Aero-assisted Pre-stage for Ballistic and Aero-assisted Launch Vehicles

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A concept of an aero-assisted pre-stage is proposed, which enables launch of both ballistic and aero-assisted launch vehicles from conventional runways. The pre-stage can be implemented as a delta-wing with a suitable undercarriage, which is mated with the launch vehicle, so that their flight directions are coaligned. The ample wing area of the pre-stage combined with the thrust of the launch vehicle ensure prompt roll-out and take-off of the stack at airspeeds typical for a conventional jet airliner. The launch vehicle is separated from the pre-stage as soon as safe altitude is achieved, and the desired ascent trajectory is reached. Nominally, the pre-stage is non-powered. As an option, to save the propellant of the launch vehicle, the pre-stage may have its own short-burn propulsion system, whereas the propulsion system of the launch vehicle is activated at the separation point. A general non-dimensional analysis of performance of the pre-stage from roll-out to separation is carried out and applications to existing ballistic launch vehicle and hypothetical aero-assisted vehicles (spaceplanes) are considered.

Nomenclature

C_D	=	aerodynamic drag coefficient
D	=	distance
F	=	thrust
g	=	gravitational acceleration
h	=	altitude
H	=	RT/g, atmospheric scale height
I_{sp}	=	specific impulse
i_{sp}	=	I_{sp}/t_H, non-dimensional specific impulse
m	=	mass of the vehicle
n	=	$F/(mg)$, thrust-to-weight ratio
p	=	atmospheric (static) pressure
q	=	dynamic pressure
R	=	specific gas constant
S	=	reference area of the vehicle
T	=	atmospheric temperature
t_H	=	$\sqrt{2H/g}$, atmospheric scale time
V	=	airspeed
V_H	=	$\sqrt{2gH}$, atmospheric scale airspeed
γ	=	pull-up g – load
λ	=	(L/D), lift-to-drag ratio

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μ	=	$\mu -$ ratio, non-dimensional atmospheric mass parameter
θ	=	flight path angle
τ	=	t / t_H , non-dimensional time
υ	=	V / V_H , $\upsilon -$ number, the non-dimensional airspeed

I. Introduction

ACCESS to space remains a very expensive component of any space flight mission. Although reusability of future launch vehicles is promising to reduce the cost of access to space substantially, the launch itself, when accomplished from the ground, requires availability of a dedicated launch site, which is expensive to build and expensive to operate. Launch of ballistic rockets requires use of dedicated ground structures, such as launch pads and launch towers. Launch of future aero-assisted launch vehicles (spaceplanes) requires use of dedicated extremely long runways, which also have to be extraordinarily smooth, to accommodate for inevitably high take-off airspeeds. This requirement is caused by a necessity to keep the wing loading as high as possible in order to minimize aerodynamic losses during ascent through the dense lower atmosphere. Furthermore, the spaceplanes also must have a strong, and thus heavy, undercarriage to ensure a long roll-out and take-off at an extremely high airspeed with the vehicle tanks full of propellant. In contrast, landing of the spaceplane with empty tanks would occur at substantially lower airspeed, with much lower loads upon the undercarriage.

On the other hand, the aerial launch, as an alternative to the launch from the ground (see a detailed review[3] on this subject) can be conducted from conventional airfields, with conventional runways. But the need to carry the launch vehicle as a passive payload to the altitude of launch places obvious limitations on the initial mass of the launch vehicle, and thus on payload mass delivered to destination orbit (trajectory).

The idea of an aero-assisted pre-stage[1,2] is to "lend" the launch vehicle (ballistic rocket, or a spaceplane) an ample wing area and strong undercarriage to ensure horizontal take-off at moderate airspeeds with short roll-out. Thus, the critical problem of separation of the launch vehicle from the launch site is resolved in a conventional, airplane-like take-off. No expensive launch pads, as for ballistic rockets, or dedicated long and extraordinary smooth runways are necessary. The ground segment of flight operations would more resemble that of a conventional airport than that of a dedicated space launch site.

