Air-Launch to Orbit

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This report details the current state of air-launch to orbit vehicles and what their capabilities are. It also touches on new systems and what development the future holds in this field. The air-launch to orbit market is primed to become the premier method of placing small satellites into orbit in a quick and cheap manner. The veritable explosion of cubesat and nanosat technology in the last decade will propel this niche market to the forefront of space launch systems.

Nomenclature

I_{sp} = specific impulse
USD = united states dollars
ΔV = delta velocity

I. Introduction

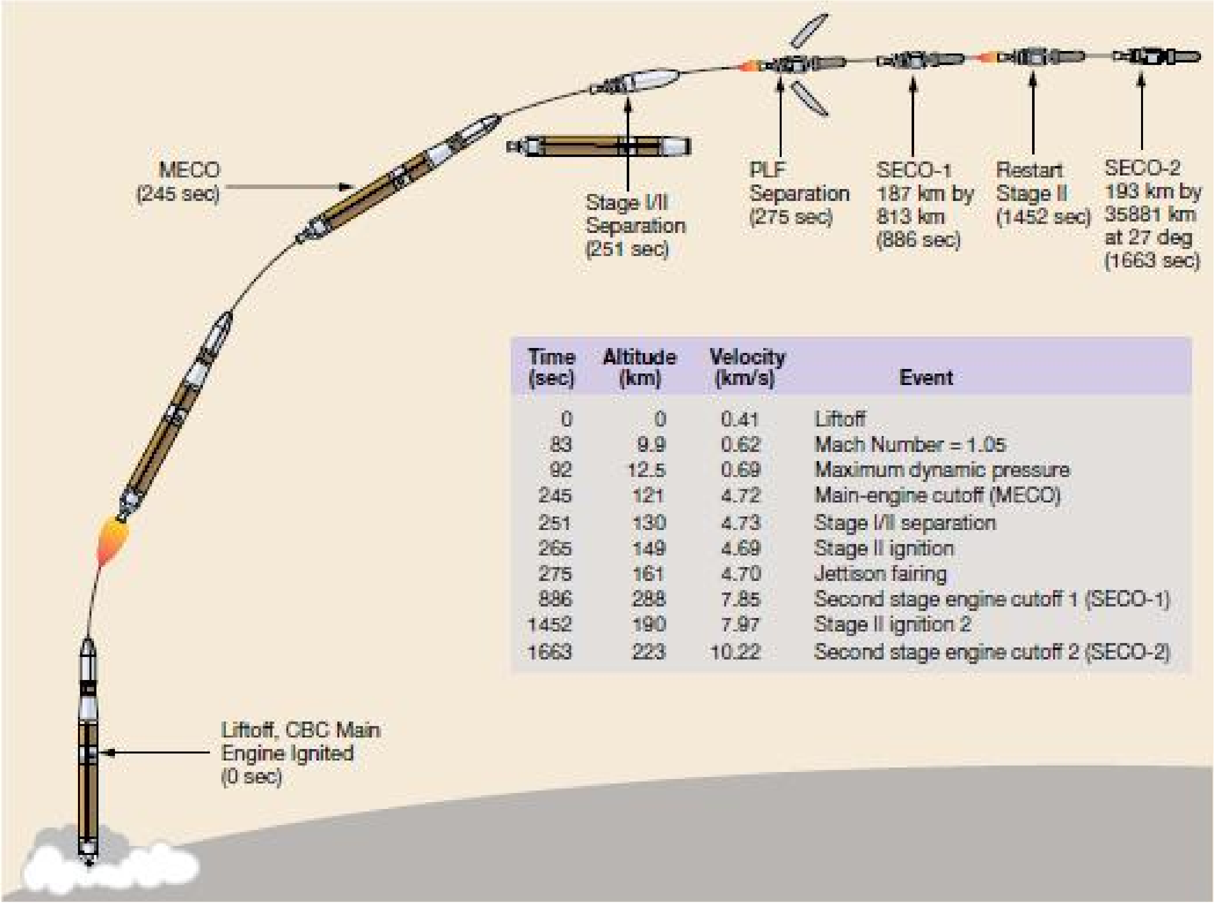
THE cost to launch satellites into space has become exorbitant over the years. While the shuttle program was developed with the idea that a launch each week and reusable boosters would drop the overall cost, this never materialized. Instead, the government watched while prices skyrocketed and as funding became scarce due to economic downturn, so did the launches. By the end of the shuttle program, the US government was shelling out an estimated $400M USD[1]. While, the return to more conventional rockets dropped this cost, it still remained high due to the lack of private investment in the field. Heavy launches aboard Delta IV and Atlas V rockets rose to prices between $150M and $200M USD[1]. Currently, if you have a high mass satellite or spacecraft, expect to pay plently of money to get it into orbit.

