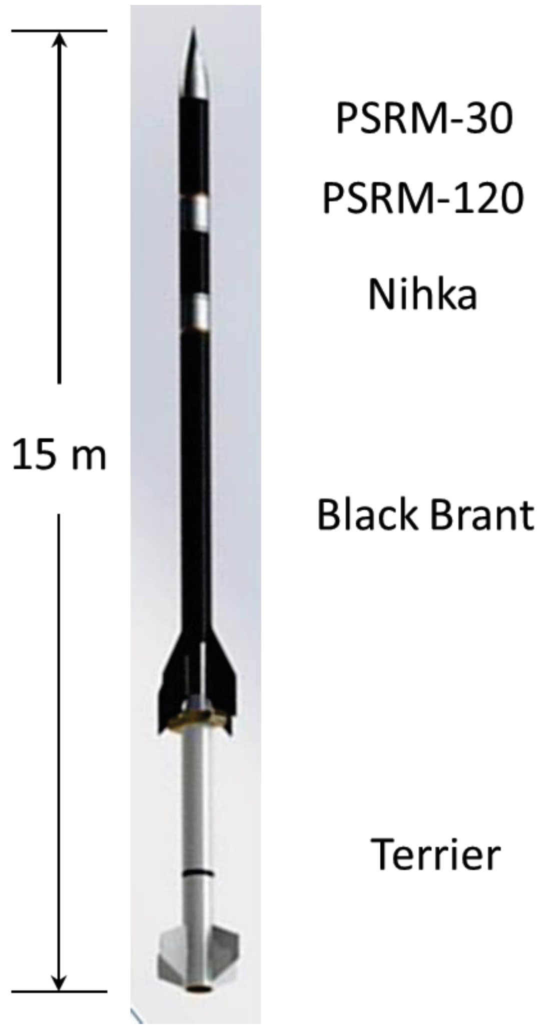

Figure 2. The baseline vehicle configuration consisting of the legacy Black Brant X (Terrier, Black Brant, and Nihka) and two printed solid rocket motors with 120 lb (PSRM-120) and 30 lb (PSRM-30) of propellant.

B. *Provide Dedicated Space Access*

The recent explosion in nano-sat, small-sat, and university class payloads has been driven by low cost electronics and sensors, wide component availability, as well as low cost, miniature computational capability and open source code. Increasing numbers of these very small spacecraft are being launched as secondary payloads, dramatically decreasing costs, and allowing greater access to operations and experimentation using actual space flight systems. While manifesting as a secondary payload provides inexpensive rides to orbit, these arrangements also have certain limitations. Small, secondary payloads are typically included with very limited payload accommodations, supported on a noninterference basis (to the prime payload), and are delivered to orbital conditions driven by the primary launch customer. Integration of propulsion systems or other hazardous capabilities further complicates secondary launch arrangements, and accommodation requirements.

The baseline system shown in Figure 1 was chosen to enable an orbital launch attempt as soon as possible and minimize upfront development costs. The first three stages are the legacy Black Brant X sounding rocket which is capable of placing two smaller stages in a position to put a 3U cubesat in orbit. The Black Brant X is routinely flown today from Wallops Space Flight Center and is an established history [5]. The two smaller uppers stages utilize additive manufacturing to reduce cost and development timelines significantly. This baseline vehicle is viewed as a starting point that allows for a relatively early orbital launch attempt.

C. *Provide Training for the Next Generation*

The evolving role of NASA has limited the hands on roles that new employees and student interns can participate in at the agency. New employees are often asked to tackle insight and oversight roles without having had the opportunity to participate in an integral way in the activities that they are asked to evaluate. Mentors and retired NASA employees are used to help these employees fill valuables roles in the space industry. However, integral involvement in building and launching a rocket provides a basis of understand that cannot be obtained in other ways. NanoLaunch offers this opportunity at a scale that is affordable.

The number of employees dedicated to NanoLaunch is kept at a minimum level. Students at the high school, undergraduate, graduate, and professional level are utilized to solve the key technical challenges faced by NanoLaunch. This provides training for these students and NASA employees and provides a fresh and innovative flow of approaches and concept to NanoLaunch.

