

Selection of a Carrier Aircraft and a Launch Method for Air Launching Space Vehicles

Marti Sarigul-Klijn¹ Ph.D. and Nesrin Sarigul-Klijn² Ph.D.

Mechanical and Aeronautical Engineering Department, University of California, Davis, CA 95616-5294

Gary C. Hudson³ and Bevin McKinney⁴
AirLaunch LLC, Kirkland, Washington, 98033

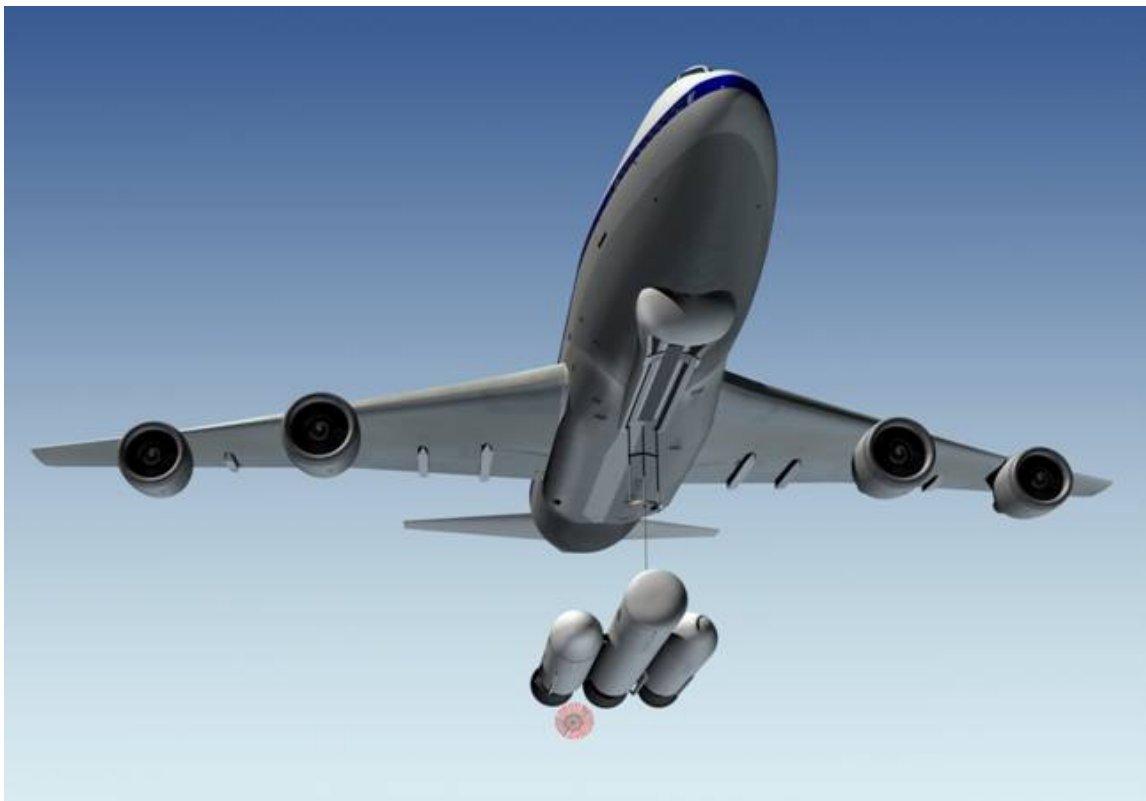
Jim Voss⁵ and Phil Chapman⁶
Transformational Space Corp, Reston, Virginia, 20190

Bob Morgan,⁷ Jim Tighe,⁷ and Jason Kramb⁷
Scaled Composites LLC, Mojave, California, 93501

Ken Doyle⁸ and Mike Quayle⁸
Protoflight LLC, Mojave, California, 93501

and

Charlie Brown⁹
Space Vector Corp., Chatsworth, California, 91311



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¹ Lecturer, UC Davis. Chief Engineer for AirDrop, AirLaunch LLC. Senior Member AIAA.

² Contact Author: Professor, nsarigulklijn@ucdavis.edu, (530)-752-0682. Associate Fellow of AIAA.

³ CEO & Program Manager, 5555 Lakeview Drive, Suite 201. Associate Fellow of AIAA.

⁴ Chief Designer, 5555 Lakeview Drive, Suite 201. Member AIAA.

⁵ Vice President for Engineering. Currently at SpaceDev, San Diego, CA. Member AIAA.

⁶ Chief Scientist, 11710 Plaza America Drive, Suite 2000. Member AIAA.

⁷ Engineer, 1624 Flight Line.

⁸ Engineer, 1122 Flight Line.

⁹ Senior Designer, 9223 Deering Avenue.

This paper describes the flight simulation and selection study that Transformational Space Corporation (t/Space) conducted for the design of a carrier aircraft to launch an earth-to-orbit launch vehicle for NASA's Commercial Orbital Transportation Services (COTS) program. A new air launch method, called Trapeze-Lanyard Air Drop (t/LAD) launch, would be used to launch the rocket. Air launching simplifies operations as compared to ground launch from a fixed range in several ways and it also greatly improves the simplicity, safety, cost, and reliability of the booster.

I. Introduction

With NASA's plans to retire the Space Shuttle in 2010, a highly responsive, safe and reliable replacement is needed. Transformational Space Corporation (t/Space) has proposed a booster launched from a carrier aircraft as the means to deliver a crew and cargo to the International Space Station (ISS) and other locations such as the planned Bigelow Aerospace habitats. The preliminary design of this booster and its carrier aircraft was funded by NASA under a \$6 million contract as precursor to its Commercial Orbital Transportation Services (COTS) program. A new air-launch method called trapeze-lanyard air drop (t/LAD) launch would also be used. A t/LAD launch eliminates the need for wings on the launch vehicle; greatly reduces ascent dynamic pressure, sideways accelerations and bending forces, and rocket engine thrust vectoring control.