As one might expect, the rise in cost has paralleled a massive push to miniaturize satellites. With this ongoing movement has come a new, niche market in the private world, air-launch to orbit. The idea behind this push is to reduce launch costs as much as possible while also providing a smaller platform for these miniature spacecraft to use for launch. This cost reduction is realized by launching a rocket from a higher altitude as to not use as much fuel, and restricting launch injection to low-earth orbit (LEO) so as not to need as much fuel onboard. Using this concept of operations (CONOPS), launch costs can be reduced by an order of magnitude ($10M-$20M USD)[1]. Without these new options for small satellite launch, the only option for a small company is to “piggyback” as a secondary payload on a major launch platform. While this cost may be cheaper, there is no flexibility when it comes to injection altitude or orbit inclination. The secondary payload is sent to the same orbit as the primary payload and must figure it out from there. If the injection orbit is desired, then this is no problem. If it is not, then this is quite unrealistic. Small satellites just do not have the propulsive capability to make major orbit changes and this is why the advent of air-launch to orbit is so valuable. This report will first analyze why air-launch to orbit capability is such a powerful concept and then will review the current and near-future options for low cost air-launch to orbit vehicles.

II. Why Air-Launch

To understand why the air-launch to orbit concept is so valuable, one must first understand the details of a current launch operation. While there are many launch platforms to analysis, the Delta IV medium launch vehicle will be reviewed due to its simple two stage design and single rocket engine with no strap-on boosters. The Delta IV M can carry an average of 8,000 kg to LEO. The rocket has a launchpad mass of 265,000 kg and uses an RS-68A LOX/LH2 main engine which has a sea level thrust of approximately 3,137 kN and sea level I_{sp} of 365 s. The first stage carries about 204,000 kg of propellant and has a burn time of 245 s[2]. As will be described, most air-launch to orbit systems drop their rocket payload at an altitude of around 12-15 km.

So, what happens from sea level to 12 km that is so important to skip? Reviewing the Delta IV mission profile shows, according to ULA, that the rocket reaches an altitude of 12.5 km from a sea level launch in 92 seconds with a velocity of 690 m/s. The overall propellant mass and burn time show an estimated fuel mass flow rate of about 833 kg/s which may be a bit higher during the initial max thrust phase of the launch. For now, assuming this average value and a burn time of 92 seconds, the rocket burns 76,604 kg of propellant or 37.6% of the total stage one propellant carried to go 12.5 km. In addition, the delta velocity (ΔV) expected using the sea level I_{sp} of 365 s and a mass ratio of 1.4 for the burn should be 1,221 m/s. The quoted value is only 690 m/s meaning that due to gravity and drag losses, only 56.5% of the expected velocity is achieved, wasting a massive amount of energy. On the other hand, look at the rest of the main engine burn profile. The main engine cuts off at an altitude of 121 km after 245 seconds of burn time. ULA quotes a velocity of 4,720 m/s at this time. In this case, we start at 12.5 km and a new initial mass of 188,396 kg after removing the expended fuel from the launch mass. At this altitude, we can use an Isp much closer to the vacuum value of 410 s and using the ideal rocket equation again get a ΔV of 4,534 m/s. Adding this to the quoted 690 m/s that would be initial velocity at 12.5 km gives an expected velocity of 5,224 m/s. This time 90% of the ideal velocity is achieved.



Time (sec)	Altitude (km)	Velocity (km/s)	Event
0	0	0.41	Liftoff
83	9.9	0.62	Mach Number = 1.05
92	12.5	0.69	Maximum dynamic pressure
245	121	4.72	Main-engine cutoff (MECO)
251	130	4.73	Stage I/II separation
265	149	4.69	Stage II ignition
275	161	4.70	Jettison fairing
886	288	7.85	Second stage engine cutoff 1 (SECO-1)
1452	190	7.97	Stage II ignition 2
1663	223	10.22	Second stage engine cutoff 2 (SECO-2)

Figure 1. Delta IV Medium Mission Profile

Therefore, by looking at a launch profile from sea level to 121 km, we see almost 38% of the stage one fuel is burned in the first 12.5 km and we can only convert ΔV to actual velocity with about 56% efficiency. Above this altitude, the drag losses are so minimal, thrust conversion to velocity is much better.

In addition to the savings in propellant mass and energy conversion efficiency, there can also be savings from nozzle efficiency. Currently, due to the max thrust required at low altitude and amount of propellant expended as shown, first stage nozzle expansion ratios are optimized for low altitude. The RS-68A engine on the Delta IV M rocket has an expansion ratio of 21.5[2]. Knowing the specific heat ratio of LOX/LH2 to be around 1.26 and the chamber pressure of the engine is about 9.6 MPa, the nozzle is optimized for an altitude between 7,500 km and 8,000 km. This altitude is under 10% of the the altitude range the nozzle will operate at. Launch from higher altitude will allow the nozzle to be optimized for a higher altitude and will generate a higher nozzle efficiency.

Concluding the analysis, the numbers for a single launch vehicle easily show that air-launch to orbit has its benefits. The real question will be related to carrier aircraft. Can a carrier vehicle be maintained and have high enough efficiency to offset the costs of a sea level launch? For small payloads, the answer is most definitely yes and some of the values associated will be detailed in the following section. For larger payloads, the anwer may not be quite so clear. The upcoming Pegasus II will most likely be the first chance we get to see an air-launch system with a payload capacity comparable to a standard launch vehicle and it will use the largest aircraft ever flown to get to a deployment altitude. Only time will tell if the cost of operation for such a system provides not only a cost benefit over surface launch, but potentially an operational efficiency benefit as well.

