BIS-RS-2014-28

The Disruptive Potential of Subsonic Air-Launch

David J. Salt
Telespazio VEGA Deutschland GmbH
Europaplatz 5, D-64293 Darmstadt, Germany; +49 (0)6151 8257-0
dave.salt@telespazio-vega.de

ABSTRACT

This paper tries to show that big launch vehicles may not be required to enable big space operations. It first highlight the essential role of space launch in enabling all space operations and indicates the dominant role that 'customer' demand has played in both enabling and constraining its development. It then discusses the advantages and drawbacks of a subsonic air-launched reusable launch vehicle (RLV); comparing and contrasting them against a wide range of other possible launcher concepts. In doing this it highlights the unique evolutionary opportunities that this concept has to offer and provides some insight as to how these may be realised and enhanced via existing technologies. Finally, the paper highlights the radical improvements in operational architectures afforded by such a vehicle. It shows how an RLV with a relatively modest launch performance of less than 5t to low Earth orbit could be capable of supporting almost all current and future launch demand by forming the key element of a fully reusable space transportation infrastructure.

KEYWORDS:

ACES = Air Collection & Enrichment System
CR = Collection Ratio
ELV = Expendable Launch Vehicle
GEO = Geosynchronous Earth Orbit
GTO = Geosynchronous Earth Orbit
IRR = Internal Rate of Return
kg = kilogram
LEO = Low Earth Orbit
Mg = Metric tonne
Mn = Mach number
SSTO = Single Stage to Orbit
TSTO = Two Stage to Orbit
RLV = Reusable Launch Vehicle

1. THE LIMITS TO GROWTH

THE frequency and complexity of space operations has evolved relatively slowly over the last three decades and is certainly much reduced in comparison with the first two decades of the Space Age, which began more than half a century ago. The reasons for this 'phase change' can be easily understood when one considers the changes in both political and economic drivers that control most space activities, especially those involving human spaceflight.

The past five decades of space activity have, to a large degree, been driven by a few specific issues such as national security and conservation of the industrial base. In contrast, the slow growth of commercial ventures has been due mainly to market and financial constraints, rather than any basic limitation of the available technology. As a consequence, the diversity and intensity of spaceflight operations have also been paced by these trends, though the manner in which they are performed, on both the ground and in space, has been radically improved by the phenomenal advances in computing and software over this same period.

1.1 The Current Space Paradigm & Potential of NewSpace

We first consider future possibilities to identify the factors that may either prevent or severely restrain their realisation. Given the importance of markets in the development of commercial activities, this assessment also considers how such factors may also influence their growth and sustainability.

i) Current Constraints

Current space activities range from pure science missions through to civil and military applications like communication, navigation and observation systems. Nevertheless, growth and evolution in all these areas is limited by a few key factors:

- government priorities and constraints;
- competition from terrestrial alternatives;
- low market 'elasticity' (i.e. lower prices stimulate only limited market growth);
- launcher cost/availability/reliability.

The first factor is important because the growth of space activities is still dominated by government programmes, both civil and military. Communication satellites represent the nearest thing to a truly commercial market sector, but government funding still underpins much of their basic R&D while the second and third factors have placed significant restraints on their growth and evolution, as witnessed by the problems of commercial ventures like Iridium, Globalstar, ICO, SkyBridge and Teledesic.

To put the situation into perspective, Figure 1 shows a breakdown of the global space industry's annual revenue, which was $304 billion in 2012. However, this was still less than the annual turn-over of a single successful commercial company like Wal-Mart [RD.2], which was founded in 1962 but has managed to outgrow the entire world space industry by servicing vastly bigger and established markets to give a turnover of $445 billion in 2011.

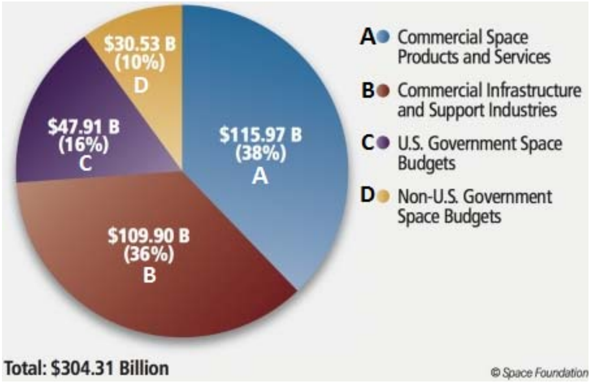


Figure 1. Global Space Activities, 2012 [RD.1]

ii) Future Potentials

A wide range of future space-based activities and associated business opportunities[1] have been discussed for many decades (e.g. space manufacturing facilities, solar power satellites) but their realisation has also been limited by a few key factors:

- large investment requirements;
- operation and utilization cost uncertainty;
- market demand and 'elasticity' uncertainty;
- launcher cost, availability and reliability.

Given these circumstances – and in the absence of a major government imperative, equivalent to that which justified Apollo (i.e. the Cold War) – it has become clear to many that the current paradigm will not lead to any significant growth of space activities in the foreseeable future. As a consequence, a number of NewSpace ventures have begun to emerge[2] that represent an attempt to change the paradigm by placing greater emphasis on entrepreneurial rather than government activities.

NewSpace ventures believe that the best way to change the paradigm is to stimulate existing and/or new markets in order to drive and sustain their growth, primarily through the power of commercial enterprise. Moreover, as launch issues are seen as the common factor that limits both current and future growth, most have chosen to address this issue first; their ultimate aim being to reduce specific launch costs by an order of magnitude to below about $1000/kg to LEO, the point where significant growth in all market sectors is expected to be triggered.

Nevertheless, it is important to realize that the NewSpace paradigm is not solely restricted to entrepreneurial start-up companies. A more thoughtful definition would also include groups working within established companies, such as Boeing, Lockheed-Martin and Orbital Sciences, who are also seeking to stimulate existing and new markets by applying novel technologies and commercial practices such as fixed-price, rather than cost-plus, contracts.

1.2 NewSpace and the Realities of Space Access

As launch services are one of the most significant constraints on the growth of future space operations, we now consider the significant improvements in vehicle design, operation and economics that will be required and the ways in which these could be realized.

It has long been recognised that the only way to achieve significant improvements in space access is via reusable launch vehicles (RLVs) instead of expendable launch vehicles (ELVs), because they offer:

- major reductions in marginal costs, as expensive components tend not to be discarded after use;
- better amortisation of investments, as costs can be spread across more users;
- higher reliability and safety, due to the intrinsic value of the vehicle.

Unfortunately government efforts to field such systems have, to date, either missed many of their original goals (i.e. Shuttle) or been outright failures (X-33/VentureStar, X-34, etc.). Moreover, commercial efforts to develop such systems have been hampered because their development costs are difficult to justify against potential markets, for example:

- many studies estimate it will cost $10-20 billion to field an operational system;
- the existing markets are insufficient to justify their development because they have limited growth and 'elasticity'[3] (i.e. lower prices stimulate only limited market growth);
- the new markets that could justify their development are far too uncertain and speculative.

Such factors show that both market and financial issues play just as important a role as the obvious technical ones. They also explain why NewSpace ventures have chosen to begin by developing RLVs to service sub-orbital markets, which demand significantly less of an initial investment, with many estimating that only $100m-$200 million will be required.

---

[1] For example, the Commercial Space Transportation Study (CSTS) performed a comprehensive review in 1994 of all current and foreseeable markets [RD.3]

[2] Summaries and links for all current ventures are at (http://www.space-frontier.org/commercialspace/)

[3] Space market elasticity is difficult to estimate due to the relatively small size and low diversity of current markets, though studies such as the CSTS [RD.3] and the NASA ASCENT Study [RD.4] have derived tentative estimates.

Nevertheless, it should be appreciated that cost isn't everything and that frequent flight availability and a timely and efficient integration process are just as important. A good example of this is NASA's Get Away Special (GAS) canisters [RD.5] that were priced on the order of $100/kg to LEO but, because of the long and complex Shuttle integration process, were undersubscribed so that many GAS canisters were filled with ballast and the service was eventually discontinued after the Columbia accident.

2. THE CASE FOR SUBSONIC AIR-LAUNCH

Having identified space launch as a fundamental enabler of future space operations, this section discusses the advantages and drawbacks of a subsonic air-launched fully reusable launch vehicle (RLV). In doing this it highlights the unique evolutionary opportunities that this concept has to offer and provides some insight as to how these may be realised and enhanced via existing technologies. It explains why subsonic air-launch is the only realistic way of enabling space launch from conventional airfields within the foreseeable future and discusses the other major operational advantages of this concept, such as: much enlarged and flexible launch windows; recovery of all flight elements to the same geographic location; increased contingency options for launch abort; the potential to harvest propellant during its cruise to the launch point.

2.1 Brief History of Air-Launch

The idea of air-launching a rocket has a long history that dates back to the early 1950's when *rockoons*, which were sounding rockets launched from helium balloons. These allowed the rocket to achieve a higher altitude so that it did not have to move under power through the lower and thicker layers of the atmosphere. Unfortunately, they had some serious disadvantages because the balloon could not be steered and so both the launch direction and the region where it fell was not easily to control. Possibly the most successful was the USAF's Project Farside, which launched six vehicles in late-1957 though only two reached their target altitude of just over 2000km.

The first aircraft launched rockets were primarily developed as anti-satellite (ASAT) weapons. The first of these was Project Pilot, which was an attempt by the Naval Ordnance Test Station (NOTS) at China Lake to orbit a 1kg payload in response to Sputnik. The vehicles, named NOTS EV-1 (NOTSNIK), were solid rockets launched by a Douglas F-4D1 Skyray and ten were flown in mid-1958, though none were successfully tracked to orbit. Similarly, a Bold Orion missile, which was air-launched from a B-47 Stratojet on 19th October, 1959, against the Explorer 6 satellite. However, this was a limited test and it was not until 13th September, 1985, that an F-15A launched an ASM-135 ASAT destroyed the Solwind P78-1 satellite flying at an altitude of 555 km. Since then, the only operational air-launched rocket has been Pegasus, which was developed by the Orbital Sciences Corporation as a commercial satellite launch vehicle and first flown on 5th March, 1990, with 42 launches to date.

