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# Design Forum

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# Flight Testing of a New Earth-to-Orbit Air-Launch Method

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**This paper describes the development and flight testing of a new air-launch method for safely launching personnel and cargo into low Earth orbit (LEO). A new rocket is also being designed that will be carried by and launched using the new air-launch method from a modified 747 airliner. This new air-launch method, called trapeze-lanyard air drop (t/LAD) launch, will greatly improve simplicity, safety, cost, and reliability of launching personnel into LEO. A t/LAD launch eliminates the need for wings or fins on the launch vehicle; greatly reduces ascent dynamic pressure, sideways accelerations and bending forces, 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. This paper reports on the flight-test results of dropping three 23%-scale drop test articles using the t/LAD launch method.**

## Introduction

WITH NASA's plans to retire human-rated space shuttle around 2010, a highly responsive, safe and reliable replacement is needed. Under NASA funding, a preliminary concept study and demonstration flight testing has been conducted.

The launch vehicle under design would be launched from a carrier aircraft, either from a specially modified 747 airliner or from a custom aircraft to be built.

Typically during an air launch, a launch vehicle will drop below the carrier aircraft and then recross the aircraft's altitude in front of it. Vehicles such as the X-15, the Pegasus rocket, and most recently, SpaceShipOne have used this forward-crossing trajectory. t/Space has baselined a unique trajectory that crosses behind the carrier aircraft. This aft-crossing trajectory has several benefits (which are described later) as compared to a forward-crossing trajectory.

Air launching means that the low outside atmospheric pressure at altitude (25,000 ft 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 *Isp* 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 psi, and the engines can run at a maximum pressure of 150 psi.

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 of propellant feed was successfully used in SpaceShipOne. Vapak eliminates costly and dangerous components such turbopumps and gas generators used in a typical pump-fed launch vehicle. According to the National Research Council,[1] 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). It also eliminates the high-pressure gas storage vessels and pressure regulators or heated gas systems (Tridyne) normally associated with pressure-fed rockets. There have been no catastrophic failures of operational pressure-fed engines, including over 50,000 AGM-12 Bullpup liquid-fueled air-to-surface missiles. Both t/Space engine stages use a single coaxial pintle injector, resulting in only one moving part per stage aside from the propellant tank fill valves.

Flight demonstrations that proved and demonstrated a key technology for the new approach to low-cost access to low Earth orbit (LEO) was conducted during May and June of 2005. This paper reports on the results of the flight tests of that technology, which is called trapeze-lanyard air drop (t/LAD) launch (Fig. 1). The t/LAD launch concept was conceived on 29 December 2004, and the first 23%-scale flight test occurred only 135 days ($4\frac{1}{2}$ months) later. Three test drops were completed over a period of three weeks, and this paper was completed within two days of the last test drop.

## Air-Launch Advantages

The actual t/Space booster will be a three-stage liquid fuel rocket. As already mentioned, air launching greatly simplifies the design

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of the booster, which simultaneously reduces costs, improves reliability, and greatly improves safety. The modest performance gain of launching at 25,000 to 35,000 ft, approximately 1100 fps to 1800 fps delta V improvement—depending on carrier aircraft flight-path angle at launch—also makes it easier for a three-stage rocket to put payloads into orbit.[2,3]

Air launching simplifies operations compared to ground launch from a fixed range in several ways: no coordination is required with other users of the range, weather constraints are avoided by flying to open sky, and there are fewer delays waiting for specific launch windows (to match desired orbits) because the vehicle can be flown to an alternate launch point that is better aligned with the desired orbit. In addition, ground launches must be postponed whenever ships enter the ocean zones near the coastal launch sites or where rocket stages are expected to drop; the carrier aircraft can avoid such delays by flying to a different release point. Crew safety is enhanced because abort-at-ignition is easier because the capsule is already high enough for parachute deployment vs the on-the-pad challenge of releasing sufficient energy in the correct direction to send the capsule high enough for the parachutes to deploy. Public safety is enhanced because the launch takes place over the open ocean, far away from any populated areas.

## Aft-Crossing vs Forward-Crossing Trajectories

t/Space has baselined an aft-crossing trajectory that has several advantages as compared to the typical forward-crossing air-launch trajectory:

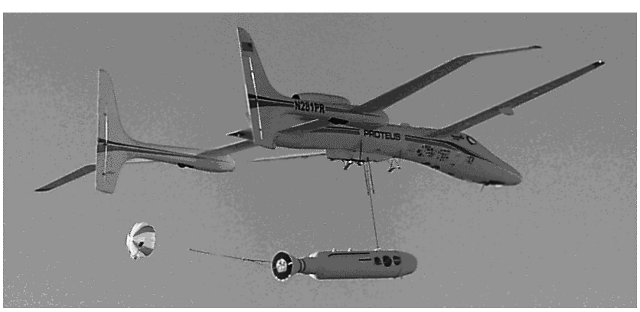



**Fig. 1 Flight testing of t/LAD air-launch method.**

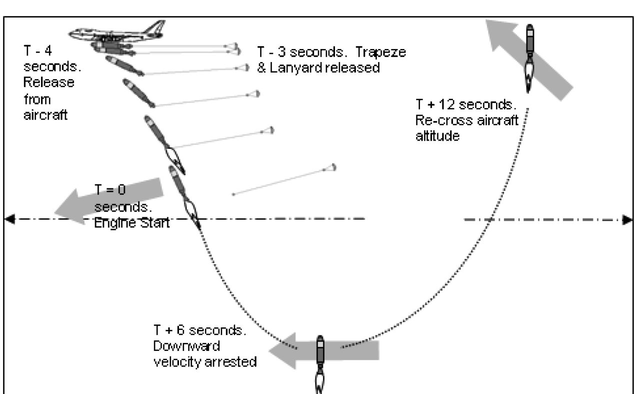



**Fig. 2 Aft-crossing trajectory.**

1) The first is no requirement for wings or fins similar to those used on the X-15, X-34, Pegasus, or SpaceShipOne. Other heavy systems such as control surface actuators, auxiliary power units, and wing and fin thermal protection are also eliminated.

2) Low sideways accelerations during the t/LAD maneuver is the second advantage. The X-15, X-34, Pegasus, and SpaceShipOne were subjected to large amounts of longitudinal bending during a 2-to 3-$g$ pull-up maneuver as they transitioned from horizontal to vertical flight. Note none of these vehicles could carry more than 63% of their gross weight as propellant—an amount insufficient to reach orbit—caused in part by a fuselage structure strong enough (and hence heavier) to take the sideways accelerations imposed by a forward-crossing trajectory.

3) There is no possibility of the carrier aircraft being struck by debris from the rocket. The rocket passes more than 1500 ft behind the carrier aircraft if the aircraft executes a clearing turn after the drop (clearing turn not shown in Fig. 2).

4) The next advantage is a reduction in peak first-stage engine thrust vectoring control (TVC) from about six deg for the forward-crossing trajectory to less than 1.5 deg for the aft-crossing trajectory.

5) The peak dynamic pressure $Q$ is cut by more than 65% from 1400 psf—such as experienced by Orbital's Pegasus air-launched rocket—to less than 500 psf. Trajectories with peak $Q$ less than 350 psf are possible from a high-flying custom aircraft (see Fig. 3).

6) Elimination of flying at high angle of attack (alpha) throughout the high-dynamic-pressure segment of the trajectory is another advantage. For the aft-crossing trajectory all maneuvering occurs under Mach 0.65. Forward-crossing trajectories (for rockets without wings on them) require flight at large values of alpha resulting in very large products of dynamic pressure $Q$ and alpha. Large $Q \cdot$ alpha increases the weight of a rocket's structure, which in turn can reduce the payload to orbit. Aft-crossing trajectories involve flight with normal values of alpha (less than one deg) when supersonic.

7) A payload increase to orbit as compared to a forward-crossing trajectory is the last advantage. Gains in payload are caused by the reduction in delta V steering losses caused by lowering first-stage TVC and the reduction in structural mass caused by lowering $Q \cdot$ alpha, dynamic pressure $Q$. One of the main contributors that allowed SpaceShipOne to be built at 20% of the weight of the X-15 and beat the X-15's altitude record, yet be capable of carrying three people instead of one, was a trajectory that had a very low peak dynamic pressure.

## Description of t/LAD Launch Method

We have invented a launch method called trapeze-lanyard air drop (t/LAD) that properly orients a rocket for an aft-crossing trajectory (see Fig. 2). As the rocket falls clear, a lanyard attached between the launch vehicle and the trapeze reels out while applying a pitch-up force on the rocket. The rocket then begins to rotate about its center of gravity because of the action of the lanyard. The lanyard pulls free of a lanyard brake mounted on the bottom of the carrier aircraft once the required amount of pitch rate is achieved. As the launch vehicle falls from the aircraft, it continues to rotate but with its pitch angle and pitch rate ameliorated by the action of a drogue parachute that is attached to its nozzle. The drogue chute also stabilizes the rocket in yaw. As the drogue chute stops the launch-vehicle's pitch