III. Air-Launch to Orbit Options

A. Pegasus

Pegasus, developed by Orbital Sciences, has placed over 78 satellites in orbit with over 40 launches since 1990. The Pegasus rocket is dropped from an L-1011 "Stargazer" aircraft at an altitude of 12 km. The current variation, Pegasus XL, contains three stages comprised of an Orion-50S XL, Orion-50 XL, and Orion-38[3]. All three are solid rocket motors developed by ATK. The first two stages are extended versions of the original Pegasus rocket, those being the only major changes to improve overall performance. The L-1011 is a conventional airliner used to carry the rocket to the desired altitude. The Pegasus has an interesting set of stabilization fins to help direct it spacewards after release. The rocket has a delta wing to help pitch the rocket up and provide lift along with tail fins to help steer the first stage. The Pegasus XL with L-1011 carrier is shown in Fig. 2.

Figure 2. Pegasus XL Dropped From L-1011

The Pegasus rocket itself has a length and diameter of 16.9 m and 1.27 m respectively. It weights approximately 23,100 kg and can carry a payload of up to 450 kg into LEO[4]. The first stage is built around an ATK Orion-50S XL solid rocket motor. It is 10.27 m long, an I_{sp} of 295 s, and a fuel fraction of 0.92. It has a burn time of 70 s and no thrust vector control of the 726 kN of thrust generated, hence, one of the reasons for the use of a delta wing and large stabilizer fins[5]. The second stage is an Orion-50 XL motor which is essentially a smaller version of the 50S. It is 3m long, has a slightly lower I_{sp} of 291 s, and a nearly identical fuel fraction and burn time[5]. As there are no fins on the second or third stages, this motor requires thrust vector control to direct the 196 kN of thrust generated. The third stage is made up of an ATK Orion-38 motor which is 1.34m long and has slightly lower performance characteristics. It has an I_{sp} of 287 s, a fuel fraction of 0.88, and a burn time of 68 s. It also has thrust vector control and generates 36 kN of thrust to get to LEO. All three stages use HTPB with 19% Aluminum as their fuel[5]. For payloads that require highly precise orbit injection, Pegasus has the option to add a fourth stage, which takes up some of the payload room and mass. This stage, called Hydrazine Auxiliary Propulsion System (HAPS), was designed by Aerojet and uses 60 kg of monopropellant hydrazine in a blowdown operation with three 220 N thrusters to help provide precision orbit injection of the payload[4]. Figure 3 shows an exploded view of the Pegasus XL.

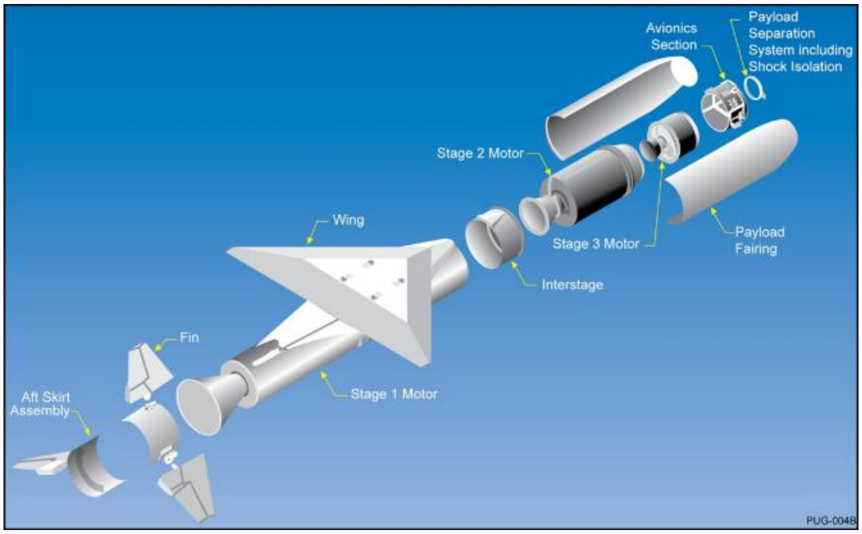


Figure 3. Pegasus XL Design

Pegasus is carried to an altitude of 12 km where it is dropped at a speed of Mach 0.82. Five seconds after release, ensuring safe separation from the carrier, the first stage ignites, burns for 70 seconds, and is dropped. After a short glide, the second stage is ignited. The second stage burns for another 70 s and midway through the burn the fairing is jettisoned. At this point the second stage is dropped and the rocket enters a coast phase with the time depending on the desired orbit. After this coast, the third stage is ignited and burns the final 67 s to orbit insertion. Typical launches average just over ten minutes to reach orbit after drop from the carrier[4]. Mission design from a Pegasus launch is shown in Fig. 4.