Most air-launch concepts carry the rocket external to the launch vehicle, either on top or under the fuselage or wing. However, a few concepts have proposed carrying the rocket inside the fuselage and 'extracting' it during launch via drag chutes, which also provide stability during the subsequent free-fall phase, before igniting the rocket motor. The USAF tested air launching a Minuteman ICBM from a C-5A Galaxy transport aircraft on 24th October 1974, but this concept was never pursued. However, the AirLaunch LLC performed significant demonstration tests in 2006 of a very similar concept called QuickReach for the DARPA/USAF FALCON programme, which launch a liquid ELV from a Boeing C-17A. Similarly, the Air Launch Aerospace Corporation proposed an air-launched system capable of placing satellites into LEO using the AntonovAn-124 "Ruslan", though this was never developed.

Other concepts proposed in the mid-1990's have envisaged towing the launcher behind an aircraft (i.e. Astroliner, proposed by Kelly Space & Technology) while others have envisaged in-air fuelling of the launcher in order to reduce take-off mass (i.e. Black Horse, proposed by Pioneer Astronautics). Neither of these approaches were ever pursued beyond the conceptual design stage, though Kelly did perform tow tests of an F-106 jet behind a C-141 cargo aircraft in early-1998 under a NASA SBIR award.

The most recent air-launch concept to attract serious attention has been the Stratolaunch Systems proposal in 2011 to build a massive aircraft by combining the wings and fuselage of two Boeing 747 airliners. However, the exact nature of the launch vehicle was not specifically defined and initial speculation was that it would be a variant of the SpaceX Falcon. It now appears that OSC will build the rocket, called Pegasus II, using two solid-stages and a cryogenic upper stage, which will be capable of launching a 6.1t payload into LEO. Two other air-launch concepts have been proposed in recent times: the Lynx III from XCOR and LauncherOne from Virgin Galactic. Both are evolved from sub-orbital launch systems but plan to launch much small satellites than Stratolaunch, on the order of 100kg, by using an expendable rocket launched from the sub-orbital vehicle: XCOR's Lynx rocket plane, separating at a high supersonic speed of around 4Mn; Virgin Galactic's WhiteKnight 2 carrier aircraft, separating at a subsonic speed of around 0.9Mn.

2.2 RLV Design Factors, Issues & Trades

Before discussing the specific benefits of a subsonic air-launched RLV, this section provides some insight of the advantages and drawbacks of the myriad possible designs that have been considered to date. Although limited in technical detail, it is based upon a synthesis of RLV conceptual designs. The synthesis is presented in more detail within the Appendix of RD.6 and is based upon a large number of authoritative papers that reported the results of detailed design studies, performed mainly for/by NASA. Most were published between the late-1980s or mid-1990s; a period that covers the last serious effort by the US government and aerospace industry to build a fully reusable launch vehicle through initiatives like NASP, DC-X and both the X-33 and X-34 projects. Sadly, with the exception of the DC-X, all of these efforts were cancelled before any significant hardware could be flown or even tested and, as a consequence, all subsequent new launch vehicle initiatives have focused upon the development and/or evolution of expendable designs.

To enable a sensible comparison of the incredibly large if not infinite variety of RLV concepts, the synthesis classified and assessed them with respect to three basic design and operational characteristics.

- *Propulsion system*; pure rocket, or some combination of rocket and air-breather (a/b)
- *Configuration*; two-stage-to-orbit (TSTO), or single-stage-to-orbit (SSTO)
- *Launch and landing mode*; vertical take-off and vertical landing (VT/VL), or vertical take-off and horizontal landing (VT/HL), or horizontal take-off and horizontal landing (HL/HL).

In addition, the impact of several design and operational issues (*flight profile*, *payload size* and *technology assumptions*) was also assessed.

i) Propulsion

Pure rocket vehicles are always lighter (dry) than vehicles with equivalent payload performance that use some form of air-breathing propulsion due to the installed mass of air-breathing engines. Assuming dry mass relates directly to research and development (R&D) and production costs (which is a reasonable first order approximation), then pure rocket concepts will be cheaper to both develop and produce. The only exception is when an existing air-breathing vehicle can serve as a TSTO booster. Moreover, as all-rocket concepts will be mechanically less complex than one using some combination of air-breathing and rocket engines, then the pure rocket concepts will be easier to maintain and so be cheaper to operate.

Pure rocket vehicles with dual-fuel propulsion are lighter (dry) than equivalent vehicles which use only hydrogen, but the extra cost of developing and operating a hydrocarbon engine in addition to a hydrogen engine, or the development of tri-propellant engine technology, will make the life cycle costs of dual-fuel vehicles significantly more than the equivalent hydrogen only vehicles. Dual-fuel vehicles using propane are lighter (dry) than those using other hydrocarbons.

ii) Configuration

TSTO concepts are lighter (dry) than equivalent SSTO concepts, but the extra complexity of developing and operating essentially two distinct vehicles in parallel means that the SSTO life cycle costs are less than those of an equivalent TSTO. The one exception to this may be the Siamese concept, in which the orbiter and booster are designed to be as similar as possible in order to minimise, or even eliminate, duplicated effort and equipment during the development, production, and operational phases.

iii) Launch & Landing Modes

SSTO rocket concepts based upon HT/HL designs are lighter (dry) than equivalent VT/HL designs, due to lower T/W engines and a lifting ascent trajectory that reduces mission delta-v, but the added complexity of a launch assist device may make their life cycle costs more than equivalent VT/HL designs. Wet-wings (containing LOX) provide a significant way of reducing the mass of HT/HL designs, possibly enough to reduce their overall life cycle cost to below that of equivalent VT/HL designs.

iv) Flight Profile Impacts

If re-entry cross-range requirements are relaxed to around 100km, then pure rocket VT/VL vehicles using ballistic re-entry will have the lightest mass (dry) and the lowest life cycle costs.

If significant launch flexibility is required, such as a launch off-set capability (in both time and position) and/or a cruise/loiter capability (for ferry or reconnaissance purposes), concepts will have to use air-breathing propulsion to some degree in order to minimise the vehicle's mass (dry).

v) Payload Size Impacts

Small payloads, around 5t and less, will favour TSTO configurations because system scaling factors tend to reduce SSTO payload fractions as absolute size decreases, plus it also becomes more feasible to consider using an existing vehicle as a TSTO booster in order to significantly reduce the R&D costs.

Large payloads, around 60t and more, will favour VT/VL with ballistic re-entry because lifting re-entry vehicles have a far-aft centre of gravity problem that tends to increase with vehicle size.

vi) Technology Assumption Impacts

SSTO air-breathing concepts will be significantly lighter (dry) than equivalent TSTO air-breathing concepts if they can use the advanced technologies envisaged for NASP to provide more than a 40% reduction in structural and system mass relative to the Shuttle (e.g. titanium metal matrix composite fuselage/wings/frames, silicon carbide hot structures, graphite composite tanks, slush hydrogen, etc.).

2.2 Benefits of Subsonic Air-Launch

There have been numerous studies of air-launch concepts and Table 2 provides an overview of a very small but representative selection of them. Significant effort was invested in developing these concepts because air-launch provides some important benefit with respect to performance, operations and the potential for evolution and these are discussed in the following subsections.

Config.	*Concept Name*	*Designer/Year*	*Air-launch Vehicle*	*Propellant*	*Reusable*	*Payload*
Captive on Top	Boeing AirLaunch	USA/1999	747	Solid	No	3.4t
	Interim HOTOL	UK/1991	An-225	LH2/LOx	Fully	7.0t
	MAKS-M	USSR/1989	An-225	RP-1/LH2/LOx	Partly	5.5t
	MAKS-OS	USSR/1989	An-225	RP-1/LH2/LOx	Partly	8.3t
	Pegasus II	USA/2011	Stratolaunch	Solid+Cryo	No	6.1t
	Saenger II	Germany/1991	Mach 4.4 turbo-ramjet	LH2/LOx	Fully	9.0t
	Spiral 50-50	USSR/1965	Mach 6 turbo-ramjet	RP-1/LOx	Partly	10.0t
	Teledyne-Brown	USA/1986	747	LH2/LOx	Fully	6.7t
Captive on Bottom	Global Strike Eagle	USA/2006	F-15	Solid	No	0.3t
	Pegasus	USA/1990	L-1011	Solid	No	0.5t
	Yakovlev HAAL	USSR/1994	Tu-160	Solid	No	1.1t

Table 2. Selection of external carriage Air-Launch concepts (excludes towed or internal carriage)

vii) Performance Benefits

Rocket operations above the dense atmosphere reduce significantly both drag and gravity losses. It also allows for a significant increase in engine specific impulse (Isp) by allowing the use of a larger expansion ratio nozzle, which is constrained at lower altitudes because over-expanded nozzle flows suffer destructive instabilities. Theoretically, the latter problem can be overcome by using some sort of altitude compensating nozzle, though the additional mass and complexity tends to cancel out any performance benefit.