The first section of this paper compares air launch with ground launch and describes the advantages and disadvantages of each method. The second section describes the design requirements for the carrier aircraft. This is followed by a description of the various means to air launch an earth-to-orbit launch vehicle. We then describe our baseline carrier aircraft and a simulator evaluation of its performance and flying qualities. Next we describe a new aft crossing trajectory that has several advantages over a traditional forward crossing trajectory that has been used in all previous air launches. Finally we describe our launch method, t/LAD, and its flight test program.

II. Ground versus Air Launch

All manned space flights have been launched from ground-based installations such as Cape Canaveral. Ground launches, however, present problems of launch delays due to inclement weather and the necessity to clear the vicinity of air traffic. For launches to the ISS, only northeast bound trajectories are permitted from Canaveral due to the concern of overflight of the east most Caribbean islands. Also current range policies do not permit a launch if there is maritime shipping traffic within the potential impact zone of lower stages, regardless of the fact that official notices were given.

In general the ISS is normally not in the proper position for an immediate ascent when a ground launch window opens. Ground launch requires waiting in a low coplanar parking orbit until the orbital phasing is correct for a transfer up to the ISS. In the worst case, the wait while in a parking orbit can range from a day to a week or more, depending on launch criteria (such as ascent lighting).

Ground launch also ties the vehicle to a range and their associated high costs and the costs of major range and launch pad infrastructure investments. Moreover, crew safety equipment (abort rockets) must remove the crew from a vehicle in the case of a launch abort or failure which may occur on the ground or very close to the ground. The reliability of equipment solely designed for emergencies such as abort rockets is much less than equipment designed for normal operations, mainly because it is unaffordable to test emergency equipment sufficiently or routinely. For example, the survival rate of aviators using ejection seats is only 50 percent.

These problems can be overcome by launching from an aircraft in flight. An air launch offers several advantages over a ground launch, such as the avoidance of weather related delays, the simplification of operations, and increases in safety, both for the crew by simplifying abort options, and for the public owing to its ability to avoid the overflight of populated areas. Astronauts have a better chance of survival with air launch in the event of rocket misfire or other launch emergency – they would just separate the capsule and land with the parachutes just as they would for a normal reentry. Air launch can occur over the open ocean, sufficiently far from populations or crowded sea-lanes near the shore. There are large off-shore areas in which there is no ocean maritime or air traffic. An air launch carrier aircraft can fly around or over launch constraining weather.

Air launch allows positioning of the launch point to intercept the ISS orbital plane that has the desired orbital phasing on the first orbital pass. Air launch can double the number of launch windows from the Kennedy Space Center (KSC) to the ISS by permitting southward launches, and it can also eliminate the time spent in parking orbit. Time from air launch to ISS arrival can be varied from as little as one hour to days of wait time on orbit.

Any runway of suitable length can serve as a launch site, missions are recallable, and the carrier aircraft serves as the launch vehicle transporter. Air launch also eliminates the acoustic reflection from the ground which tends to size the bottom of launch vehicles. Finally, there are no major infrastructure expenditures for new launch pads.

In addition, air launching presents design options that simplify the operation of the launch vehicle engine. In particular, air launch allows the use of higher area ratio nozzles for a given engine pressure due to the decreased atmospheric pressure at altitude. The low outside atmospheric pressure at altitude (25,000 feet or greater) allows a pressure-fed launch vehicle to use high area ratio nozzles while operating at relatively low engine pressures. This approach provides weight and specific impulse I_{sp} performance that is competitive with high-pressure turbopump-fed systems without the associated safety, cost, or complexity issues. Launch vehicle tank pressures do not have to exceed 200 pounds per square inch (psi), and the engines can run at a maximum pressure of 150 psi. Furthermore, nozzle expansion ratio can be set closer to ideal since atmospheric back pressure varies less throughout the ascent trajectory with an air launch.

Altitude launch also allows the use of vapor-pressure (Vapak) propellant feed. Vapak is based on using the internal energy of a liquid stored in a closed container to provide the pressure and to perform the work required to expel the liquid from the container. This method was successfully used for *SpaceShipOne's* oxidizer feed, as originally recommended by the 3rd and 4th authors. Vapak eliminates costly and failure prone components such as turbopumps and gas generators used in a typical pump-fed rocket, and also eliminate heavy high pressure gas tanks for typical tank-pressure-fed engines.

A lower pressure engine is also a safer solution because no operational pressure fed rocket has ever exploded. According to the National Research Council¹ the benign failure ratio (failures/engine flights) of pump fed engines is 0.6% and the catastrophic failure ratio is 0.2% (loss of vehicle/engine flights). Vapak improves safety in pressure-fed rockets by eliminating the high-pressure gas storage vessels and pressure regulators or heated gas systems (such as Tridyne) normally associated with them. Safety and reliability are also enhanced through simplification and reduction of complexity since the only moving parts in a Vapak engine are valves for propellant fill and drain, and to turn on the propellant flow to the rocket engine.

The modest performance gain of launching at 25,000 to 35,000 feet, approximately 1,100 feet per second (fps) to 1,800 fps delta V improvement - depending on carrier aircraft flight path angle at launch - also makes it easier for a multi-stage rocket to put payloads into orbit.^{2 or 3}

III. Carrier Aircraft Design Requirements

The NASA COTS basic requirement is to transport cargo or three astronauts to and from the ISS. The baseline rocket sized to accomplish this was a single barrel two-stage-to-orbit launch vehicle that weighed about 290,000 pounds with a diameter of 13.5 feet, shown in Figure 1. After we had completed most of our carrier aircraft trade studies and as a result of those studies, the launch vehicle was changed to a three barrel, three-stage-to-orbit launch vehicle that had a diameter of 7.25 feet and a weight of 207,000 lbs.

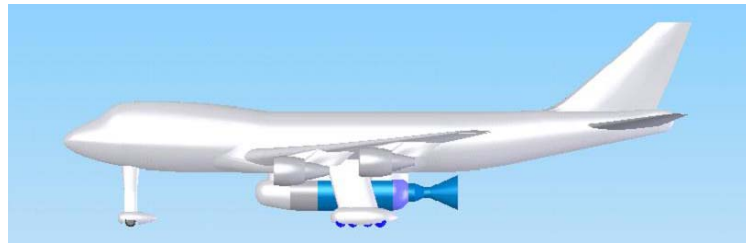


Fig. 1 Original 13.5 foot diameter Booster compared to 747

The change from 2-stage to 3-stage-to-orbit vehicle meant the payload to orbit remained the same despite the reduced weight.