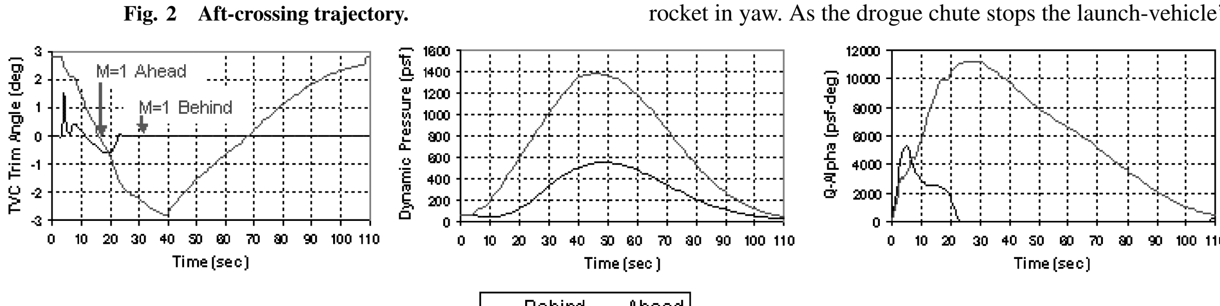



**Fig. 3 Comparison of aft-crossing (behind) and forward-crossing (ahead) trajectories.**

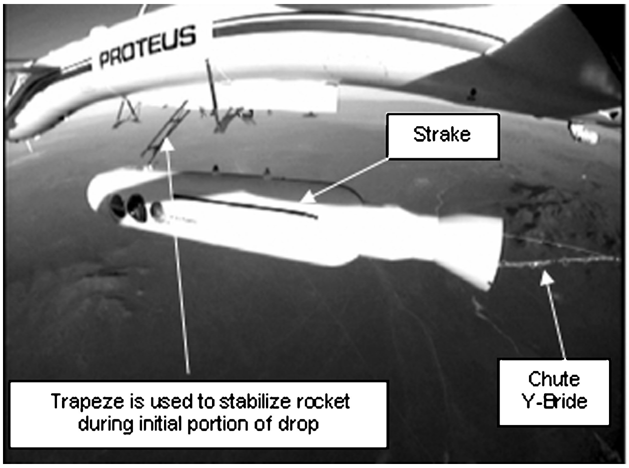



**Fig. 4a Trapeze is used to stabilize rocket during initial portion of drop.**

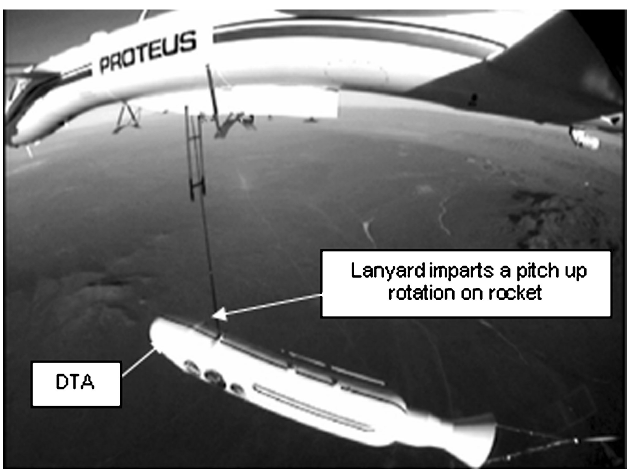



**Fig. 4b Lanyard imparts a pitch up rotation on rocket.**

rate, the rocket's nose points toward the vertical, placing it in the proper orientation for an aft-crossing trajectory. At this point, the chute risers are burned away by engine start. The launch vehicle then continues downward for another 6 s as the engine's thrust arrests the downward velocity. Twelve seconds after engine start (and 16 s after release), the launch vehicle recrosses the carrier aircraft's altitude. At this point, the launch vehicle transitions to a standard gravity-turn-type trajectory to LEO.

The t/LAD system consists of three main components: a trapeze, a lanyard, and an orientation parachute. The trapeze initially stabilizes and gently guides the launch vehicle away from the aircraft by imparting a slight nose-down pitch rate to ensure that the launch vehicle clears the near-field aerodynamics effects of the carrier aircraft (Fig. 4a). It replaces the normal ejector foot found on conventional bomb racks. An ejector foot uses a pyrotechnic charge to push a bomb away from an aircraft, and they tend to impart a large shock on both the aircraft and the bomb, and the foot tends to destabilize the bomb. The trapeze also nulls out any rocket yaw or roll motions at separation release from the carrier aircraft. It allows routing the lanyard from forward part of the booster to a lanyard brake system located near the aircraft's center of gravity. The trapeze prevents any slack from developing in the lanyard during the first part of the drop.

The lanyard's main function is to impart a pitch-up rotation to the rocket. It is routed around the trapeze so that the lanyard can be attached near the aircraft's center of gravity (Fig. 4b). This routing means that lanyard tension does not impart any nose-down moments on the aircraft as the lanyard reels out. A secondary function of the lanyard is to help stabilize the rocket in yaw and roll as the lanyard reels out. The length of the lanyard and the tension on the lanyard depends on the length of the fall time desired prior to rocket engine start. Fall time is determined by safety considerations—the distance desired between the carrier aircraft and the rocket at rocket engine start. For example, if a short time of fall is desired then the rocket needs to rotate quickly from the horizontal to the vertical. This can be accomplished by putting a large amount of tension in the lanyard. A lanyard brake installed in the aircraft pylon applies tension to the lanyard as it reels out. Alternately, the tension can remain unchanged, but the lanyard can simply be made longer. In contrast if a long fall time is desired, then the lanyard tension should be low or the lanyard length should be short, or a combination of short length and low tension can be used.

