Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Affordable Launch Opportunities for Small Satellites

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Air Launch
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Problem area
The cost for launching a satellite in orbit is significant with respect to the total cost of a space mission. At present, the costs associated with launching small satellites (1 - 30 kg) are too high for a dedicated launch; consequently, small, relatively inexpensive satellites (e.g. CubeSats) are often launched together with larger satellites, and at lower costs. However, for the small satellite, a major disadvantage is that the primary client determines the final destination and launch date. This leads to various limitations in fulfilling its mission. Currently, no affordable dedicated launch systems are available for small satellites.

Description of work
An air-launch platform concept is a proposed solution to fulfil launch market developments, forecast and needs.
A technical feasibility study is performed by a conceptual multi-stage launcher system design using the Lynx space plane and F16 fighter jet as air-launch platforms for a 10 kg satellite in Low Earth Orbit. Both launcher designs and performances are supported by modelling tools and sub-optimal trajectory simulations.

This report is based on a presentation held at the Small Satellites Systems and Services Symposium, Portoroz (Slovenia), 5 June 2012.

Results and conclusions
Current launch market analysis and forecast shows significant growth in nano- / microsatellite launch demand. Thereby, it is expected that availability of affordable launch opportunities has a strong influence on increasing satellite market size developments in the future. An air-launch platform, such as XCOR/Lynx or F16, has the potential to make dedicated space access needs of small satellites more affordable. An estimated launch price of $50K per kg for 10 kg payload is considered competitive although cheaper piggyback launch prices exist for Russian decommissioned military missiles.

Applicability
Primary reasons for conducting the ALOSS project are to develop knowledge and technology, and to proactively participate in commercial aerospace product development. As such, NLR innovates with a focus on the market, while also increasing its competitive position.

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Summary

At present, small, relatively inexpensive satellites (1 - 30 kg) are often launched together with larger satellites at lower costs. This leads to limitations such that the full potential of small satellite's mission is not always reached. The costs associated to a dedicated launch for these small satellites are very high, when compared to the costs of building the satellite itself.

An air-launch platform concept is a proposed solution to fulfil launch market developments, forecast and needs. Using a carrier like a commercial sub-orbital plane (XCOR/Lynx) or a fighter jet F16, space access for small satellites can become more affordable. This is especially true if the carrier can also be used for other purposes, such as space tourism, micro-g experiments, and/or transport. Without these extra options, the investment in rocket technology might be too high to compete with existing conventional launches using Russian decommissioned military missiles.

This TP presents a feasibility study for a three-stage launcher system design using a F16 fighter jet as an air-launch platform to launch a 10 kg satellite in Low Earth Orbit (LEO). The launcher's conceptual design, including subsystems: Propulsion, Attitude Control, Structure and Avionics, is supported by modelling tools and trajectory simulations. The F16 launcher has potential to launch more than 10 kg payload in LEO.

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Abbreviations

ALOSS	Affordable Launch Opportunities of Small Satellites
DOF	Degrees Of Freedom
LEO	Low Earth Orbit
ORS	Operationally Responsive Space
RCS	Reaction Control System
RPA	Rocket Propulsion Analysis
SXC	Space Expedition Curacao
TVC	Thrust Vector Control
US	United States

1 Introduction

The cost for launching a satellite in orbit is significant with respect to the total cost of a space mission. At present, the costs associated with launching small satellites (1 - 30 kg) are too high for a dedicated launch; consequently, small, relatively inexpensive satellites (e.g. CubeSats) are often launched together with larger satellites, and at lower costs. However, for the small satellite, a major disadvantage is that the primary client determines the final destination and launch date. This leads to various limitations in fulfilling its mission. Currently, no affordable dedicated launch systems are available for small satellites.

A recent trend in the development of satellites is miniaturisation enabling a significant mass reduction. Moreover, cost reduction becomes possible using commercial off-the-shelf available hardware whenever possible. The CubeSat technology is one example. These trends offer opportunities to more companies, universities and governments to operate satellite missions if affordable launch capabilities are provided. This creates a commercial market for cheap and flexible launch opportunities for small satellites. Also for defence organisations, the concept of Operationally Responsive Space (ORS) can be applied in a more financially attractive manner. A solution for these 1 - 30 kg satellites is to develop a dedicated launcher system which can be released at high altitudes by a carrier. One could think of aircrafts, both civilian and military, operating at high altitudes. Also one could think of commercial space vehicles for space tourism used by emerging entrepreneurs like Space Experience Curacao SXC.