Roll-out and take-off of the pre-stage assembly stacked with the launch vehicle would essentially be similar to that of a jet airplane with low-wing loading and high thrust-to-weight ratio. After the take-off and the orientation of the launch vehicle into the desired ascent trajectory, the pre-stage is separated from the launch vehicle, performs a U-turn, and then glides back to the launch site. Since the mass of the pre-stage itself is much less than that of the combined stack with the launch vehicle at take-off, the glide and landing airspeeds would be substantially lower than those at take-off. In this study, the aero-assisted pre-stage is envisioned in the form of a delta-wing glider carrying the launch vehicle on its upper surface, with the flight directions of the pre-stage and launch vehicle co-aligned as illustrated in Fig.1.

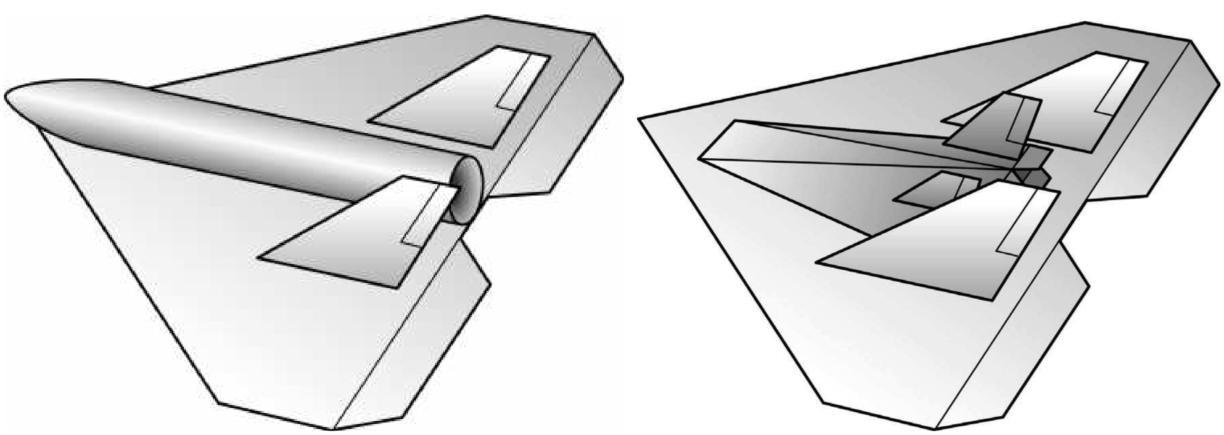


Figure 1. Notional diagrams of the assembly (stack) of the aero-assisted pre-stage with ballistic (left) and aero-assisted (right) launch vehicles.

II. Analysis of flight dynamics of the launch vehicle with aero-assisted pre-stage

We will conduct a simplified parametric analysis of the flight dynamics of the launch vehicle mated with the aero-assisted pre-stage from the begin of roll-out to separation. We will use a non-dimensional approach developed in author's earlier paper [2]. The summary of the approach and its application to this case are presented below.

The approach is based on the use of two non-dimensional parameters, $\upsilon-$number and $\mu-$ratio, which combine key dimensional parameters of the flight vehicle analyzed and of ambient atmosphere. The $\upsilon-$number represents the airspeed V of the vehicle measured in units of atmospheric scale airspeed $V_H=\sqrt{2gH}=\sqrt{2RT}$. It turns out that at any flight regime, the ratio of dynamic pressure q to static pressure p is simply $q/p=\upsilon^2$. The $\mu-$ratio represents the mass of atmospheric column over a unit area above the given flight level p/g in units of the ballistic coefficient of the vehicle $m/(C_D A)$. Essentially, this ratio defines an extent to which the ambient atmosphere can impact the trajectory of the vehicle.