The orientation parachute is attached directly to the engine nozzle at two points with a Y-bridle. The chute, in conjunction with the Y-bridle, stabilizes the rocket in yaw and roll. The chute is sized so that its aerodynamic drag slows and stops the rocket's pitch-up rotation by the time the booster is pointing vertically.

Strakes on the booster help prevent the rocket from rolling. In the real rocket, they also serve as the propane downcomers to the first-stage engine.

## Flight-Test Hardware

For the flight demonstration, a subscale boilerplate booster test article, known as the drop test article or DTA, was dropped from Scaled Composites' Proteus aircraft. The Proteus is multipurpose manned aircraft and is powered by two Williams FJ44-2E turbofan engines. The aircraft is of canard configuration and is 56.3 ft long and has a wingspan of 77.6 ft. Its gross weight is 12,500 lb, and it can carry a payload of 2200 lb to 55,000 ft mean sea-level (MSL) altitude.

The DTA is a 23%-scale model of the t/Space booster. The DTA is 250 inc. long (20.83 ft), 37.4 in. in diameter, and weighs 2018 lb. It has a steel cylindrical body with a fiberglass nozzle and nose structure. The DTA is equipped with a data-acquisition system (DAS) and a telemetry (TM) system to transmit positional pitch, yaw, and roll attitude, rate, and acceleration data to both the Proteus aircraft and to a chase aircraft. The DAS uses an inexpensive Cloudcap Crista inertia measuring unit (IMU), while the TM system is based on a Freewave wireless 900-MHZ spread spectrum transceiver (Wi-Fi). The DTA's IMU is updated with corrections from the Proteus's onboard combination global positioning system (GPS) and IMU just prior to the drop.

The DTA is attached to the Proteus via a modified F-4 Phantom fighter bomb rack that is installed in the Proteus's centerline pylon fairing (Fig. 5). Instead of using pyrotechnic carriages to release the bomb rack hooks, a pneumatic air source is used. Also the ejector foot was capped off so that its function was inhibited.

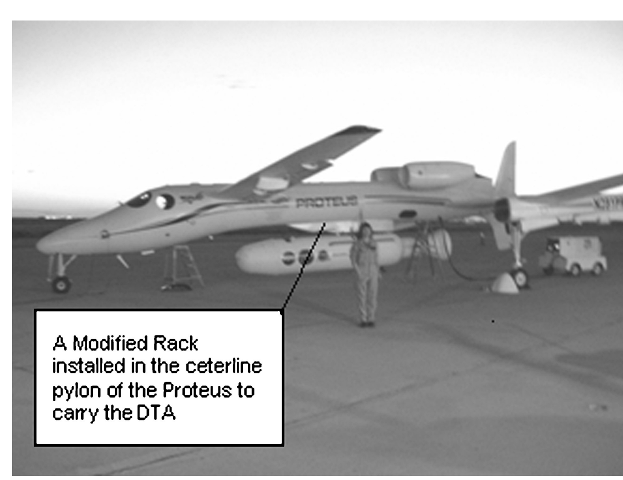



**Fig. 5 Booster Test Article attached to Proteus aircraft via a rack installed in the centerline pylon fairing prior to flight.**

The lanyard strap is an off-the-shelf flat polyethylene strap with a breaking strength of 600 lb. The lanyard is designed to break in the event the lanyard brake jams and the strap acts as a mechanical fuse to prevent damage to the Proteus. The lanyard is wound around a modified off-the-shelf motorcycle brake assembly installed in the Proteus centerline pylon. The brake can be adjusted to apply a 200- to 350-lbf tension in the strap, and the length of the strap can be varied from 6 to 20 ft long.

The orientation parachute is a readily available 6-ft-diam modified rib-less guide surface chute with 12 canopy gores and liners, and it generates approximately 350 lbf of drag at the test conditions. It is the same chute used on the Virgin Atlantic Global Flyer. Normally reefing the chute can vary the drag of a parachute. Reefing involves restraining a parachute from fully opening by placing a line around the canopy. Unfortunately a guide surface chute cannot be reefed. The parachute forces from this off-the-shelf parachute were higher than desired for the demonstration. To compensate, the lanyard tension and length were set to achieve a relatively high pitch rate, which in turn results in a short time (about 2.6 s) between DTA release from the Proteus and release of the parachute.

The chute was released by an electrical release device that was signaled by a computer program resident in the DAS. The chute was set to release when the DTA's pitch rate was zero during the transition from positive pitch rate to negative pitch rate. This is also the point of maximum pitch-up attitude.