This TP presents a feasibility study ([1]) for a three-stage launcher conceptual system design using a F16 fighter jet as an air-launch platform.

2 Market Opportunities

2.1 Market Developments And Needs

Figure 1 shows that the current market share of small satellites in the 1-10 kg satellite class (or nano-sats) is dominated by the civil sector including universities and research institutes.

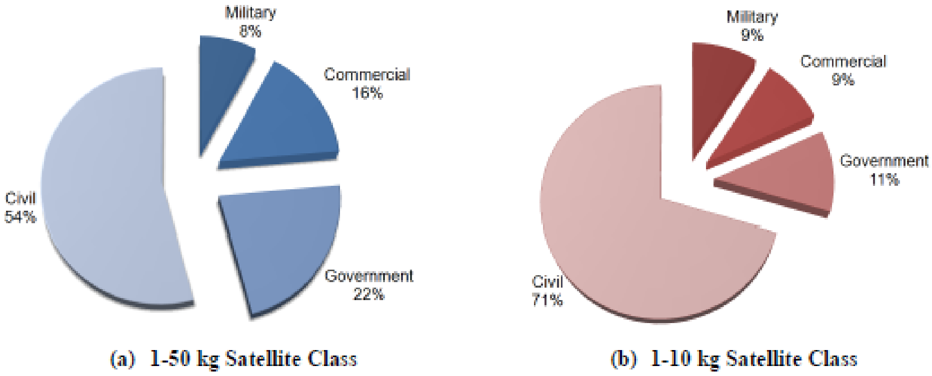


Figure 1 Market size small satellites (source: [2])

Each sector has specific needs with respect to launch capabilities. For the military time-to-orbit in the order of a few days is important within the framework of Operationally Responsive Space whereas commercial operators require reliable continuous launch opportunities allowing for updated services. The civil sector has limited financial resources and would favour flexible launch opportunities to limit risks due to satellite development delays.

The current number of nano-sats (incl. CubeSats) in development by both emerging and developing nations is about 200-250 and is growing. Its popularity is expected to grow even more with increasing launch opportunities and reduced launch costs. Furthermore, CubeSats do not have only technology demonstration mission potential, but become more mature for science and commercial missions as well.

According to [3] a lack of dedicated space access for CubeSat developers will continue to be a major limitation on utilization unless one or more of nano-launch vehicle initiatives are implemented. A solution offered within the current study is an air-launch-based platform.

2.2 Air-Launch Concept

Air-launch is preferable with respect to conventional ground launches for a number of reasons:

- Weather independent to increase launch possibilities in time (launch on demand).
- Flexible launch locations and orbits.
- Reduction in range safety costs.
- Less velocity losses due to drag and gravity by launching at higher altitude. Payload fraction increases.
- Less structural weight due to lower aerodynamic and acoustic loads. Payload fraction increases.
- Launcher potential being smaller and therefore cheaper.

In addition to the above stated reasons, the following disadvantages should be taken into account:

- Launcher limited size and weight capacity depending on carrier.
- Additional technologies required.
- Cost of carrier operation (depending on type).

Several air-launch concepts are found worldwide:

- US Orbital Sciences Pegasus up to 500 kg satellite capacity. Only active air-launch system.
- US Scaled Composites, Dynetics and SpaceX in Stratolaunch using a Falcon-9 air-launch for larger heavy payloads.
- US Space Propulsion Group, Premier Jets, Whittinghill Aerospace and Spath Engineering in Nanolaunch project for launching nano-satellites (1 - 10 kg) and micro-satellites (10 - 100 kg) in LEO using the F-15 Eagle as the platform.
- US XCOR Aerospace NanoLauncher for 1 - 10 kg satellites.
- Europe, CNES, CDTI, DLR in ALDEBARAN, a launch vehicle demonstrator using Rafale fighter jet for launching up to 300 kg in LEO.
- Many studies found on the internet by universities, national space agencies and companies.

2.3 Air-Launch Platform Selection

For the current study two air-launch platforms are identified (Figure 2):

1. Lynx, suborbital space plane under development by XCOR Aerospace.
2. F16 fighter jet as operated by the Royal Netherlands Air Force.