III. CHALLENGES

The number of attempts to produce an affordable small vehicle that have failed to reach maturity attests to the difficulties faced in this field. NanoLaunch has determined that when current practices are used the cost of the required propulsive stages is less than one fifth of the cost required to prepare and place a vehicle on the rail ready for launch. Furthermore, the range and handling requirements imposed on large launch vehicles are applied at the nano-scale. Thus, the scope of factors to be considered when addressing affordable options penetrate deeper and extend beyond the major launch vehicle systems and are among the key drivers that must be considered as the following challenges are addressed.

A. *Fixed Costs*

The enormous energy required to reach orbit has traditionally required independent manufacturing, processing, assembly, and range facilities for orbital launch vehicles. Manufacturing facilities for automobiles, ships, and even airplanes have not required the same level of scrutiny and tracking of materials and processes. Thus, the full burden of the substantial fixed cost incurred by these facilities is incurred by the space launch and exploration community. To date these costs have not been remunerated by launch rate. As the costs have risen, reliability and success criteria have been driven to the point that "failure is not an option" for space flight. This in turn has required independent production lines for virtually all space rated avionics and hardware where once again the fixed cost of maintaining these lines falls fully on the space launch community.

B. *Qualification and Certification Requirements*

Nanolauch vehicles must obey the same physics as large launch vehicles. This results in the perception that all qualification and certification requirements that pertain to large launch vehicles apply to the nano-scale. For physics based requirements this is clearly correct. However, all requirements, certifications, verifications, and analysis should be reviewed to identify appropriate tailoring. Special attention should be given to those requirements that are already being validated by other market segments that process much higher volumes so that the aerospace industry does not have to maintain the full burden of fixed costs.

C. *Scaling Mega-lifters to NanoLaunchers*

Several key factors change when scaling from large vehicles to the nano-scale.

- As the diameter (D) of the vehicle decreases the cross sectional area decreases with D^2 while the mass of the vehicle decreases $\sim D^3$ resulting in steeply increasing drag losses as the ballistic coefficient decreases rapidly.
- As the scale decreases manufacturing limitation soon begin to drive design optimization versus physical constraints such as propellant tank pressure. Minimum build thickness or minimum gage often determine key inert masses.
- Key components such as valves, interstages, flight termination charges, and reaction control systems do not exist at this scale. Several promising options exist in the automotive and hobby markets but performance for a launch vehicle application must be verified.
- Correlations to predict cost and schedule are derived from vehicles at least an order of magnitude larger with the majority of the data points from the expendable launch vehicle fleets which are 3-4 orders of magnitude larger. This makes predicting cost and schedule very difficult.
- On the positive side, achieving a high thrust to weight is more easily achieved because of the square/cubed law explained for drag. This allows liquid and hybrid systems to obtain adequate thrust to weight levels.

D. *Range Operations and Requirements*

The primary range challenges facing nanolaunch have already been described under *Fixed Costs and Qualifications and Certifications*. However, the importance of range operations and the range's impact on launch vehicle costs deserves special consideration. A launch vehicle can in principle be launched from anywhere. Ranges have been established in key strategic locations to optimize launch performance and minimize the chance of harm to the public. Incredible capability for handling, assembling, launching, and tracking have been established at these facilities.

Launch ranges have an excellent record. Harm to the public has been limited to equipment and property even with several catastrophic failures. This record attests to the effectiveness of current launch procedures and practices.

The fixed infrastructure and personnel associated with these capabilities must be maintained. To date it appears that nanolaunch vehicles will be assessed the same fraction of these costs that larger launch vehicles have been assessed. When these costs are added to the launch vehicle bill of material and assembly costs the resulting bill is often too much for a single cubesat customer to absorb.