The 2DOF system of equations of flight dynamics for the case considered can be written in the form:

$$\begin{cases} \dfrac{d\upsilon}{d\tau}=n-\mu\upsilon^2-\sin\theta \\ \upsilon\dfrac{d\theta}{d\tau}=\lambda\mu\upsilon^2-\cos\theta \\ \dfrac{d\ln\mu}{d\tau}=\dfrac{n}{i_{sp}}-2\upsilon\sin\theta \end{cases} \tag{1}$$

By its intention, the pre-stage is assumed to be used at low altitudes, for a period, which is negligible as compared to the total time of operation of the launch vehicle. Then it can be assumed that $\mu=\text{const}$, and the third equation of the system Eq.(1) can be dropped. The remaining equations are considered for two phases of operation of the pre-stage mated to the launch vehicle:

Phase I: Roll-out, take-off and hold near the ground until enough airspeed is gained to initiate the next phase.

Phase II: Pull-up at a constant g – load until the desired flight path angle θ is achieved.

These phases are considered below separately. For sake of simplicity of this analysis we assume that the thrust-to-weight ratio n, as well as the lift-to-drag ratio λ, remain constant throughout both phases.

A. Phase I: Roll-out, take-off and hold

In this phase, the flight path angle remains at zero, and the first equation of the system Eq.(1) can be written in the form:

$$\frac{d\upsilon}{d\tau}=n-\mu\upsilon^2 \tag{2}$$

It can be integrated analytically. We have:

$$d\tau=\frac{d\upsilon}{n-\mu\upsilon^2}$$

which yields

$$\tau(\upsilon)=\frac{1}{2\sqrt{n\mu}}\ln\left(\frac{\sqrt{n}+\sqrt{\mu}\upsilon}{\sqrt{n}-\sqrt{\mu}\upsilon}\right) \tag{3}$$

and

$$\upsilon(\tau) = \sqrt{\frac{n}{\mu}} \cdot \tanh\left(\sqrt{n\mu}\tau\right) \tag{4}$$

where we assume that at the begin of the roll-out $\tau = 0$ and $\upsilon = 0$. The take-off of the launch vehicle mated with the aero-assisted pre-stage occurs at $\upsilon = \upsilon_0$, when the lift force balances gravity, and $\lambda\mu\upsilon_0^2 = 1$. Corresponding $\upsilon -$ number is:

$$\upsilon_0 = \frac{1}{\sqrt{\lambda\mu}} \tag{5}$$

Corresponding non-dimensional time $\tau_0 = \tau(\upsilon_0)$ is obtained from Eq.(3):

$$\tau_0 = \frac{1}{2\sqrt{n\mu}} \ln\left(\frac{\sqrt{\lambda n} + 1}{\sqrt{\lambda n} - 1}\right) \tag{6}$$

After take-off, the stack has to gain additional airspeed for safe pull-up to attain the right altitude and attitude at separation. For sake of simplicity of this analysis, we assume that pull-up occurs at a constant g – load γ. Eq.(2), as well as its solution, Eqs.(3), (4) still hold. The pull-up at constant γ is initiated at $\upsilon = \upsilon_1$, when the lift force balances the g – load γ, and, correspondingly $\lambda\mu\upsilon_1^2 = \gamma$. Corresponding $\upsilon -$ number is:

$$\upsilon_1 = \frac{\gamma}{\sqrt{\lambda\mu}} \tag{7}$$

and corresponding non-dimensional time $\tau_1 = \tau(\upsilon_1)$ obtained from Eq.(3) is:

$$\tau_1 == \frac{1}{2\sqrt{n\mu}} \ln\left(\frac{\sqrt{n} + \sqrt{\mu}\upsilon_1}{\sqrt{n} - \sqrt{\mu}\upsilon_1}\right) = \frac{1}{2\sqrt{n\mu}} \ln\left(\frac{\sqrt{\lambda n} + \gamma}{\sqrt{\lambda n} - \gamma}\right) \tag{8}$$

B. Pull-up at a constant *g* – load

In this phase, the stack increases both the altitude and flight path angle until the desired separation point is achieved. The flight dynamics is described by two first equations of the system Eq.(1):

$$\begin{cases} \dfrac{d\upsilon}{d\tau} = n - \mu\upsilon^2 - \sin\theta \\ \upsilon\dfrac{d\theta}{d\tau} = \lambda\mu\upsilon^2 - \cos\theta \end{cases} \tag{9}$$