The XCOR/Lynx space plane is chosen because it can deliver advantageous launch conditions (in terms of altitude). Furthermore, it is of interest since Space Expedition Curacao, a Dutch entrepreneur, is planning to use the Lynx for commercial space tourism activities. Thereby, additional pioneering applications, like small satellite launches, might become economically viable due to combined usage of the Lynx with space tourism. The Lynx is under development by XCOR Aerospace in the US. Reference [4] states a corresponding estimated customer launch cost of $500,000. However, the Lynx has limited volume and mass capacity.

The F16 is chosen because of its operational capabilities and higher mass capacity and is part of The Royal Netherlands Air Force military infrastructure for which the concept of Operationally Responsive Space is of interest.

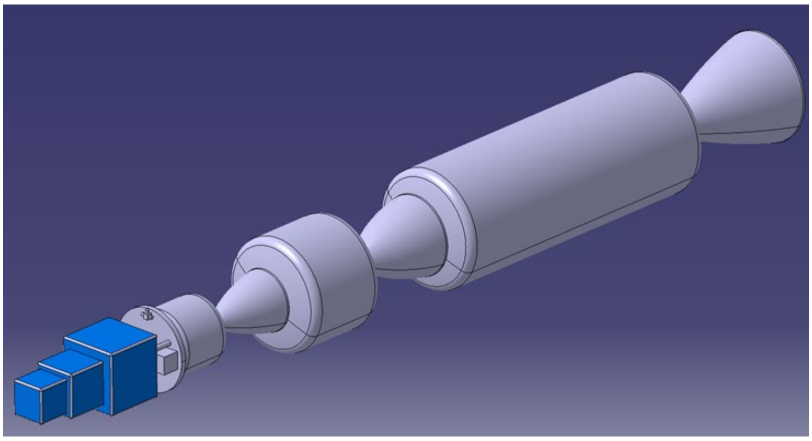
Figure 2 XCOR/Lynx and F16 launch cases

3 Launcher System Design

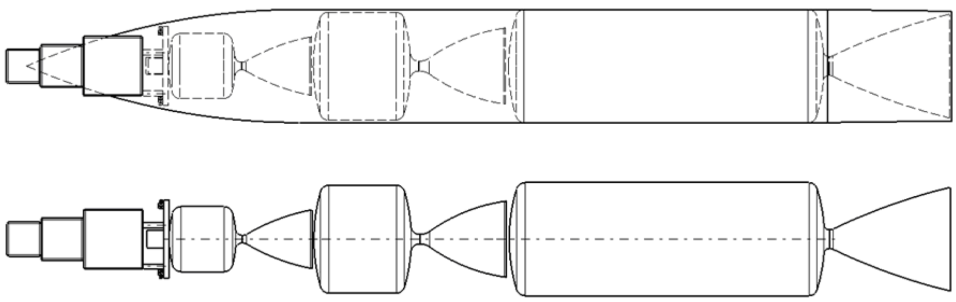
3.1 F16 Launcher

The conceptual design of a three stage F16 launcher (Figure 4) is based on an existing 370 gallon external fuel tank (Figure 3) volume capacity to limit the F16 flight envelope performance, certification procedures and cost as much as possible.

Figure 3 F16 with external fuel tank



a)



b)

Figure 4 F16 launcher stages: a) overview; b) top/rear view

Sizing of subsystems: Propulsion, Attitude Control, Power/Avionics and Structure are supported by several modelling tools including Rocket Propulsion Analysis (RPA) and Matlab scripting. The launcher's stage characteristics are shown by Table 1.

Table 1 F16 launcher stage characteristics

Stage characteristics	**Stage 1**	**Stage 2**	**Stage 3**
Mass before burn [kg]	1,379.5	388.6	87.2
Mass at end burn [kg]	516.7	143.8	26.5
Mass propellant [kg]	862.8	244.8	60.7
Mass insulation [kg]	5.8	5.4	1.4
Mass chamber [kg]	48.5	20.9	4.9
Mass nozzle [kg]	45.9	13.5	3.5
Mass TVC [kg]	22.9	6.7	1.7
Mass interstage/fairing [kg]	5/none	5/5	none/none
Mass avionics	none	None	5
Mass payload	none	None	10
Dry mass [kg]	128.1	56.5	26.5
Propellant mass fraction [-]	0.87	0.81	0.70
Mass flow [kg/s]	17.9	5.0	3.1 to 0.9 (regressive)
Thrust [kN]	48.3 (constant)	14.1 (constant)	8.6 to 2.6 (regressive)
Max acc. (at end burn) [g's]	9.5	10	10
Thrust duration [s]	47.4	49.4	34
ΔV [km/s]	2.65	2.83	3.33

