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Australian Space Port for Small Satellites: Launch Concept

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Abstract

The purpose of this study is to design a launch vehicle for small satellites with maximum commonality suitable for ground and air launch. Type of air launch operations and potential launch sites in Australia, such as Woomera and Northern Territory, were also investigated. Common rocket equation and System Tools Kits (STK) were used in design process. Launch vehicle geometry and additional features, such as strap-on boosters for ground launch were studied and compared with existing launch vehicles with similar performance. The carrier aircraft, B757-200 was selected as the carrier aircraft for air launch due to its performance and its availability on the used-aircraft market.

Keywords: Small satellites, Air launch methods, Launch vehicle

Introduction

The design of small satellites is becoming increasingly popular with university research groups, but also with larger organisations, such as defence and telecommunication companies. Particularly nanosatellites (< 10 kg) are becoming popular in terms of mission frequency and variety, use of off-the-self technology and cost effectiveness.

The comparison between ground and air launch methods showed differences in terms of safety and performance. Air launch methods can provide a higher launch frequency due to aircraft-like operations from any suitable airport, while ground launch methods are constrained to a launch pad with restrictions on launch direction and orbit inclination. Air launch offers more mobility and flexibility. The required velocity to reach orbit (ΔV) for altitude launch is slightly less than for ground launch, ie. 400-600 m/s [1]. This can reduce cost for fuel and a small launch vehicle. However, Orbital ATK is currently the only commercial air launch service provider with a Pegasus launch vehicle attached to the bottom of a L-1011 TriStar aircraft. Other organisations, such as Virgin Galactic and Stratolaunch are proposed air launch services.

Significant benefits of ground launch are safety of operation, less crew related to launch activities, launch vehicle is not limited in size or mass and less insurance cost.
This study acknowledges the benefits and positive spin offs if Australia had its own spaceport by taking advantage of the remote areas and existing facilitators such as the Woomera Prohibit Area.

Proposed Concept

This study focuses on developing a launch vehicle specifically for micro satellite (1 to 100 kg) to Low Earth Orbit (LEO) as the primary payload. A launch vehicle that can use both air and ground launch methods with high level of commonality offers flexibility to customers in terms of fast operation, selection of desired orbit and payload mass. Commonality in the design the launch vehicle is preferred to reduce production cost per unit. The higher thrust required for ground launch can be achieved by strap-on boosters.

Launch vehicle design methodology

The design process determines size and weight for the air launch vehicle which was based on 50 kg. payload to 300 km LEO. Additional components for ground launch, such as strap-on boosters were calculated and analysed. System Tools Kits (STK) was used to determine ΔV. According to [1], air launch ΔV is reduced by 935-1225 m/s compared to ground launch. So, ΔV_{air} was determined as a reduction relative to ΔV_{ground}, ie. 9500 m/s.

The ideal ΔV produced by a launch vehicle propulsion system is given by Eq.1

$$\Delta V = I_{sp} g_0 ln \frac{m_i}{m_f} \qquad \text{Eq.1}$$

Propellant mass of the first stage is derived from Eq.1, given m_{prop1} in Eq.2

$$m_{prop1} = \frac{\left\{\frac{m_{prop2}}{MR_2} + m_{extra2} + m_{satellite}\right\} \left\lfloor e^{\left\{\frac{dv}{9.81\, Isp_1} \frac{Isp_2}{Isp_1} \ln\left(\frac{\frac{m_{prop2}}{MR_2} + m_{extra2} + m_{satellite}}{\left(\frac{1}{MR_2} - 1\right) m_{prop2} + m_{satellite}}\right)\right\}} - 1 \right\rfloor}{\left\lfloor \frac{1}{MR_1} - \left(\frac{1}{MR_1} - 1\right) e^{\left\{\frac{dv}{9.81\, Isp_1} \frac{Isp_2}{Isp_1} \ln\left(\frac{\frac{m_{prop2}}{MR_2} + m_{extra2} + m_{satellite}}{\left(\frac{1}{MR_2} - 1\right) m_{prop2} + m_{satellite}}\right)\right\}} \right\rfloor} \qquad \text{Eq.2}$$

Chemical reaction between kerosene $C_{12}H_{26}$ and liquid oxygen O_2 is shown in Eq.3

$$2C_{12}H_{26} + 37O_2 = 24CO_2 + 26H_2O \qquad \text{Eq.3}$$

From Eq.3, molecular weight of fuel and oxidizer are used to calculated mass of each tank so that the summation of total mass equal to propellant mass of each stage.

$$\frac{x}{2 \times 170} = \frac{y}{37 \times 32} \qquad \text{Eq.4}$$

$$x + y = m_{prop,n} \qquad \text{Eq.5}$$

where n is stage number, x is mass of kerosene, y is mass of liquid oxygen

For simplification, propellant tanks are cylindrical shape such that length of the tanks can be calculated from Eq.6. with the radius of 0.5 m, assumed from engine specification [2].