Our studies for a carrier aircraft initially focused on the basic questions of how high to fly, how fast to fly, and how big of an aircraft. Obviously increasing the launch vehicle size had the largest effect on payload size. This implies we want the largest carrier aircraft possible, which depends on availability and affordability. Our carrier aircraft size was fixed by the need to carry a 290,000 pound booster (later changed to 207,000 pounds).

Other than the carrier aircraft size, we had previously found in references 2 and 3 that carrier aircraft launch velocity had the largest effect on payload size, followed by launch flight path angle, and finally launch altitude. We eliminated supersonic launch velocities since they are not economically viable. The military, after 50 plus years of development, has not built and operated a large supersonic aircraft with a low lifecycle cost. The SR-71, an aircraft much smaller than what we needed, was retired with high cost cited as one of the reasons. The Concorde, another expensive supersonic aircraft, is also much too small for our carrier aircraft requirements. We had determined that a flight path angle of 30 degrees above the local horizon provided about a 15% increase in payload to orbit as compared to a level launch. Flight path angle is the angle between the launch vehicle velocity vector and the local

horizon. Flight path angle either above or below 30 degrees resulted in less payload to orbit. Finally we also discovered that air launching above about 50,000 feet had little benefit in terms of additional payload to orbit.

Hence we initially settled on a requirement for a subsonic aircraft capable of carrying a 290,000 pound booster to altitudes of 25,000 feet required (for Vapak), to 50,000 feet desired (for best payload mass to orbit), combined with flying a flight path angle of at least 0 degrees with 30 degrees desired (for best payload mass to orbit).

IV. Air Launch Method Trade Studies

A. Tow Air Launch

We considered towing a large glider that would carry the launch vehicle. The advantage of this approach was easy separation from the towing aircraft and low cost modifications to the towing aircraft. Safety concerns include broken towlines and a towing aircraft takeoff abort. A large airliner such as a 747 would have only about 50% of its thrust available as excess available to tow a glider. For a 747 at 25,000 feet, this excess thrust would amount to about 50,000 pounds force, enough to tow perhaps a 400,000 pound glider (assuming a relatively optimistic lift to drag ratio of 8 for the glider with rocket attached). Cost considerations eliminated building such a large glider.

B. Balloon Air Launch

Balloon launch was also considered, however it was rapidly eliminated as the size of the balloon would be enormous. Since the location where the balloon touches down is undetermined, the potential of damage to either the balloon or to things on the ground is high. Also launch would be limited to a calm day and launch location is not precisely controllable.

C. Captive on Top Air Launch

We considered three different captive-on-top launch concepts. No examples of captive-on-top launch vehicles have been actually built, but the Space Shuttle's approach and landing demonstrator, the Enterprise, used this method to test its landing. Advantages of this method include the capability to carry a large volume rocket on top of the carrier aircraft. Disadvantages include extensive modifications (high cost) to the carrier aircraft. Further, placing a launch vehicle on top of the carrier aircraft destroys the lift produced by the fuselage and causes a large amount of drag that in turn limits launch altitude. For example, during its approach and landing test flights, the Space Shuttle orbiter was launched at altitudes between 19,000 to 26,000 feet from its carrier Boeing 747, even though a clean 747 normally cruises at 38,000 to 45,000 feet.

1. Wings

We reviewed adding expendable wings to the rocket. This concept had been proposed by Boeing for their solid fueled AirLaunch concept (originally proposed by the 4th author as a consultant to Boeing). The disadvantage of this concept was that the wings needed to be one-third the size of the 747 wings in order to support the launch vehicle at separation from the carrier aircraft. In addition, the launch vehicle must have active controls at release from the carrier aircraft to prevent it from hitting the carrier aircraft. After the launch vehicle had pulled up into a vertical ascent trajectory, the wings would be discarded. We did not select this concept because of low launch altitude, the cost of the replacing or repairing the booster wing after every flight, and the need for active controls at release.

2. Trapeze Top Launch

Our second top launch concept was to add a trapeze between the launch vehicle and the carrier aircraft. The carrier aircraft would conduct a zoom climb similar to that used in astronaut zero G training. As the carrier aircraft nose is pushed over into a zero G trajectory, the launch vehicle would be released and the trapeze would guide the rocket clear of the carrier aircraft's tail. We successfully simulated the separation dynamics in the dynamic simulation program, Working Model 2D. We did not select this concept because of low launch altitude and perceived high risk.

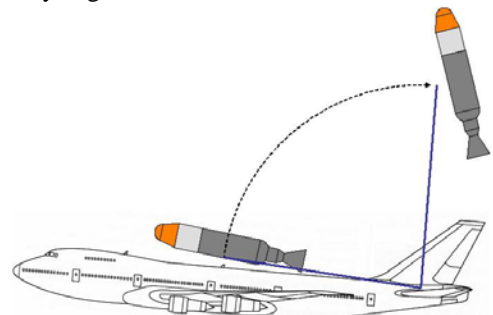


Fig. 2 Trapeze Top Launch

3. Barrel Roll

Our third captive on top concept was to have the carrier aircraft fly a barrel roll. Airliners have been rolled inverted before using a barrel roll maneuver, notably by Tex Johnson when he demonstrated the first Boeing 707 (Dash 80 version) airliner. In a barrel roll, the airline crew always experiences positive acceleration (directed from

head to toe) throughout the maneuver. At the top of the roll, when the aircraft was inverted, the launch vehicle would be released. To help ensure separation from the rocket, the pilot would push forward on the controls to cause the carrier aircraft to fly level flight while inverted. This would cause the airline crew to experience negative acceleration (directed from toe to head) for a short period of time. We flew simulations of this maneuver in a high fidelity flight simulator. We discovered when an airliner such as a 747 was barrel rolled starting with a reasonable entry airspeed (280 knots indicated) that when inverted its airspeed was very slow (in the order of 180 knots indicated airspeed). Because of the slow airspeed it could not fly level flight while inverted. Hence we could not ensure separation between the launch vehicle and the carrier aircraft.

