Air Launch

A project present to
The Faculty of the Department of Aerospace Engineering
San Jose State University

in partial fulfillment of the requirements for the degree
Master of Science in Aerospace Engineering

By

Alireza Forouzandeh Tabrizi

May 2015

approved by

Dr. Nikos Mourtos
Dr. Gonzalo Mendoza
Faculty Advisor

San José State
UNIVERSITY

Table of Contents

Plan of action

The purpose of this project is to design and manufacture a vertical air launch system capable of launching a 55 lb, solid-fuel rocket from an altitude of 5,000 ft. The performance results of the air launch system will then be compared to those recorded from the ground launch of an identical rocket. The main objective is to compare the results of the two launch methods in order to determine which is better.

The project is broken down into 3 phases:

Phase 1: A scaled model of the air launch system capable of carrying and launching a 5.5lb rocket from 5,000 ft will be designed and manufactured. This is meant to be a cheap way of encountering and rectifying any unforeseen challenges in manufacturing and operations of the system.

Phase 2: The actual air launch system is designed and manufactured. This phase will benefit from lessons learned in phase 1.

Phase 3: A ground launch of the 55lb rocket system is conducted. The data from this launch will be compared to those obtained in phase 2. This will allow for reaching a conclusion as to exactly how beneficial air launch is compared to ground launch.

Current Status

Presently, phase 1 is 80% complete. The 5.5 lb launch system has been designed and is in the process of being manufactured. The necessary F.A.A. exemptions and rocketry certifications required to conduct the mission are concurrently being pursued by the author at this time.

Literature Review

To most effectively study air launch a subset of literature has been selected based on the following questions:

1. What is air launch?
2. What are the advantages of air launch as opposed to ground launch?
3. Is air launch feasible?
4. Is air launch currently in use?
5. How varied are air launch systems/platforms?
6. What is the future of air launch?

It is also important to note that due to the highly experimental/commercial nature of air launch a great deal of information and designs are either proprietary or classified putting them outside of the reach of this author.

What is Air Launch?

Air launch is a blanket term for alternative methods of launching payloads into earth orbit or beyond. The desired payload is carried to a determined altitude inside of a rocket, attached to a carrier craft, and is then launched (Bartolotta, 2011).

What are the Advantages of Air Launch as Opposed to Ground Launch?

The increasing need for low-cost access to space and the advent of nano and micro-satellites demand a more efficient and specialized launching method. One such method is carrying a winged launch vehicle on an airplane to cruise altitude. The launch vehicle will then separate and carry the payload into space. Starting from cruise altitude has the following benefits: lower air pressure, lower air density (which translates to less drag), lower required structural strength and weight, and a 1 to 2% increase in total propulsive efficiency. The advantages ultimately lead to lower cost per launch (Feaux,1989).

Air launching provides mobility and deployment advantages over ground launching. It enables the users to achieve any desired launch azimuth without out-of-plane orbital maneuvers that consume large amounts of propellant as well as launch any small to medium payload in an on-demand fashion. The nozzle of the rocket launching the payload will be designed for a much smaller range of air pressures and will therefore be much more optimized (Sarigul-Klijn, 2001).

Another advantage of air launch, as pointed out in Bartolotta's publication, is the fact that given the appropriate system, it can reduce the dollar-per-pound-to-LEO figure from $10,000 to just under $8,900. Bartolotta also mentions that while an air launch system would not be able to carry very large payloads such as the space shuttle, it will still be viable to carry small and medium payloads(up to 15,0000lbs) which make up the bulk of the space traffic today (Bartolotta, 2011). The military advantages of air launch are numerous. As mentioned by Thomas McCants, air launch will yield an affordable and effective missile defense against both tactical and long-range ballistic missiles. The affordability is a result of a conventional transport aircraft (such as a Boeing 747) carrying a large number of missiles while staying at a desired location and a desired altitude. The aircraft is then able to perform a multiple of simultaneous offensive and defensive missions. The same system can also be used for other missions such as launching a satellite at other times (US 7,849,778 B1, 2010).

Is Air Launch Feasible?

According to Bartolotta, the idea of air launch has been in circulation since the days of Wernher von Braun. In the 50s, von Braun envisioned a reusable space shuttle-like logistics vehicle to supply a space station. However, it was determined that the technology of the time was not advanced enough to support such a mission. In the 60s, a similar two-staged vehicle was proposed for the Space Shuttle program, but the technologies needed were found to be immature and too expensive to develop. In 1972 the Space Shuttle design was fixed as we know it today. The same happened in 1984 when a $2 billion DOD-NASA program was cancelled due to the required technologies not being sufficiently mature. In the late 80s and 90s, a number of programs were put forth in Germany, Britain, and the U.S. These programs advocated the use of turboramjet-powered engines. The skyrocketing research and development costs overcame any return on investment. This last failure however, made the experts aware of the immense potential of using already available subsonic aircraft as a first stage carrier in the launch system. As a result in late 2010, NASA-DARPA conducted an extensive study into the use of subsonic carrier aircraft and was able to find a way to create a system to carry payloads of up to 20,000 lb into orbit at a cost less than that of ground launch (Bartolotta, 2011).

Is Air Launch Currently In Use?

Currently, only one company utilizes the use of air launch. Orbital Sciences' "Pegasus" launch vehicle can carry and place into LEO satellites weighing up to 1,000 pounds. Although revolutionary, the Pegasus launch system has been a commercial failure. It has had 42 missions in 24 years which translates to an average of 2 missions per year. Although the system has maintained a perfect record since 1996, this lack of launch demand makes its costs unjustifiable. This lack of demand is due to the fact that Pegasus is simply too small for the bulk of government and commercial satellites being developed today. Another reason for the high cost of the program is the need for a dedicated carrier aircraft. The Pegasus rocket can only be deployed by it highly-modified Lockheed L-1011 TriStar carrier aircraft. The necessity for maintaining the aircraft (the only aircraft capable of launching the Pegasus) has substantially increased the operational cost of the program.

What is the Future of Air Launch?

Utilizing the lessons learned from the Pegasus program (which used to be a DARPA program), the Defense Advanced Research Projects Agency has granted Boeing a contract to develop and build the Airborne Launch Assist Space Access (ALASA). The goal of this project is to develop an air launch system that can place a 100 lb payload into orbit for less than $1 million per mission. ALASA will be the next step from Pegasus. The entire concept of air launch operations has changed. To drive down the costs of launching into orbit, DARPA has determined that the launch vehicle must have the capability to be launched from any aircraft without requiring any modifications. Boeing, for example, is designing the launch vehicle to be launched from the F-15 Eagle. This would mean that ALASA will not need a dedicated aircraft. This allows for the aircraft to be used in its regular functions in addition to use as a carrier aircraft making the launch costs a very small margin of the overall operations cost of the aircraft.

How Varied are Air Launch Systems/Platforms

Air Launch vehicles can be categorized with respect to their sizes into 2 main categories: small and large. The above-mentioned ALASA and Pegasus launch vehicles are part of the “small” launch system category. These platforms offer inexpensive and dedicated launch services for Small, Micro, and Nano satellites. The need for putting heavier payloads into LEO will be met by larger launch platforms such as Orbital Sciences’ Thunderbolt rocket. This Strato-Launch system will be capable of putting 10,000 lb payloads into LEO orbit. Orbital Sciences is scheduled to start flight testing this system in 2016.

Design Concept

1) Assessment of Need and Mission Requirements

The advent of the nano-sat has sparked a revolution in the space industry. A market that was once exclusive to governments and large private firms is now open to smaller firms, research institutes, and even private citizens. This shift in satellite design philosophy requires a cheaper and easier way of delivery into space. The traditional method of launching (Ground Launch) is wasteful and very expensive. Since ground launch rocket engines were designed to carry very large vehicles into orbit and to other planets, they consume immense amounts of fuel and have marginal performance for a considerable portion of their flight (in the lower altitudes with thicker atmosphere). In order to make financial sense for their expensive rocket engines, companies are forced to carry a great number of nano-sats inside one rocket. This introduces unnecessary delays and risks for the customers. In the event of a launch failure, the destruction of the payload, damage to the launch pad, and extensive delays are imminent. It appears then that a faster and cheaper way of launching nano-sats into space must be employed. Air-launch is the answer.

Air-launch is advantageous for the delivery of small payloads into space for a number of reasons. Launching from a higher altitude means the rocket will have to fly through a much thinner atmosphere. This translates into less drag which then means that only a small amount of fuel is required. There is currently no need to design and manufacture an airplane for the specific purpose of launching rockets from the sky. Indeed, there are already many aircraft that are capable of accomplishing that task such as the F-15 and the Lockheed L-1011 TriStar.

Currently Orbital is using a Lockheed TriStar as the launch vehicle for the Pegasus rocket with an 88% success rate. The USAF is also conducting extensive research into using modified F-15s for the purpose of launching small payloads into space.

Currently, all efforts have been concentrated on Horizontal Air Launch (HAL) which consists of attaching the rocket (and the payload within it) to the bottom (B-HAL) or top of an aircraft (T-HAL), carrying it to altitude, and launching it with the carrying aircraft being more or less horizontal. While HAL is somewhat of a step in the right direction, it does still come with unnecessary costs. The costs are mostly related to B-HAL. Between the time of the rocket's release and ignition, the rocket will be falling and therefore losing altitude. This, as will be demonstrated in the following sections, is an unnecessary loss of energy that must be remedied by burning more fuel. Also, since the rocket is launched horizontally, it will require complex control laws to point it in the correct attitude for orbit. This will increase the financial cost of designing the rocket. It will also mean that the rocket must have movable fins, actuators, and a large array of attitude determination and control equipment (ADC) which will increase the weight of the rocket.