Based on the assumption of constant g – load, $\lambda\mu\upsilon^2 = \gamma$, the system Eq.(9) can be rewritten as

$$\begin{cases} \dfrac{d\upsilon}{d\tau} = n - \dfrac{\gamma}{\lambda} - \sin\theta \\ \upsilon\dfrac{d\theta}{d\tau} = \gamma - \cos\theta \end{cases} \tag{10}$$

Dividing the first equation of the system Eq.(10) over the second equation of this system yields:

$$\frac{d\ln\upsilon}{d\theta}=\frac{n-\frac{\gamma}{\lambda}-\sin\theta}{\gamma-\cos\theta} \tag{11}$$

Equation (11) can be integrated analytically. We have:

$$d\ln\upsilon=\frac{n-\frac{\gamma}{\lambda}-\sin\theta}{\gamma-\cos\theta}d\theta=\left(n-\frac{\gamma}{\lambda}\right)\frac{d\theta}{\gamma-\cos\theta}+\frac{d\cos\theta}{\gamma-\cos\theta}$$

which yields

$$\ln\upsilon(\theta)=F(\theta)+C,$$

where

$$F(\theta)=\left(n-\frac{\gamma}{\lambda}\right)\frac{2}{\sqrt{\gamma^2-1}}\arctan\left(\frac{\sqrt{\gamma^2-1}}{\gamma-1}\tan\frac{\theta}{2}\right)-\ln(\gamma-\cos\theta) \tag{12}$$

Then, analytic relation between the $\upsilon-$ number and flight path angle θ during pull-up at constant g – load has the form:

$$\upsilon(\theta)=\upsilon_1\exp[F(\theta)] \tag{13}$$

Using either of equations in the system Eq.(10), we can numerically integrate the dependence $\tau(\theta)$ and thus obtain dependencies $\theta(\tau)$ and $\upsilon(\tau)$. At this point it is advisable to switch from non-dimensional quantities υ and τ to airspeed V and time t, which makes it possible to obtain dependencies of distance D and altitude h on time t.

III. Parametric study of performance of the aero-assisted pre-stage

The framework of parametric analysis presented above was used for exploration of the space of parameters involved to determine the usable limits of those. The primary figures of merit were the distance and altitude of separation of the pre-stage. Of course, the flight path angle at the separation point may vary depending on the specific launch vehicle. Because of this, the trajectory calculations were conducted up to the maximum value of the flight angle of 90º, and corresponding distance and altitude represented upper limits of values to be expected for particular combinations of parameters.

Analytic expressions derived above indicate that the suite of relevant parameters is as follows:

Thrust-to-weight ratio, n
$\mu-$ ratio at the level of the launch site
Lift-to-drag ratio, λ
Pull-up $g-$ load, γ

To convert the results of this study into tangible dimensional values, we use the rounded values of relevant geophysical parameters. Incidentally, these values also result in conveniently round values of derived parameters:

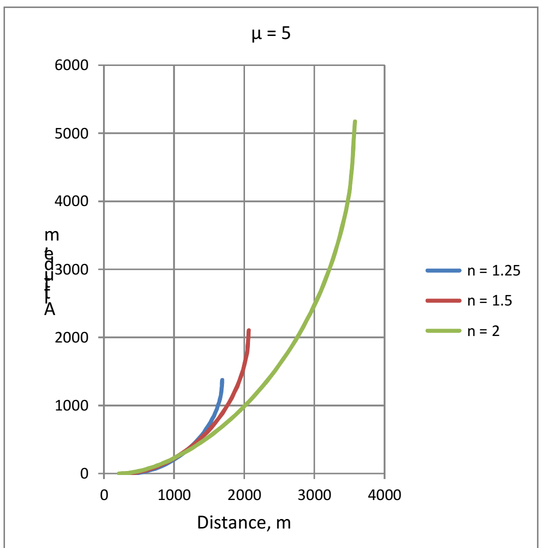
Gravitational acceleration, $g=10$ m/s^2
Atmospheric scale height, $H=8000$ m
Atmospheric scale airspeed, $V_H=\sqrt{2gH}=400$ m/s
Atmospheric scale time, $t_H=\sqrt{2H/g}=40$ s