D. Internally Carried Air Launch

Internal launch was considered such as used by AirLaunch LLC for their QuickReach rocket launched from the C-17 aircraft. Reference 4 describes a recent successful internally carried airdrop of the largest and heaviest single item ever dropped from a C-17 aircraft. Drop occurred at a density altitude of 34,000 feet and airspeed of Mach 0.58. Advantages of internally carried air launch include little or no modification to the carrier aircraft. Most propellant boil-off concerns are minimized since the launch vehicle is not subject to either radiation heating from the sun or convective heating from the atmosphere. The rocket is in a benign environment inside the carrier aircraft that allows maintenance and safety problems to be detected prior to launch. Release altitude can be at a higher altitude because the launch vehicle does not increase the carrier aircraft's drag. The main disadvantage is that the rocket must be sized to fit inside the carrier aircraft. Although internal carriage looked promising and remains so for smaller sized launch vehicles, we eventually selected a captive on bottom concept.



Fig. 3 QuickReach Dropped from C-17

E. Captive on Bottom Air Launch

The captive on bottom launch method is a method of air launching that has been successfully demonstrated before. Examples include the X-1, X-15, and *SpaceShipOne*. Advantages include proven and easy separation from the carrier aircraft and in the case of a Reusable Launch Vehicle (RLV), leeward side penetrations and hard points on the RLV that eliminate some Thermal Protection System (TPS) concerns, lighter RLV landing gear sized for landing, and the option of sizing the wing smaller than required for level flight at the release altitude and airspeed. Disadvantages include limits to launch vehicle size due to under the carrier aircraft clearance limitations.

1. Custom Aircraft

A new design carrier aircraft with tall landing gear can eliminate the clearance limitations. Scaled Composites LLC of Mojave, California completed a preliminary sizing of such a new design carrier aircraft. The aircraft was sized for a heavier payload than our requirements. The launch aircraft had a takeoff gross weight 60% larger than a 747. It could carry a 680,000 pound payload to an altitude of 50,000 feet and launch at Mach 0.7. Unfortunately, the cost and schedule to build eliminated this very capable design from our consideration.

2. Modified Airliner

Next we evaluated various transport aircraft as possible carrier aircraft. We selected the Boeing 747-200 as the best aircraft for a carrier aircraft in terms of maximum payload, low cost, and best availability. The 200 has a

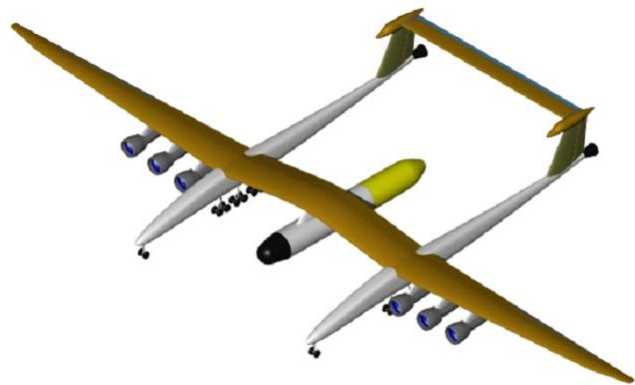


Fig. 4 Custom Launch Aircraft

structural payload of at least 244,000 pounds and used aircraft in excellent condition can be obtained for about \$6.25 million to \$11.6 million after required phase checks. We also examined other wide body aircraft such as the 747SP, 777, DC-10, MD-11, L-1011, and A340. We visited and examined the Shuttle Carrier Aircraft (SCA) 747-100 at NASA Dryden, and discussed with NASA management at the Johnson Space Center possible use of these NASA aircraft after Space Shuttle retirement. Although the SCA can carry a 235,000 pound Shuttle, its structural payload for our application is only about 169,000 pounds. The Shuttle's wings provide lift that off loads the SCA wings and allows the higher weight of the Shuttle. Thus the 747-200 was judged superior in terms of high structural payload, low cost, and excellent availability.

Table 1 Comparison of Airliners

Aircraft	Gross Weight (lb x 1,000)	Number of Engines	Payload (lb x 1000)	Cost Used (\$ x million)
747-100	710	4	169	1.5
747-200	833	4	244	6 to 11
747-300	836	4	153	11
747-400	833	4	249	90
747SP	696	4	85	3
777-200	769	2	141	40
777-300	763	2	154	60
DC-10-10	440	3	120	3
DC-10-30	555	3	153	6
DC-10-40	555	3	149	6
L-1011	496	3	92	3
MD-11	633	3	204	44
MD-10-30	580	3	178	8
A340	573	4	102	40

We also determined that the 747-200 structural payload could be increased to over 300,000 pounds (lb) by off loading fuel (range to and from launch would still be 1,000 nautical miles). Flying in turbulence with such a payload would require reducing turbulent penetration airspeed from 290 knots indicated airspeed (KIAS) to 265 KIAS (Mach 0.76 at 30,000 feet) to prevent the aircraft from exceeding its wing bending limits. The 747 wing is designed to FAR Part 25 paragraph 25.337 limit of 2.5 g's. FAA (Federal Aviation Administration) FAR (Federal Aviation Regulations) Part 25 regulations are airworthiness standards that airliners must be designed to. Concentrating the weight of the rocket on the aircraft centerline makes the wing spar the critical structural component.

3. Tall Gear 747

In order to provide enough room under the 747 for the launch vehicle we considered a tall fixed gear 747 concept. We discovered that landing touch down tire spin up loads could have magnitudes as much as 50% of the vertical landing loads. Extensive analysis was performed on this option by Scaled Composites. Extending the gear for the tall gear concept meant the wing and fuselage experienced large aft bending moments from the landing gear at landing touch down. Structural reinforcement would be required throughout the wings and fuselage to deal with these loads. We determined this option to be cost prohibitive.