$$volumn = \pi R^2 L = \frac{m}{\rho} \qquad \text{Eq.6}$$

The influence of structural mass is mainly depended on propellant mass. The relationship between propellant mass and structural mass is presented by a structural ratio in Eq.7 where λ is structural ratio typically 0.07.

$$\lambda = \frac{m_s}{m_p + m_s} \qquad \text{Eq.7}$$

Based on Newton's second law in Eq.8, acceleration varies with time due to reduction of propellant mass and drag at different altitudes as shown in Eq.9

$$\sum F = ma \qquad \text{Eq.8}$$

$$T(t) = m(t)a(t) + m(t)g(t) + D(t) \qquad \text{Eq.9}$$

$$D(t) = \frac{1}{2}\rho(h)V^2(t)C_D A \qquad \text{Eq.10}$$

Where A is a frontal area of launch vehicle.

To determine acceleration, altitude and velocity at specific time during flight, STK was used to generate the required parameters. The integration was applied to determined average thrust required for 600 seconds flight duration. As an air launch vehicle is released from a carrier aircraft at about 10 km altitude, this will be a starting condition, using the same Eq.8 - Eq.10 to calculate thrust. For ground launch extra thrust will be provided by strap-on boosters.

Carrier aircraft selection

From obtained launch vehicle size and mass which is approximately 7000 kg. The first proposed concept was to attach under the aircraft wing, due to structural of the wing that are not designed to withstand higher additional mass, the attachment has to be changed. As from previous study, a captive on bottom similar to Pegasus XL is considered. In Table 1, performance of each commercial aircraft is compared. The dimension of wheel base and height from ground to forward fuselage are critical for this method.

Table 1: Carrier Aircraft Comparison

Aircraft	**Maximum Payload (kg)**	**Range (nm)**	**Service Ceiling (ft)**	**Wheel Base (m)**	**Height btw Ground and forward fuselage (m)**	**Fuselage diameter (m)**	**Cost ($US)**
L-1011	41,050	5,600	39,000	18.79	2.07	5.97	N/A
B737-900	20,240	3,200	41,000	17.70	1.45	3.76	N/A
B757-200	27,215	4,100	42,000	18.29	2.24	3.76	9,500,000
B767-300	64,169	3,270	39,000	22.76	1.78	5.03	12,000,000
A330-200	49,500	6,749	41,450	22.18	2.23	5.64	N/A

Result

The sizing and weight estimation for the launch vehicle are shown in Table 2.

Table 2: Launch vehicle characteristics summary

Characteristics	Air LV	Ground LV
First stage length (m)	7.83	
Second stage length (m)	2.45	
Nosecone length (m)	1.84	
Interstate length (m)	0.5	
Total Length (m)	12.62	
Diameter of stages (m)	1.2 Identical for all stages	
Diameter of nose cone (m)	0.8 Identical for all stages	
Lift-off mass (kg)	6866	
First stage mass (kg)	6142.78	
Second stage mass (kg)	723.12	
First stage propellant type and mass (kg)	Fuel: Kerosene 1099.58	
	Oxidizer: Liquid Oxygen 3829.11	
First stage propellant type and mass (kg)	Fuel: Kerosene 118.91	
	Oxidizer: Liquid Oxygen 414.09	
Thrust (kN)	107.71	122.68
Additional number of boosters	-	2
Additional booster mass (kg)	-	500 each
Additional booster length (m)		2.36
Additional booster diameter (m)		1

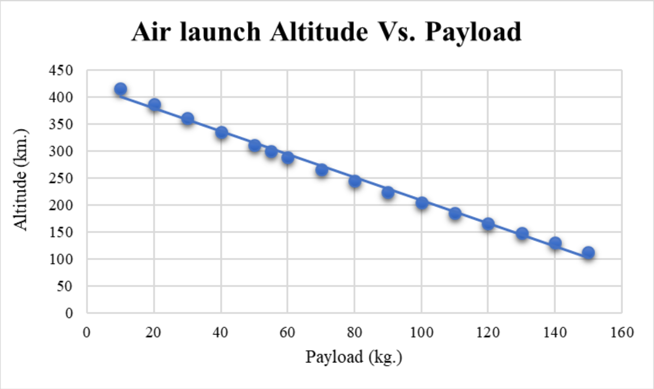

Fig. 1: Altitude vs. Payload for Air launch vehicle

Discussion

According to Table 3 the characteristics and performance of the designed launch vehicle will be validated by comparing with existing small launch vehicles. The comparator launch vehicles were chosen from altitude, and payload mass criterion.