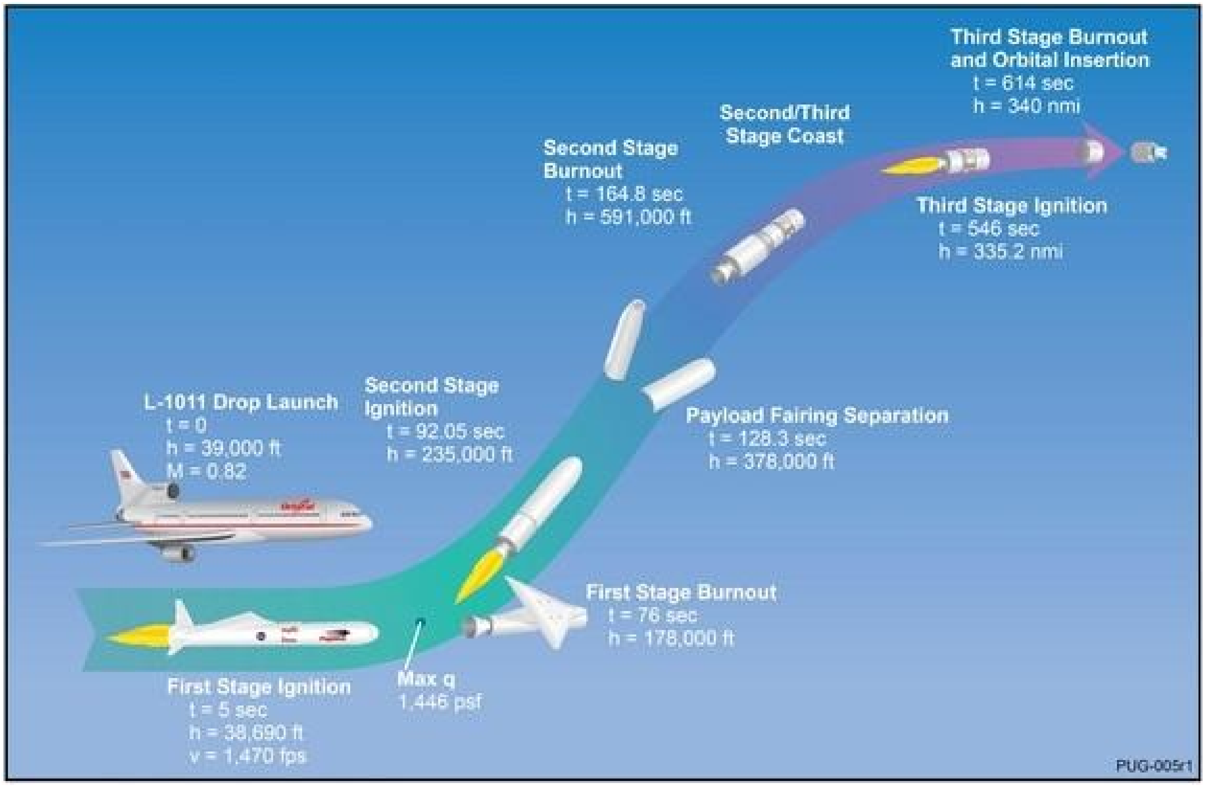


Figure 4. Pegasus XL Mission Profile

Pegasus is easily the most successful air-launch to orbit system currently available. This legacy will continue in the near future as Orbital Sciences develops the Pegasus II. This is a major step for the entire air-launch industry. Orbital Sciences has teamed up with Stratolaunch systems to develop a new carrier and launch platform. The carrier will be a massive, two fuselage, six engine aircraft built by Scaled Composites. If successful as designed, it will be the largest aircraft ever flown with a wingspan of 117 m. For comparison, the Spruce Goose has a wingspan of 97.5 m and the A-380 airliner has a wingspan of 80 m. The new Pegasus rocket will be much larger than the current system. ATK is again developing the stages for this rocket. The first two will be carbon composite solid rocket motors with thrust vector control. The third stage will use 2 Pratt and Whitney RL-10 LOX/LH2 engines and an optional fourth stage will have a single RL-10 engine. The rocket is expected to have a diameter of about 3.7 m and 36.6 m long[3]. Current mass estimates put it around 200,000 kg, mainly to demonstrate reliable launch prior to paring the system mass down as much as possible. This size is more comparable to the current major launch vehicles used today and the reason for such a large scale carrier. This size will allow the Pegasus II to place up to 6,100 kg with a 5 m fairing into LEO. The optional fourth stage would use a 4m fairing and provides the ability to launch 2,000 kg into a 15° inclination Geostationary Transfer Orbit (GTO)[3]. Once reliable service has been proven, the system will undergo further enhancement to provide more orbit injection options. Interestingly, Stratolaunch

Figure 5. Stratolaunch Design

initially contracted with SpaceX to provide the rocket for launch. SpaceX began development on the Falcon 9 Air system, but after some disagreements on the direction of the overall program, both sides decided to part ways and Stratolaunch then looked to Orbital Science. The carrier aircraft is expected to begin testing in 2015 and the rocket in 2016[6]. The entire system is expected to launch soon after. While the price of a launch is unknown at this time, one of the major reasons for this development has been to lower the current costs of launch. SpaceX launches cost aroung $50M USD and the current Pegasus XL has a price ranging from $15M-$30M USD depending on the amount of support required[7].

B. SpaceShipOne / SpaceShipTwo

Figure 7. SpaceShipOne and White Knight One

Probably the system with the most publicity, SpaceShipOne (SS1), seen in Fig. 7, is built by Scaled Composites as well. The major difference with this system versus Pegasus is that SS1 and the future SpaceShipTwo (SS2) will be used primarily for space tourism. SS1was designed as a high-altitude manned research prototype aircraft with a hyrid rocket engine made up of nitrous oxide and HTPB. It is carried to altitude by White Knight One, which looks like a very small version of the Stratolaunch aircraft with only one fuselage[8]. SS1 was truly designed to be a first tier proof-of-concept for what is currently under development now as SS2 and White Knight Two. SS2 will be the second tier system that will be run by Virgin Galactic to take tourists into the sub-atmosphere for a price of around $250K USD. Virgin has also hinted that if SS2 is a major success, they will move to expand to a third tier system. SS1 completed six powered flights, reaching an altitude just over 100 km and speeds ranging from Mach 1.5 to Mach 3. After reaching max altitude, the aircraft glides back to the ground, using a novel wing tilting capability. The two wings are turned up to “shuttlecock” the vehicle and create a stable glide path even if control is lost. This ensures the safety of the return flight and alleviates pressure on the pilot[9].