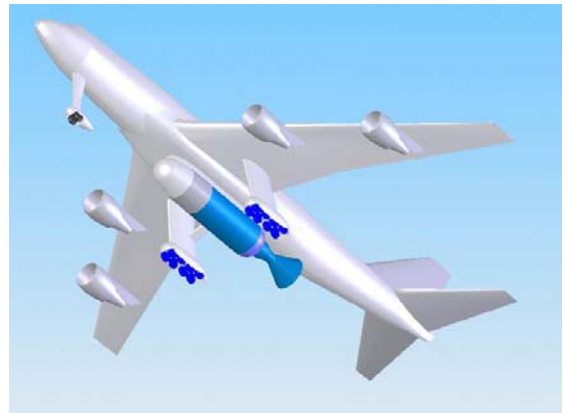


Fig. 5 Tall Gear 747

4. Sled Launch 747

To eliminate the need to structurally reinforce the 747 gear attachments, wings, and fuselage, we considered a sled launch. In this concept, the 747 with its gear up would be loaded on a launch sled. The launch sled would support the 747 via its landing gear jacking hard points. Hard points are provided on all aircraft so that landing gear can be retracted for maintenance and ground tests. The launch sled would have its own pilot. The 747 would provide the thrust to move the 747/sled combination on the ground and for takeoff, but the sled pilot would steer. After the 747 lifts off from the sled, the sled pilot would brake the sled to a stop on the remaining runway. The main disadvantage with this concept was there was no way to bring the launch vehicle back in the event of an aborted launch attempt. If further economic analysis shows the abort risk is acceptable, then this alternative may remain viable.

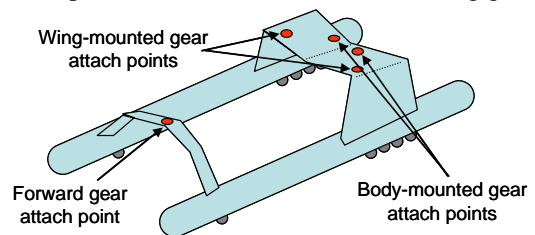


Fig. 6 Sled Launch 747

At this point we changed the booster's design from a single barrel two-stage-to-orbit to a three barrel three-stage-to-orbit (3STO) launch vehicle. The diameter of rocket was decreased from 13.5 feet to 7.25 feet and the booster's weight was reduced from 290,000 to 207,000 pounds. The switch to 3STO provided the same mass to orbit. Only

minor modifications are required to the 747 landing gear to get the clearance needed to carry the new booster underneath the aircraft.



Fig. 7 747 Carrier Aircraft with 3 barrel, 3-stage-to-orbit Launch Vehicle

V. Carrier Aircraft Modifications

To get sufficient clearance to carry a 7.25 foot diameter rocket under a 747, we would use a system similar, but much simpler, than used with the AV-8 Harrier landing gear. In the Harrier aircraft after takeoff, the oleo oil in the landing gear is allowed to bleed into an accumulator. This allows the landing gear to be retracted into smaller gear wells with the oleos not extended. Then when the Harrier landing gear is extended for landing, a pump is used to refill the oleos. For our 747 carrier aircraft, we would do something similar. Normally during taxi and takeoff only about 4 inches of the 747's 26.5 inch long gear oleo is extended. We would add more oil to the landing oleo to extend the landing gear oleo by another 17 inches for takeoff, enough to provide sufficient clearance under the 747 for the rocket plus the 7 inch ground clearance required by FAA FAR Part 25 paragraph 25.925.

The maximum landing weight of the 747 carrier aircraft would have to be reduced from a maximum landing weight of 630,000 pounds to 415,000 pounds in order to comply with FAA landing gear regulations (FAR Part 25 paragraphs 25.471 to 25.519) with the available 747 landing gear oleo stroke reduced from 26.5 inches to 12.5 inches (plus the 4 inches of tire compression). A landing weight of 415,000 pounds is sufficient to land with the empty rocket and capsule (rocket has provisions to dump all of its propellant) with sufficient fuel onboard the 747 so that a 200 nautical mile divert in instrument weather conditions can be completed after a missed approach. Note we don't have a requirement to land at 630,000 pounds since our carrier aircraft does not have to land with a full load of passengers and baggage. The landing weight reduction to 415,000 pounds is sufficient to ensure that the landing gear does not exceed any FAR Part 25 landing gear load requirements such as vertical descent, tire spin-up, gear spring back, side, rebound, brake roll, turning, pivoting, reversed braking, and towing loads.

A pylon is required to attach the booster to the



Fig. 8 Cargo Conversions LLC's 10 Air Tanker

747 carrier aircraft. The pylon design will be patterned after the structural design used to attach the water tanks on Cargo Conversions LLC's 10 Air Tanker. The 10 Air Tanker can carry 101,000 pounds of water and was modified from a DC-10-10 for about \$15 million in less than 2 years.

A water ballast system is required to move the overall Center of Gravity (CG) of the 747 and rocket to within the allowable forward limit (approximately 8.5% mean aerodynamic chord, MAC). The rocket's Airborne Support Equipment would be installed in the 747 such that when empty the aircraft CG is at the aft allowable limit (approximately 33% MAC). With the fueled rocket attached the overall CG is forward of the allowable limit. The water ballast system with about 20,000 pounds of water installed in the aft end of the 747 passenger compartment moves the CG back inside the forward limit with the fueled rocket attached. The water ballast system uses a dual redundant dump system developed for the 10 Air Tanker so that the water can be dumped in less than 4 seconds when the rocket is released. However if the water is trapped then the overall CG will be at about 45% MAC without the fueled rocket. The aircraft is trimable and flyable in at this CG position; but its long period pitch oscillation mode (Phugoid) would be lightly damped. The aircraft is not unsafe, but it is more difficult to fly. Training of the pilot in a simulator should ensure the safety of flying in this condition

The last modification is the Trapeze-Lanyard Air Drop (t/LAD) system. It will be described in section VIII.