Table 3: Launch vehicle validation

Launch vehicle	Vector-R [7], [8]	Electron [9]	LauncherOne [10]	Pegasus [11]	Designed Launch vehicle
Method	Ground	Ground	Air	Air	Air and Ground
Payload capability	70 kg to 200 km. LEO	225 kg to 500 km. LEO	150 kg to 500 km. SSO	468 kg to 200 km. LEO	55 kg to 300 km. LEO
No. of stages	2	2	2	3	2
Length (m)	13	17	16	16.9	12.62

Diameter (m)	1.2	1.2	1.62	1.26	1.2
Lift-off mass (kg)	6,060	12,550	10,400	23,139	6,866
Propulsion system	Liquid Propylene /LOX	Kerosene / LOX	RP-1/LOX	Solid: HTPB	Kerosene/LOX Booster: AP-Al HTPB
Average Thrust (kN)	81	162	327	726	Air :107, Ground:122
No. of Engines	Stage 1: 3 Stage 2: 1	Stage 1: 9 Stage 2: 1	Stage 1:1 Stage: 2	1 engine all stages	Stage 1: 1 Stage 2: 1
Status	Developing	In service	Developing	In service	Preliminary design

The performance of the designed launch vehicle, shown in Fig. 2, was compared with other competitor launch vehicles. Vector-R is rather similar to this design in terms of geometry, weight and performance. Vector-R can achieve 70 kg. to 200 km while the designed launch vehicle can achieve lower weight but higher altitude which is reasonable. Vector-R can reach 200 km while this design can achieve 266 km. Slightly heavier of this design compared to Vector-R is from the propellant mass that need to burn to higher altitude. LauncherOne has a higher mass due to its payload capability so it is compatible for the designed launch vehicle that has lower weight.

Vehicle length and diameter are similar to Vector-R but can offer higher altitude compared with all launch vehicle. Also, it is not longer than other higher performance launch vehicles. Overall, the performance and geometry of the design launch vehicle are satisfied and reasonable compared to other candidate launch vehicles

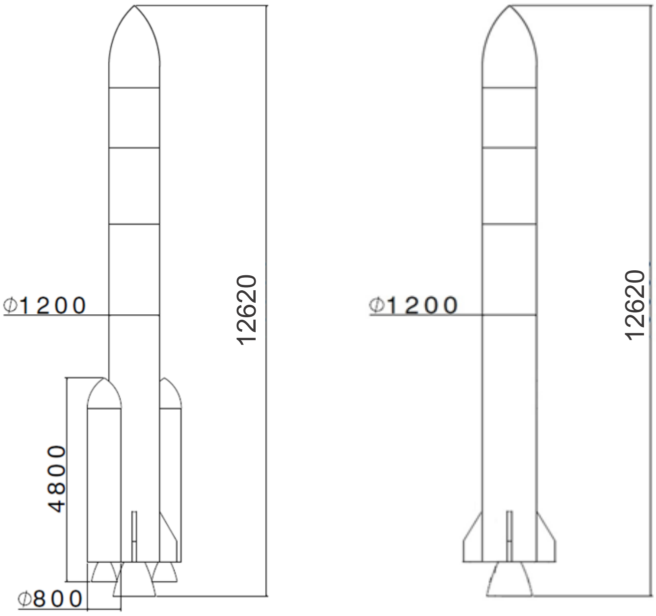

Fig. 2: Designed Launch vehicle, Ground launch vehicle (left), Air launch vehicle (right) in millimetre (mm).(CAD Model by Navaporn)

Aircraft Selection

Attachment under the fuselage of the carrier aircraft was selected based on drag sensitivity analysis, level of modifications required, cost effectiveness and safety. The geometry of selected carrier aircraft was considered to ensure launch vehicle clearance. The geometry of Pegasus and the L-1011 was used as a reference, where Pegasus has a length of 17 m and a diameter of 1.3 m and the proposed launch vehicle has a length of 13 m. and a diameter of 1.2 m.

Table 4: Carrier aircrafts compared with L-1011 TriStar

Aircraft	**A-Wheel base (m)**	**B-Space left from landing gear (m)**	C-Height from ground to fuselage **(m)**	**D-Space left from ground (m)**
L1011 TriStar	18.79	1.79	2.07	0.77
B737-900	17.7	4.7	1.45	0.25
B757-200	18.29	5.29	2.24	1.04
B767-300, Freighter	22.76	9.76	1.78	0.58
A330-200	22.18	9.18	2.23	1.03