The final solution is Vertical AirLaunch (VAL). Similar to HAL, the rocket can be attached to the bottom (B-VAL) or top (T-VAL) of the carrying aircraft. The rocket is then carried to a desirable altitude and launched from the carrier aircraft at which point the aircraft itself will acquire a vertical (or near-vertical) attitude and then launch the rocket. The two most important advantages of VAL are as follows:

1. The rocket is attached to the aircraft using detachable, telescopic rails. Therefore, it does not need to be separated from the aircraft before it is launched.
2. Since the aircraft is used as the aiming mechanism and the pre-launch stabilizer, the rocket will not need any of the expensive and heavy ADC equipment. This means cheaper and lighter rockets. In this sense, given a stable enough aircraft, the process essentially becomes identical to a ground launch.

It must be noted that this specific version of VAL (with the telescopic rails) has never been (to the best knowledge of the authors) tried or studied before. The purpose of this project will be to design and build such a vehicle but on a small scale. The aircraft will fly the rocket to 5,000 ft and then launch it. The rocket climbs to its apogee at which point a parachute is deployed enabling the rocket and the payload within to land safely back on the ground. After the launch, the airspeed, static pressure, altitude, and the trajectory of the rocket will be recorded.

1.2) Mission Profile

Figure 1 shows the mission profile of the aircraft.

1-2: Taxi	6: Launch rocket
2: Take-off	6-7: Loop
2-3: Climb	7-8: Finish loop/start descent
3-4: Stabilize/cruise	8-9: Descent
4-5: Climb	9: Land
5-6: Stabilize	9-10: Taxi

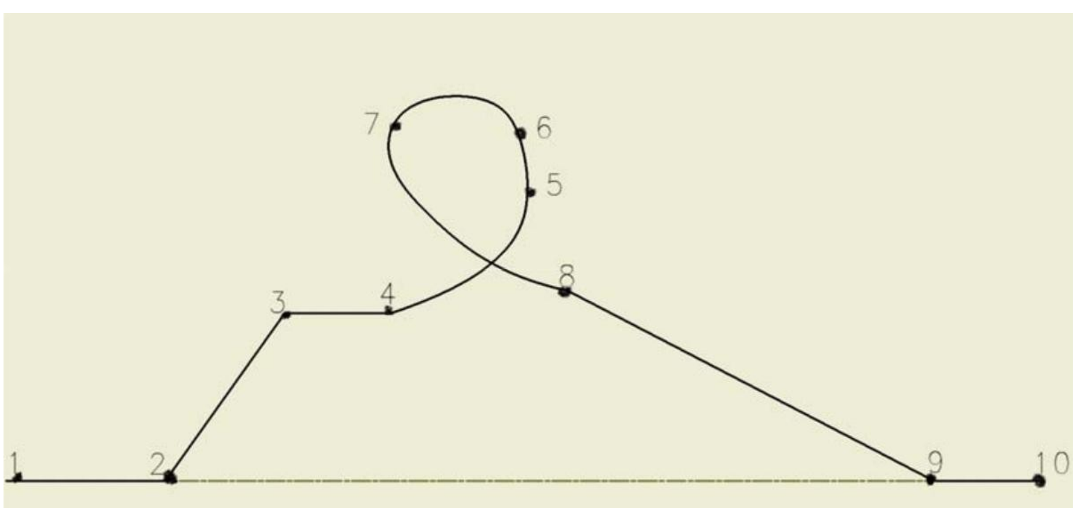


Figure 1: Mission Profile

2) Basic Configuration Selection

2.1) Wing Placement: A straight high wing design was chosen. The high wing design has a natural dihedral effect, therefore eliminating the need for a dihedral angle. It will also be easier to install the rocket to the bottom of the aircraft. Since the aircraft will be climbing vertically to launch the rocket, a high wing design will be desirable in order to avoid the wing from getting hit by the rocket.

2.2 Empennage Selection: The empennage will be a conventional configuration with the horizontal stabilizers mounted on the fuselage at the base of the vertical stabilizer. The empennage will include a fully-moving horizontal stabilizer and a very large rudder-to-fin ratio. The fully-moving horizontal stabilizer configuration is considered to allow for smaller deflections and to also enable the airplane to stabilize itself while in the launch attitude (AOA ~90^{o}) and very low speed. This will also allow for trimming the aircraft at the two extremely different CG positions it will have during the mission (CG is considerably more aft when the rocket is attached).

2.3 Fuselage Selection: The fuselage will be a cylindrical shape. Since the payload will not be inside the fuselage, it eliminates the need to create extra space. Another advantage of using a cylindrical fuselage is that it produces less drag. Later iterations of the fuselage will change the shape in order to reduce drag and reduce the chances of scraping the tail on takeoff.

2.4 Propulsion Installation: Based on the mission requirements, the chosen propulsion installation will consist of two conventional tractor-mounted props attached to the wings. One of the main reasons why this was chosen is because a pusher configuration will not be as effective when the aircraft climbs vertically.

3) Performance of similar aircraft

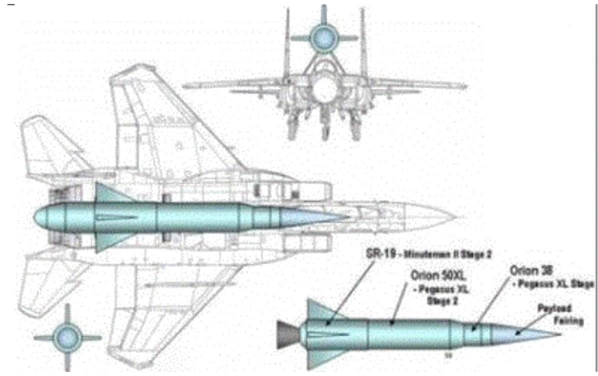
Other aircraft that have accomplished the same mission requirements include the F-15 and the Lockheed TriStar. The F-15 is able to launch a rocket flying horizontally as well as climbing to a vertical climb. The Lockheed TriStar was only able to launch a rocket while flying horizontally. As previously mentioned, launching a rocket while flying horizontally is not as cost effective as a VAL. Below are some of the performance specifications for both aircraft.

Lockheed TriStar

Maximum operating altitude = 42, 000 feet
Maximum Speed = Mach .9 Cruise Speed = 600 MPH
Stall Speed with Max Weight = 124 MPH

F-15

Maximum operating altitude = 60,000 ft Maximum Speed = Mach 2.2 Cruise Speed = Not available
Stall Speed with Max Weight = Not available
Thrust/weight: 1.07



4) General Proposed Layout

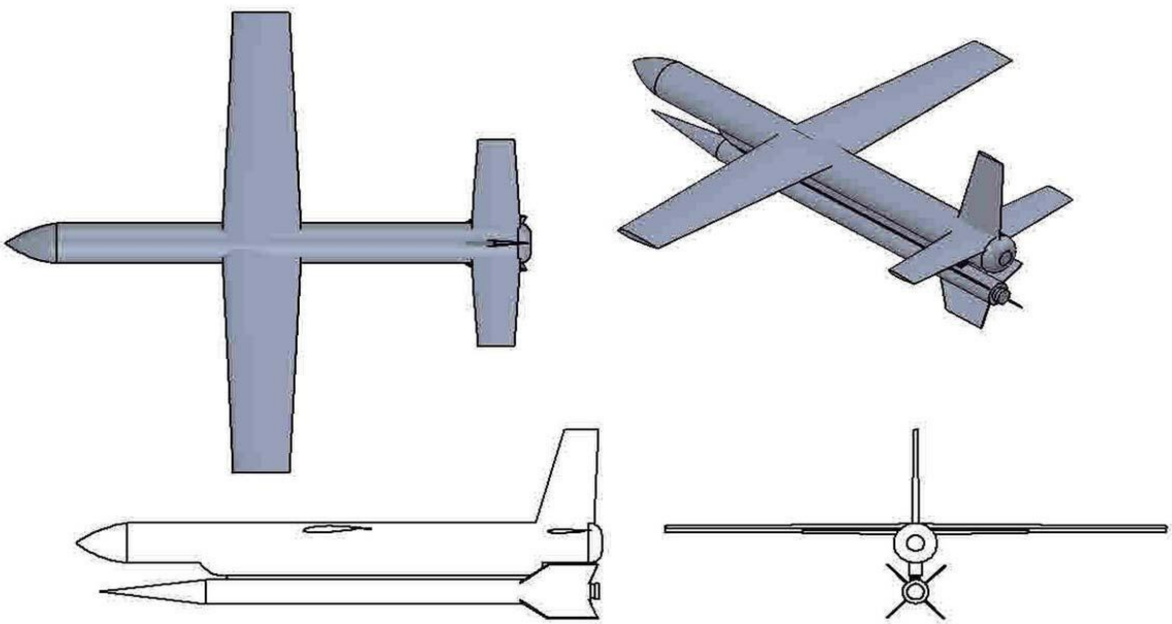


Figure 2: Conceptual CAD Model Design

5) Mission Driven Specifications, Relation to Configuration

The aircraft will be designed to launch the rocket slightly above 5,000 feet, therefore the cruising altitude will be 5,000 feet. The cruise speed will be about 80 ft/s at which time the rocket will be launched. Since the aircraft does not experience any compressible effects at the cruise speed, the wings do not need to be swept. The density at the cruise altitude is half the density at sea level which means that a high C_l is needed. A high AR is also desirable in order to decrease the induced drag. Since the aircraft will be climbing vertically, the thrust to weight plus drag ratio has to be greater than 1. Furthermore, some analysis will be required to determine the energy loss due to G forces exerted by the climb. This is necessary to ensure the aircraft preserves enough energy to complete its loop maneuver.