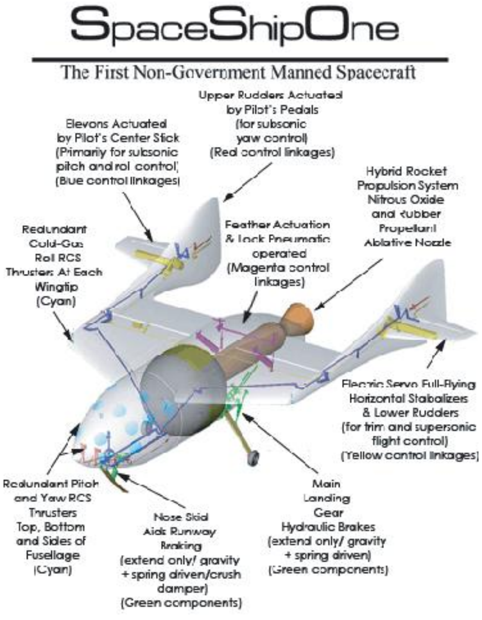


Figure 6. SpaceShipOne Design

The success of the program revolves around development of a reliable rocket engine that is safe enough to be certified for human transport. This led to the use of a hybrid rocket engine using nitrous oxide and HTPB. This engine can provide a thrust of 74 kN and an I_{sp} of 250 s with a burn time of about 87s, imparting a ΔV of about 1.7 km/s. About 2,400 kg of oxidizer was placed in a large spherical tank built by ATK in the back of the fuselage with the solid HTPB motor and ablative bell nozzle sticking out the back[9]. After each powered flight, the single piece case, throat, and nozzle are replaced. A bulkhead was placed between the oxidizer tank and the cockpit for added safety, not to mention the system could be shut off at any moment and nitrous oxide and HTPB by themselves are completely benign. The vehicle itself has an expected length of 18 m and a span of 8.25 m^9.

SS1 can carry one pilot and two passengers. It is taken to an altitude of 15 km where it is dropped. After it safely clears the carrier, it ignites and begins an 87 s burn at the end of which it is moving at three times the speed of sound. After burnout, the aircraft continues on its glide up to an apex of just over 100 km. From here, it glides back to land which takes about 18 minutes[9].

SS2 is now in full development and testing. As of the beginning of 2014, over 30 successful test flights have occurred. The new system is about three times the size of SS1 and the new White Knight carrier vehicle is approximately three times the size of White Knight One with two fuselages instead of one. SS2 will be the first true sub-orbital tourist vehicle once operational sometime in late 2014[10]. It will carry two pilots and six passengers. Not much is known about the new hybrid rocket engine named RocketMotorTwo developed by Sierra Nevada, but it is expected to provide a slightly higher velocity and an estimated 270 kN of thrust. While tourism is the primary market for this system, Virgin has also marketed the system for research where a payload could be taken up to the peak altitude of 110 km and experience about four minutes of microgravity. This has some benefits due to the low 'g' loading that the vehicle experiences compared to sounding rockets, which are the only other microgravity option other than true launch to orbit[10].

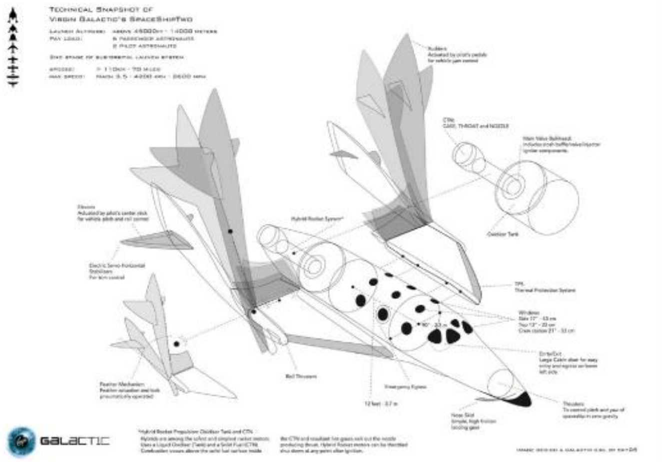


Figure 8. SpaceShipTwo Design

The SS2 program did suffer a major setback in 2007 when an explosion occurred during cold-flow testing of the hybrid rocket. This was a major surprise to all involved and brought to the forefront the fact that hybrid rockets, while safer than most other systems, are still fairly new in the world of operational rockets. This led Scaled Composites to further increase their research in the field, working with Sierra Nevada to finish development of RocketMotorTwo[11].