IV. Current State

Multiple agencies are pursuing small launch vehicle development including:

- Super-Strypi sponsored by the Defense Department's Operationally Responsive Space (ORS) [6]
- The Airborne-Launch Assist Space Access (ALASA) program sponsored by the Defense Advanced Research Projects Agency (DARPA) [7]
- The Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) sponsored by the U.S. Army Space and Missile Defense Command (USASMDC) [8]
- GOLauncher 2 Generation Orbit Launch Services, Inc. (GO) sponsored by NASA's Launch Services Enabling eXploration and Technology (NEXT) contract [9]

In addition to the government sponsored programs multiple small businesses have recognized the need for small launch vehicles. NanoLaunch is not a competitor to these efforts, rather it offers a path to mature critical technologies for these efforts.

A. New Technologies and the Critical Path

As outlined in the challenges for nanolaunch, current launch vehicles do not allow new technologies in the critical path. Thus, the technology evolution is slowed. Businesses that are the correct size to develop a nanolaunch vehicle cannot take on the full burden of vehicle development. Most have been stopped after a few successful stage tests.

B. Restrictions on Secondary Payloads

Secondary payloads are constrained to fly when the primary payload is ready and must eliminate risk to the primary payload. This has the largest impact on new propulsion technologies for cubesats. These restriction are justified by the relative cost of the primary payload compared to the cost of the cubesat class payload. It is not reasonable to remove these restrictions. A dedicated launch vehicle is required at an affordable price point.

V. Approach

NanoLaunch has started with the development of the orbital insertion stage and is progressing down the vehicle stack from the smallest stages to the largest. This approach allows for the development and implementation of manufacturing techniques, new propulsion designs, and approaches at a small, more affordable scale. For additive manufacturing NanoLaunch is pushing the build volume limits; however, the rate at which additive manufacturing is progressing should keep pace with our incremental development approach. Once these approaches along with verification and validation plans have been demonstrated for the insertion stage they can be applied to the larger stages.

A. Eliminating Fixed Costs

Our approach centers on eliminating fixed costs. Advances in manufacturing techniques and microelectronics have resulted in the emergence of several key industry bases which are supported by the general public but can be exploited to reduce orbital access cost. The key factors used to identify these market niches are:

1) Is the microbusiness self sustaining? Can it survive independent of our purchases?

2) Do the standard manufacturing techniques and catalog components meet our requirements? Can we meet our requirements without standing up an independent product line that only NASA supports?

The case of the first Printed Solid Rocket Motor (PSRM-10) was built using electron beam melting and filled with ~10 lb of propellant. Design work for the case, grain, and insulation was completed on July 9, 2012. The contract to have the case additively manufacture was released. The case was built and returned to MSFC to be insulated. The insulated case was delivered to AMRDEC where propellant was mixed and cast in the motor. The loaded motor was returned to MSFC and successfully test fired on October 16, 2012, a little over three months from the completion of the design, as shown in Figure 3. This demonstrated a significant reduction in cost and schedule for solid rocket motor development.

Figure 3. Static test firing of the first "printed" titanium solid rocket motor case.

B. *Low-cost Relevant Flight Environments*

The NanoLaunch Program has used high power amateur rockets to test propulsion and avionics subsystems. The high power rockets have been able to create anticipated flight environments such as max acceleration and heating rates. This allows the program to purchase commercially available rockets and verify that off the shelf avionics will survive flight environments. These tests do not replace traditional environmental testing requirements, but they do add confidence to the validity of a COTS approach.

To date we have used these rides to test multiple options for inertial measurement units, GPS systems, candidate flight computers, telemetry, and data recording systems. We have also tested additively manufactured materials used for both the airframe and solid rocket motor domes.

Figure 4. NanoLaunch 1a flight at Phoenix missile works in Talladega, Alabama.