VI. Carrier Aircraft Performance and Flying Qualities

The performance and flying qualities of the 747 as a carrier aircraft were evaluated in February 2006 at the NASA Ames Boeing 747 flight simulator located at the Crew-Vehicle Systems Research Facility. The 747 simulator has a six-degree-of-freedom motion system, a visual system that depicts realistic out-of-window scenes, and the crew compartment that is fully detailed to replicate current 747 cockpits. All instruments, controls, and switches operate as they do in the actual aircraft, and the flight controls and performance duplicate an actual aircraft.

The evaluation was conducted over the course of a half day, involving about 3 hours flight simulation time and 5 evaluators flying a total of 40 simulated t/LAD air launches. The primary focus was an evaluation on the effect of dropping a rocket booster from the 747 with the associated large and instantaneous shift in aircraft center of gravity (CG) from the aircraft forward limit to the aft CG limit. Handling quality evaluations of the vehicle's longitudinal and lateral responses were assessed in the course of performing these tasks.

The landing gear of the 747 was lowered to simulate the additional drag of the rocket and the directional destabilizing effects of the booster. Aircraft weight was set at 700,000 pounds and the aircraft CG was located at the forward limit of 8.5 % MAC. To simulate the drop of the rocket, the simulator operator would instantly reduce the aircraft weight to simulate the release of the booster and the ballast water and move the CG to the aft limit of 33% MAC. At the same time, the pilot not flying would retract the landing gear by raising the landing gear handle.

With the landing gear down and at 700,000 pound weight, the absolute ceiling was determined to be approximately 23,900 feet above mean sea level (MSL) at 243 KCAS (knots calibrated airspeed), equal to about 600 feet per second true airspeed or Mach 0.6. The drag of the rocket booster is expected to be less than the extended landing gear, so an actual launch is expected to occur at a higher altitude, in the order of 30,000 to 35,000 feet. Note the Orbital Sciences modified L-1011 Tri-Star airliner drops the *Pegasus* launch vehicle at 39,000 feet and Mach 0.82, approximately the same altitude and airspeed the aircraft flies in passenger airline service.

During a simulated rocket launch, the 747 would pitch up as much as 5 to 10 degrees. With the slats up, the aircraft stall warning would sound and the aircraft would exhibit a slight wing rock as it entered an accelerated stall. Lowering the slats was found effective in eliminating both the stall warning and the accelerated stall. The first position of the cockpit flap lever deploys the leading edge slats only and the airspeed limit for slat deployment is 280 KCAS. The slats down configuration should increase drag somewhat and could reduce launch altitude. An effective technique was to climb to the clean wing altitude ceiling and then lower the slats just prior to launch.

For a level launch, a technique of trimming the nose down prior to launch was found effective in reducing the pitch up of the 747 at rocket release from about 10 degrees nose up without using the technique to less than 5 degrees pitch up with the technique. Pitch trim in the 747 is controlled with a thumb switch located on the control wheel yoke. Pitch trim operates a jackscrew that slowly moves the horizontal stabilizer. Just prior to the drop, nose down pitch trim was applied (this causes the stabilizer to move leading edge up). To counter the nose down moment from the stabilizer, the pilot would move the control yoke back almost to its aft stop (this causes the trailing edge of the elevator to move up). At launch vehicle release, the pilot would rapidly move the control yoke forward to its forward stop and start adding additional nose down trim.

As previously mentioned, up to a 15% increase in payload to orbit could be achieved with a launch with a flight path angle above the horizon. A zoom climb launch consisted of pushing the aircraft into a 10 degree nose low dive to pick up airspeed. At about 260 to 265 KCAS, the control yoke was moved aft to pull about 1.3 g's of nose up

acceleration. The aircraft would bottom out in the dive at 280 KCAS, the slat extension speed limit. The pilot would continue to pitch the aircraft to about 20 to 25 degrees nose up. At this point the booster would be released. Approximately 2 seconds later, the pilot would enter a left hand clearing turn. The immediate loss of the booster weight and the reduction in drag meant the 747 had plenty of excess power to continue to climb in a nose high attitude. The zoom climb launch did not need the technique of trimming nose down prior to launch.

The flying qualities of the 747 during both level and zoom climb launches required some pilot compensation to achieve the desired performance. The Cooper-Harper Handling Qualities Rating (HQR) scale shows that the t/LAD launch maneuvers rate a ranking of at least 4. A ranking of 1 means an aircraft has excellent or highly desirable flying qualities while performing a maneuver, while a ranking of 10 means the aircraft has major deficiencies and control would be lost during some portion of the flight. A HQR of 4 means desired performance requires moderate pilot compensation and the aircraft has minor but annoying deficiencies. However, the maneuver was flyable by even low-time pilots.

VII. Aft Crossing versus Forward Crossing Trajectories

While existing air-launched, captive-on-bottom vehicles use different types of carrier aircraft, each of these launch vehicles employs a forward trajectory that carries it in front of its carrier aircraft. Typically the launch vehicle will drop below the carrier aircraft and then re-cross the carrier aircraft's altitude in front of it. Vehicles such as the X-15, the *Pegasus* rocket, and *SpaceShipOne* have used this forward crossing trajectory. These vehicles use wings in order to transition from the horizontal to vertical orientation when using this forward crossing trajectory.

Using wings subjects these vehicles to large longitudinal bending stress during the 2–3 g pull-up maneuver they must do as they transition from horizontal to vertical flight. This high sideways acceleration requires a stronger and heavier booster fuselage structure. In addition to the inert weight of the wings, the added weight of control surface actuators, auxiliary power units (APUs) to power the actuators, and wing thermal protection has historically limited the propellant mass fraction of winged vehicles to no more than 63 percent – an amount insufficient to reach orbit.