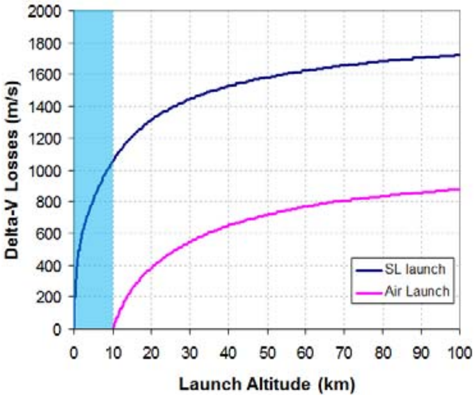


Figure 2. Delta-V Loss Comparison

Figure 2 illustrates the delta-V losses encountered by a rocket as a function of launch altitude for both sea-level and the 10km case, which represents a subsonic air-launch. It shows a major reduction in velocity losses and, more specifically, that these losses represent around 20% of the ideal ascent delta-V for a typical sea-level launch (i.e. 7.7km/s to LEO), but only around 10% of an air launch.

Another small but positive benefit of air-launch is that the launch point may be chosen to match the inclination of the target orbit. This not only allows for maximum exploitation of Earth's rotation (~400m/s for equatorial orbit), it also reduces trajectory losses by reducing or even removing the need for plane changes to achieve the target orbit.

viii) Operational Benefits

Air-launch offers the only realistic way to operate a space launch system from existing airfields, including the possibility of one day operation out of major civil airports. This is because the launch aircraft uses air-breathing propulsion as opposed to a pure rocket, which enables an enormous reduction in noise during take-off due to the reduced exhaust velocity. However, concepts that use a supersonic military jet will never be as 'quiet' as those that use a subsonic transport and will also be penalised because of their much reduced payload capacity, which will likely be at least one order of magnitude less.

Using an existing military or commercial aircraft also means that the air-launch system can build upon this vehicle's inherent safety, reliability, maintainability and availability. Moreover, these will be extremely valuable if rapid and/or frequent launch is one of the primary system requirements. In addition, it leads to a launch system whose elements are all processed and operated horizontally, which helps to streamline the maintenance and launch workflow as it simplifies access to the vehicle.

As already mentioned, air-launch offers the possibility to choose the launch point to match the inclination of the target orbit. An additional but extremely important benefit is that the launch point can be 'tracked' so that the launch window for rendezvous with an orbiting target can be widened significantly. This not only improves operational flexibility but, as already stated, also reduces the need for plane changes to achieve the target orbit and so has the potential to reduce the size of the upper stage by reducing the on-orbit propellant requirements.

Figure 3 presents a schematic of the operational profile of a generic subsonic air-launch RLV and also shows another operational advantages of this concept, which is that it can use the launch aircraft to ferry the rocket back to the launch site if it should have to land at an alternate. More importantly, it also highlights the potential to use the cruise phase to harvest liquid oxygen, which would require the aircraft to carry an Air Collection and Enrichment System (ACES) and is discussed in more detail within the next subsection. Additionally, it indicates the potential to refuel the aircraft in-flight in order to either reduce its take-off mass or extend its cruise and/or loiter capability.

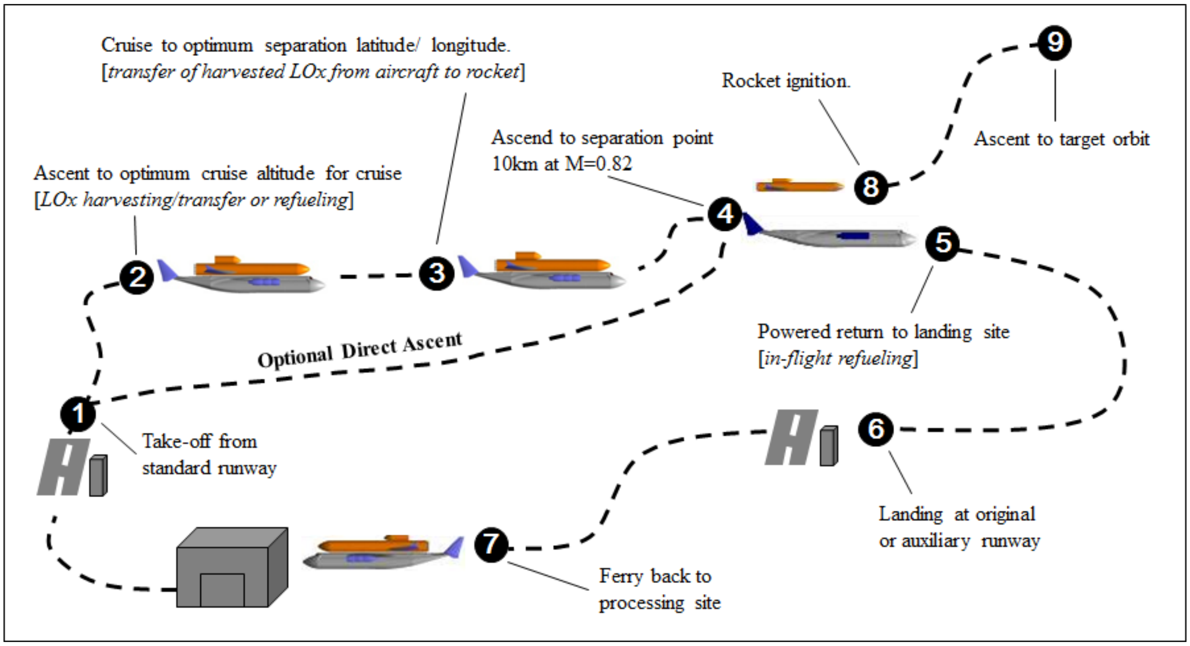


Figure 3. **Subsonic Air-Launch Operations [*optional in-flight LOx harvesting/transfer or in-flight refueling*]**

Another capability that is not obvious from the figure but could have very important operational benefits is the ability to fly the launch vehicle up-range so that the 1st stage booster of any TSTO RLV can return directly to the launch site after staging, thus avoiding the need to fly or glide back up-range. Requiring the booster to fly-back up-range is a very constraining problem for ground launched TSTO RLVs because it either:

- limits the staging to around 3Mn at 30km altitude to ensure the booster has sufficient ‘energy height’ to glide back to the launch site;
- forces the booster to carry extra propellant in order to perform an up-range boost-back manoeuvre;
- forces the booster to carry an additional air-breathing propulsion system in order to fly back up-range;
- requires an additional landing site down-range of the launch site as part of the basic infrastructure.

For an SSTO RLV, it also means that an aborted launch could fly-back directly to the launch site should the abort occurred sufficiently early in the mission. Thus, air-launch also increases the number of abort options and so improves both safety and operational robustness.

ix) Evolutionary Benefits & ACES

Air-launch offers the ability to adapt an existing ground launched system and increase its performance by acting as a high altitude launch platform. As an example, the Pegasus system uses Orion solid rocket motors and adds an a wing structure to ensure a high flight path angle during the initial boost phase in order to maximise its performance. In this way, it may be possible to evolve an existing sub-orbital launcher into an orbital launcher, or at least improve its payload performance.

As increasing vehicle size tends to increase both development and operational costs, air-launch could offer an importance path for commercial ventures. However, the orbital payload performance of any air-launch concept is fundamentally limited by the aircraft’s carrying capacity and, more specifically, its maximum take-off mass. Currently, the world’s largest operational aircraft is Russia’s An-225 but this is a one-off design, based upon a heavily modified An-124, which is likely to be an impractical option for an air-launch system. Commercially available options include the Airbus A380 and the Boeing 747-400, though the former is relatively new and so is very expensive. Two 747-100 aircraft (SCA-905 & SCA-911) were converted to carry the Space Shuttle Orbiter for both test and ferry flights. The mass of the drop/glide tests orbiter (OV-101 Enterprise) was 68Mg, though later orbiters had an empty mass of 78Mg, so there is good reason to believe that a second-hand 747-400 would be a good candidate for an air-launch concept. Table 3 gives an overview of the relevant performance of the most likely candidate aircraft and includes a rough estimate of the maximum payload mass, taken from RD.7, they could deliver to LEO if used as the basis for an air-launch system.

Candidate Aircraft	***External Mass (Mg)***	***Max. P/L to LEO (Mg)***
An-225	200	13.8
A380-800F	120	7.8
747-100 SCA -911	109	7.0
747-400F	140	9.1
Dual-fuselage C-5	350	23.7
Stratolaunch Carrier	120	6.1

Table 3. Candidate Aircraft for Air-Launch

The gross mass of any launch vehicle that uses liquid oxygen (LOx) as an oxidiser will be dominated by the amount of LOx it must carry. Typical oxidiser/fuel ratios of 5.2 and 2.3 respectively for liquid hydrogen (LOx/LH2) and kerosene (LOx/RP-1) fuelled rockets mean that the LOx will account for more than half the launch vehicle's gross mass at take-off. Therefore, it is reasonable to think any design approach that enables the LOx to be loaded *after take-off* should offer a number of significant advantages such as:

- increased payload performance for any given aircraft;
- improved safety during ground operations and take-off due to elimination of the LOx.

A cursory reflection on this idea may well lead one to think it illogical as, without LOx, the rocket cannot function and the mission will be futile. However, more thoughtful consideration shows the idea has some merit and that two approaches appear possible:

i) transfer the LOx in-flight from a 'tanker' aircraft;
ii) utilise the cruise phase to harvest the LOx from the atmosphere.

Though the first approach is the most obvious, it requires not only an additional aircraft but also the ability to transfer very large amounts of LOx in-flight between two independent vehicles, separated by many tens of meters – something that has never been attempted, to date. The second approach also requires technology that has yet to be fielded aboard an aircraft (i.e. the separation and liquefaction of LOx from the atmosphere), though it is a process that is performed routinely on-ground by industrial facilities. However, if an Air Collection and Enrichment System (ACES) could be 'miniaturised' sufficiently to fit inside an aircraft, it offers the possibility of mounting it within the carrier aircraft and so avoids the need for an additional vehicle.

There is actually a long history of RLV concepts that have used air collection as the basis for their propulsion cycle; the earliest being the USAF's Aerospaceplane programme of the late-1950s and early 1960s to develop a hypersonic airplane. Since then, studies of this approach have tended to focus upon SSTO RLVs using the Liquid Air Cycle Engine (LACE), though the resulting designs were always judged to be too complex and heavy, due to the mass of the LACE engine having to be carried all the way into orbit.