C. *Standardized Assembly and Integration*

In 1999, Jordi Puig-Suari and Bob Twiggs began the definition of "a standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches." The CubeSat Design Specification that resulted from this initiative has demonstrated the effectiveness of standardization. With this standard in place, launch service providers have opened up and are now confidently providing multiple rides for payloads that meet the defined standard. Satellite component suppliers have been able to focus their product lines and are now offering generic combinations of hardware and software packages that conform to the CubeSat specifications. [10]

The NanoLaunch Program is attempting to do something similar for stages and components that lead to affordable launch systems. Standardizing the interfaces and requirements of a Nanolaunch vehicle will allow academia, industry, and government laboratories to focus on the development of critical technologies. They will not be required to foot the bill for the entire rocket, which in the past has been prohibitive. It will streamline range approval by defining a set of standards that each stage must comply with to safely operate. It will eliminate the need to define a unique launch vehicle for new technology that desires entry into the launch market. This standardization process is an essential component of any ADAS path.

D. *Strong Partnering with Acedemia and Industry*

The NanoLaunch Program relies heavily on its academic and industry partners for infusion of new ideas. To realize affordable space access many of these ideas need to be brought to a maturity level where they can be integrated into a launch vehicle demonstrating manufacturing, integration, and operational costs which are difficult if not impossible to predict accurately. Our partners often have the resources for stage and component development. They seldom have the resources for a full vehicle development.

The realization of a "plug and play" NanoLaunch vehicle will help to alleviate this roadblock. New technologies will have a focus and a vehicle to test cost and performance claims on. The focus that NanoLaunch provides is displayed in the work of our university partners.

Over a dozen universities have participated in various projects in support of NanoLaunch. These projects include reaction control system design studies, truss interstage design and test, "printed" hybrid fuel grains, compliant gimbal mounts, additively manufactured valves, full vehicle trade studies, adaptive drag control, nozzle optimization, in flight measurement of aerodynamic coefficients, and regeneratively cooled nozzles.

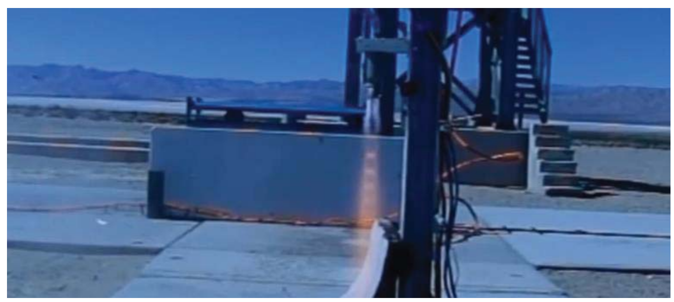

Figure 5. The University of California, San Diego liquid oxygen/RP additively manufactured engine static test firing.

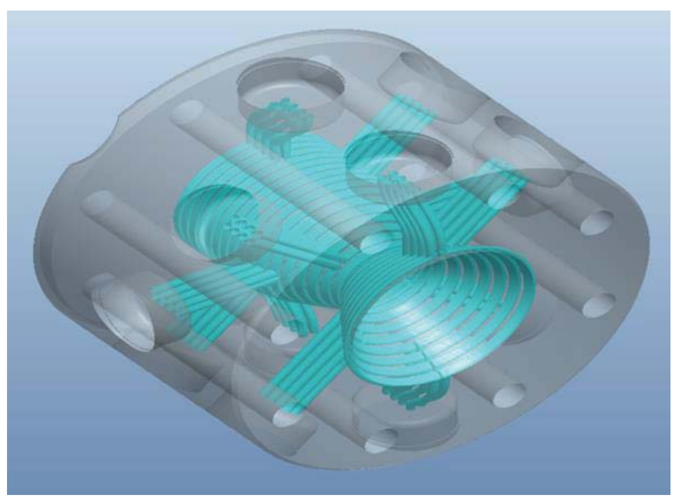

Figure 6. An additively manufacture nozzle with integral cooling channels for use as a calorimeter being tested at the University of Tennessee, Knoxville.

Figure 7. A scaled model of Brigham Young Universities isotruss interstage built out of ABS plastic.

Figure 5 -7 highlight three university projects.