- Cruise Speed = 80 ft/s
- Cruise Altitude = 5,000 feet
- T/(W+D) > 1
- Climb Rate = 60 ft/s
- Max_load_factor=5

The rocket's configuration is mostly out of the author's hands since it is built from a kit. However, the length of the rocket was chosen in order to provide favorable stability characteristics. Another measure that could be taken is enlarging the rockets fin area. This will move the C_p of the rocket aft which will further increase stability. Increasing the fin area will also introduce other issues with aeroelasticity and mounting.

6) Estimated Weight and Basic Aerodynamic Data

The estimated empty weight of the aircraft is about 10 lbs. The payload consists of a 3 pound rocket as well as a J580 motor that weighs 2.3 pounds. The estimated weight of the entire payload without the required telemetry equipment will be 5.5 pounds. The total estimated weight of the aircraft with the payload is 15.5 pounds.

Basic aerodynamic data is shown below:

- Aspect Ratio = 10
    - This number was chosen by studying heavy-lift cargo airplanes such as the C-130 and the C-5 Galaxy.
- Oswald Efficiency (e) = 1.05
    - The Oswald efficiency was calculated using the empirical formula provided in Anderson's Aerodynamics textbook: $e=1.78(1-0.045*AR^{0.68})-0.64$
- Cdo = 0.007
    - This number was calculated using boundary layer theory
- Clmax =1.8
    - This value was chosen per Roskam's recommendation for typical heavy-lift cargo aircraft during cruise without flaps.
- Clmax_TO = 2
    - This value was chosen per Roskam's recommendation for typical heavy-lift cargo aircraft during take-off with flaps.
- Clmax_L = 2.5
    - This value was chosen per Roskam's recommendation for typical heavy-lift cargo aircraft during landing with flaps.

7) Powerplant Selection

The powerplant will consist of two propeller-driven, electric motors. Gas-powered motors were abandoned due to the weight management difficulties brought on by the extreme maneuvering required to perform the launch. Gas-powered motors are also too costly and cumbersome for the scale of this project. A thrust to weight plus drag ratio greater than 1 could be achieved with a single-motor configuration, but this configuration was deemed unsafe since in the event of an engine out, the airplane is not assumed to have satisfactory gliding characteristics (specially with the rocket attached).

8) Landing Gear Placement and Type

The landing gear will be a tricycle configuration. One of the advantages of this configuration is that the aircraft will be level during taxi which will also help keep the rocket in a level position. It will also make it easier to attach the rocket to the bottom of the aircraft. The gear will be made retractable to protect it from the rocket exhaust during launch, and avoid adverse aerodynamic effects during the vertical cruise. The aft wheels will be placed behind the loaded CG position (CG position with the rocket attached).

Detailed Design

Power and Weight Sizing

Weight Sizing

Table 1: Weight Table

Component	Weight (lb)	Qty	Total Weight (lb)
Aerobee Kit	2.5	1	2.5
Rocket Motor: J-580	3	1	3
Fuselage	2.4	1	2.4
Wing	1	1	1
Horizontal Tail	1.5	1	1.5
Vertical Tail	1	1	1
Landing Gear	2	1	2
Engine	1	2	2
Batteries	2	2	4
ESC	0.25	2	0.5
Rocket Avionics	0.3	1	0.3
Rocket Avionics Battery	0.1	1	0.1
Remote Launch Module	0.2	1	0.2
Plane Avionics	0.5	1	0.5
Plane Avionics Battery	0.1	1	0.1
Rail	1.5	1	1.5
Servos	0.08	5	0.4
Total Weight			**23**

Power Sizing

The zero lift drag coefficient of the aircraft was calculated to be around .0403. The zero lift drag coefficient of the rocket was calculated to be about .02 using a software called OpenRocket. This was added to the plane’s zero lift drag coefficient. In order to factor in the interference drag due to the rocket, the overall zero lift drag coefficient was increased by 23%. The matching graph was completed by using Advanced Aircraft Analysis software (AAA). The weight used in the matching graph was increased to 25 lbs instead of the current estimated total of 23 lbs in order to compensate for minor weight additions that are unforeseen thus far.

Table 2: Data Used for Performance Sizing

Prop Efficiency	85%
e	0.85
cd_0	0.074
c_l_max	2

Table 3: Performance Requirements

Rate of Climb	
Rate of Climb (ft/s)	18
Power(at 5000 ft) / P(Take off)	0.86
Cruise Speed	
Cruise Speed (ft/s)	80
Altitude (ft)	5000
P(Cruise) / P(Take off)	0.5
Loop	
Load Factor	3
P(Maneuver) / P(Take off)	1
Velocity (ft/s)	80

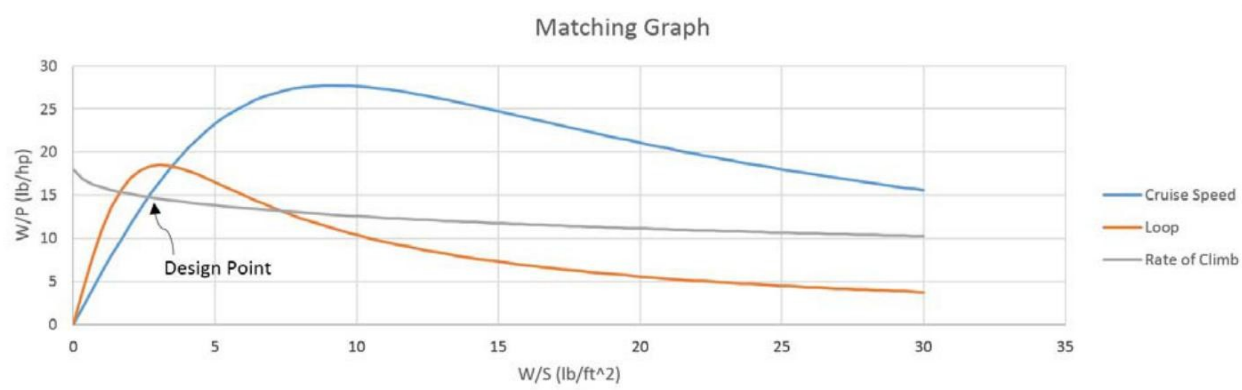


Figure 1: Matching Graph

Table 4: Performance Sizing Results

W / S (lb/ft^2)	2.67
W / P (lb/hp)	14.7
S (ft^2)	9.36
P (hp)	1.70

The power requirement and the results of the matching graph indicate a required power of 1.7 horsepower (1300 watts). However, while searching for proper power plants, it was discovered that no electric motor rated for 1300 watts produces the required amount of thrust necessary to satisfy the T > D+W requirement. This is due to propeller size limit. There is a direct relationship between the diameter of the propeller and the amount of amps used by the motor. Lower-rated motors are limited to smaller propellers which produce fewer pounds of thrust. To overcome this problem, it was decided to "oversize the power plant". In its current state, the propulsion subsystem consists of two 1650 watt, brushless, outrunner motors. Each motor will produce a maximum thrust of 11.5 lbs at sea level. Two obstacles are very likely to force another upgrade of the motors. The first is that the maximum burst current allowed through the engines is limited to 12 seconds by the ESC. This means that the 11.5 lb thrust rating cannot be sustained for the duration of the launch maneuver. The second is that propeller performance degrades with altitude which means that the maximum thrust provided by the motor will be even lower at launch altitude. The next available motor is the E-flite Power 92 and it is rated at 1800 watts. This motor will provide 15 lb_f of thrust at sea level and 13 lb_f at 5,000 feet. As mentioned before, the main concern with upgrading the power plant is added weight. However, in this case, upgrading the motors will actually improve the thrust-to-weight ratio of the aircraft. This is due to the fact that the weight increase is much smaller compared to the amount of thrust increase.

Basic Systems Architecture

1. Power/Fuel Systems
    a. Aircraft Power System: The primary power for all systems aboard the aircraft will be provided by a pair of 6 cell Lithium Polymer batteries. This includes all avionics, servos, and sensors aboard the aircraft.
    b. Rocket Power Systems: All avionics and electronics aboard the rocket will be powered by two to four 9-volt batteries, as needed.
2. Avionics
    a. Flight Avionics Unit: An on-board flight avionics module will provide live video feed, inertial metrics such as acceleration and pressure data in addition to power monitoring.
    b. Control Actuation Systems
        i. Ground Steering: Taxiing and ground steering will be made possible by a quad wheel landing system where the front wheels will dictate steering with an attached servo.
        ii. Air Steering: Two servos will be used for the Ailerons installed within the main wing. The rudder and the elevator will be controlled by single servos dedicated to each control surface.
        iii. Rocket Release and Launch systems: The release safety lock system for the rocket launch guide rail will be controlled by a dedicated servo.
3. Propulsion
    a. Speed Control: An electronics speed control unit will be responsible for throttle management for both electric motors propelling the plane.