ACES can therefore be regarded as a variation of this general approach that avoids most of the performance penalties by placing the heavy machinery outside of the rocket (i.e. within the launch 'platform'). In fact, several patents have been issued for ACES designs [RD.8 & RD.9] and some work has been performed to develop and test representative hardware [RD.10 & RD.11]. Moreover, air-launch concepts based upon such devices have already been proposed that involve both subsonic [RD.10] and supersonic [RD.12] separation of the rocket stage.

A schematic of the ACES cycle and its key components is shown in Figure 4. The operating principle is that, while cruising to the launch point, the ACES device generates liquid oxygen by ingested air from the atmosphere and separating out the nitrogen component through a series of heat exchangers and a rotational fractional distillation unit. The heat exchangers use LH2 to super-cool incoming air, which is either tapped off the aircraft's main engines or drawn in by a dedicated compressor. The resulting LOx is then pumped from the ACES system on the carrier aircraft into the empty LOx tanks of the launch vehicle during flight. The tank holding the LH2 that super-cools the incoming air is sized by the volume of LOx required by the rocket, so this 'collection ratio' (CR) is an important performance characteristic of any ACES concept.

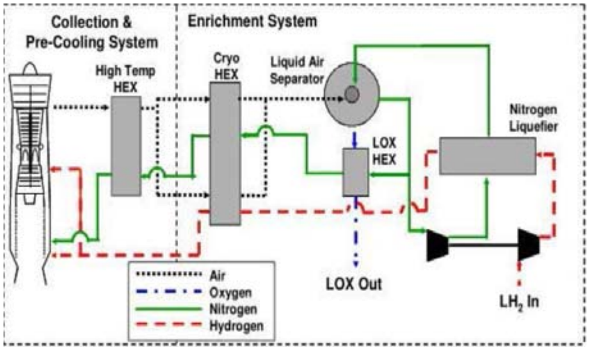


Figure 4. ACES Cycle Schematic [RD.12]

Perhaps because of its novelty, the ACES concept has rarely featured in launch vehicle design studies, though recently it was considered within a NASA-DARPA assessment of air-launch concepts [RD.7]. Although the study did not include ACES within any of its three vehicle point designs, its preliminary screening task did include a trade-off of ACES against others technologies (e.g. high-energy propellants) and found it to be the most promising option, in terms of cost/benefit, to enhance air-launch performance. The results of these findings are considered in more detail in the next subsection, which uses them as the basis for a more detailed assessment of the likely payload performance gains achievable by a design that includes ACES.

2.3 Benefits of ACES

The following high level assessments are presented merely to illustrate the potential benefits of augmenting an existing air-launch concepts with ACES. As such, the absolute magnitudes of the payload performance gains must be considered with a degree of caution and should in no way be thought of as definitive.

Analysis Level	Screening	Screening	PD-2	PD-3
Stage Reusability (1st/2nd)	Yes/No	No/No	No/No	No/No
Stage Fuel Type (1st/2nd)	RP/LH2	RP/LH2	RP/LH2	LH2/LH2
Separation Mach Number (Mn)	---	---	8.4	11.7
Reported Payload Performance to LEO (Mg)				
Baseline	6.4	7.4	5.7	8.1
Baseline + ACES	---	---	7.7	9.9
Baseline + In-Flight LOx transfer	---	---	7.8	9.9
Impact of ACES	---	---	*+35%*	*+21%*
Impact of 1st Stage Reusability	---	*-14%*	---	---
Estimated Payload Performance to LEO (Mg)				
Reusable 1st stage	---	6.4	4.9	7.0
Reusable 1st & 2nd stages	---	5.5	4.3	6.1
Reusable 1st & 2nd stages + ACES	---	7.4	5.8	7.4

Table 4. Payload performance Summary [from RD.7] & Extrapolations

i) DARPA/NASA Study

In 2010, NASA and DARPA commissioned a joint study to assess horizontal launch concepts for military and civilian applications. Its goal was to recommend system concepts for subsonic and supersonic carrier aircraft options and to identify technology gaps for potential investments that included a near-term horizontal launch demonstration. The final results were published in October, 2011 [RD.7].

Payload market projections limited the detailed systems study to expendable concepts because the additional costs of reusability could not be justified for the assumed launch rate of 6 flights per year. Nevertheless, the initial screening analysis did compare the payload performance to LEO and lifecycle costs of a TSTO concept (LOx/RP 1st stage and LOx/LH2 2nd stage) with both a reusable and an expandable 1st stage. These results showed that, although life cycle costs were similar, 1st stage reusability reduced the payload performance by around 14% (i.e. 7.4Mg down to 6.5Mg). A simple extrapolation suggests that a fully reusable design would therefore experience at least another 14% reduction (i.e. around 30% in total) and so reduce the payload performance to around 5Mg.

Following the initial screening, detailed design tools and methods were then used to develop ‘point designs’ for three expendable launcher concepts:

- PD-1, a *three*-stage design using solid rockets on all stages;
- PD-2, a *two*-stage liquid design using LOx/RP on the 1st stage and LOx/LH2 on the 2nd stage;
- PD-3, a *two*-stage liquid design using LOx/LH2 on both stages.

Mass budgets were presented for each point design, along with trajectory, reliability and cost breakdowns that provide a very useful insight upon the impacts of propulsion choice. The point designs were also used as the basis for assessing cost/benefits of alternate technologies, which included both ACES and in-flight LOx transfer. Table 4 presents a short summary of the payload performance to LEO – 185km, due East – of four relevant designs and then estimates the impact of ACES, based upon the results of the technology trades.

As would be expected, the reported performance values from the initial screening were rather optimistic with respect to those of the point designs (i.e. 7.4Mg compared to 5.7Mg). However, the impact of ACES, though clearly beneficial, was somewhat unexpected. The overall O/F ratio of the LH2/LH2 design (i.e. PD-3) means it should carry a larger proportion of LOx than the RP/LH2 design (i.e. PD-2) and so benefit more from ACES, but the results show the reverse (i.e. +35% for PD-2 and +21% for PD-3). Initial suspicions suggest that the density-volume impacts of the LH2 fuel in the 1st stage may have resulted in a heavier dry mass, which is also compounded by the higher separation velocity (11.7Mn for PD-3 and 8.4Mn for PD-2) that shifts the energy split between 1st and 2nd stages and so results in a larger booster.

ii) Parametric Assessments

In order to investigate these interesting results in a little more depth, a spread-sheet model was developed by the author that used vehicle mass and performance characteristics from both the DARPA/NASA study [RD.7] and the Future European Space Transportation Investigations Programme (FESTIP) [RD.13, RD.14, RD.15]. The baseline vehicle design and mission assumptions are listed in Table 5, which includes key performance characteristics and design factors used for assessing the impact of ACES.

The mass breakdown for the PD-2 and PD-3 designs were rescaled to account additional mass for reusability, which included wings and TPS as well as scaling of tanks and fuselage. As the FESTIP concept (FSSC-16) was a fully reusable TSTO design that used LOx/LH2 propulsion on both stages, the design re-scaling mainly accounted for performance effects relating to separation speed and the impact of using RP1 instead of LH2 in

	RLV Design & Mission
1	Baseline mission delta-v to 400km LEO = 7820 m/s
2	Delta-v loss: 1750 m/s from sea-level; 850 m/s from 10km
3	Existing rocket engines (e.g. Merlin 1C & RL10A-4-2)
4	Oxydised/Fuel ratio: 2.28 for LOx/RP; 5.24 for LOx/LH2
5	Isp: 450s @10km for LOx/LH2; 300s @10km for LOx/RP
6	Current available structural materials (i.e. TRL 6+)
7	TPS mass: 5% Booster dry mass; 20% Orbiter dry mass
8	Wings + Empennage + body flap: 7% dry mass
	ACES Characteristics [RD.11]
1	LOx collection plant (LCP) mass / volume = 4Mg / $6m^3$
2	Collection Ratio (CR) = 2.0 (i.e. 1kg LH2 => 2.0kg LOx)
3	LOx collection purity = 90% (i.e. 10% N2)
4	LOx collection rate = 9 kg/sec
5	Isp = 292s @10km for LOx/RP with 90% purity LOx
6	Isp = 435s @10km for LOx/LH2 with 90% purity LOx

Table 5. Air-Launch Model – Assumptions

the 1st stage. The scaling rules applied to these models are outlined in Table 6.

The mass budget and payload performance of the vehicle was modelled for a range of separation speeds by splitting the baseline mission delta-v between the two stages but accounting the full delta-v loss only on the 1st stage. The resulting payload performance for each concept was then estimated for a range of separation speeds, crudely associated with Mach number by a simple linear interpolation, which gave specific point designs as shown in Table 7.

Wing & TPS Mass: Scales directly with materials factor (S) and the change, with respect to the baseline, in the sum of Fuselage, Tank, Systems, and Engine masses (Ms3 + Ms4 + Ms5 + Ms6).

Fuselage Mass: Scales directly with materials factor (S) and the change, with respect to the baseline, in the propellant tank mass (Ms4).

Tank Mass: Scales directly with materials factor (S) and change, with respect to baseline, in propellant mass (Mf) raised to the power of 2/3.

Systems & Engine Mass: Scales directly with the change in the propellant mass (Mf), with respect to the baseline.

Table 6. Air-Launch Model – Scaling Rules

When plotted together, these points produced curves that indicated an 'optimum' split for each concept and these are shown in Figure 5. In addition, each 'optimum' was then re-scaled to assess the impact of improved ACES performance with respect to the Collection Ratio and LOx purity. The impact of using a less capable carrier aircraft was also assessed, assuming the carrying capacity of a 747-100 instead of a 747-400 (see Table 3), while the impact of assuming more advanced structural materials (i.e. 10% lighter) was also investigate to show how far the payload performance from a 747-100 could be 'evolved'.

