Cost effective design of a nano-launcher with ASTOS

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Abstract: The scientific community is showing an increased interest in CubeSats in the last years: small cubic satellites with 10 cm dimension and 1-2 kg mass. Therefore, it is not surprising to see first commercial solutions based on CubeSat on the market (e.g. Planet Dove). The limiting factor is still the access to space: how can you place a CubeSat in a useful orbit. Current possibilities are piggyback on a normal launcher or released from the International Space Station (ISS) via Nanoracks dispenser. Both approaches present several disadvantages. An alternative solution could be a dedicated launcher for CubeSats: a nano-launcher. The German Aerospace Center is evaluating the feasibility of such a vehicle with a strong focus on the economic aspects: can a nano-launcher compete with the price of the current solutions?
Astos Solutions has a long experience in the field of launcher design and trajectory optimization. Its software ASTOS including its Multi-Disciplinary Optimization (MDO) capabilities has been applied to identify the most efficient solution considering several types of starting platform, the most promising number of stages, the propellant types and the material for the structural parts. The feasible configurations are rated based on their recurring costs: production, operational and insurance costs.

1. INTRODUCTION AND STATE OF THE ART

The scientific community is showing an increased interest in CubeSats in the last years: small cubic satellites with 10 cm dimension and 1-2 kg mass. It is now possible to perform complex tasks in a reduced space and mass envelope due to the miniaturization of the electronics. This is evident when considering the computation capabilities and the sensor accuracy of current smartphones. Therefore, it is not surprising to see first commercial solutions based on 3-CubeSat on the market (e.g. Planet Dove [1] and Spire [11]). The limiting factor is still the access to space: how can you place a CubeSat in a useful orbit. Current possibilities are piggyback on a normal launcher or released from the ISS via Nanoracks [2] dispenser. Both approaches present several disadvantages: the final orbit cannot be selected by the Cube-sat provider; the launch time is subject to the decision and availability of the main satellite provider or to the ISS resupply plans. Finally yet importantly, in case of problems during the launch, the secondary payloads are not released or placed in wrong orbits [3]. An alternative solution could be a dedicated launcher for CubeSats: a nano-launcher. The German Aerospace Center (DLR) is evaluating the feasibility of such a vehicle with a strong focus on the economic aspects. Technically speaking the design of such a vehicle presents no critical aspects, but it is of paramount importance to understand if a nano-launcher can compete with the price of the current solutions (i.e. Nanoracks). The performed market analysis shows the forecast of 250-330 nano/micro satellites in 2020 with an annual increase higher than 10%, see Figure 1. This is less than the forecast presented in 2016 and the reason is the lower number of satellites launched in 2016 due to launcher problems.

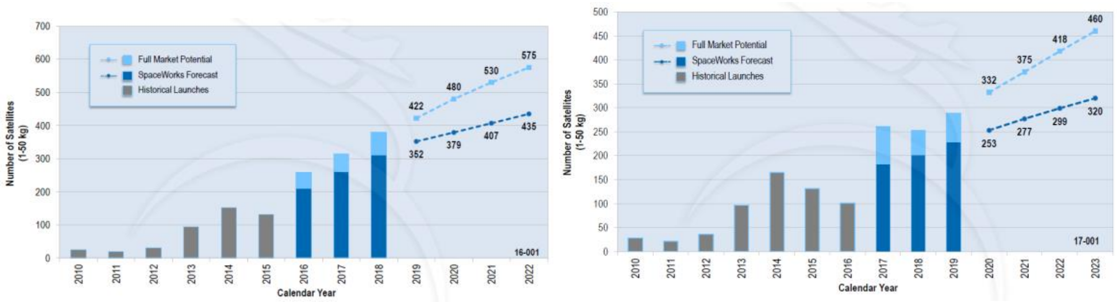

Figure 1. Market Forecast 2016 (right) and 2017 (left), SpaceWorks Enterprises [9].

2. COMPANY EXPERTISE AND SOFTWARE

Astos Solutions [4] has a long experience in the field of launcher design, trajectory optimization and guidance navigation and control (GNC) design. The company has been prime and subcontractor for the European Space Agency (ESA), other space agencies like DLR, Brazil IAE, South Korea KARI and commercial companies in Europe and Asia. In particular, it has supported the design of several class of launchers: from 500 kg up to 20000 kg of payload.

This company has developed for more than 20 years the Analysis Simulation and Trajectory Optimization Software for space scenarios (ASTOS [12]). This is designed to cover most space scenarios with its model library supporting all project phases, but focusing on feasibility and preliminary design. Under several ESA projects, MDO capabilities have been included to improve the fidelity while designing a launcher. This is achieved also via interfaces to commercial available software fully integrated in the ASTOS graphical user interface (GUI): Rocket Propulsion Analysis (RPA) [5], Missile Datcom [6] for the aerodynamic coefficients and ODIN [7] for the computation of the thickness of the structural elements and the respective masses. These tools has been used extensively during the project. A realistic 3D visualization and animation completes the software, Figure 2.