- An undergraduate student team at the University of California San Diego designed a liquid oxygen/kerosene injector and thrust chamber. The injector featured impinging doublets, the chamber was film cooled, and the nozzle was regeneratively cooled. The whole assemble was additively manufactured.
- In close conjunction with Marshall Space Flight Center the University of Tennessee in Knoxville, Tennessee is determining the maximum heat flux that can be absorbed in an additively manufactured Inconel nozzle. A nozzle with 6 water cooled axial stations has been additively manufactured. Heat flux measurements have been obtained for low heat flux settings. The heat flux will be increased until the nozzle fails.
- A senior design team at Brigham Young University in Provo, Utah designed, manufactured, and tested an isotruss interstage. The model shown similar to Figure 7 was built on a Makerbot and withstood an axial load of ~600 lb before failing in due to buckling. A prototype using carbon fiber rope is being constructed for testing.

E. *Right-sizing the Management Approach*

The challenge with managing the NanoLaunch project is centered in its diverse student derived workforce. Tools that allow for the turn over of key project members without the loss of technical data are needed. Several model based systems engineering tools are being exercised in an attempt to capture the key functions, interfaces, and requirements that need to be tracked to insure the system integrity.

The NanoLaunch Project recognizes that a large portion of the fixed cost incurred go to support the salary and wages of the workforce. To be affordable at this scale, team members must have multidisciplinary skills. With the correct skill mix a streamlined operation, and simplified standard design, five good people should be able to integrate and launch a rocket.

VI. Operational Concept

The trajectory and operational concept for the baseline vehicle is similar to SCOUT. The vehicle has an initial acceleration of around 10 gees to enable rapid spin stabilization as it leave the rail. The Terrier has a short burn time and then the vehicle coasts for a few seconds before the Black Brant is ignited. After the Black Brant burns out the vehicle coasts until it is out of the atmosphere.

After exiting the atmosphere the Black Brant will separate and the shroud will be deployed. The reaction control system will despin the vehicle and a large pitch maneuver will be performed prior to Nihka ignition. The Nikha will separate at burnout and the reaction control system will despin and point the vehicle in preparation for PSRM 120 ignition. This will be repeated for the PSRM 30 ignition and burn. The flight computer and reaction control system will be housed on the PSRM 120 stage.

Note that all critical separation and maneuvering events occur after the vehicle has left the atmosphere.

VII. Conclusions

Affordable access to space can be realized in a timely manner. The NanoLaunch vehicle being developed by MSFC will provide a test bed for testing of new propulsion technologies. Each test flight will have a dedicated payload. These orbital missions provide focus and rigorous requirements to the NanoLaunch propulsive stages and components.

Acknowledgment

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Figure 8, Fuel film cooling circuit for a liquid oxygen/propane injector.

REFERENCES

[1] E. Zapata, C. McClesky, J. Martin, R. Lepsch, T. Hernani, "Life Cycle Analysis of Dedicated Nano-Launch Technologies."

[2] P. Tank and J. Williams, "The SCOUT Launch Program," LTV Launch Systems

[3] The Scout Launch Vehicle Family, http://en.wikipedia.org/wiki/Scout_(rocket_family)

[4] Vought Missiles and Space Company, "Advanced Small Launch Vehicle Study," NASA CR-112054, 1972.

[5] NASA Sounding Rocket Handbook, Goddard Space Flight Center, Wallops Flight Facility, 2005

[6] ORS and Super-Strypi. Program information at: http://cires.colorado.edu/events/lidarworkshop/LWG/Oct12/presentations/003-ORS Briefing to Lidar Winds Workshop--101612.pptx

[7] ALASA. Program information at: http://www.darpa.mil/Our_Work/TTO/Programs/Airborne_Launch_Assist_Space_Access_%28ALASA%29.aspx

[8] "Boeing Targets 66 Percent Launch Cost Reduction with ALASA". Available at: http://www.spacenews.com/article/military-space/40023boeing-targets-66-percent-launch-cost-reduction-with-alasa

[9] SWORDS. Program information at: http://www.smdc.army.mil/FactSheets/SWORDS.pdf

[10] Cubesat Design Specification, CDS Rev 13, California Polytechnic University, Feb 2014.