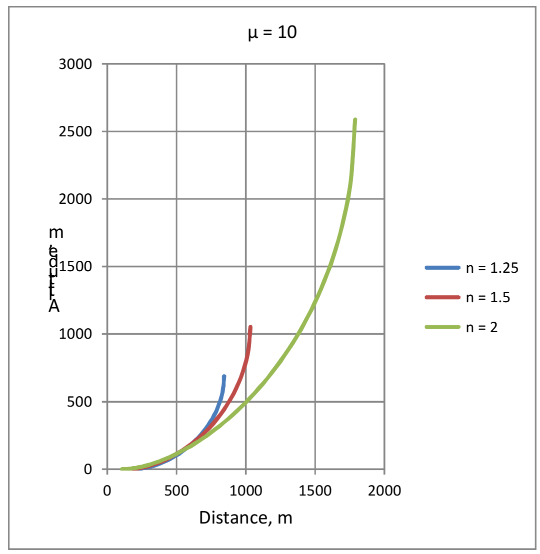
A. Evaluation of the performance of the pre-stage in the non-dimensional parameter space

In this study, we have chosen moderate fixed values for lift-to-drag ratio and pull-up $g-$load:

$$\lambda = 8,\ \ \gamma = 2$$

The set of figures that follow show plots of altitude vs. distance for various combinations of the $\mu-$ and thrust-to-weight ratios. It should be reminded that the pre-stage is, essentially, intended for a safe separation of the launch vehicle from the ground and glide back to the launch site after releasing of the launch vehicle. For this reason, the desirable combinations of parameters are those, which provide separation at lowest altitudes and shortest distances from the launch site were achieved. On the other hand, we did not intend to pose any limitation on the flight path angle θ at the separation point, so as to leave it driven by intended ascent profile of the LV itself. Thus, integration of the flight path of the pre-stage mated with the LV was conducted until reaching $\theta = 90^{\circ}$.





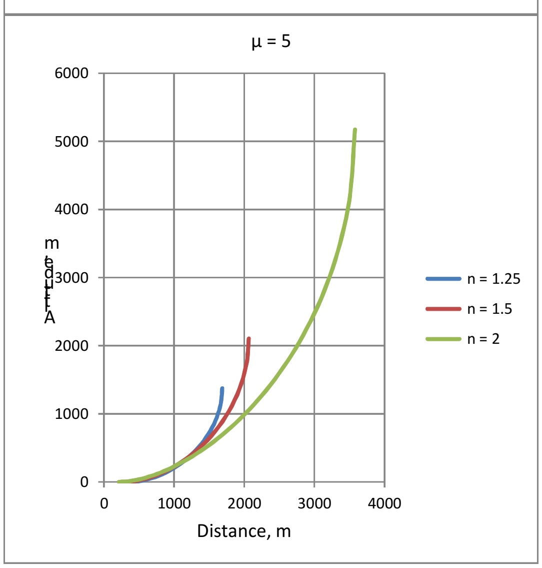


Figure 2. Plots of altitude vs. distance for the pre-stage/LV stack for various $\mu-$ and thrust-to-weight ratios.

Table 1 below presents the values of the airspeed, distance and altitude for key events during the flight of the pre-stage/LV stack: (1) pull-up, and (2) reaching $\theta = 90^{\circ}$.

Table 1.

Parameters	μ = 20			μ = 10			μ = 5		
	n = 1.25	n = 1.5	n = 2	n = 1.25	n = 1.5	n = 2	n = 1.25	n = 1.5	n = 2
V_{PU}, m/s	45	45	45	63	63	63	89	89	89
D_{PU}, m	89	73	53	178	146	107	357	292	214
V_{90}, m/s	75	101	186	106	143	262	150	203	371
D_{90}, m	422	517	895	844	1033	1789	1688	2066	3578
h_{90}, m	344	526	1294	687	1053	2587	1374	2105	5174

As can be seen from the plots and the table above, the distance/altitude envelope widens with the decrease of the $\mu -$ratio, which corresponds to the increase of wing loading, and this can be expected from general dynamical considerations. Also apparent is the strong dependence on thrust-to-weight ratio: with its increase, the velocity is gained faster, and the increasing centrifugal force counteracts increase of the flight path angle, which, correspondingly, occurs slower. This effect will be seen in the next Subsection, where analogous computations are done for selected launch vehicles with aero-assisted pre-stages of commensurate sizes.