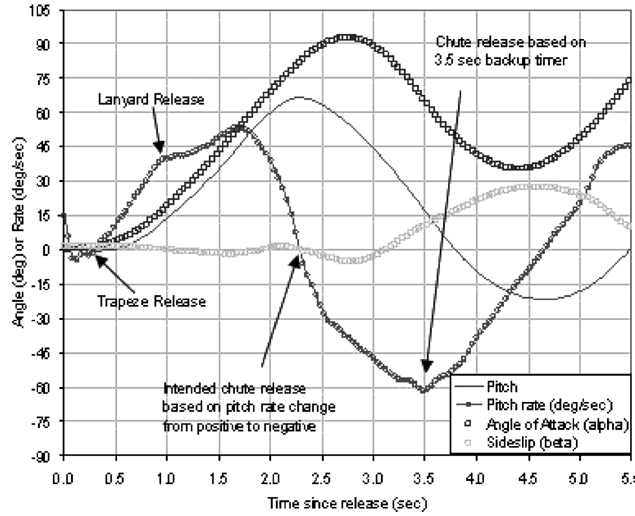



**Fig. 6 First drop test results.**

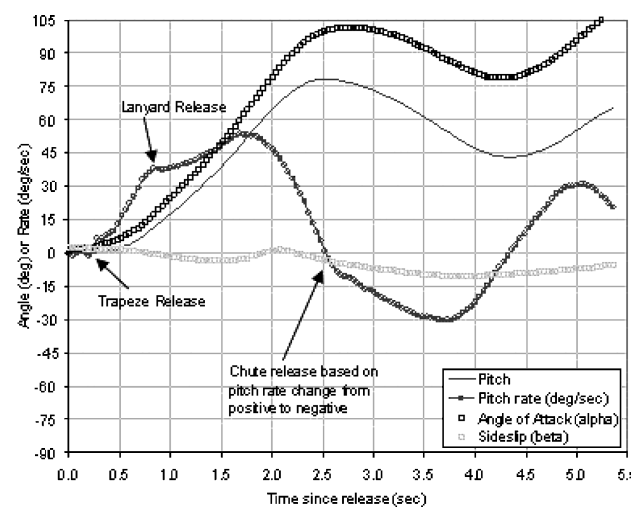



**Fig. 7 Second drop test results.**

## Scope of Flight Tests

A series of three drops and a captive carry test were completed. The captive carry test occurred on 13 May 2005 and was used to evaluate the carriage characteristics of the DTA on the Proteus aircraft, practice the procedures used during a drop, test the parachute deployment and jettison, and test the DAS and TM systems. Everything worked as expected.

The first DTA drop occurred in level flight at a true airspeed of 120 nautical miles an hour (KTAS) at 12,000 feet above MSL on the morning of 24 May 2005.

A second drop occurred in level flight at 110 KTAS airspeed and at 7000 ft MSL altitude on 7 June 2005.

A third and final drop differed from the first two in that the release flight-path angle (gamma) was 20 deg above the horizon. The drop occurred at 110 KTAS at 7000 ft MSL on 14 June 2005. Trajectory studies have shown using a zoom climb launch with the real rocket increases the mass inserted into orbit by 15%. However the rocket can be expected to cross closer behind the carrier aircraft.

## Flight-Test Objectives

The data from the tests were used to validate drop simulations, validate the trapeze and lanyard release method, confirm that the DTA rotates mostly in pitch without much yaw or roll instability, determine when to light the actual booster and sever the chute, evaluate the postignition descent stability of the booster, and confirm a clean separation of the booster and launch aircraft.

## Flight-Test Results and Discussion

The appendix presents a series of photos that show the drop sequence. Figure 6 presents the results from the first drop test. The DTA pitched up to a maximum pitch angle of 66 deg relative to the horizon at 2.3 s after release. Angle of attack (alpha) was 82 deg at this point. Angle of attack is the angle between the centerline of the rocket and the relative wind. The DTA exhibited very little sideslip (less than two deg beta) during the pitch-up maneuver. This was a pleasant surprise given that the DTA's mass moment of inertia is more than 1800 times smaller than the real booster. Mass moment of inertia is a measure of a body's resistance to rotation when subject to a moment or torque. It is easier to rotate an object that has a small mass moment of inertia. Hence the DTA should be very susceptible to yaw disturbances, whereas the actual rocket should not be.

At 2.3 s after drop, the DAS chute release algorithm should have released the parachute as the pitch rate transitioned through zero from a positive nose-up pitch rate to a negative nose-down pitch rate. A sign convention error in the chute release algorithm resulted in a backup time-out release at time step 3.5 s instead of a pitch rate release at 2.3 s after the drop. The chute released after the DTA had developed a 62 deg/s nose-down pitch rate instead of the desired 0-deg/s pitch rate.

Figure 7 presents the results from the second drop test. The DTA pitched up a bit higher to a maximum pitch angle of 78 deg relative to the horizon at 2.6 s after release. Angle of attack (alpha) was 100 deg at this point. Again the DTA exhibited very little sideslip (less than four deg) during the pitch-up maneuver. The DAS chute release algorithm properly released the parachute as the pitch rate transitioned through zero. The DTA's nose remained pitch up above the horizon with very little sideslip for the next 3 s. Notice that the DTA has a stable trim point at about 90 deg alpha because when alpha was greater than 90 deg (at about time step 2.8 s) the nose pitched nose down, and when alpha was less than 90 deg (at about time step 4.3 s) the nose pitched up.