The limits of this relatively simple modelling are indicated by the payload performance differences between the PD-2/PD-3 and FSSC-16 results, which should be the same if the models were truly equivalent. Nevertheless, the curves are reasonably coherent and so their differences can be taken to indicate the level of modelling uncertainty and are shaded accordingly. More importantly, the models do show a consistent benefit of the ACES concept, which increases the baseline payload on the order of 40%. This value is in reasonable agreement with the DARPA/NASA study findings (Cf. Table 4.), although their result for the all-LH2 design (i.e. PD-3 with only a 21% increase) does seem rather low considering its much higher oxidizer/fuel ratio.

As mentioned before, the analysis was performed to simply illustrate the potential benefits of augmenting an existing air-launch concepts with ACES and should not be thought of as definitive. Though promising, these results have yet to include other design and operational issues that may have both positive and negative impacts, such as:

- the need to cruise for ~4 hour in order to harvest the required mass of LOx, based upon a nominal collection rate of 9kg/s;
- effects on carrier aircraft (e.g. lift, stability and cruise range) of increasing mass during LOx harvesting, which may reach as much as 20%;
- using sub-cooled hydrogen (e.g. stored at 16K instead of 20k, with a higher para-hydrogen fraction) to increase both its density and heat absorption capacity, which promises to reduce both LH2 tank size and LH2 boil-off during cruise while also increasing the ACES collection ratio (CR);

Separation Mach number (Mn) = 12	***Air-Launched***	***+ACES***		***Air-Launched***	***+ACES***
Materials density scaling factor (S) [%]	1.00	1.00		1.00	1.00
TSTO Booster Details			***TSTO Orbiter Details***		
Specific Impulse (Isp) [sec.]	450	435	Specific Impulse (Isp) [sec.]	450	435
Rocket equation factor (R=Exp(dV/Isp/g)	2.5968	2.6836	Rocket equation factor (R=Exp(dV/Isp/g)	2.7448	2.8421
TSTO Gross Mass (MTg=MBp+MBs+MBf) [kg]	138576	200848	Orbiter Gross Mass (M0g=MOp+MOs+MOf) [kg]	34857	48908
Booster Dry Mass (MBs=SUM(MBs1:MBs6)) [kg]	18508	25933	Orbiter Dry Mass (MOs=SUM(MOs1:MOs6)) [kg]	5379	7139
Wings Mass (MBs1) [kg]	*1414*	*1981*	*Wings Mass (MOs1) [kg]*	*615*	*817*
TPS Mass (MBs2) [kg]	*1014*	*1421*	*TPS Mass (MOs2) [kg]*	*1090*	*1446*
Fuselage Mass (MBs3) [kg]	*3390*	*4399*	*Fuselage Mass (MOs3) [kg]*	*1251*	*1588*
Tank Mass (MBs4) [kg]	*3509*	*4555*	*Tank Mass (MOs4) [kg]*	*1508*	*1914*
Systems Mass (MBs5) [kg]	*2020*	*2987*	*Systems Mass (MOs5) [kg]*	*677*	*968*
Engines Mass (MBs6) [kg]	*7162*	*10590*	*Engines Mass (MOs6) [kg]*	*854*	*1222*
FSSC-16 Defined Propellant Mass (MBf) [kg]	85211	126006	FSSC-16 Defined Propellant Mass (MOf) [kg]	22158	31700
Booster Payload (MBp=MOg, Orbiter Gross Mass) [kg]	34857	48908	Resultant TSTO Payload (MOp) [kg]	7320	10070
Booster delta-V loss (LdV) [m/s]	850	850	Orbiter delta-V loss (LdV) [m/s]	---	---
Booster delta-V (BdV) [m/s]	3363	3363	Orbiter delta-V (OdV) [m/s]	4457	4457
ACES Details			***TSTO System Details***		
LOx fraction of TSTO gross mass	65%	66%	Total Mission Delta-V [m/s]	8670	8670
Total LOx propellant [kg]	90165	132436	TSTO Dry Mass (MTs=MBs+MOs) [kg]	23887	33072
LCP mass [kg]	---	4000	TSTO Gross Mass (MTg=MTs+MBf+MOf+MOp) [kg]	138576	200848
LH2 for ACES [kg]	---	66218	TSTO Gross Mass without LOx [kg]	---	68412
ACES 'kit' Mass [kg]	---	70218	TSTO Gross Mass without LOx + ACES [kg]	---	**138630**

Table 7. TSTO Performance Analyses - FSSC-16 using 747-400

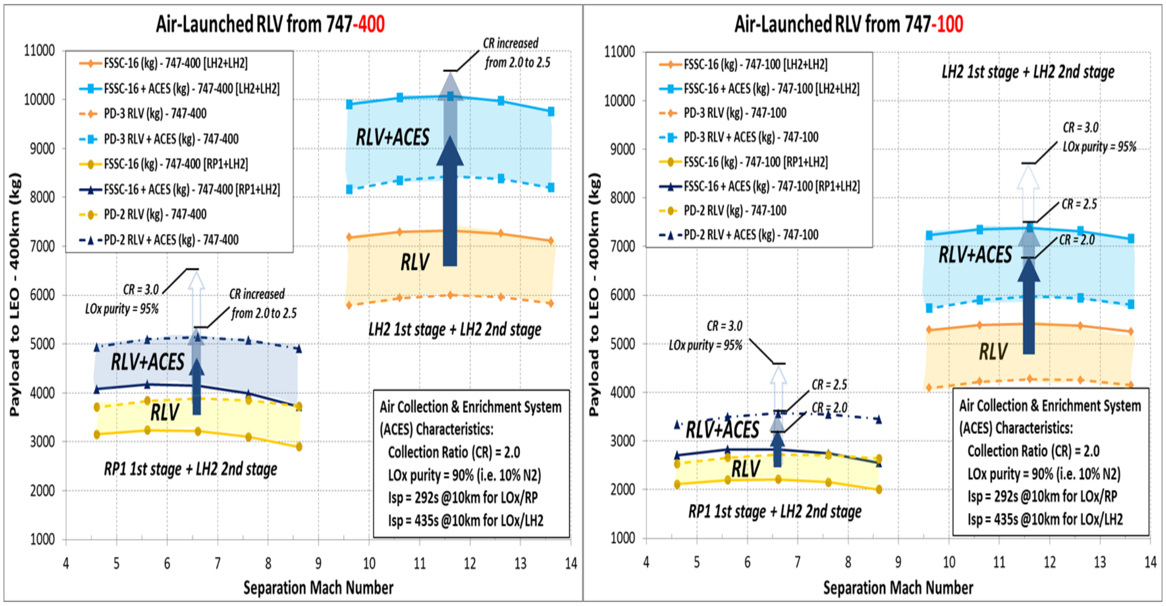


Figure 5. Air-Launched RLV – Payload Performance Sensitivity

- using hydrogen to fuel the aircraft's gas turbines [RD.10] and also to boost their thrust, via afterburning in the bypass duct, to increase flight-path angle at separation and so improve payload performance [RD.16].

Nevertheless, the current results give some confidence to the idea that an existing commercial aircraft could be used as a platform for air-launching a fully reusable TSTO rocket capable of placing 'commercially significant' payloads (i.e. ~4000kg) into low Earth orbit – a subject that is discussed in more detail within the next main section.

iii) Conclusions

The inherent operational principles the ACES concept (i.e. aircraft take-off without LOx) increases safety and makes use of the cruise phase the launch point to harvest LOx in a synergistic manner. More importantly, it offers a realistic way of 'evolving' an existing or planned air-launch RLV by increasing its payload performance to LEO by around 35% or more. In addition, it also holds out the potential to increase this to 80% or more if key ACES characteristics can be improved (i.e. Collection Ratio and LOx purity). Such a major performance boost could also widen the potential range of aircraft that could prove suitable for air-launch, which may be a very important factor for any future commercial venture – something that is discussed in more detail within the next section.

3. OPERATING BEYOND THE LIMITS

This final section highlights the radical improvements in operational architecture afforded by a subsonic air-launched RLV. It shows how such an RLV with a relatively modest launch performance of between 4-6t into low Earth orbit could be capable of supporting the majority of current and future launch demands by forming the key element of a fully reusable space transportation infrastructure. It identifies the RLV technologies and systems that are common to both orbital transfer vehicles and Lunar landers, as well as the synergistic way their development and production could be coupled in order to both reduce their costs and to increase their reliability, availability and safety. More importantly, it indicates how all these factors can be combined to radically improve the business case for pursuing these ventures as a commercial enterprises, funded almost entirely by private investment.

3.1 LEO Operations & Beyond

The science fiction writer Robert A. Heinlein is quoted as saying that "once you reach low orbit, you're halfway to anywhere in the Solar System", referring of course to mission energy rather than distance. Viewed in this way, it's clear to see why many regard Earth-to-orbit launch vehicles as *the* key enabler to opening up space for all humanity. However, simply reaching LEO is only part of the problem because most missions, both in and beyond LEO, are severely constrained by issues of both cost and schedule (i.e. operational factors such as the availability and frequency of launch are just as important as low cost). While reusing a launch vehicle may help reduce costs by eliminating the need to procure new hardware, the cost of maintaining both the vehicle and its associated ground infrastructure (i.e. facilities and people) may offset any savings if its flight rate is too low. Indeed, this was the critical factor that undermined the cost effectiveness of NASA's Space Shuttle, which was 'sold' on the basis that it could support 64 flights/year.

i) Availability & Launch Windows

Beyond launch frequency and the obvious requirements for reliability and safety, the availability to launch at short notice and to support as wide a range of launch azimuths and launch windows as possible are also important factors for missions requiring interception and/or rendezvous with an on-orbit target. Air-launch offers a very attractive and realistic solution to these requirements and Figure 6 illustrate this by showing how the cruise range increases the number of launch opportunities (i.e. from two per day from a fixed launch site to more than six for air-launch) and, by definition, a wider range of launch azimuths because it can move the launch to a point where the launch ascent ground track will not fly over populated regions (i.e. over open oceans). It also shows a typical 'dog-leg' manoeuvre that may be required when operating from a fixed launch site in order to enable injection into a specific orbital plane for rendezvous, which an air-launch can reduce significantly or even eliminate.