B. Evaluation of performance of the pre-stage with selected launch vehicles

This evaluation requires specification of one more relevant geophysical parameter:

Atmospheric mass over unit area, $p/g = 10000$ kg/m^2

Also, we need to specify the aerodynamic drag coefficient of the pre-stage/LV stack. We assume a relatively conservative number:

$$C_D = 0.2$$

The interested reader can easily recalculate the results obtained below for any preferred value of C_D.

Table 2 contains data on a number of selected launch vehicles used in this evaluation. All data refer to the instant of take-off. The mass of the aero-assisted pre-stage is assumed to be negligeable, as compared to the mass of the launch vehicle fully loaded with propellant. It is assumed that the pre-stage has a planform of a delta wing, with the wingspan and length of the central chord are equal to the height of the launch vehicle.

Table 2.

Launch vehicle	**Mass, kg**	**Height, m**	**Thrust, kg**	**Source**
Delta IV	249,500	67.5	338,041	[5]
Atlas V	334,500	58.3	423,673	[6]
Pegasus	18,500	16.9	49,657	[7]
Minotaur IV	86,300	23.88	224,490	[8]
Falcon 1	38,555	21.3	46,327	[9]
Falcon-9	333,400	54.3	510,204	[10]
Soyuz	308,000	45.6	405,837	[11]
Zenit	444,900	58.3	834,694	[12]

Table 3 below shows the values of time, airspeed, distance and altitude for key events during the flight of the pre-stage/LV stack: (1) pull-up, and (2) reaching $\theta = 90^\circ$.

Table 3.

Parameters	Delta IV	Atlas V	Pegasus	Minotaur IV	Falcon 1	Falcon 9	Soyuz	Zenit
Height, m	67.5	58.3	16.9	23.88	21.3	54.3	45.6	58.3
Mass at TO, kg	249,500	334,500	18,500	86,300	38,555	333,400	308,000	444,900
Thrust at TO, kN	338,041	423,673	49,657	224,490	46,327	510,204	405,837	834,694
μ	18.3	10.2	15.4	6.6	11.8	8.8	6.8	7.6
n	1.35	1.27	2.68	2.60	1.20	1.53	1.32	1.88
t_{PU} , s	3.7	5.3	2.0	3.1	5.2	4.7	6.3	4.0
V_{PU} , m/s	47	63	51	78	58	67	77	72
D_{PU} , m	89	173	51	122	159	161	249	150
t_{90} , s	12.6	16.6	27.6	39.7	15.2	19.0	20.5	23.7
V_{90} , m/s	89	107	483	668	92	158	140	258
D_{90} , m	500	843	3019	6219	697	1203	1316	2014
h_{90} , m	452	707	6215	12338	539	1259	1149	2699

As can be seen from Table 3, the stacks of the pre-stage mated to Minotaur IV and Pegasus, the launch vehicles with highest thrust-to-weight ratio n , reach the 90-deg separation point at greatest altitudes and distances. On the other hand, the stacks with Delta IV and Falcon 1 having lowest thrust-to-weight ratio reach the 90-deg separation point at smallest altitudes and distances. These results correspond to the non-dimensional analysis above illustrated by Figs.1-3 and Table 1.

Figure 3 below shows plots of altitude vs. distance calculated for resulting pre-stage/LV stacks. The plots for Pegasus and Minotaur IV are not included so as not to dwarf plots for other vehicles. Note that the plot for Zenit, the launch vehicle next to Pegasus and Minotaur IV in terms of thrust-to-weight ratio, dominates the plots for other launch vehicles.