Detailed Aerodynamic Choices

Airfoil and Control Surface Choices

Table 5 shows the candidate airfoils that were chosen for the wing and empennage. FX 74-C15-140 MOD was chosen for the wing due to its high maximum coefficient of lift. Since the coefficient of lift for this airfoil is high, no flaps were selected for the airplane. During the sizing of the flaps with the eppler airfoil, it became obvious that the large size of the flaps required to have a meaningful increase in coefficient of lift would interfere with the desired size of the ailerons. Therefore, the eppler airfoil was abandoned and the FX74 was chosen. The FX 74-C15-140 airfoil will later be tested in San Jose State University's wind tunnel for aerodynamic performance and characteristics verification. Another reason why this airfoil was chosen is because even though it produces more lift, the coefficient of drag of the airfoil is still low throughout the angle of attacks that the airplane will experience. Figure 2-5 shows the airfoil data.

The airfoil that was selected for both the horizontal and vertical tail is the NACA 0018. This airfoil was chosen since it is widely used for the empennage. Table 6 shows the parameters of the wing and empennage.

The control surfaces that were selected for the airplane include ailerons, elevator, and rudder. Table 7 shows the dimensions that were calculated for the control surfaces. The control surface areas were calculated by using AAA software. The horizontal tail surface area was calculated without the rocket configuration since the CG moves back and thus causes a smaller moment arm. The control surface to surface ratio was obtained from Roskam.

Table 5: Airfoil Parameters

Parameter	FX 74-Cl5-140 MOD	NACA 0018
Max Thickness (%)	13.1	18
C_l_max	2.2	1.3
C_l_alpha	0.1	0.11
Stall Angle (Degrees)	12	15

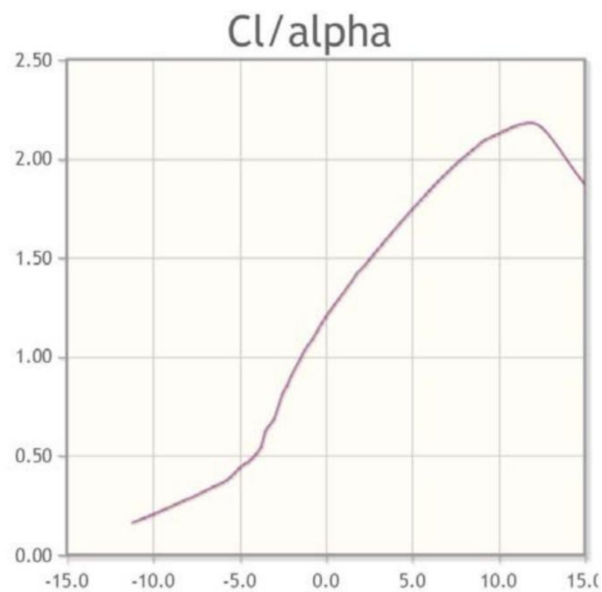


Figure 2: Coefficient of Lift vs. Angle of Attack

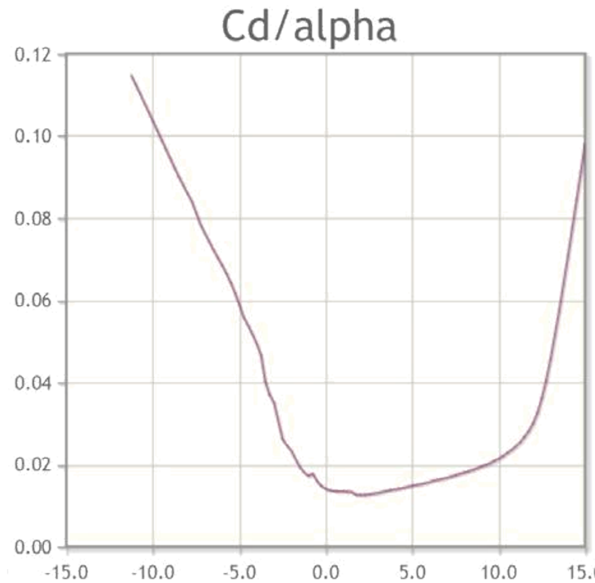


Figure 3: Coefficient of Drag vs. Angle of Attack

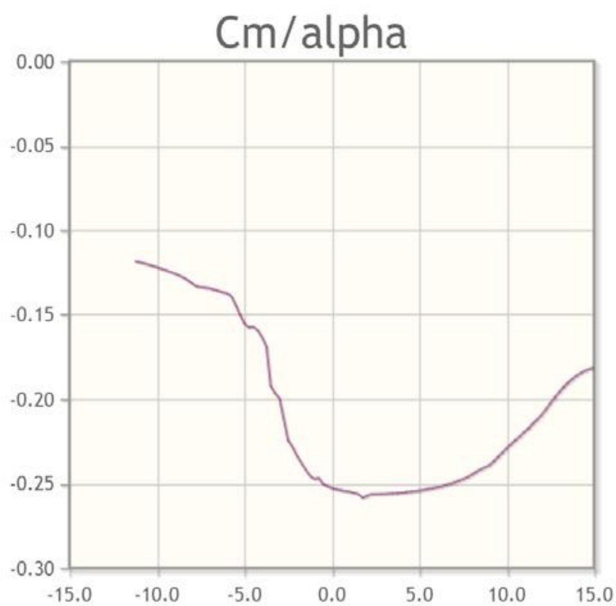


Figure 4: Coefficient of Moment vs. Angle of Attack

Table 6: Surface Area Parameters

Parameter	Wing	Horizontal Tail	Vertical Tail
Airfoil	FX 74-Cl5-140 MOD	NACA 0018	NACA 0018
Aspect Ratio	10	4	1
Surface Area (ft^2)	10	4.33	3.5
Chord (ft)	1	1.04	1.87
Span (ft)	10	4.16	1.87
Taper Ratio	1	1	0.5
Dihedral Angle (Degrees)	0	0	N/A
Incidence Angle (Degrees)	0	0	0

Table 7: Control Surface Parameters

Parameter	Ailerons	Elevator	Rudder
Control Surface Area / Area	0.07	0.35	0.3
Control Surface Area (ft^2)	0.70	1.52	1.05
Span (ft)	2.33	3.64	1.40
Chord (ft)	0.3	0.42	0.75

Stability Derivatives

Tables 8 and 9 show the longitudinal and lateral/directional stability derivatives. These derivatives were calculated using AAA software. They show that the airplane has natural stability both in the longitudinal and lateral/directional direction.

Table 8:
Longitudinal Stability Derivatives

Longitudinal	
Steady State	
C_{D_1}	.1174
C_{L_1}	.3698
C_{m_1}	-.3018
Speed	
C_{D_u}	0
C_{L_u}	.0021
C_{m_u}	.0007
Angle of Attack	
C_{D_α}	.0049
C_{L_α}	.0864
C_{m_α}	-.073
A.0.A Rate	
$C_{D_{\dot{\alpha}}}$	0
$C_{L_{\dot{\alpha}}}$	.0491
$C_{m_{\dot{\alpha}}}$	-.1666
Pitch Rate	
C_{D_q}	0
C_{L_q}	.2461
C_{m_q}	-.7415

Table 9:
Lateral/Directional Stability Derivatives

Lateral/Directional	
Sideslip	
C_{y_β}	-.0116
C_{l_β}	-.0069
C_{n_β}	.004
Sideslip Rate	
$C_{y_{\dot{\beta}}}$	-.0002
$C_{l_{\dot{\beta}}}$	0
$C_{n_{\dot{\beta}}}$	-.0001
Roll Rate	
C_{y_p}	-.001
C_{l_p}	-.0083
C_{n_p}	-.0016
Yaw Rate	
C_{y_r}	.0082
C_{l_r}	.0055
C_{n_r}	-.0039

Control Derivatives (Cruise at 80 ft/s):

The longitudinal and lateral/directional control derivatives were also calculated using AAA software. They were calculated during the cruise stage of the airplane with no rudder, elevator, or aileron deflection.

Table 10: Longitudinal Control Derivatives

Longitudinal Control	
Stabilizer	
$C_{D_{i_h}}$	.0017
$C_{L_{i_h}}$	.0276
$C_{m_{i_h}}$	-.0937
Elevator	
$C_{D_{\delta_e}}$	.0006
$C_{L_{\delta_e}}$	.0108
$C_{m_{\delta_e}}$	-.0368

Table 11: Lateral/Directional Control Derivatives

Lateral/Directional Control	
Aileron	
$C_{y_{\delta_a}}$	0
$C_{l_{\delta_a}}$	.003
$C_{n_{\delta_a}}$	-.003
Vertical Tail	
$C_{y_{i_v}}$	-.009
$C_{l_{i_v}}$	-.0016
$C_{n_{i_v}}$	.0036
Rudder	
$C_{y_{\delta_r}}$	-.0035
$C_{l_{\delta_r}}$	0
$C_{n_{\delta_r}}$	0

Flight Dynamics (Cruise at 80 ft/s)

The time history plot and bode plots were obtained by using Matlab.