Figure 8 presents the results of the third DTA drop. The third DTA was dropped from the Proteus while the Proteus was in a 20-deg climb. This drop was used to examine the issues of using a zoom climb. For the real rocket, the carrier aircraft would fly a parabolic roller coaster maneuver similar to that used to achieve weightless flight for astronaut training. The aircraft would first climb to its maximum altitude. Next the plane would be pushed over to about 10 deg nose low to increase its speed. The plane would then be

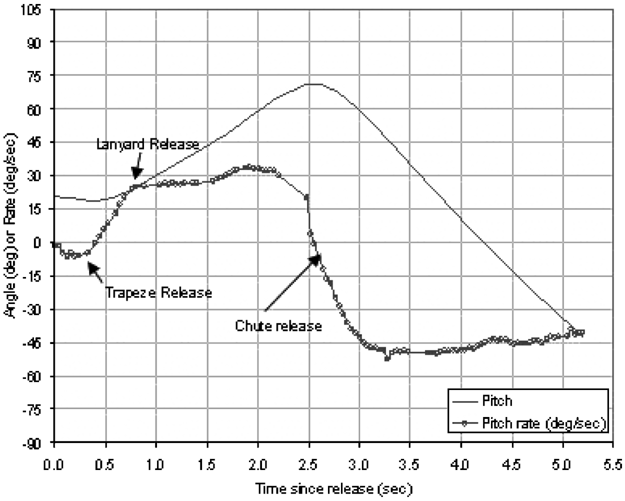



**Fig. 8 Third drop test results.**

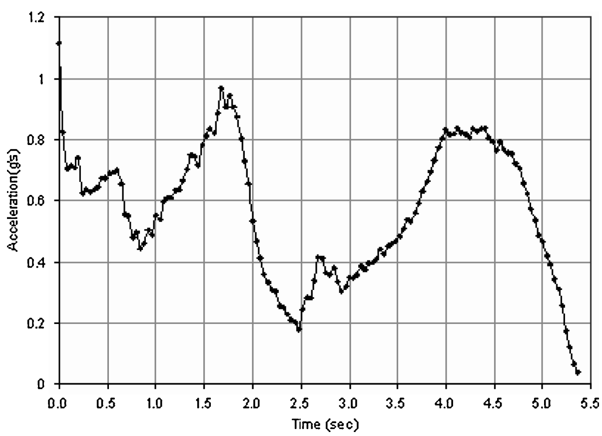



**Fig. 9 DTA acceleration during second drop.**

smoothly pulled up at about 1.8 $g$. At the bottom of the pull out, the aircraft would be about 3000 ft below its initial altitude. The pull up is then continued until the nose is about 25 deg above the horizon at which point the rocket is released. The advantage of this maneuver is that it increases payload mass to orbit by about 15% (see Refs. 2 or 3). Proteus aircraft airspeed limitations prevented it from duplicating the real maneuver.

Angle of attack (alpha) and sideslip (beta) data are not presented in Fig. 8 because the data had unreliable heading estimates from the Proteus, which did not correlate with the GPS ground track, and so we were unable to calculate a good estimate for the initial wind vector. Because the DTA did not have a pitot static system, accurate wind at release is needed to compute alpha and beta from the DTA's IMU data. Also pitch up was much less than expected. The lanyard broke after only 4.5 ft of runout. As already mentioned, the lanyard strength was only 600 lbf to protect the Proteus from structural overloads.

Figure 9 shows that the acceleration during a t/LAD launch will be significantly less than that experienced using wings because there is no aerodynamic pull-up maneuver. If these were data from a real launch, then axial acceleration would increase to 3 or more $g$ when the rocket lights.

These drops confirmed that the DTA rotated mostly in pitch without much yaw or roll instability during the pitch-up maneuver toward the vertical. The DTA drops also validated the trapeze and lanyard release method, t/LAD. The DTA demonstrated a clean separation from the Proteus with no tendency to recontact the carrier aircraft.

The drops validated the numerical drop simulations. A three-degrees of freedom (DOF) simulation was completed using the program Working Model 2D and a six-DOF simulation was completed using Visual NASTRAN 4D. Aerodynamics was modeled with Missile DATCOM and with the computational fluid dynamics (CFD) program FLUENT. CFD showed that the strakes helped move the DTA's center of pressure so that there was a stable trim point at about 90-deg angle of attack. An example of the CFD results is shown as Fig. 10, and an example of the six-DOF simulation is shown in Fig. 11.