Stage characteristics	Stage 1	Stage 2	Stage 3
Average Isp [s]	275	290	285
Chamber pressure [bar]	30	30	30 to 9.1 (regressive)
Chamber wall thickness [mm]	2.1	2.0	1.2
Regression rate [mm/s]	5.6	5.6	5.6 to 4.0 (regressive)
Nozzle area ratio [-]	30.4	60.8	60.8
Nozzle throat diameter [cm]	11	5.7	4.4
Nozzle exit pressure [bar]	0.12 (15 km)	0.05 (20 km)	0.05 (20 km)

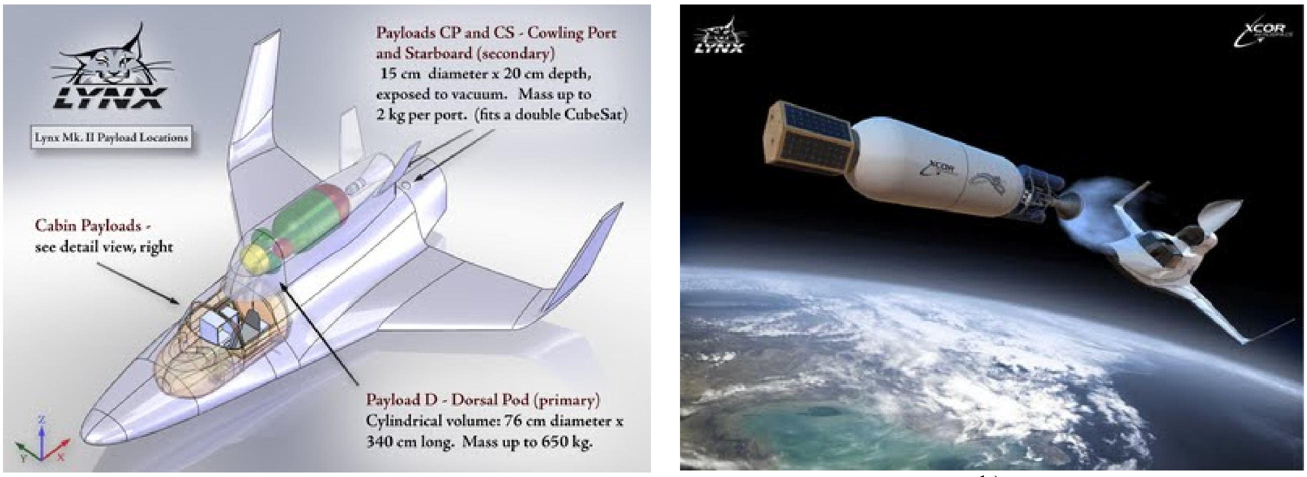
The propulsion system of the three stages is based on a solid composition (fuel: 18% Powdered Aluminium ; Oxidant: 71% Ammonium Perchlorate ; Binder: 11% Hydroxyl-Terminated PolyButadiene HTPB). The propulsion performance of each stage is supported by RPA according to an iterative design process. By providing a few engine parameters such as combustion chamber pressure, propellant selection, and nozzle parameters, the program obtains chemical equilibrium composition of combustion products, determines its thermodynamic properties, and predicts the rocket performance. None of these parameters are fully optimised yet, but serve as a first iteration step towards a more optimum design.

Attitude control for pitch and yaw during powered flight (rocket engine is fired) is obtained by two electro-mechanical actuators steering the nozzle for Thrust Vector Control (TVC), whereas gold gas thrusters are responsible for roll controllability. Two cold gas thruster modules, with each three thrusters and a nitrogen tank, are located in opposite directions at the interface structure between the third stage and the launcher's payload. In addition to powered flight, the launcher's attitude (roll, pitch and roll) is controlled by the gold gas system during coast flight (rocket engine is off).

A comparison with high performance rocket engines (e.g. STAR) indicates that mass estimations of propulsion system components for stage 1 and 2 may be overestimated. This indicates that the launcher has the potential to launch more than 10 kg in LEO.