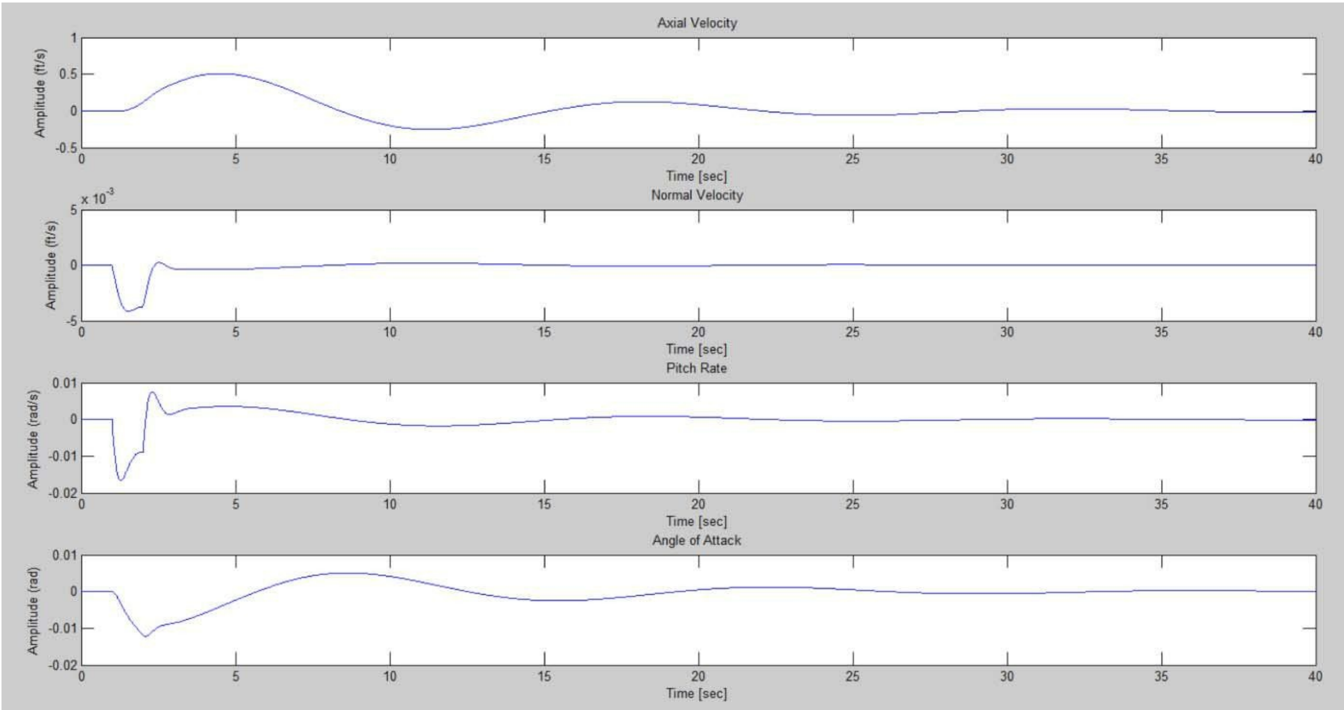


Figure 5: Response to +1 deg. step elevator input

Figure 5 shows that the axial velocity, normal velocity, pitch rate, and angle of attack dampen back to zero after a +1 degree elevator step input. The axial velocity slightly oscillates and stabilizes after 30 seconds. The normal velocity oscillates and stabilizes quickly at around 5 seconds. Pitch rate and angle of attack oscillate after the 1 degree elevator step input and stabilize after 25 seconds. All the graphs settle back to the initial condition.

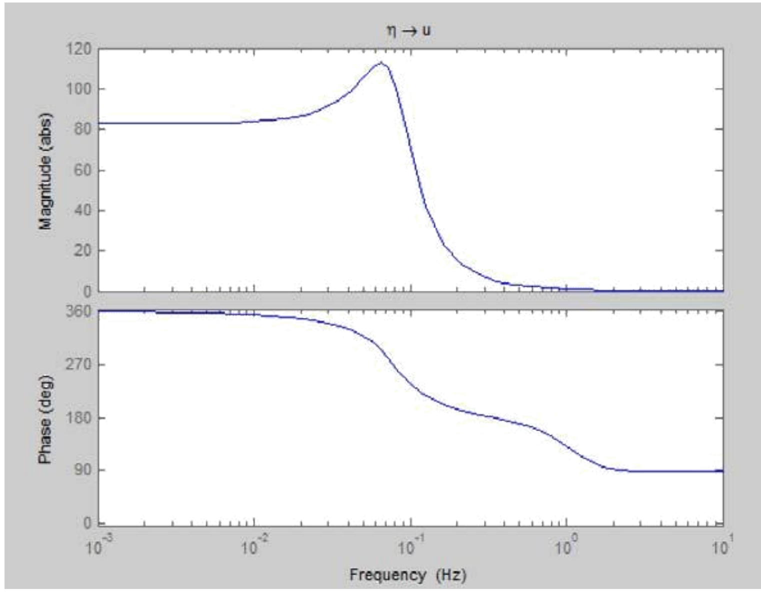


Figure 6: u/de

Figure 6 shows the phugoid mode with a magnitude of about 113 abs which translates to approximately 2 feet per second per degree. This occurs around .065 Hz. The graph begins at 360 degrees out of which is believed to be equivalent to 0 degrees (in-phase). There is a phase of 300 degrees at this location which is also equivalent to -60 degrees. There is no response after the short period mode.

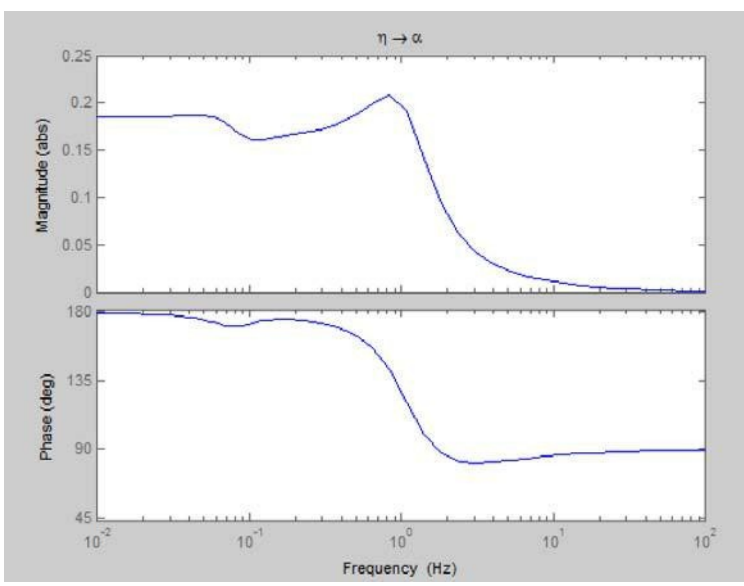


Figure 7: Alpha/de

Figure 7 shows the phugoid mode with a magnitude of about -.185 degrees AOA per degrees elevator deflection. This occurs around .0058 Hz. The phase begins at 180 due to a sign shift. The short period mode is located at -.208 degree per degree at a frequency of .835 Hz. There is no response after the short period mode.

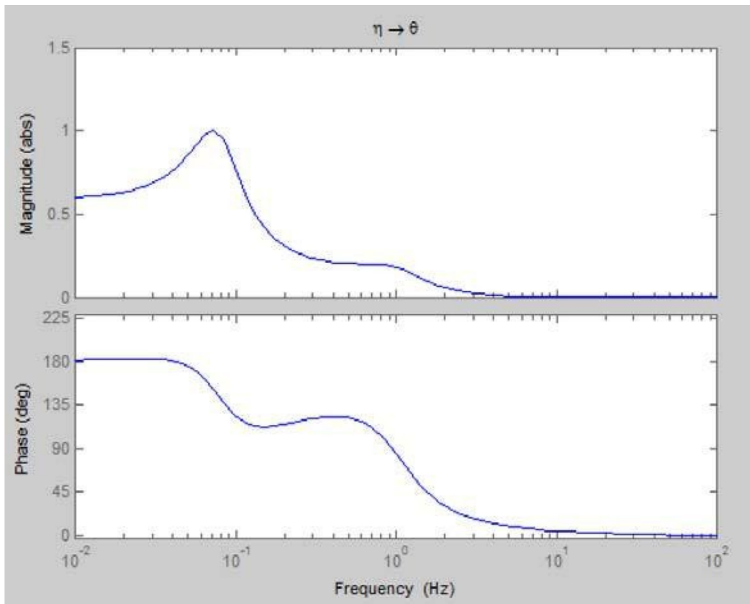


Figure 8: Theta/de

Figure 8 shows the phugoid mode with a magnitude of about -1 degree per degree. This occurs around .0728 hz. The phase also begins at 180 due to a sign shift. The short period mode is located at -.2 degree per degree at a frequency of .831 Hz. There is no response after the short period mode.

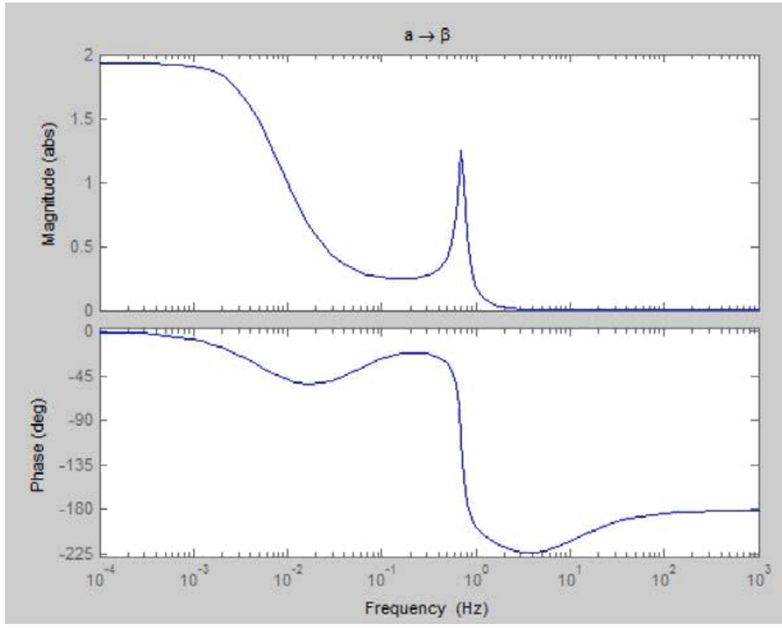


Figure 9: beta/da

Figure 9 shows that the dutch roll occurs around .705 Hz. There is no response after the dutch roll.