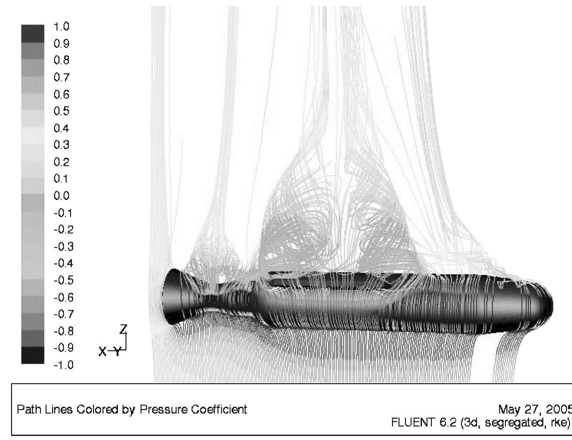



**Fig. 10 CFD results at 90 degrees angle of attack.**

## Scaling Issues

There were several scaling issues with the 23%-scale DTA. As mentioned earlier, the DTA's mass moment of inertia was more than 1800 times smaller than the actual booster. Very small moments or torques can easily turn the DTA.

Also the ballistic coefficient (BC) was only 13% of the actual t/space booster. BC is the ratio of the mass of an object divided by its drag area. A low BC means that the DTA is much more susceptible to aerodynamic effects as compared to the real booster. A low BC also means that the sideways accelerations experienced by the DTA are much higher than the sideways accelerations the real rocket would experience. In any event, sideways accelerations imposed on the DTA by the t/LAD maneuver were very small anyway (see Fig. 9).

The Reynolds number $Re$ for the DTA is about 15% of the actual booster. The Reynolds number is a dimensionless ratio that portrays the relative magnitude of dynamic forces and viscous forces, and it increases with an object's size and velocity, but decrease with altitude. When the Reynolds number is low, viscous or friction forces predominate; when the Reynolds number is high, dynamic and inertia forces predominate. The DTA's Reynolds number was low, so that again it should be more susceptible to aerodynamic effects as compared to a full-scale rocket.

The combination of low mass moment of inertia, low ballistic coefficient, and low Reynolds number meant that the DTA is like throwing a light piece of balsa wood or foam out the window of a speeding car, whereas the real booster is like throwing a brick. The bottom line is that if t/LAD dynamics are okay for the DTA, then the same pitch-up dynamics will work even better for the full-scale booster.

Another scaling factor was the low launch speed of the Proteus carrier aircraft. True airspeed at drop was less than 200 fps, compared to about 600 fps for a modified 747 carrier aircraft. After 2.6 s the DTA's flight-path vector is almost 25 deg below the horizon for a Proteus launch [arcsin (32.2 ft/s$^2$ $\times$ 2.6 s/200 fps)]. Maximum pitch-up angle at chute release should be limited so that angle of attack (alpha) does not excessively exceed 90 deg; otherwise, the parachute will destabilize the booster. Thus for a level Proteus launch the maximum DTA pitch up should be limited to less than 65 deg above the horizon. For the full-scale booster—even with a longer time of fall to provide greater clearance from the carrier aircraft—the pitch angle can be up to 80 deg. Of course, launching during a carrier aircraft zoom climb allows the rocket's pitch angle to be

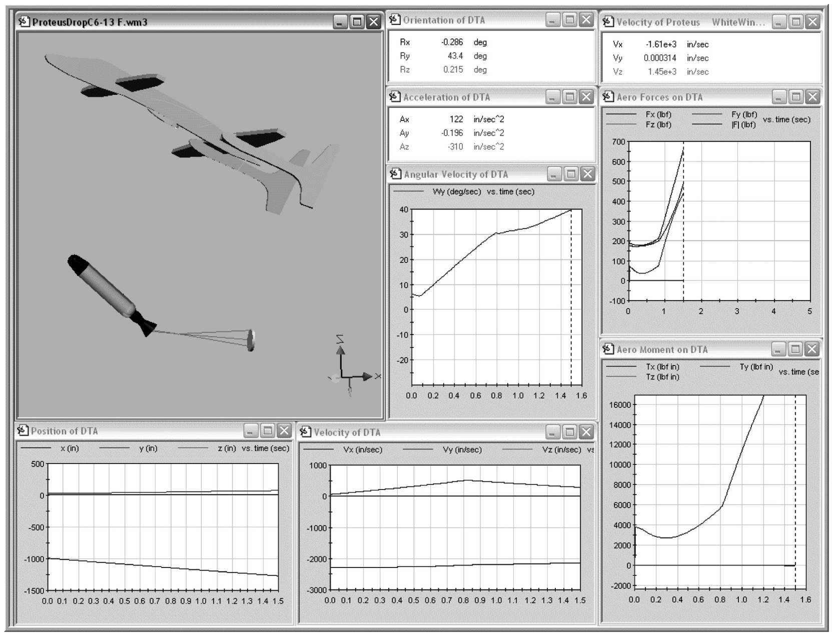



**Fig. 11 Six-DOF simulation of a t/LAD launch.**

increased to the pure vertical without fear that the booster's angle of attack will exceed 90 deg.

As mentioned earlier, the parachute force could not be adjusted during this test demonstration. To compensate for the higher-than-needed parachute force, the lanyard tension was set relatively high to establish an initial pitch-up rate of about 40 deg per second. The separation between the Proteus and the DTA was 110 ft as the DTA reached its peak pitch attitude (and simulated booster engine start point). The DTA's pitch-up rate is greater than what is desired for a full-scale booster because more separation between the booster and carrier aircraft would be wanted at engine start.