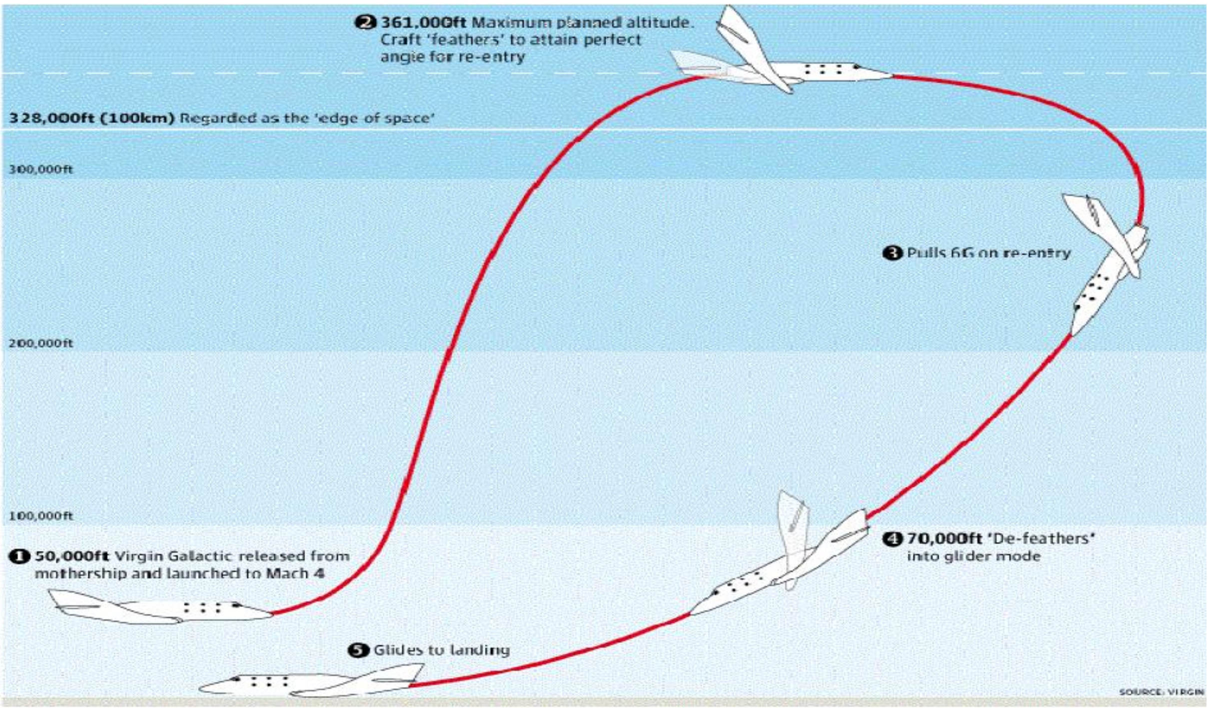


Figure 9. SpaceShipTwo Mission Profile

C. LauncherOne

Stemming from the development of SS1 and SS2, Virgin Galactic bought out the entire launch system from Scaled Composites and began development of a new air-launch to orbit system mirroring Stratolaunch. The concept, which began development in 2008, would use the White Knight Two carrier for the SS2 and strap a rocket on instead. White Knight Two was even developed with an open architecture so changes like this could be made. Virgin is developing their own rocket engines designated NewtonOne and NewtonTwo that will become the two stages of the rocket vehicle. They have successfully test-fired both LOX/RP-1 engines capable of 16 kN and 210 kN respectively[12]. The first launch is tentatively scheduled for 2016. The vehicle will have the capability to launch up to 225 kg inside a 1 m diameter fairing to LEO and has stated up to 100 kg into Sun-synchronous orbit (SSO). The current price estimate for a launch is about $10M USD. If this holds, it will be the cheapest option to launch payloads into space[13]. Up to this point, Virgin Galactic has been secretive about any additional specifications related to the rocket design.

Figure 10. LauncherOne Concept Design

D. GOLauncher 1 / 2

GOLauncher 1 and 2 are systems developed by Generation Orbit, a US company out of Georgia. Both systems use a Gulfstream G-III business jet as the carrier aircraft. GOLauncher 1 provides more scientific research possibilities as a sub-orbital launcher and can be used for experiments relating to microgravity and hypersonic testing. GOLauncher 2 provides the actual orbit insertion capability needed for satellite deployment[14].

GOLauncher 1 is a single stage rocket with a payload capacity ranging from 13 kg to 90 kg. It does not do orbit insertion, but can reach an altitude of 300 km and provide up to seven minutes of microgravity for research experiments. For hypersonic research, the trajectory can be suppressed to allow sustained captive-carry or free-flight hypersonic testing.

GOLauncher 2 is a two stage rocket with a payload capacity up to 45 kg. It can provide access to orbits up to 750 km and any range of inclinations. This rocket is optimized for microsats, nanosats, and cubesats. In fact, NASA has contracted Generation Orbit to launch three cubesats in 2016[14].

Figure 11. GOLauncher Concept Design

The GOLauncher rocket engine is somewhat unique in this market. It uses a hybrid rocket engine with a paraffin motor and LOX as an oxidizer. The engines are developed by Space Propulsion Group (SPG), a company working diligently to become the leading expert in hybrid rockets. SPG has been working to inform the industry specifically to some of the dangers of using nitrous oxide after the disaster with SS2. The single stage paraffin/LOX hybrid motor has a length of 6 m and diameter of 0.44 m and weighs 590 kg. The cylindrical payload fairing has a diameter of 15.6 in and height of 11.7 in. The rocket has thrust vector control and four stabilizer fins. The GOLauncher 2 will utilize two stages, but at this time the final rocket motor designs are unknown. SPG claims advancements in their motors will lead to a vacuum I_{sp} of about 340 s with a nozzle expansion ratio of 70[15].