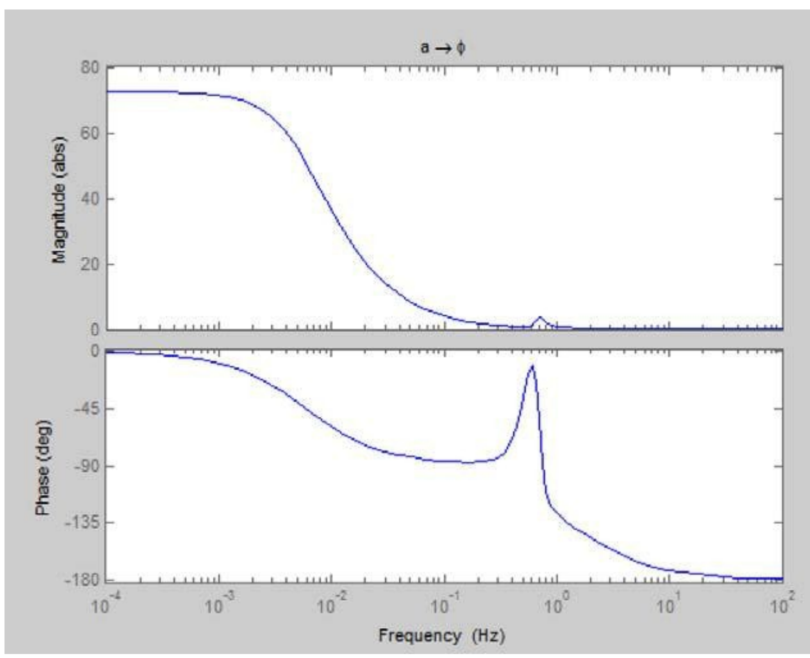


Figure 10: phi/da

Figure 10 shows that there is not a lot of bank at the dutch roll. There is no response afterwards.

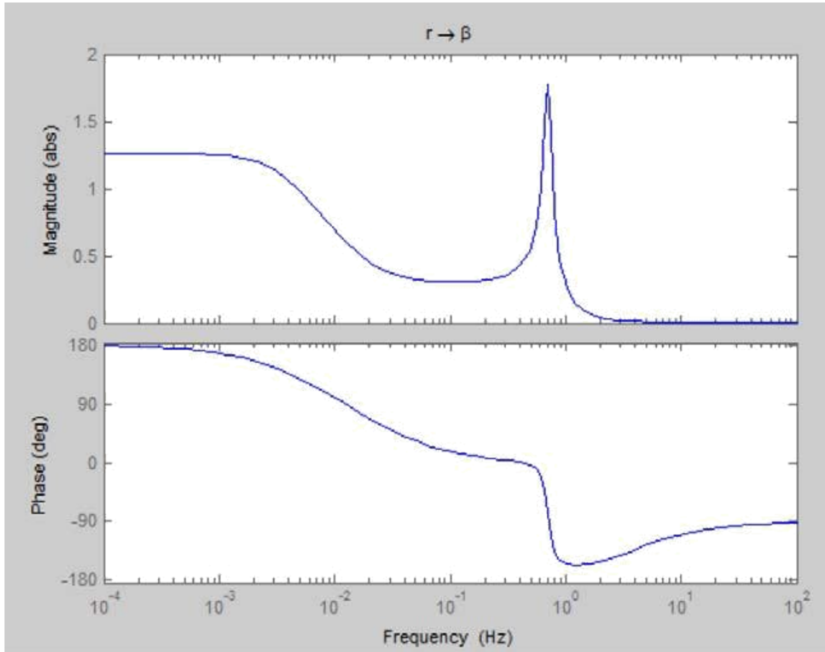


Figure 11: beta/dr

Figure 11 shows that there is no response after the dutch roll. The phase starts at 180 degrees because beta goes the other way due to a spiral response.

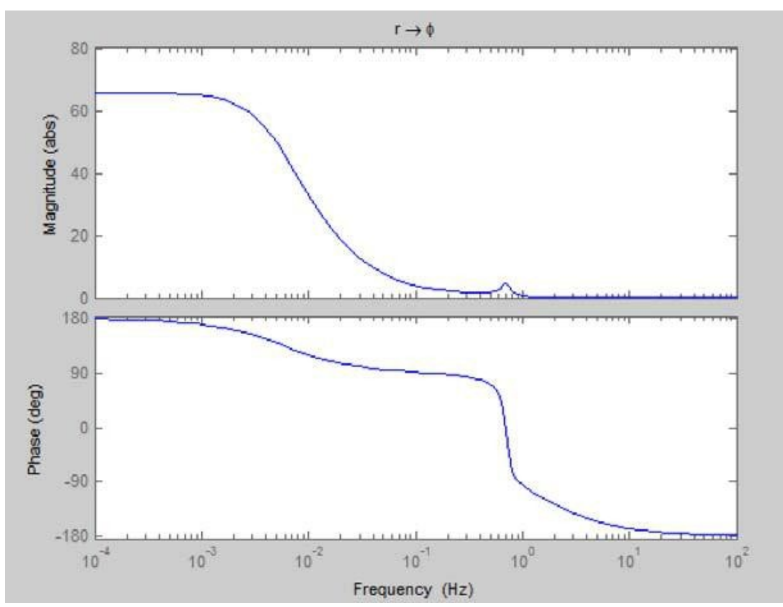


Figure 12: phi/dr

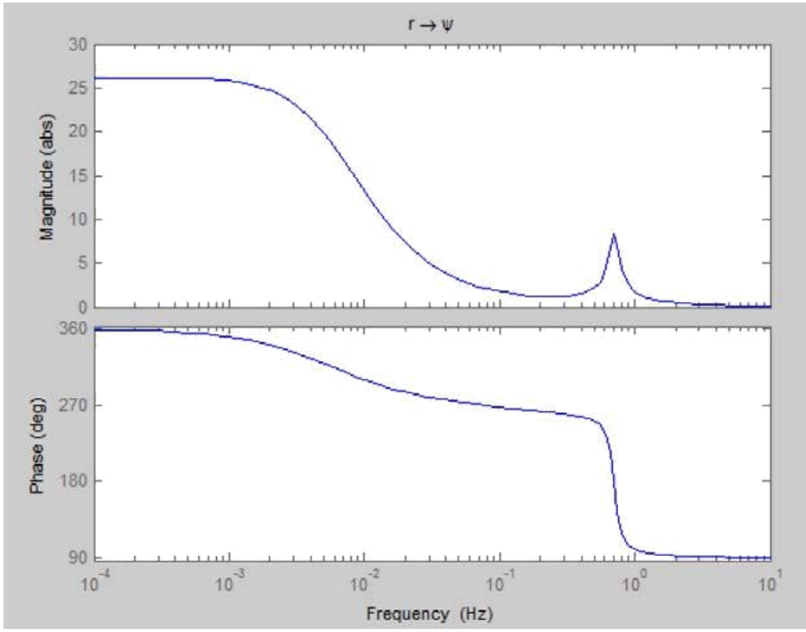


Figure 13: psi/dr

Figure 12 and 13 also show that there is also no response after the dutch roll.

Weight and Balance

Table 12 and 13 show the weight and location of each component. The center of gravity was then calculated. The CG slightly moves back without the rocket since the CG of the rocket is slightly forward of the CG of the plane. As there is no active fuel consumption aboard this aircraft, the weight sensitivity ends up being binary: loaded with the rocket, and without. The moment of inertias with both the load and unloaded configurations is shown in table 14.

Table 12: Weight and Balance (Loaded)

Component	Weight (lb)	X (ft)	W*X (lb-ft)	Y (ft)	W*Y(lb-ft)	Z (ft)	W*Z(lb-ft)
Rocket (with avionics)	5.9	3.76	22.184	0	0	-3.56	-21.004
Fuselage	2.4	4.25	10.2	0	0	0	0
Wing	1	4.56	4.56	0	0	0.18	0.18
Horizontal Tail	1.5	7.41	11.115	0	0	0.17	0.255
Vertical Tail	1	7.45	7.45	0	0	0.83	0.83
Front Landing Gear	1	2.24	2.24	0	0	-0.45	-0.45
Main Landing Gear	1	4.44	4.44	0	0	-0.45	-0.45
Motor 1	1	4.25	4.25	-1.33	-1.33	0.15	0.15
Motor 2	1	4.25	4.25	1.33	1.33	0.15	0.15
Battery 1	2	2.33	4.66	0	0	-0.13	-0.26
Baterry 2	2	2.33	4.66	0	0	0.11	0.22
ESC 1	0.25	3.82	0.955	0	0	0.09	0.0225
ESC 2	0.25	3.82	0.955	0	0	-0.02	-0.005
Remote Launch Module	0.2	4.11	0.822	0	0	-0.13	-0.026
Plane Avionics	0.5	3.37	1.685	0	0	-0.2	-0.1
Plane Avionics Battery	0.1	2.98	0.298	0	0	-0.2	-0.02
Spacer	1.5	3.04	4.56	0	0	-0.35	-0.525
Servo 1	0.08	4.61	0.3688	4.54	0.3632	0.21	0.0168
Servo 2	0.08	4.61	0.3688	-4.54	-0.3632	0.21	0.0168
Servo 3	0.08	7.41	0.5928	1.48	0.1184	0.26	0.0208
Servo 4	0.08	7.41	0.5928	-1.48	-0.1184	0.26	0.0208
Servo 5	0.08	7.45	0.596	0.1	0.008	0.75	0.06
Total	**23**		**91.80**		**0.008**		**-20.8973**
CG (ft)		3.99		0.00			-0.91