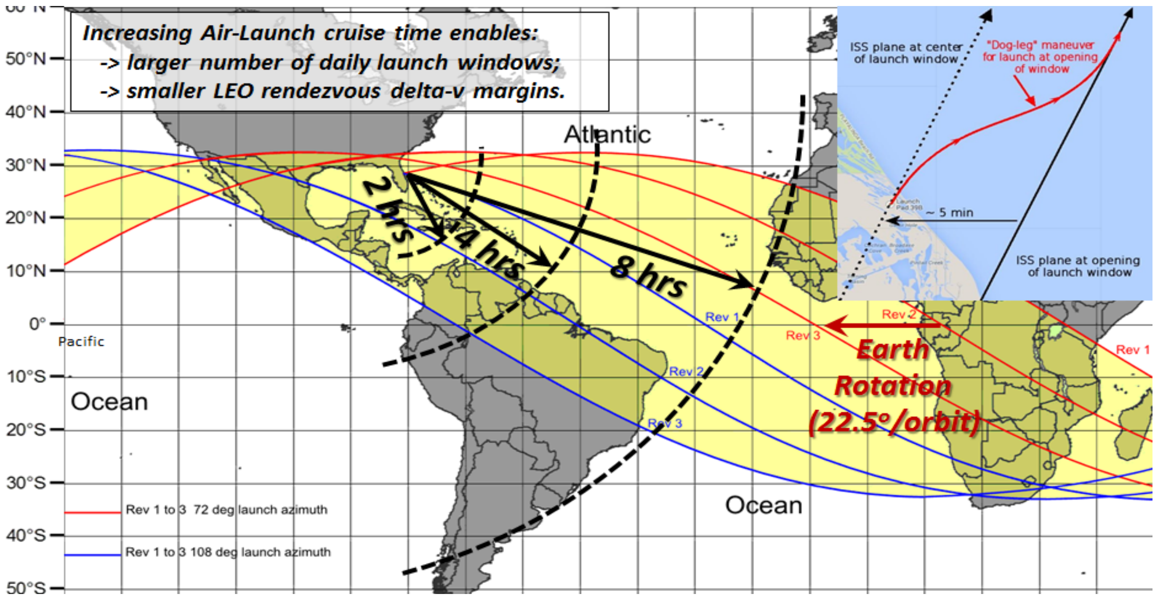


Figure 6. **Impact of Air-Launch cruise time on launch LEO windows**

These important operational benefits are why many concepts for rapid reaction launch vehicles have involved Air-launch. This is significant because military programmes like DARPA's XS-1, which aims to develop a reusable first stage of a space transport system that can reach Mach 10 or higher and fly 10 times in 10 days, see air-launch as a likely solution and so may represent an important stepping stone towards a viable air-launched RLV that could eventually be put into commercial service.

ii) Logistics & Crew Transportation

The success of any commercial venture requires both the capability to provide a service and a market that needs this service. More importantly, the size of the market must be sufficient to justify the initial investment while its 'elasticity' will be important to ensure growth and secure future investment.

ISS Servicing Vehicles	***LEO Mass (Mg)***
Soyuz (Government – Russian)	7200
Progress (Government – Russian)	7200
ATV (Government – European)	20200
HTV (Government – Japanese)	19000
Dragon (Commercial – SpaceX)	6000
Cygnus (Commercial – OSC)	4500

Table 8. **ISS servicing vehicles mass in LEO**

Beyond individual scientific satellites, primarily in polar orbits to support Earth observation missions, the International Space Station (ISS) currently represents the only significant market in LEO that needs frequent and routine transport services. They are currently supported by a fleet of both government and commercial vehicles, which are listed in Table 8. As can be seen, a number of them have an injected mass into LEO that appears compatible with the payload performance of an air-launched RLV that uses ACES. This suggests that ISS logistics resupply may be potential market for any commercial venture, especially as two of these vehicles are already built and operated by commercial companies that have secured commercial resupply contracts with NASA. Note that the reusable X-37B, which has a mass of just under 5000kg, could also represent be another potential LEO payload though its military nature may make this possibility somewhat more unlikely.

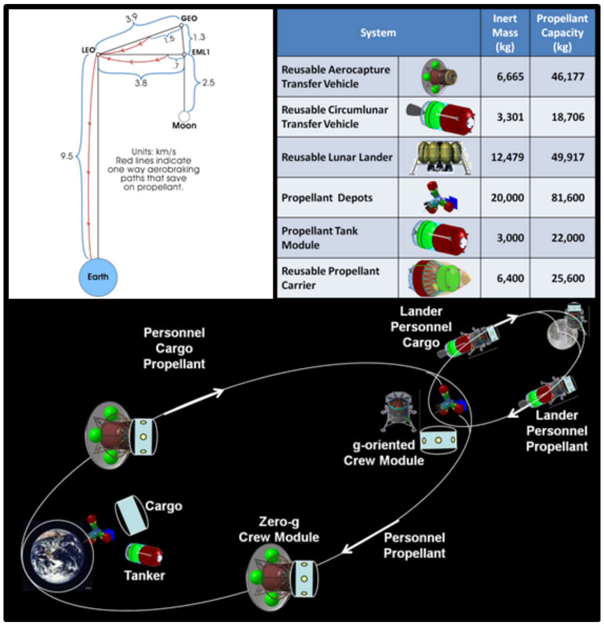
Future commercial LEO space stations, like those planned by Bigelow Aerospace, represent another potentially lucrative market because they are predicated upon the availability of routine and frequent launch services. Like the ISS, they will also require the transportation of crew and so demand a demonstrated level of safety much greater than that needed for cargo re-supply. However, such levels should be more easily achievable via a fully reusable launch vehicle because its inherent value will demand better operational contingency options in addition to a crew escape system.

iii) Propellant Depot Resupply

A future LEO mission that may prove far more lucrative than those already mentioned is as the first leg of a space transportation infrastructure that consists of a set of operational nodes and transfer vehicles, namely:

- Space stations and human-tended experimental platforms;
- propellant depots to support missions both in, around and beyond LEO;
- short-range orbit maneuver vehicles (OMVs) to capture and transfer payload in and around LEO;
- long-range orbit transfer vehicles (OTVs) for travel to/from GEO and lunar orbits;
- OTVs fitted with legs and throttlable engines for lunar surface descent/ascent missions.

Details of one such space transportation architecture are shown in Figure 7, which also presents the delta-v required to reach each node and the representative masses of each of the key elements. Interestingly, the dry mass of many of these elements falls within the payload launch performance of an air-launch RLV using ACES. However, a more important point to note is that the majority of each element's mass is propellant.



System		Inert Mass (kg)	Propellant Capacity (kg)
Reusable Aerocapture Transfer Vehicle		6,665	46,177
Reusable Circumlunar Transfer Vehicle		3,301	18,706
Reusable Lunar Lander		12,479	49,917
Propellant Depots		20,000	81,600
Propellant Tank Module		3,000	22,000
Reusable Propellant Carrier		6,400	25,600

Figure 7. LEO-Lunar transport architecture [RD.17]

Analysis of the launch requirements for the build-up and operation of such an infrastructure [RD.17] show that the vast majority (~80%) of the mass launched into LEO is propellant. This is very significant because propellant can be infinitely subdivided and so would be the ideal payload for a small RLV capable of supporting both rapid and frequent launch and rendezvous missions. It therefore suggests that most of this architecture could be either launched and/or serviced by a subsonic air-launched RLV.

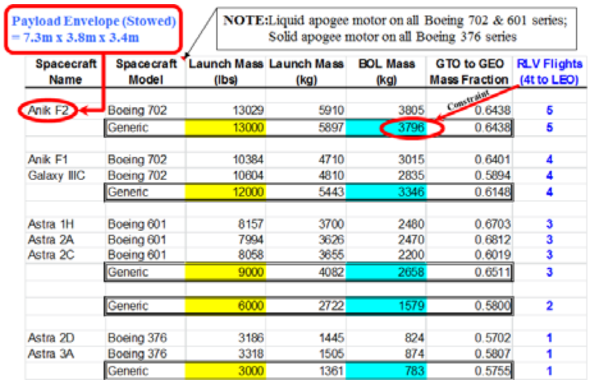
3.2 Commercial GEO Operations

Unfortunately, the markets identified so far are considered insufficient to justify the commercial development of a subsonic air-launched RLV because they are either too small or too speculative. Currently, the largest and most lucrative commercial launch market sector is the delivery of geostationary communications satellites (GEO comsats) into geosynchronous transfer orbit (GTO), with a perigee height ~200km and an apogee height ~ 36000km.

Any commercial business case for developing a subsonic air-launched RLV should therefore assess the viability of addressing the GEO comsat market sector, even though a cursory look at the LEO payload performance estimates presented in Figure 5 may appear to rule this out.

i) GEO Comsat Characteristics

An analysis of typical comsat mass characteristics is presented in Table 9 and indicates that the majority have a beginning of life (BoL) mass ~35% below their launch mass. This is because a significant fraction of their launch mass is propellant that they use during their transfer burn from GTO to GEO. More importantly, it suggests that any vehicle capable of delivering a 4t payload into LEO could service the majority of currently planned GEO comsats if some sort of kick-stage were available on-orbit to perform the LEO to GEO transfer.