3.2 XCOR/Lynx Launcher

A similar analysis has been performed for the Lynx case, which confirmed the initial results from XCOR. Figure 5 shows the Lynx dorsal pod dimensions for the NanoSat launcher to launch a small satellite.



a) b)

Figure 5 a) XCOR/Lynx with NanoSat Launcher inside dorsal pod, b) Artist impression (source: XCOR)

4 Trajectory Simulation

The launch trajectory simulation for the F16 launcher stages is performed by an in-house-developed simulator by NLR in Matlab/Simulink including:

- Rotating Earth including gravity.
- 6-DOF dynamics.
- Model of atmosphere (density, pressure, drag on launcher).
- Aerodynamic model depending on Mach number.
- Predefined thrust profile and corresponding momentary mass.
- Predefined pitch angle guidance.

The sub-optimal launch trajectory simulation corresponds to Table 1 and the following time frame (in seconds) to reach a circular, zero-inclined orbit of about 780 km:

1) 0 – 47.4: stage 1 burn.
2) 47.4 – 48.4: stage 1 separation.
3) 48.4 – 97.8: stage 2 burn.
4) 97.8 - 552.8: coast flight and stage 2 separation.
5) 552.8 – 586.8: stage 3 burn.

Initial conditions:

- Altitude = 15 km above the equator.
- M = 0.8 (236 m/s).
- Pitch angle = 50º.

Simulation results are shown for:

- Thrust and acceleration.
- Velocity and losses.
- Trajectory and altitude.

4.1 Thrust And Acceleration

Figure 6 shows the launcher's thrust profile, drag, momentary mass, and acceleration. The thrust profile and its momentary mass are input for the trajectory simulation to limit accelerations of 10 g's. Drag is experienced during burn time of stage 1 only.

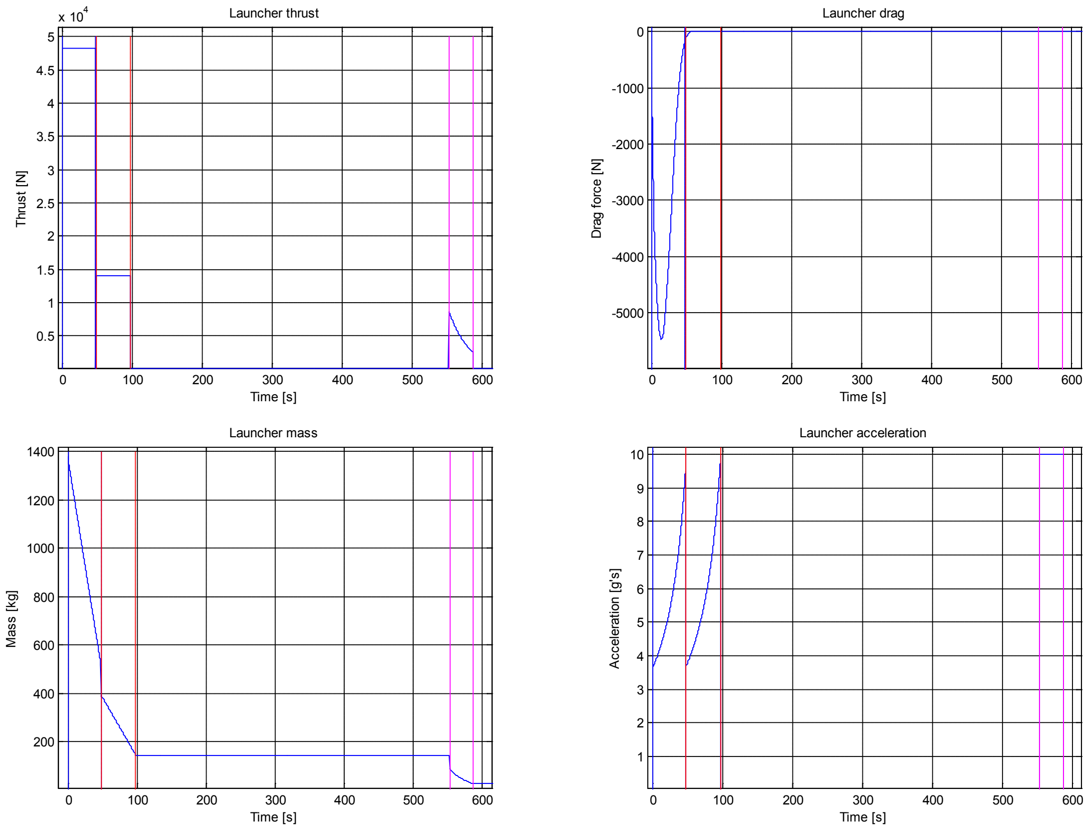


Figure 6 Thrust, drag, acceleration and mass versus time

4.2 Velocity And Losses

Figure 7 shows the launcher's velocity and losses due to gravity and drag. Total gravity loss for this trajectory is about 1.8 km/s and drag loss accounts for 165 m/s.