GOLauncher has multiple mission profiles depending on the launcher type. The carrier aircraft flies to a specified location for the mission. At about 13 km the rocket is dropped by the carrier aircraft. After a five second drop the rocket ignites. For a GOLauncher 1 sub-orbital trajectory the rocket pitches up and heads to the required altitude. For a GOLauncher 1 hypersonic test, the vehicle pitches up only slightly and then accelerates to match the desired Mach number. For GOLauncher 2, the first stage burns out after a large pitch up motion, then after a short coast, the final stage ignites for orbit injection. The SPG hybrid motors have some thrust control ability to ensure the correct profile is met[14]. The various GOLauncher mission profiles are shown in Fig. 12.

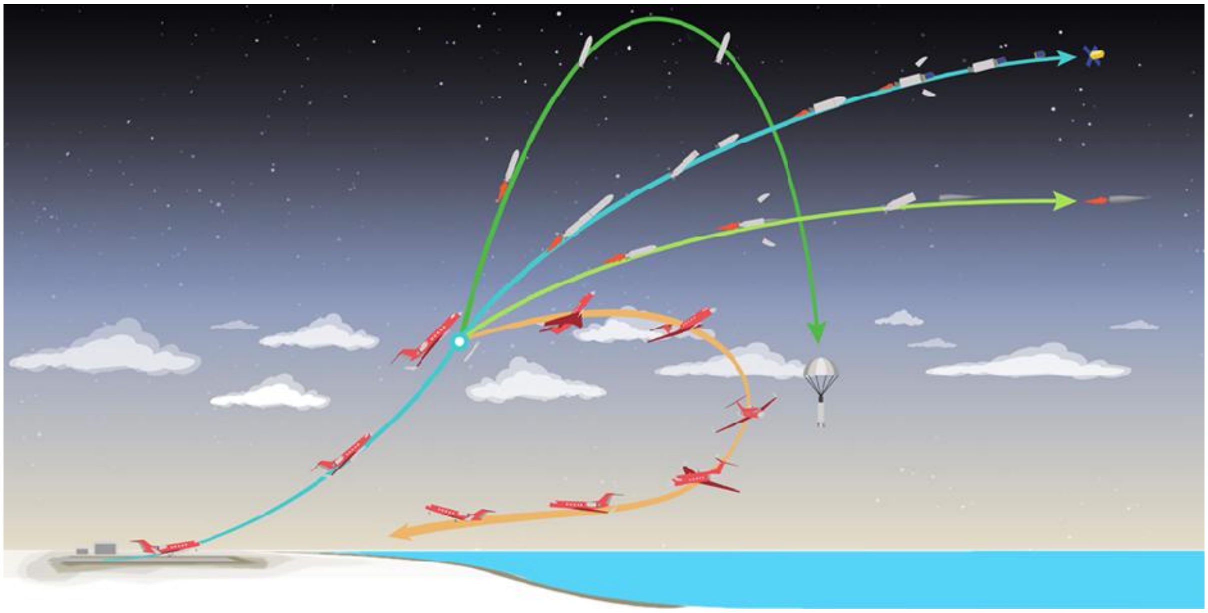


Figure 12. GOLauncher Mission Profile

E. IAR-III / HAAS 2

ARCA is a Romanian space systems company with an interesting new air-launch system. The carrier aircraft is called the IAR-III Excelsior and is essentially a supersonic jet that can carry a large rocket as a payload. The jet can be used as a carrier to drop the rocket at altitude or it can be used as a sub-orbital tourism vehicle[16].

The IAR-III has a length of 24 m and wingspan of 12 m. It can reach Mach 2.6 at 30 km and has a rate of climb of 250 m/s. The IAR-III is designed to launch and land on the water and has no landing gears. It is powered by an Executor engine also built by ARCA. This is a LOX/RP-1 rocket engine that can generate 240 kN of thrust. This engine is truly interesting in its design. To save development cost, ARCA decided to build the engine with almost all aluminum and composites. To ensure stability, layers of silica phenolic and graphite epoxy were used to beef up parts of the structure. These lightweight materials gives the engine a thrust to weight ration of 110. The engine has a diameter of 0.7 m, length of 2.2 m, and weight of 250 kg. It has a vacuum I_{sp} of 312 s. The engine is pictured in Fig. 14[17].

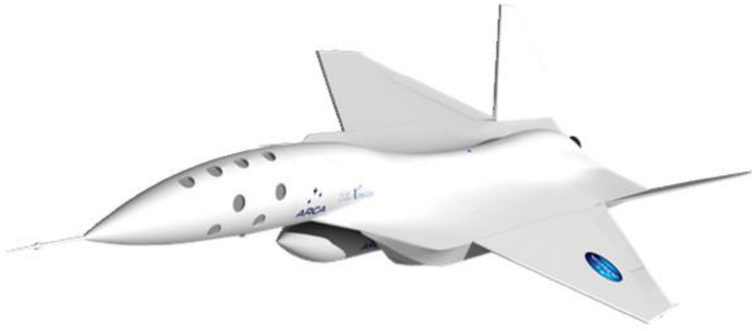


Figure 13. IAR-III Excelsior

The HAAS 2 rocket is a two stage variant of the ground-launched version. The first stage uses the same Executor engine as the IAR-III. The second stage is comprised of another engine developed by ARCA called the Venator. It is also a LOX/RP-1 engine. The Venator has a diameter of 0.8 m, length of 1.8 m, and weight of 70 kg. It has a vacuum I_{sp} of 317 s and generates 25 kN of thrust[18]. The HAAS 2 plans to provide a payload capability of 400 kg to

LEO. The exact orbit parameters are unknown at this time. It will be dropped by the carrier aircraft from an altitude of around 16 km[19]. Other than the engines, the development of this program has been kept relatively quiet. ARCA previously cancelled some of their air-launch programs involving lifting with helium balloons and are now holding on to some of the finer details until they have more confidence in the development of the new program.