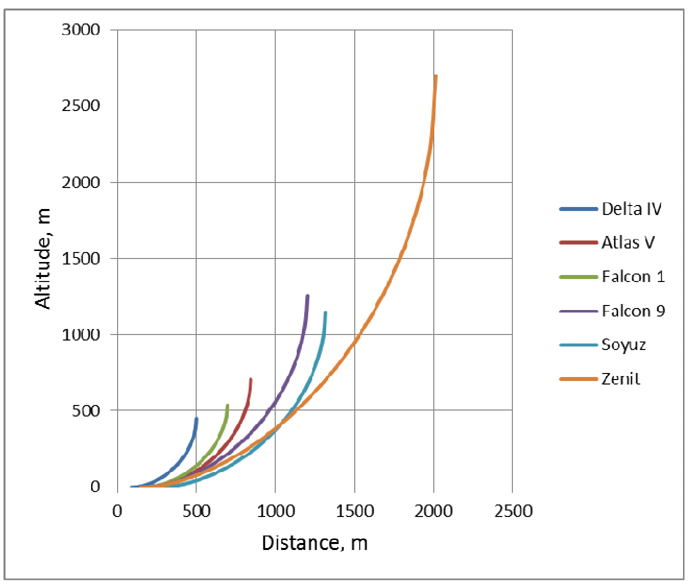


Figure 3. Plots of altitude vs. distance for stacks of the pre-stage mated with selected LVs.

IV. Discussion and conclusion

This aero-assisted pre-stage was conceived as a means to enable the launch of space launch vehicles from conventional runways without placing any extra limitations on the take-off airspeed and distance as compared to conventional aircraft. Also, it was conceived that separation of the pre-stage from the launch vehicle occurs as soon as practicable, essentially, within altitudes and distances within the traffic pattern of a conventional airport, so that the pre-stage is able to glide back to the launch site (runway) for subsequent re-use.

The results of quantitative analysis indicate that there exist a domain of relevant parameters, where these requirements can be met with a pre-stage matching the size of the launch vehicle in a wide range of vehicle's geometric dimension (height), take-off mass and thrust. The non-dimensional analysis of Subsection III.A indicates that higher wing loading numbers (obvious) and lower thrust-to-weight numbers (not that obvious) are preferred. The dimensional analysis of Subsection III.B indicates that a number of types of launch vehicles currently in operation, when mated with a pre-stage of commensurate size, can, in principle, be flown from conventional runways.

Of course, all the launch vehicles considered in this study are designed under an assumption that most of the load during the launch and ascent are axial, and lateral loads are negligible. Thus, these launch vehicles, especially those using liquid rocket propellant cannot be operated with this aero-assisted pre-stage without any redesign. But one can expect that this redesign – essentially, enforcement in lateral direction – would result in relatively minor increase of the take-off mass, and conclusions of the above analysis remain valid.

All launch vehicles considered in this study are purely ballistic rockets. Nevertheless, the results obtained should also be applicable to future aero-assisted launch vehicles, if their geometrical dimensions, take-off mass and thrust are in the range explored.

As it was pointed out in the Introduction, there are two alternative options of implementation of the aero-assisted pre-stage: non-powered and powered. The powered option is, of course, associated with increased complexity in design, due to addition of the propulsion system, but this option ensures preserving the propellant of the launch vehicle up to the point of separation. Also, as the results of this study indicate, for launch vehicles with high thrust-to-weight ratio n, use of the pre-stage with *reduced* ratio n enables a gain in performance of the pre-stage due to reductions in altitude, distance and airspeeed at the separation point, as well as in time from launch to separation.

In conclusion, in author's opinion, the results of this study indicate that the concept of the aero-assisted pre-stage for launch vehicles may be instrumental in making access to space more affordable and thus will contribute to ongoing process of space exploration.

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[8] Minotaur IV http://en.wikipedia.org/wiki/Minotaur_IV

[9] Falcon 1 http://en.wikipedia.org/wiki/Falcon_1

[10] Falcon 9 http://en.wikipedia.org/wiki/Falcon_9

[11] Soyuz http://en.wikipedia.org/wiki/Soyuz_%28rocket%29

[12] Zenit http://en.wikipedia.org/wiki/Zenit_%28rocket_family%29