Note that the circular target orbit is zero-inclined resulting in the most advantageous launch case in terms of required ΔV, because the Earth's rotation comes for free (considering launch trajectories in Eastern direction). In addition to a zero-inclined target orbit, a polar orbit (e.g. Sun synchronous) requires the most ΔV. In that case, the launcher's payload capacity would drop significantly or a lower orbit can be achieved.

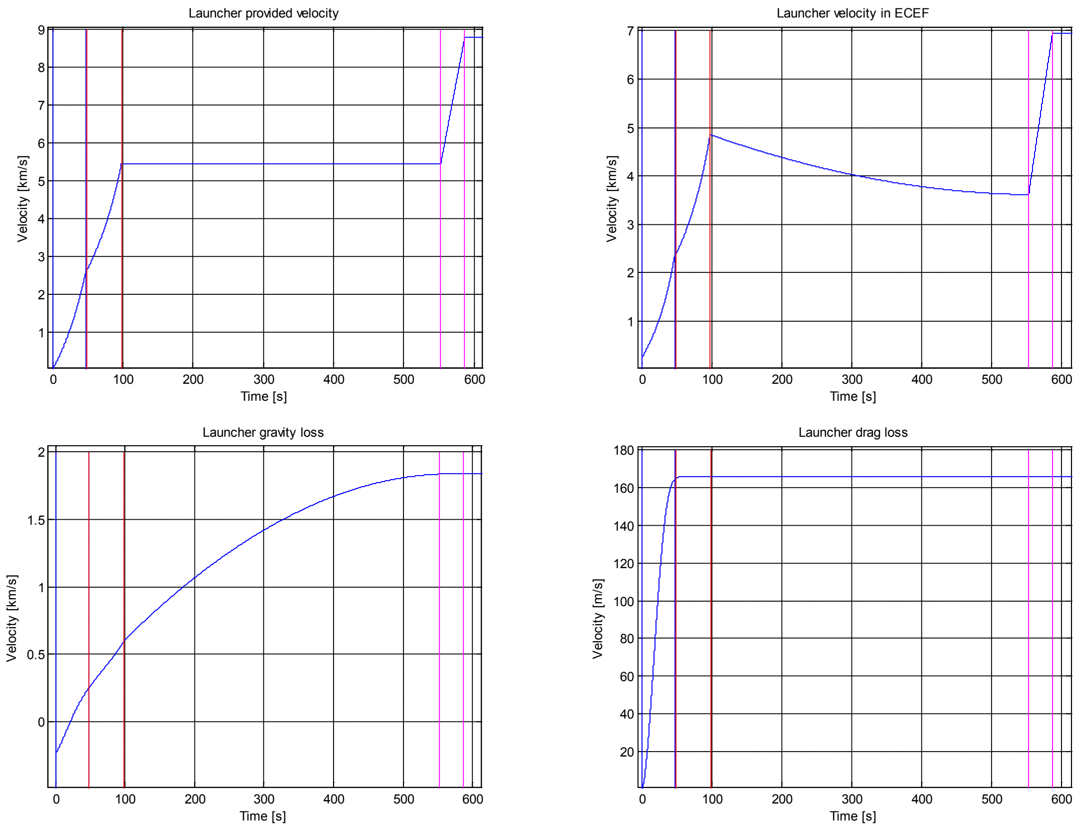


Figure 7 Velocity and losses versus time

4.3 Trajectory And Altitude

Figure 8 shows the launcher's trajectory and altitude. The target altitude of 780 km and ΔV by stage 3 corresponds to a circular orbit. For stage 1, a predefined pitch angle of 50º is maintained while for stage 2 a pitch angle varies between 50º and 18º. During coast flight, the pitch angle is reduced to 0º and maintained by stage 3.