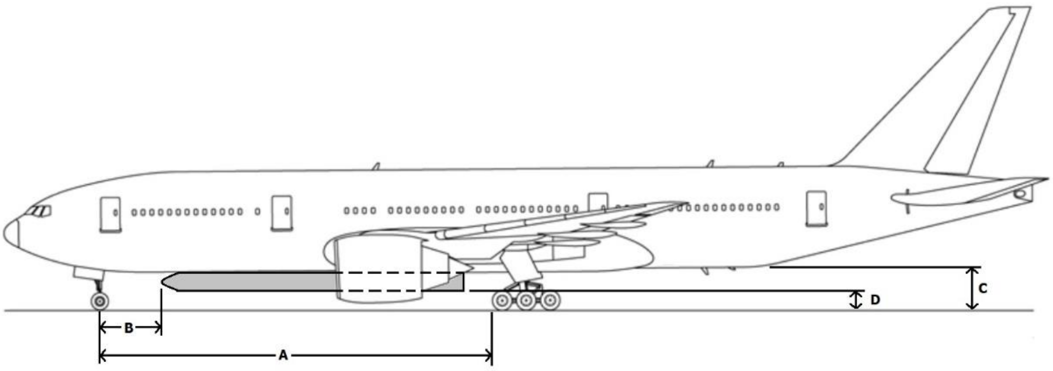

Fig. 3: Launch vehicle attached distance as explained in Table 4

The most appropriate aircraft carried for design launch vehicle is B757-200. Both space and height left allow sufficient attachment and operation. The space left from landing gear of B757-200 is quite large but 1.04 m. space left from ground is in a suitable range which can provide distance for release mechanism and fin. Even B737-800 offer the closer value of space left from landing gear but the height form ground might not feasible when attach release mechanism.

Launch location discussion

Woomera tends to be ready from its capability with full of facility and operation support. Woomera can be a ground launch facility as well as air launch. Since, there are sufficient area and runway for air operation. However, Woomera is away from the equator compared with launch sites in Norther Territory, resulting in higher ΔV required with circular orbit. Instead, Woomera benefit in polar orbit so satellites can be launched anywhere with this orbit.

The performance gained form Nhulunbuy and Port Stephen in term of proximity to equator is comparable. Both are near ocean, provide more safety and reliability. The separation of boosters can be ensured by these sites. In conclude, Woomera is the most interesting choice if applied the proposed method of having both ground and air launch in the same facility. Since, air launch operation can be taken off anywhere to gain a velocity advantage from low earth orbit, Woomera will not be a problem.

Conclusion

The purposes of this study are to respond with rapid demand for access to space by small satellite among university and other organisation such as defence and communication, investigate available launch method and proposed launch concept. Preliminary design launch vehicle for ground and air launch method with maximum commonality to deliver 50 kg. payload to 300km Low Earth Orbit (LEO) and investigate on Australia space capability and launch location. The method is mainly based on research, evaluate by sensitivity analysis and evaluate with previous studies and mission. The result of preliminary launch vehicle given comparable performance and geometry with servicing launch vehicle such as Pegasus XL and Electron. Ground launch vehicle is proved by additional booster that can provide sufficient thrust to defined altitude. B757-200 is selected to be a carrier aircraft by considering its dimension and performance include range, maximum payload, wheel base and height from ground. Attach location between launch vehicle and aircraft parameters are compared with Pegasus XL – L1011 aircraft to attain approximate and appropriate location. The proposed method and launch vehicle component including device and mechanism assisting in satellite deployment and deploying launch vehicle are commercial of the shelf technology which highly save development time and cost. Attractive launch location is Woomera due it highly equips, and operation process as shown in the past.

References

[1] M. W. v. Kesteren, "Air Launch versus Ground Launch: a Multidisciplinary Design Optimization Study of Expendable Launch Vehicles on Cost and Performance," 2013.

[2] B. T. C. Zandbergen, "Simple mass and size estimation relationships of pump fed rocket engines for launch vehicle conceptual design," presented at the 6TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS), 2015.

[3] Tristar500. (2018). *SPECIFICATIONS Lockheed L-1011-385-3 TriStar 500*. Available: https://www.tristar500.net/specifications.htm

[4] B. C. Airplanes, "737 Airplane Characteristics for Airport Planning," 2013.

[5] B. C. Airplanes, "757-200/300 Airplane Characteristics for Airport Planning," 2002.

[6] B. C. Airplanes, "767 Airplane Characteristics for Airport Planning " 2005.

[7] Vector-R, "Vector-R Payload User’s Guide," 2016.

[8] Vector-R, "Vector-R Forecasted Launch Service Guide Version 2.0," 2016.

[9] RocketLab. Rocket Lab Payload user's guide [Online]. Available: https://www.rocketlabusa.com/assets/Uploads/Payload-User-Guide.pdf.

[10] L. VirginOrbit. VIRGIN ORBIT LAUNCHERONE SERVICE GUIDE V1.0 [Online]. Available: https://static1.squarespace.com/static/5915eeab9de4bb10e36a9eac/t/598882d003596ea150e8f3aa/1502118612306/service-guide.pdf.

[11] OrbitalATK. Pegasus User’s Guide [Online]. Available: https://www.orbitalatk.com/flight-systems/space.../pegasus/.../Pegasus_UsersGuide.pdf