Table 13: Weight and Balance (Unloaded)

Component	Weight (lb)	X (ft)	W*X (lb-ft)	Y (ft)	W*Y(lb-ft)	Z (ft)	W*Z(lb-ft)
Fuselage	2.4	4.25	10.2	0	0	0	0
Wing	1	4.56	4.56	0	0	0.18	0.18
Horizontal Tail	1.5	7.41	11.115	0	0	0.17	0.255
Vertical Tail	1	7.45	7.45	0	0	0.83	0.83
Front Landing Gear	0.75	0.5	0.375	0	0	0.25	0.1875
Main Landing Gear	1.25	6	7.5	0	0	-0.25	-0.3125
Motor 1	1	4.25	4.25	-1.33	-1.33	0.15	0.15
Motor 2	1	4.25	4.25	1.33	1.33	0.15	0.15
Battery 1	2	2.33	4.66	0	0	-0.13	-0.26
Baterry 2	2	2.33	4.66	0	0	0.11	0.22
ESC 1	0.25	3.82	0.955	0	0	0.09	0.0225
ESC 2	0.25	3.82	0.955	0	0	-0.02	-0.005
Remote Launch Module	0.2	4.11	0.822	0	0	-0.13	-0.026
Plane Avionics	0.5	3.37	1.685	0	0	-0.2	-0.1
Plane Avionics Battery	0.1	2.98	0.298	0	0	-0.2	-0.02
Spacer	1.5	3.04	4.56	0	0	-0.35	-0.525
Servo 1	0.08	4.61	0.3688	4.54	0.3632	0.21	0.0168
Servo 2	0.08	4.61	0.3688	-4.54	-0.3632	0.21	0.0168
Servo 3	0.08	7.41	0.5928	1.48	0.1184	0.26	0.0208
Servo 4	0.08	7.41	0.5928	-1.48	-0.1184	0.26	0.0208
Servo 5	0.08	7.45	0.596	0.1	0.008	0.75	0.06
Total	**17.1**		**70.81**		**0.008**		**0.8817**
CG (ft)		4.14		0.00			0.05

Table 14: Moment of Inertia

Configuration	Ixx (lbs*ft^2)	Iyy (lbs*ft^2)	Izz (lbs*ft^2)
Loaded	2.593	15.281	13.134
Unloaded	0.263	10.995	11.179

Structural Concepts

Primary structural element identification

Carbon fiber composites will be used to manufacture all of the plane's structures. All of the parts of the aircraft (fuselage, horizontal & vertical stabilizers, and the wing) will be hollow shells made from alternating layers of 2K plain and 12K twill carbon fiber. The omission of separate supporting structures (I-beams in the wings and support beams in the fuselage) allows for a lower empty weight. This reduction in structural integrity will be compensated for by adding additional plies of the previously-mentioned material in the aircraft's structure. With the above in mind, the primary structural elements of the aircraft are:

A. Fuselage

B. Wing

C. Horizontal Stabilizer

D. Vertical Stabilizer

E. Landing Gear Support

Attachments

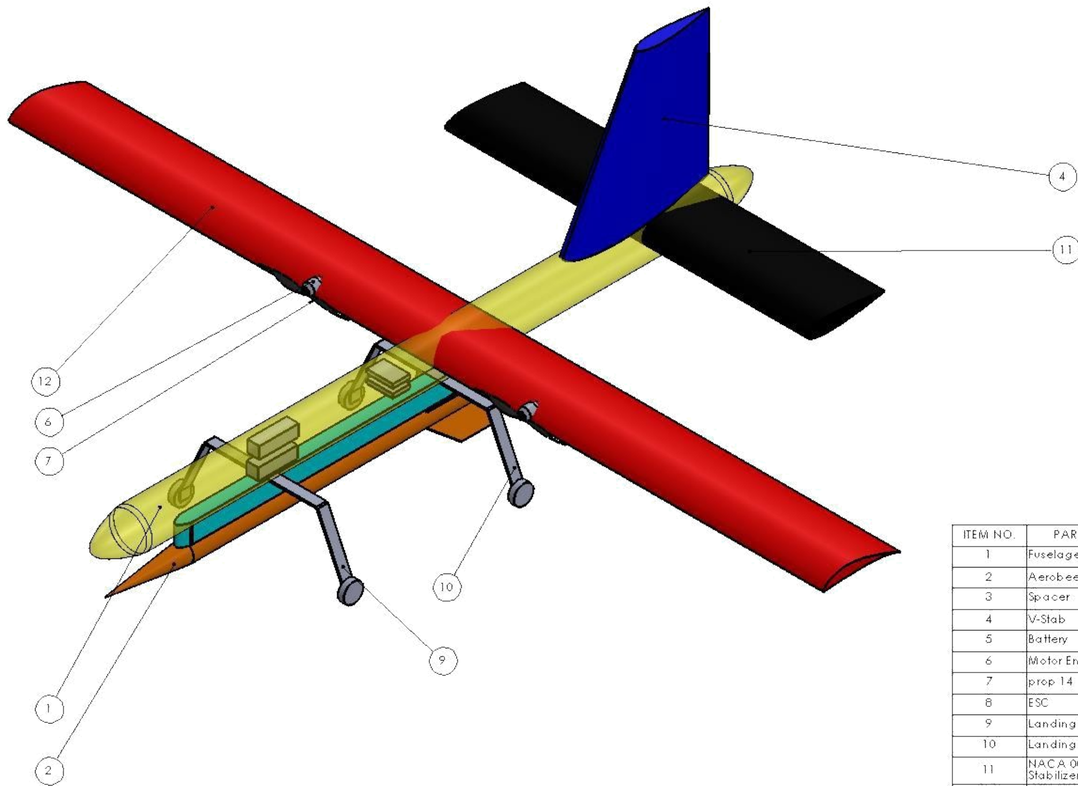
The only external attachments are the 2-piece telescopic rail, Aerobee rocket, and the safety pin.

All of the above-mentioned components are store-bought. The structural integrity of the rocket's design has been proven in previous launches. The ejection and guiding capabilities of the telescopic rail will be tested under a 3g loading with the rocket attached. This is to ensure that the rail is capable of guiding the rocket away from the plane in case unknown anomalies cause the rocket motor to ignite before the airplane is in its launch attitude.

The safety pin will be modified to break under any force larger than 15 lbs. This is to allow for the rocket to fly away from the plane in case a situation similar to that explained in the previous paragraph develops.

Preliminary layout

Figures 14 shows the preliminary layout of the aircraft with the rocket attached. The placement of the rocket down the centerline of the fuselage makes the use of a singular "nose" landing gear impractical. Therefore, it was decided to use a main gear setup for the front of the aircraft as well as the back. This added extra weight to the aircraft and has presented some difficulties with providing a steering mechanism, but it has been the only solution to the nose gear problem.



ITEM NO.	PART NUMBER	QTY.
1	Fuselage	1
2	Aerobee Rocket	1
3	Spacer	1
4	V-Stab	1
5	Battery	2
6	Motor Enhanced	2
7	prop 14	2
8	ESC	2
9	Landing Gear	1
10	Landing Gear-Main	1
11	NACA 0018 Horizontal Stabilizer	1
12	FX74 Wing	1

Figure 14: Preliminary layout of the Airplane

References

Bartolotta, P. (2011). *Horizontal Launch: A Versatile Concept for Assured Space Access* (p. 140). NASA.

Feaux, K., Jordan, W., Killough, G., Miller, R., & Plunk, V. (1989). *Low Earth Orbit Rider (LER) Winged Air Launch Vehicle Concept* (Vol. 1, p. 61). Auburn, Alabama: Auburn University.

Sarigul-Klijn, M., & Sarigul-Klijn, N. (2001). A Study of Air Launch Methods for RLVs. *AIAA*. Retrieved February 4, 2015, from https://wiki.umn.edu/pub/AEM_Air_Launch_Team/LaunchTrajectoryDesign/aiaa2001-4619.pdf

McCants, T.H. (2010). *U.S. Patent No. 7,849,778 B1*. Washington, DC: U.S. Patent and Trademark Office.

Foust, J. (2014, June). Air launch, big and small. *TheSpaceReview,*108-113. Retrieved from: http://www.thespacereview.com/article/2543/1

Waters, E.D. (2013). Air Launch: Examining Performance Potential of Various Configurations and Growth Options. *NASA Technical Reports Server*. Retrieved from: http://ntrs.nasa.gov/search.jsp?R=20140003206

van Keseren, M.W. (2013). Air Launch versus Ground Launch: a Multidisciplinary Design Optimization Study of Expendable Launch Vehicles on Cost and Performance. Retrieved from : http://repository.tudelft.nl/view/ir/uuid%3A16093448-e5bf-4ee7-a895-67168fc9e2c2/

Appendix A: Pegasus Launch System: Fact Sheet

Pegasus®

Patented Air Launch System

Orbital ATK

Overview

Pegasus was specifically developed to provide cost-effective access to space for the small satellite community. The Pegasus air-launch system is the industry's workhorse, providing launch services for technology demonstration, scientific investigation, remote sensing and communications missions. The three-stage Pegasus boosts small satellites weighing up to 1,000 pounds (450 kilograms) into low-Earth orbit. Pegasus is carried aloft by an L-1011 carrier aircraft to approximately 40,000 feet (12,000 meters) over open ocean, where it is released and then free-falls in a horizontal position for five seconds before igniting its first stage rocket motor. In a typical mission Pegasus delivers its payload into orbit in a little over ten minutes.