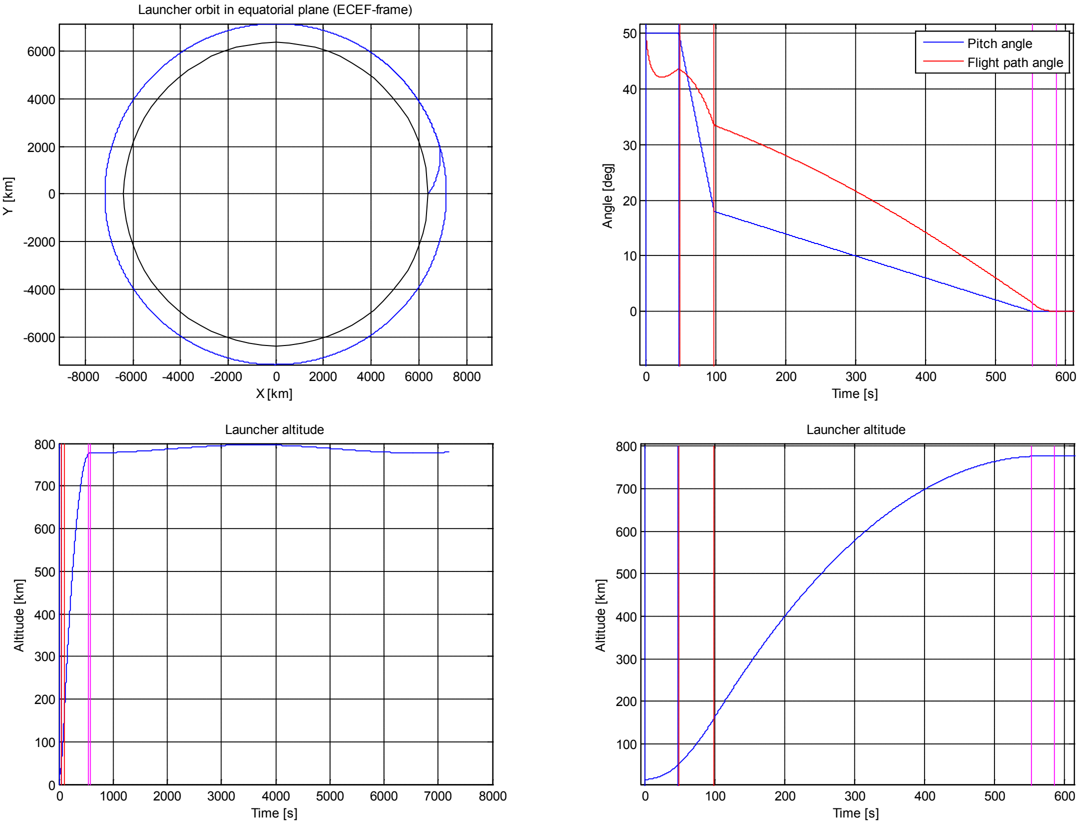


Figure 8 Trajectory and altitude versus time

5 Conclusions

Current launch market analysis and forecast shows significant growth in nano- / microsatellite launch demand. Thereby, it is expected that availability of affordable launch opportunities has a strong influence on increasing satellite market size developments in the future. In the beginning, customers are expected to pay a higher price with respect to current piggyback launch opportunities, because of the dedicated launch capability without limitations. Gradually, the number of launches can be increased enabling production facilities with series production of launchers to increase affordability.

An air-launch platform, such as XCOR/Lynx or F16, has the potential to make dedicated space access needs of small satellites more affordable, by using simpler, and thus cheaper, launchers. However, this way of launching small spacecraft is considered affordable only if the carrier can also be used for other purposes, such as space tourism, micro-g experiments, and/or transport. Without these extra options, the investment in rocket technology might be too high to make it economically viable with respect to existing conventional launchers. An estimated launch price of $50K per kg for 10 kg payload is considered competitive although cheaper piggyback launch prices exist for Russian decommissioned military missiles.

The F16 three-stage launcher conceptual design is not fully optimised yet, but based on practical design considerations and serves as a starting point for further detail design. More design iterations are necessary when more details levels become available. Increasing launch capacity becomes possible when trajectory and launcher stage design are further optimised. This could be incorporated within a future launcher design tool combining optimisation features.

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