Payload Envelope (Stowed) = 7.3m x 3.8m x 3.4m

NOTE: Liquid apogee motor on all Boeing 702 & 601 series; Solid apogee motor on all Boeing 376 series

Constraint

Spacecraft Name	Spacecraft Model	Launch Mass (lbs)	Launch Mass (kg)	BOL Mass (kg)	GTO to GEO Mass Fraction	RLV Flights (4t to LEO)
Anik F2	Boeing 702	13029	5910	3805	0.6438	5
	Generic	13000	5897	3796	0.6438	5
Anik F1	Boeing 702	10384	4710	3015	0.6401	4
Galaxy IIIC	Boeing 702	10604	4810	2835	0.5894	4
	Generic	12000	5443	3346	0.6148	4
Astra 1H	Boeing 601	8157	3700	2480	0.6703	3
Astra 2A	Boeing 601	7994	3626	2470	0.6812	3
Astra 2C	Boeing 601	8058	3655	2200	0.6019	3
	Generic	9000	4082	2658	0.6511	3
	Generic	6000	2722	1579	0.5800	2
Astra 2D	Boeing 376	3186	1445	824	0.5702	1
Astra 3A	Boeing 376	3318	1505	874	0.5807	1
	Generic	3000	1361	783	0.5755	1

Table 9. Typical GEO ComSat mass characteristics

The key to servicing these markets with such a small reusable launcher is, therefore, the on-orbit assembly of a kick-stage capable of delivering the comsat directly into GEO, as illustrated in Figure 8. Such an operation would demand a rather special set of vehicle performance characteristics, namely the ability to perform:

- orbital rendezvous and docking;
- in-orbit propellant transfer or assembling sets of plug-in propellant modules;
- multiple launches within a short time period (e.g. a few days) to avoid effects of atmospheric drag, if low altitude orbits are used.

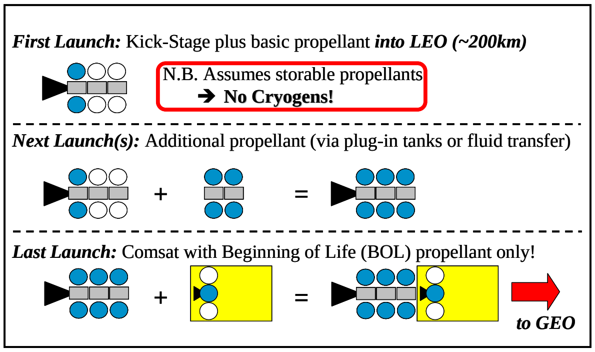


Figure 8. Orbital Assembly Scenario (Std. Comsat)

Such a vehicle would require an evolution of the basic orbital vehicle's capabilities but the upgrades to enable rendezvous and docking are not considered too major a technological challenge since they have already been demonstrated successfully by both Japanese and US spacecraft (i.e. ETS VII and Orbital Express). However, it is very unlikely that GTO customers would be willing to risk their satellites being launched in this manner until its operational complexity had been thoroughly proven, even if the launch price was half that of existing ELVs!

Nevertheless, GEO comsat missions are currently the most commercially viable market sector for any new launch vehicle and so this operational scenario is used as the basis for a brief business case analysis, which is described in more detail in the following sub-sections.

ii) Business Model Assumptions

Justifying the commercial development of a subsonic air-launched RLV requires more than just an assessment of the vehicle's design, operations and performance. It also requires an assessment of the associated costs and, more importantly, the revenue that it can be expected to generate from selling its services to commercial customers.

Development and operating costs can be based upon past estimates but will be highly uncertain. However, they can be used to bound the analysis and so indicate the range of values required to justify any investment.

Assessment of the potential market can be based upon data in RD.18, which gives annual projections for the number of GEO satellites within different mass groups and is summarized in Table 10. These market projections and estimated costs can then be used to construct a business model spreadsheet that generates an Income Statement and a Cash Flow Statement for any given scenario, which enables the performance of the venture to be assessed [RD.19].

Satellite Mass (kg)	Total No. (2013-2022)	Annual Average (2013-2022)	% of Total
Below 2200	29	2.9	13%
2200 to 4200	62	6.2	27%
4200 to 54000	46	4.6	20%
54000 and above	91	9.1	40%
Total Forecast	228	22.8	100%

Table 10. GEO ComSat size forecast [RD.18]

From the investors' point of view, the key is to get an acceptable return on any investment. A common yardstick to measure this is the internal rate of return (IRR), which is defined as *"the rate of return at which the present value of the cost of the investment and the present value of the future income stream equate"* – in simplistic terms, this is somewhat akin to the annual interest rate of a savings account. For high risk aerospace investments, the IRR has to be 20-30% for such projects to merit serious consideration. Another parameter of interest is the end-of-year (EOY) cash balance, which gives a good indication of the level of cash assets a company is generating and, more importantly, allows the payback period – the time needed to recoup the initial investment – to be assessed.

There are three or four fundamental parameters that drive the results: the available *market*; the *cost of services* (development and direct plus indirect operations cost); the revenue that can be generated by selling services at a given *price per flight*; and the *annual number or flights*. Other factors such as depreciation, taxes, amortisation and insurance generally have a relatively minor impact on the final result. Therefore, in order to simplify the analysis in the face of so many unknown or ill-defined values, a number of shortcuts or approximations were applied.

a) All up-front *investment* was expensed (i.e. put down as business expenses) in the same year it was applied. Strictly speaking, investments related to flight hardware and other capitalised equipment should be depreciated over their expected lifetime, however, as no useful breakdown is available here, they were expensed as they were incurred.
b) *Depreciation* was not accounted since it has only a marginal effect upon taxable income – it may change a 20% IRR into a 23% IRR, but not much more – and only occurs after the assets are paid for and in use.
c) Vehicle insurance, which could have been addressed by including at least one additional vehicle as an added expense (i.e. "self-insurance" against hull replacement), was simply taken as a nominal cost of $0.2M per flight against third party liability.

d) *Interest* was taken at a nominal annual rate of 10%, though this can vary and should be put to zero if the venture can be funded entirely by equity rather than debt, as assumed here. A more reasonable estimate for an all debt scenario could be 12-13%, which is essentially what it cost before taxes to borrow money at a corporate level in the US during the late-1999s, though this would have had minimal impact on the results.

e) *Tax*, which was accounted after interest and before the net income, was written-off when the venture incurred losses in the early years – in other words, it got a "tax credit" which could either be used to offset future gains or shared amongst the investors to offset gains in other investments. Therefore, assuming losses could be expensed against other gains, the net effect of taxes in the early years – especially during the development phase, which covers about three years – was to reduce the total out-of-pocket investment.

In addition, a set of financial and operational business parameters, shown in Table 11, was also developed in order to bound the business model and to investigate its sensitivity against changes in the baseline assumptions. A key point to note here is that the price per flight was only allowed to vary up to a maximum of $20M to ensure a reasonable margin against competing ELVs (e.g. Falcon 9 with a launch price of around $60 million for 4900kg GEO comsat, which would require 4 RLV launches). Also, as the kick-stage was assumed to be expendable, its cost were included within the overall variable cost and estimated to be around $2 million.

iii) The R LV Business Case

Business Parameter	***Value range***
Total R&D investment	$500-1000 million
Fleet size	3 operational vehicles
Price per flight	$10-20 million
Variable cost (per flight)	$2-10 million
Fixed annual operating cost	$40 million
Income tax rate	40%-60%
Interest rate	10% (for debt finance)
Annual flights (fleet max.)	100
First commercial launch	4 years after start

Table 11. RLV business model parameters

Assuming the maximum payload mass for the air-launched RLV is 4000kg, the number of flights needed for each class of GEO comsat are shown in the far right column of Table 9. This number was then uses to calculate the number of flights per year if 100% of the projected market was captured, which gave an average of 85 per year. However, a capture factor – nominally taken as 40% – was then applied to account for the fact that in the real-world a 100% market capture is considered as infeasible because at least one other competitor must be considered in any commercial scenario. The resulting annual flight rate, along with specific values for each of the business factors identified in Table 11, was then used to calculate the IRR and EOY cash balance over a ten year period from the venture's start.

This exercise was repeated for variations to the following key parameters in order to assess their overall impact:

- capture factor (25%, 40%, 55% & 70%);
- investment ($1000 million, $750 million & $500 million);
- price per flight ($10 million, $15 million & $20 million).

The results of this 'sensitivity' analysis are presented in Figure 9, which shows the evolution of IRR and EOY cash balance over the a ten year period from the venture's start with respect to a sub-set of the above values.

The plots show the impact of increasing market share (25% to 55%) and reducing launch price ($20M to $15M) for the $1000 million investment case, but also include one $500 million case ($15M price & 40% market) to illustrate the very significant impact of a reduced investment requirement.

Assuming that an IRR above 20% will be sufficient to justify investment in the venture, it is clear that an investment requirement of $1000 million *would not be acceptable* if the price per flight was $15 million (i.e. the price needed to be competitive with Falcon 9) and market capture was held at 40%. However, it *would become acceptable* if the market share could increase to 55% or the investment requirement was substantially reduced (e.g. down to $500 million).

iv) Observations on the Business Case

Clearly, this business case analysis is far too crude to judge the true commercial viability of such a venture. However, given these results, the general conclusion is that there are some good reasons for thinking that a fully commercial air-launched RLV venture may prove to be successful, particularly if its investment requirements can be kept around the $500 million mark and its launch price can be kept below $15 million. ***The major caveat here is that a development cost of $500 million appears extremely low for vehicles with such a payload performance, based upon current launcher development experience***.

As a point of comparison, the estimated development cost of the PD-2 concept [RD.7] was $940 million. However, being expendable, its per flight cost was $120 million, of which $112 million was for the production of each new vehicle and $8 million was for launch operations. Obviously the development costs for an RLV will be somewhat higher but the launch operations costs should be similar or better, which lends come credibility to the results of this rather simplified business case assessment.