Figure 14. Executor LOX/RP-1 Engine

F. Launch Platforms on the Horizon

There are two other major programs on the horizon in the realm of air-launch to orbit programs. The first is the Airborne Launch Assist Space Access (ALASA) program. This program is managed by the Defense Advanced Research Projects Agency (DARPA). The goal of the program is to develop a new air-launch to orbit system that costs $1M USD or less. The rocket is under development by Boeing and is expected to be carrier by an F-15E fighter jet. It will be as small as 7.3 m in length and must carry a payload of 45 kg to LEO. An additional goal of the program is to develop technology regarding smaller scale powerful rocket engines that can still provide decent thrust and high I_{sp}. Flight tests and demo are expected to occur in 2015 or 2016[20].

The second major air-launch program is being developed by Swiss Space Systems (S3). The goal of S3 is to provide unmanned spaceplane capability to launch up to 250 kg into LEO. They plan to strap a small shuttle similar in design to the Sierra Nevada Dreamchaser to the top of an Airbus A300 and launch it from an altitude of 10 km. This program just started in 2013 and plans to begin test flights in 2017[21].

Figure 15. Swiss Space Systems Concept Design

IV. Conclusion

Currently Orbital Sciences is the only company with a solid history of air-launch to orbit. That is about to change. The advancements in small satellite technology have demanded a new way to reach LEO and many of these companies are trying to meet those needs. One thing to worry about is oversaturization of the market. As was seen with the major launch platforms, the customer base is not always large for space launch. While we currently see a major customer base for small satellites, this could change rapidly as we start to crowd LEO with space junk. An oversaturated market would most likely lead to the demise of the smaller companies, similar to the current space launch market with United Launch Alliance (ULA) as the main operator. What is interesting is the fact that price seems to be dropping, but only to a threshold. Most of the smaller launchers are looking to advertise in the $1M - $10M USD range. Once within this threshold, the driving factors seem to be launch convenience and specifically, the ability for a small satellite customer to have the ability to dictate the exact orbital parameters desired. This is a huge leap from the current model where small satellites launch as secondary payloads for around $5M USD and have no say in the final orbit provided. With that being said, the future looks bright for both the companies involved in this development and the customers looking for a broad spectrum of launch options to meet their desired missions.

References

[1] "Cost, Price, and the Whole Darn Thing," *Encyclopedia Astronautica*.

[2] United Launch Alliance, "Delta IV Launch Services User's Guide."

[3] KSC, E. M., "NASA - Special Delivery: The Pegasus XL Rocket" Available: http://www.nasa.gov/mission_pages/launch/L-1011-pegasus.html.

[4] "Pegasus User's Guide," Apr. 2010.

[5] "ATK Space Propulsion Products Catalog," Sep. 2012.

[6] Norris, G., "Stratolaunch quietly making progress," *Aviat*, Oct. 2013.

[7] "Stratolaunch and Orbital – The Height of Air Launch | NASASpaceFlight.com."

[8] Leonard D., Special to Space, "Virgin Galactic Spaceliner Steps Forward," *Space.com* Available: http://www.space.com/3507-virgin-galactic-spaceliner-steps.html.

[9] "SpaceShipOne," *Encyclopedia Astronautica*.

[10] "Welcome to Spaceshiptwo."

[11] "Explosion Kills Three at Mojave Air and Space Port," *Space.com* Available: http://www.space.com/4123-explosion-kills-mojave-air-space-port.html.

[12] "Virgin Galactic unveils LauncherOne satellite vehicle," *Engadget* Available: http://www.engadget.com/2012/07/11/virgin-galactic-unveils-launcherone-satellite-vehicle/.

[13] R. C., SPACE com, "Virgin Galactic Unveils LauncherOne Rocket for Private Satellite Launches," *Space.com* Available: http://www.space.com/16530-virgin-galactic-satellite-launches-launcherone.html.

[14] "Generation Orbit Partners With Space Propulsion Group," *Citizens In Space*.

[15] Messier, D., "Generation Orbit, SPG Team Up for Smallsat Launcher at Parabolic Arc."

[16] ARCA Space, *IAR-111 Supersonic Aircraft*.

[17] ARCA Space, *Executor Rocket Engine*.

[18] ARCA SPace, "Venator Rocket Engine."

[19] "The second stage of Haas 2C rocket," *Google Lunar XPRIZE* Available: http://www.googlelunarxprize.org/teams/arca/blog/second-stage-haas-2c-rocket-0.

[20] Gruss, M., "Boeing Targets 66 Percent Launch Cost Reduction with ALASA," *Space News*, Mar. 2014.

[21] "Mission - Goals" Available: http://www.s-3.ch/en/mission-goals.