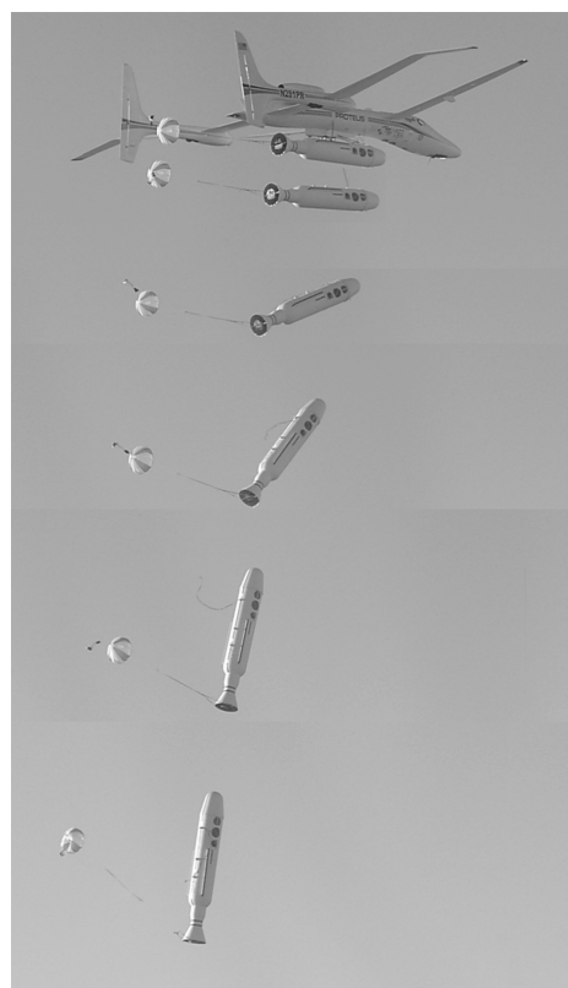
Both the trapeze and the lanyard had scaling issues. The trapeze disengages from the rocket after about 30 to 40 deg of trapeze rotation. For the 23%-scale DTA, this occurs after about 2 ft of separation from the Proteus at a downward velocity of about 10 fps relative to the Proteus. For the full-scale booster, the trapeze would disengage after about 8 ft of fall at about 20-fps downward relative velocity. Hence the trapeze would provide greater stabilization to the full-scale booster.

The 23%-scale DTA's lanyard was wound around an off-the-shelf motorcycle brake. Consistent braking occurred at a relatively high force of 200 to 350 lbf with this off-the-shelf unit. To get the desired DTA pitch-up rate, the lanyard length had to be limited to between 6 to 11 ft. For the full-scale rocket, a much longer lanyard would be used—in the order of 50 to 100 ft—to minimize the size of the lanyard brake. The longer lanyard would provide greater yaw and roll stabilization to the full-scale CXV booster.

## Conclusions

Despite the scaling issues just discussed, the t/Space Drop Test Article (DTA) flight-test program shows that trapeze-lanyard air drop launch method works as intended. This launch method promises to contribute to improving the simplicity, safety, cost, and reliability of launching personnel and cargo into low Earth orbit. 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. The next step to further develop the t/LAD launch method would be to drop full-scale (>200,000 lb) DTA's ballasted with water from either a modified 747 aircraft.

## Appendix: t/LAD Drop Sequence



Dale Shell

**Fig. A1 Sequence of images from second DTA drop. Proteus is in level flight. Images are taken 0.533 s apart.**

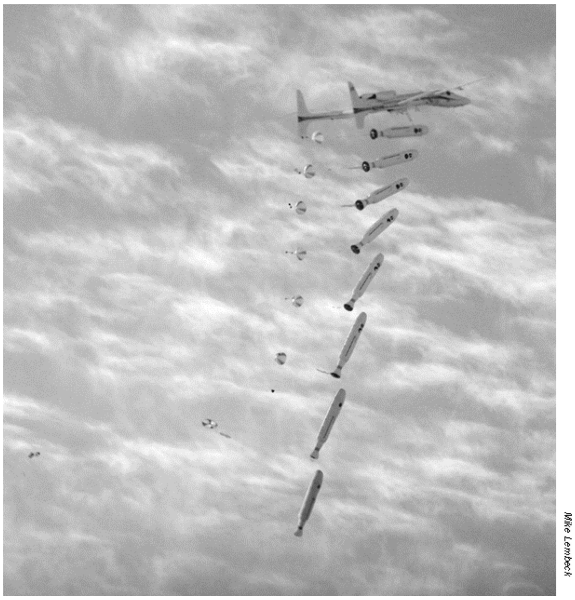



**Fig. A2 Sequence of images from third DTA drop. Proteus is in a 20-deg climb. Images are taken 0.333 s apart.**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