One important observation here is that the business case can be improved significantly if some degree of leverage can be applied to reduce the initial investment.

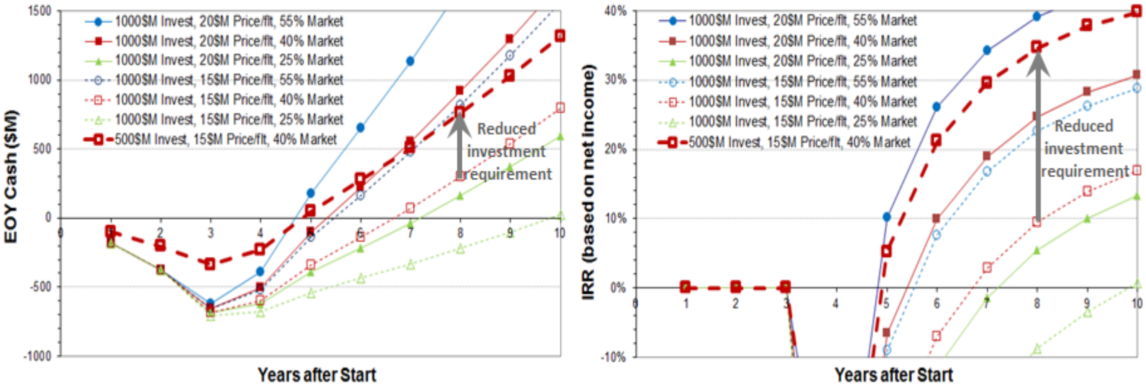


Figure 9. **Air-Launched RLV business base sensitivity analysis**

One obvious way to achieve such leverage would be to develop key elements of the system through a separate venture or business phase. DARPA's XS-1 initiative may be provide just such a leverage, while a business venture to service the nascent sub-orbital market may represent another. Whether these would be practical or sufficient to leverage development of an orbital RLV has yet to be determined. However, there are a number of real-world examples, both current and past, that may justify this approach, for example:

- SpaceX leveraging their NASA contracts to support development of the Dragon capsule;
- Boeing leveraging their USAF contracts for the KC-135 to support development of the 707.

Whatever the form of the leverage, this analysis serves to underscore the value of building up any space launch business in a series of small steps rather than one giant leap.

4. CONCLUSIONS

This paper has identified the key reasons why space activities have so far failed to achieve the great expectations set out at the dawn of the space age, over half a century ago. It has also described the ways in which small groups of people are attempting to change the current paradigm but, in doing so, has tried to indicate the enormity of the challenges they must overcome in order to realize their ultimate goal.

Having identified access to LEO (i.e. launch vehicles) as one of the main constraining factors for in-space developments and operations, it has assessed one very promising launch vehicle concept (i.e. the air-launched RLV) and identified potential technologies that could produce significant improvements in both its safety, operability and payload performance.

Based upon these insights, it has then shown how a relatively small air-launched RLV could improve space access and thereby enable new in-space transportation infrastructures that will deliver a significant increase in future space-based operations for the purposes of both exploration and resource exploitation. In short, it has shown that we do not necessarily need big launchers to enable big space operations!

In addition, it has also tried to show that such developments could be driven by commercial investments, though there is still much scope for governments to foster them in a synergistic manner by funding new capabilities (e.g. DARPA's XS-1) or procuring operational services (e.g. NASA's Commercial Resupply Services).

One major caveat of these results is that subsonic air-launch should be regarded as an enabling capability, since the majority of the technology/cost challenge resides within the RLV that performs the bulk of the work needed to place any payload into orbit. Nevertheless, it does relax the RLV design constraints significantly and so makes these challenges far more tractable, realistic and affordable.

As a final synthesis of all these ideas, an attempt has been made to consolidate them together by briefly sketching out some likely steps for achieving this new space paradigm. Table 12 presents these steps and includes a tentative timeline, covering the next decade, along with their likely impacts upon future in-space activities.

Clearly, many of these steps will slip, change or may never be realized. In fact, this new space paradigm may prove to be unachievable because of fundamental constraints that have yet to be discovered. So, although there is good reason for cautious optimism, it would be better to regard such developments as experiments within a process of Darwinian evolution rather than the milestones of some overarching space program, established by the directive of a government space agency.

Nevertheless, given the current number of new space ventures and their success to date, it seems reasonable to believe that some may manage to "boot-strap" themselves into orbit within the next decade and finally begin to open the space frontier in order to harness the infinite resources of outer-space for the benefit of all mankind.

Timeframe	*Future Steps*	*Impacts*
Proof of Concept (2012-2018)	COTS payload services to ISS (~2012)	MODEST: Increased microgravity experimentation
	Frequent reusable suborbital services for tourist passengers (~2016)	SIGNIFICANT: Rapid flight vehicle turn-around and passenger training
	COTS crew rotation to ISS (~2018)	MODEST: Improved human in-situ servicing and support
Concept Maturation (2018-2025)	Commercial space station & ELV support (~2020)	SIGNIFICANT: Increased human in-situ servicing and support
	Air-launched RLVs for ISS cargo and GEO satellite launch (~2020)	VERY SIGNIFICANT: Increased satellite missions and space infrastructure development
	Air-launched RLVs for passenger services to ISS and commercial stations (~2023)	VERY SIGNIFICANT: Increased human in-situ activities supporting complex space developments
	In-orbit propellant depots for crewed exploration missions (~2025)	VERY SIGNIFICANT: Enables deep space exploration missions and exploitation of space resources

Table 12. Steps towards a new space paradigm

REFERENCES

[1] Space Foundation publication “The Space Report 2012” URL: http://www.spacefoundation.org/programs/research-and-analysis/space-report/20-space-economy

[2] “Wal-Mart Annual Report, Eleven-Year Financial Summary”, p.26/27 URL: http://www.walmartstores.com/sites/annual-report/2012/WalMart_AR.pdf

[3] “The Commercial Space Transportation Study, 1994” URL: http://www.hq.nasa.gov/webaccess/CommSpaceTrans

[4] “NASA ASCENT Study Final Report”, Futron Corporation 2003 URL: http://www.futron.com/pdf/resource_center/reports/ASCENTFinalReport_V1.pdf

[5] NASA Get Away Special Wikipedia page URL: http://en.wikipedia.org/wiki/Getaway_Special

[6] “Salt, D.J. “Could a subsonic air-launched RLV enable a paradigm shift in space operations?”, AIAA-2014-1897 SpaceOps 2014, Pasadena, California, 5-9 May 2014

[7] “Horizontal Launch: A Versatile Concept for Assured Space Access”, NASA SP 2011-215994 URL: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120000791_2012000836.pdf

[8] Breugelmans F., et al. “Process and device for collecting air, and engine associated therewith” US Patent 6644016 B2, Issued November 11, 2003 URL: http://www.google.co.uk/patents/US6644016

[9] Giffin R.G., “Methods and Systems for Operating Oxydizer Systems” US Patent US8127527 B2, Issued Mar 6, 2012 URL: http://www.google.com/patents/US8127527

[10] Verstraete D., Bizzarri D., Hendrick P. “In-Flight Oxygen Collection for a Two-Stage Air-Launch Vehicle: Integration of Vehicle and Separation Cycle Design” Progress in Propulsion Physics 1 (2009) 551-568 (DOI: 10.1051/eucass/200901551) URL: http://www.eucass-proceedings.eu/articles/eucass/pdf/2009/01/eucass1p551.pdf

[11] Crocker A. M., et al. “Alchemist - An Enabling Technology for Low Cost Access to Space” NASA Phase I Small Business Innovation Research (SBIR) contract Award ID: 51951, Program Year: 2001 URL: http://www.sbir.gov/sbirsearch/detail/89845

[12] Crocker A. M., et al. “ACES: An Enabling Technology for Next Generation Space Transportations” AIP Conf. Proc. 699, 213 (2004) & AIAA-2003-4890, July, 2003 & IAC-03-S.5.03, Sept/Oct, 2003 URL: http://dx.doi.org/10.1063/1.1649577

[13] Dujarric C., “Possible Future European Launchers – A Process of Convergence”, ESA Bulletin 97 – February 1999 URL: www.esa.int/esapub/bulletin/bullet97/dujarric.pdf

[14] Stadler R. “Results for a Fully Reusable TSTO-Launch Vehicle Concept”, AIAA-98-1504

[15] Bayer M. “Description of the FESTIP VTHL-TSTO System Concept Studies” unpublished study report URL: http://thehuwaldtfamily.org/jtrl/research/Space/Launch/Vehicles/FESTIP-FESTIP-Two Stage To Orbit Launch Vehicle, Bayer.pdf

[16] DeLong D., Stuhlinger E. “Proposed Concept for a Spaceplane” AAS 86-463, AAS Proceedings Volume 64, Part 1 & Spaceflight (ISSN 0038-6340), vol. 29, Dec. 1987, p. 413-416

[17] Bienhoff D. “From Importing to Exporting: The Impact of ISRU on Space Logistics” AIAA 2011-7112, AIAA Space 2011 Conference & Exposition, Long Beach, California, 27-29 September 2011 URL: http://arc.aiaa.org/doi/abs/10.2514/6.2011-7112

[18] “2013 Commercial Space Transportation Forecasts”, a report by the FAA’s Associate Administrator for Commercial Space Transportation (AST) and the Commercial Space Transportation Advisory Committee (COMSTAC), May 2013 URL: http://www.faa.gov/about/office_org/headquarters_offices/ast/media/2013_GSO_NGSO_Forecast_Report_June.pdf

[19] “Salt, D.J., & Lindroos, M, “The Business Case for Small RLVs”, TN200, Issue 3, 20th January, 1999 (deliverable item under ESA Contract No. 970801).