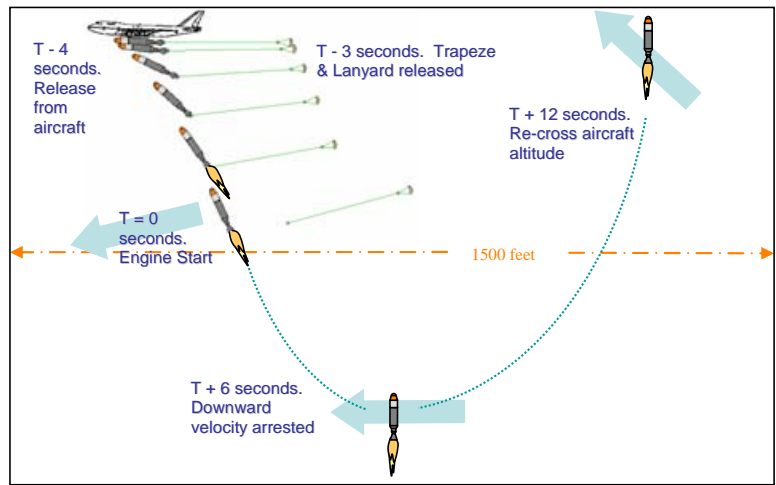


Fig. 9 Aft Crossing Trajectory

An alternate is to fly a forward crossing trajectory without wings. This requires rocket flight at large angles of attack at high dynamic pressure during the transition from horizontal to vertical flight. This imposes high loads due to the very large products of aerodynamic pressure and angle of attack and requires a stronger fuselage structure, thereby increasing the weight of the launch vehicle and offsetting the weight savings by eliminating the wings in the first place.

Another disadvantage of flying the forward crossing trajectory without wings is the need for greater peak first stage engine thrust vectoring control (TVC). The engine thrust vectoring assists in the change of orientation from horizontal to vertical of the launch vehicle, and helps to maintain stability during this orientation transition.

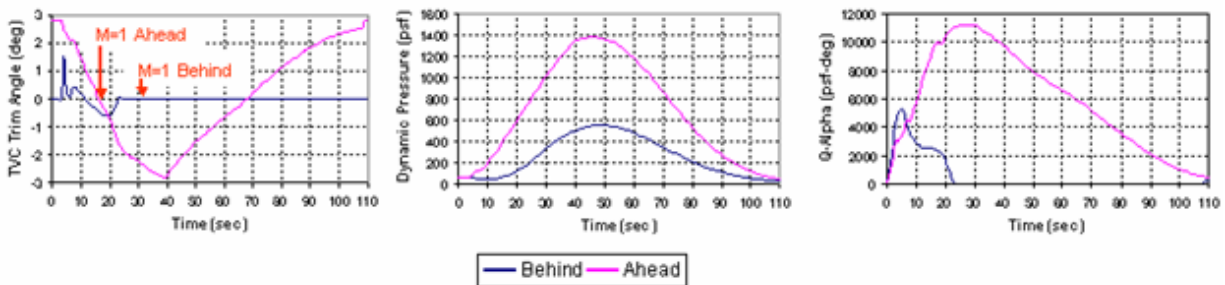


Fig. 10 Comparison of Aft Crossing (Behind) and Forward Crossing (Ahead) Trajectories

Lastly, there is the safety concern during a forward crossing air launch, though minimized through careful planning, of the possibility of falling debris from the launch vehicle hitting the carrier craft, either accidentally or as a result of the launch system's operation.

In contrast, an aft-crossing trajectory as shown in Figure 9 eliminates flying at high Angle of Attack throughout the high dynamic pressure segment of the trajectory, reduces peak aerodynamic pressure by more than 65% as compared to a forward crossing trajectory to less than 500 psf, reduces peak 1st stage engine TVC from about 6 degrees for a forward crossing trajectory to less than 1.5 degrees for an aft crossing trajectory, and completely eliminates the possibility of the carrier aircraft from being struck by debris from the rocket. In addition, the launch method we use (t/LAD) in conjunction with an aft crossing trajectory eliminates the need for heavy wings, control surface actuators, APUs, and wing thermal protection and subjects the rocket to very low (less than 0.5 G) sideways accelerations. Figure 10 compares the TVC angles, dynamic pressure (Q), and the product of Q and angle of attack.

VIII. The t/LAD Launch Method

We have invented and successfully flight tested a new method of air launching called Trapeze Lanyard Air Drop (t/LAD). t/LAD causes a rocket to transition from a horizontal orientation under the carrier aircraft to a substantially vertical orientation behind and below the carrier aircraft. Reference 5 describes the series of three flight tests over Mojave, CA in June 2005 using Scaled Composites Proteus aircraft. A scaled mockup of the rocket was dropped using t/LAD and the tests proved the viability of this new method for air-launching spacecraft.

The t/LAD components are shown in Figure 11. A trapeze controls the motion of the launch vehicle as it falls away from the carrier aircraft. The arrangement of the trapeze ensures that the launch vehicle cannot impact the carrier aircraft as it clears the near-field aerodynamic effects of the carrier aircraft. It also nulls out any launch vehicle yaw or roll motions at separation release from the carrier aircraft.

A flexible line or lanyard with one end attached to a braking mechanism mounted on the carrier aircraft and the other end connected to the launch vehicle causes the rocket to rotate. The brake has a spool about which the lanyard is wound. As the launch vehicle falls clear of the trapeze, the lanyard unwinds from the brake spool under a preselected tension. The tension causes the launch vehicle to rotate nose up. The rate of rotation can be adjusted by setting either the length of the lanyard or the amount of the brake tension. At the desired rotation rate (approximately 5 rpm) the lanyard separates from both the rocket and the carrier aircraft.

A drogue parachute stabilizes the launch vehicle in yaw and roll as it drops down and rearward. A Y bridle attachment with the parachute risers attached to the outer edges of the engine nozzles at the 9:00 and 3:00 o'clock positions provided the best combination of yaw and roll stability. The load from the parachute is small, less than 10% of the engine thrust.

The drogue chute also progressively reduces the rate of rotation and when the launch vehicle nears its maximum vertical attitude, the rotation stops for a moment and at that moment ($T = 0$ seconds) the vehicle's rocket engines are ignited, burning through the chute riser lines and releasing the drogue chute. This method of chute release is not only simple, but improves overall system reliability and eliminates pyrotechnic cutters. Ignition occurs when the vehicle is about 240 feet from the aircraft, but with the vehicle descending at 100 feet per second down and 50 feet per second aft relative to the aircraft.