System Features

- Inertially guided three stage solid rocket propulsion
- Horizontal satellite integration and simplified launch operations
- Carrier aircraft provides on-board payload monitoring and control
- Air-launched mobility enables launch from anywhere, worldwide:
  - Demonstrated launch capability from U.S. Air Force Western Range (WR), Eastern Range (ER), NASA's Wallops Flight Facility, Canary Islands and Kwajalein launch sites
  - Flight-proven with a demonstrated success record:
    - 42 missions conducted
    - 28 consecutive fully successful missions
- Flexibility to support unique user needs

FACTS AT A GLANCE

World's leading small-class space launch vehicle.

42 missions conducted; flawless record since late 1996.

Launches conducted from California, Virginia, Florida, the Canary Islands and the Kwajalein Atoll in the Marshall Islands.

Pegasus "Firsts"

- World's first privately developed space launch vehicle.
- Maiden 1990 mission marked the first all-new, unmanned space launch vehicle developed in the U.S. in more than 20 years.
- First winged vehicle to accelerate to eight times the speed of sound.
- First air-launched rocket to place satellites into orbit, using its carrier aircraft as an "air breathing reusable first stage."

Pegasus in flight

Pegasus®

Performance

- Flight verified systems performance
- Optional Hydrazine Auxiliary Propulsion System (HAPS)
  - Precision injection capability
  - Increased performance to higher LEO altitudes
- Any inclination can be achieved by varying launch point

Payload Accommodations

Standard Accommodations

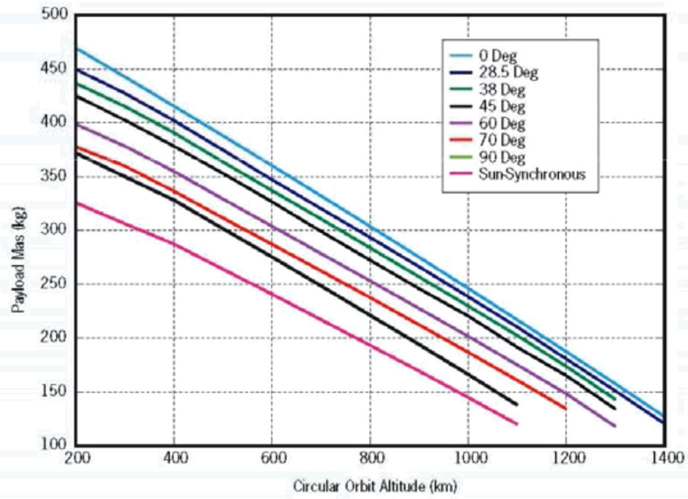
- Temperature, humidity control
- Class 8 (100,000) cleanliness

Enhanced Accommodations

- Class 7 (10,000) cleanliness
- Nitrogen purge

Flight-Proven Dual Payload Accommodations

Performance



More Information

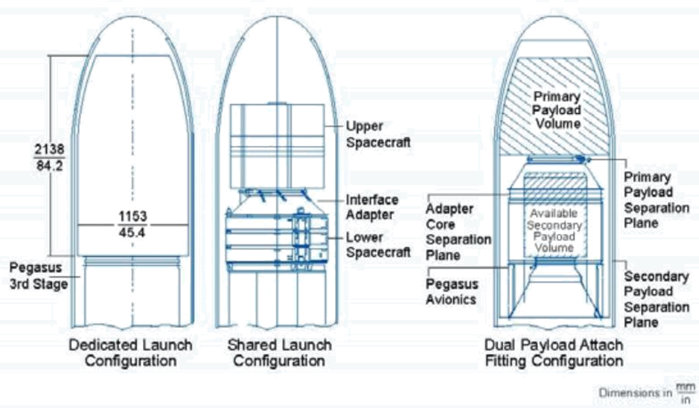
For additional information and a complete Pegasus Users Guide, please visit: www.OrbitalATK.com/LaunchSystems/Publications/Pegasus_UsersGuide.pdf

Key Contacts

Bryan Baldwin,
Pegasus Program Manager
(703) 948-2264
baldwin.bryan@orbitalatk.com

Warren Frick,
Advanced Projects Program Manager
(703) 948-8192
frick.warren@orbitalatk.com

Payload Accommodations



Appendix B: Strato-Launch System: Fact Sheet

Stratolaunch Eagles

Intermediate-Class Launch Vehicle

Orbital ATK

Overview

The Stratolaunch Eagles program is a Paul Allen project designed to address the space industry's need for a responsive and flexible space launch system capable of increased flight rates for intermediate-class payloads. Eagles will employ the world's largest aircraft developed by Scaled Composites, builder of the White Knight aircraft, as an air breathing reusable first stage to launch larger classes of payloads than any similar platform. To help make the Stratolaunch vision a reality, Orbital ATK is leveraging its vast launch vehicle and launch operations expertise to develop the Air Launch Vehicle. Orbital ATK is applying technology from its patented Pegasus® air-launch system and the Defense Advanced Research Projects Agency (DARPA)-sponsored Taurus® program that was designed for easy transportability and rapid launch, to reduce cost and provide unparalleled flexibility to operate from virtually anywhere on Earth with minimal ground support.

The Air Launch Vehicle is a multistage rocket that combines demonstrated rocket technologies and a proven winged configuration on a large scale. The Eagles system is designed to be EELV compliant, capable of launching payloads in the 10,000 pound class to low-Earth orbit (LEO), and smaller payloads to geostationary transfer orbit (GTO). The Air Launch Vehicle design utilizes Orbital ATK's proven Modular Avionics Control Hardware (MACH), engineering standards and common vehicle and payload integration processes utilized in the Pegasus, Taurus, Minotaur and Antares™ launch vehicle families.

Key Features

- Incorporates both solid and liquid stages
- 5 meter fairing to accommodate large payloads
- Compatible with Vandenberg Air Force Base, Edwards Air Force Base, Kennedy Space Center and other sites
- 1,000 nmi range to launch window
- Rapid launch readiness
- Austere ground operations
- World's largest aircraft
  - Over 500,000 lb payload capacity
  - 385 ft wing span
- Substantial payload performance to any orbital inclination (including sun synchronous)
- Design evolution for crewed payloads

Stratolaunch Systems — A Paul G. Allen Project

Scaled Composites

FACTS AT A GLANCE

- Intermediate Class Launch Vehicle
- 10,000 lb class payloads to low-Earth Orbit
- Affordable and flexible payload delivery system
- Designed to EELV requirements
- Flight testing begins in 2016

Mission Partners

Stratolaunch Systems

Prime organization offering launch services; program management and overall system direction

Orbital ATK

Launch vehicle and mission design; system integration; integrated ground systems

Scaled Composites

Carrier aircraft development, fabrication and flight testing; aircraft facilities and operations

Stratolaunch gives customers the flexibility to rapidly launch payloads to any orbit, any time

Stratolaunch Eagles

Air Launch Vehicle – "Thunderbolt"

Manufacturer:	Orbital ATK
Length:	131 ft
Wingspan:	40 ft
Weight:	500,000 lb
Stage 1 and 2:	ATK Solid Rocket Motors
Stage 3:	Liquid hydrogen/oxygen with two RL10C engines

Designed for maximum performance using a combination of proven and reliable rocket propulsion technologies

Payload Accommodations

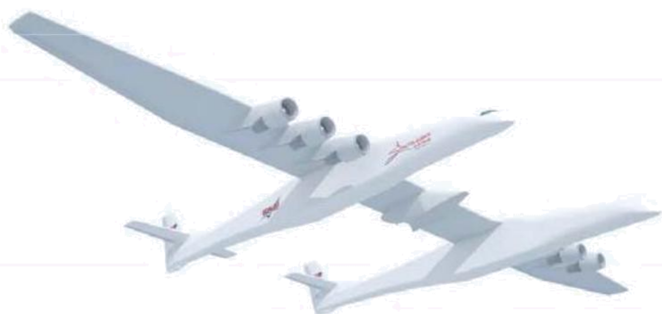
- EELV compatible fairing envelope
- Temperature and humidity controlled payload environment

The Stratolaunch Systems air launch concept allows for payload performance to be tailored to mission unique requirements.

Carrier Aircraft – "Roc"

Manufacturer:	Scaled Composites
Length:	238 ft
Height:	50 ft
Wing Span:	385 ft
Max Gross Weight:	1,300,000 lb
Launch Window Range:	1,000 nmi
Maximum Altitude:	45,000 ft
Runway Requirement:	12,500 ft x 200 ft

All Composite Airframe
Crew of 3 plus two jump seats
Six 747 PW4056 turbofan engines
56,750 lb thrust at sea level



For more information:

Stratolaunch Systems
P.O. Box 22132
Huntsville, Alabama 35814
www.stratolaunch.com

Orbital ATK

www.orbitalatk.com

 FS006_13_3695