The engine then comes up to full thrust. Because of the relatively low thrust to weight (compared to most air launched missiles) of its engines, the vehicle takes another 500 feet of altitude to arrest its descent at $T + 6$ seconds, about 750 feet below the carrier aircraft. At $T + 12$ seconds the launch vehicle crosses the altitude of the carrier aircraft behind and separated from carrier aircraft by more than 1000 feet. Four seconds later the launch vehicle transitions to a standard gravity turn trajectory to low-earth orbit. The horizontal velocity vector is about 600 feet per second when the launch vehicle is dropped from the carrier aircraft and this velocity allows greater payload to orbit. The launch vehicle retains a substantial portion of the aircraft's velocity with the t/LAD launch method.

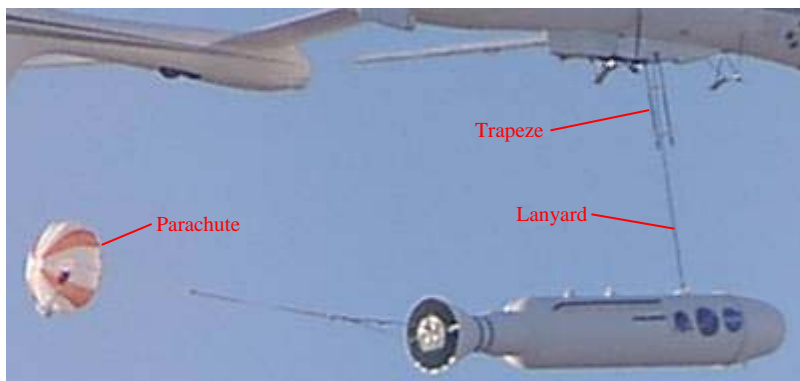


Fig. 11 t/LAD System Components

IX. Conclusions

A thorough evaluation was completed of many different methods of air launching an earth-to-orbit booster and of carrier aircraft types. We have determined that a Boeing 747-200 could be modified for a Trapeze-Lanyard Air Drop (t/LAD) launch for about \$15 million using the structural modifications demonstrated in the 10 Air Tanker aircraft. Simulation in the NASA Ames 747 flight simulator shows that such a carrier aircraft should be capable of launching a 207,000 pound booster at altitudes above 30,000 feet at flight path angles above 20 degrees and at approximately Mach 0.6. A t/LAD launch eliminates the need for wings or fins on the rocket; greatly reduces ascent dynamic pressure, sideways accelerations, and rocket engine thrust vectoring control; and allows the use of a simple and very safe vapor pressurization (Vapak) engine cycle for the launch vehicle. A Vapak booster launched using t/LAD from a modified 747 carrier aircraft promises to improve the simplicity, safety, cost, and reliability of launching personnel and cargo into low earth orbit (LEO).

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Tom Brosz was the artist for Figure 7 and Mark Maxwell was responsible for the 1st page illustration and the rocket insert illustration in Figure 7.

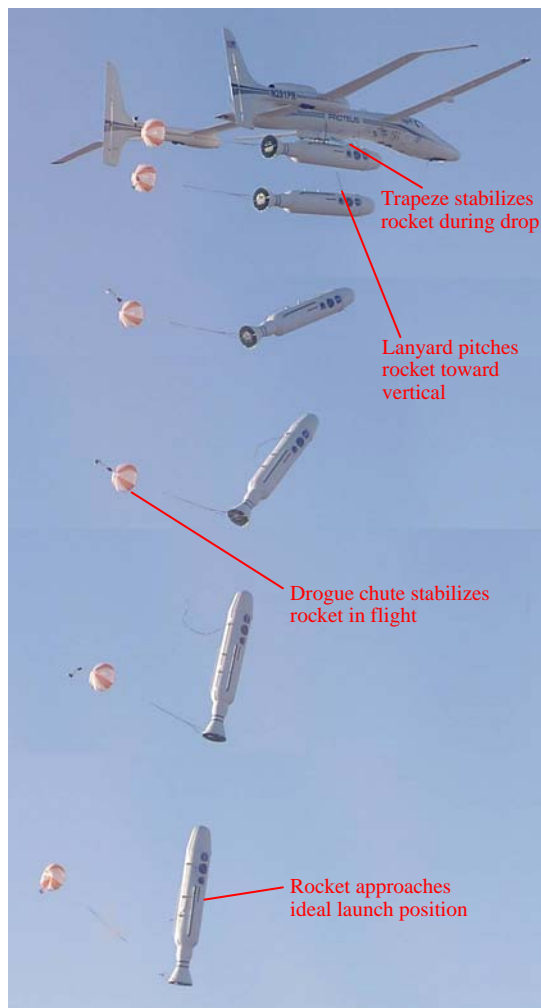


Fig. 12 t/LAD Launch

XI. References

1. National Research Council, "From Earth to Orbit, an Assessment of Transportation Options," National Academy Press, 1992.
2. Sarigul-Klijn, N., Sarigul-Klijn, M., and Noel, C., "Air-Launching Earth-to-Orbit: Effects of Launch Conditions and Vehicle Parameters," AIAA Journal of Spacecraft and Rockets, Vol. 42, No. 3, 2005.
3. Sarigul-Klijn, N., Sarigul-Klijn, M., and Noel, C., "Air Launching Earth-to-Orbit Vehicles: Delta V gains from Launch Conditions and Vehicle Aerodynamics," (AIAA 2004-872), 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2004.
4. Sarigul-Klijn, M., Sarigul-Klijn, N., Hudson, G.C., Holder, L., Fritz, D. Webber, C. Liesman, G., Shell, D., and Gionfriddo, M., "Flight Testing of a Gravity Air Launch Method to Enable Responsive Space Access," (AIAA 2007-6146), AIAA Space 2007, Long Beach, CA, 2007.
5. Sarigul-Klijn, M., Sarigul-Klijn, N., Morgan, B., Tighe, J., Leon, A., Hudson, G., McKinney, B., and Gump, D., "Flight Testing of a New Earth-to-Orbit Air-Launch Method," AIAA Journal of Aircraft, Vol. 43, No.3, 2006.