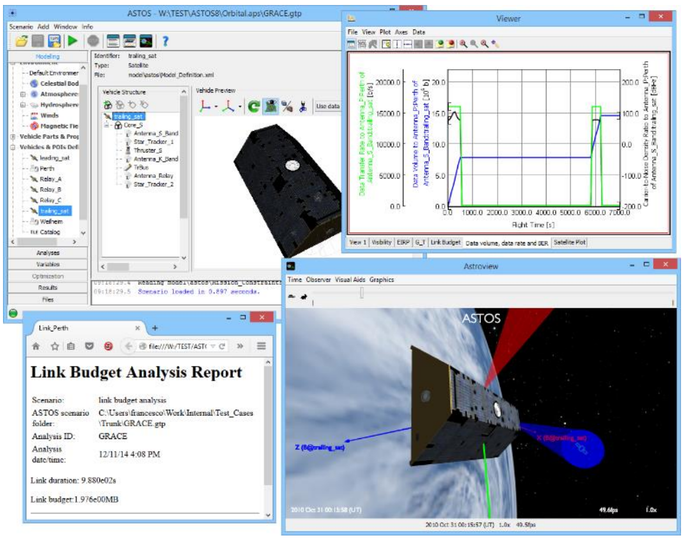

Figure 2. ASTOS 8 for mission analysis.

For the economic evaluation of the concepts it has been used TRANSCOST [8] and [13]. Additionally a bottom-up method has been developed in house to better estimate the recurring costs of a launcher so different from the existing vehicles.

3. TECHNICAL EVALUATION

ASTOS has been applied to identify the most efficient solution to place 6 kg payload in a 400 kilo-meter altitude circular orbit with high inclination (SSO). This considering several types of starting platform: vertical launch-pad, rail or air-launch; several geographic locations and altitudes. Additionally the most promising number of stages is identified in correlation with a wide range of propellant types: solid, hybrid, storable liquid, semi-cryogenic liquid and full cryogenic liquid. The structural aspects are also considered with a trade-off between composite material (CFK) and aluminum alloy.

3.1 Launch type

The launch can be performed from air of from ground. The air-launch can be additionally divided in subsonic airplane launch (e.g. Orbital Pegasus), supersonic airplane launch or balloon launch. A first set of configurations has been used with optimizable propellant mass and thrust level in each stage. The vehicle is formed by 2 liquid stages and a solid upper stage spin-stabilized. The gross lift-off weight (GLOW) comparison between the ground launch and the air-launch shows the supersonic airplane at 60%, the balloon at 70% and the subsonic airplane at 80%.

The balloon solution has to be discarded due to the high cost of the balloon sub-system (in the order of 200 K€); this solution is interesting only for bigger payload. The supersonic airplane solution has criticalities in the dimensions and masses that can be allocated below the airplane. Considering the F-104 as platform, the cost would be in the order of 20k€, but the allowed dimensions are too small [10]. The use of bigger airplanes (e.g. Panavia Tornado) would increase the sub-system cost. The subsonic airplane is the only feasible solution, but the advantage in term of mass reduction would difficultly repay for the additional sub-system required (airplane) and the more complex ground operations.

The comparison between a rail start and a vertical launch-pad shows that the rail can be implemented only considering high level of accelerations at lift-off; this is required to have a correct gravity turn phase. Therefore, only solid propulsion can be considered. Even assuming 4 stages, the accelerations on the vehicle and on the payload are higher than 5 g for several seconds. This has negative effects on the accuracy provided by economical avionics: expensive avionics are not affordable considering the vehicle cost target. For this reason a vertical launch-pad has been selected for later analysis.

Additionally a comparison between potential launch-pad in term of geographic location and altitudes is shown in terms of GLOW in Figure 3. The reference location in near Stornoway Airport (Scotland - UK). The GLOW of the launcher is compared with a similar vehicle starting from Andoya (NO), north-west of Spain, Tenerife Island (SP), Cape Verde Island and Kourou (GUF). It is interesting to note that a lower latitude presents small advantages (up to 4%) even when considering SSO target orbit. The reason is the bigger Earth radius at the Equator. A second comparison is performed considering a starting pad at 1000 meter and 2000 meter. The reduced atmospheric density and pressure provide clear advantages (between 8% and 12%) due to the reduced drag and increased thrust at lift-off (less backward pressure). Disadvantages could be found in the logistic aspects related to the transport of the vehicles and people to the launch-pad. The selection of the Teide mountain in Tenerife (around 2300 meter above see-level) could reduce the GLOW of 10%.

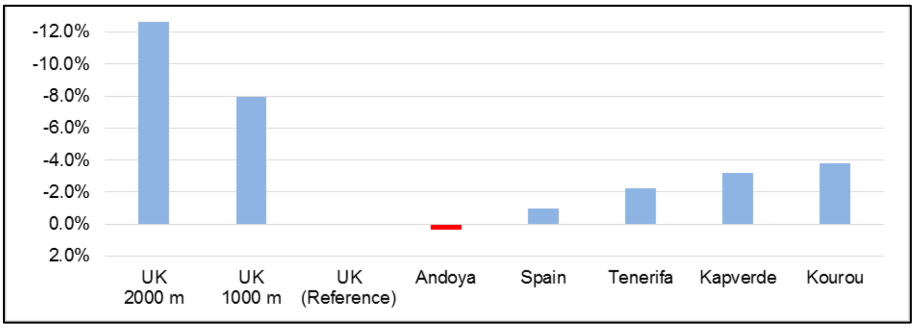

Figure 3. GLOW comparison between different launch-pads.

3.2 Number of stages and propellant type

A trade-off has been performed between 2 and 3 stages. Considering the first option, the second stage has an inert mass of 50-70 kg. Therefore the payload mass is a low fraction of the mass that reach orbit; this means a higher cost in term of vehicle mass and higher risk in case of underperformance of the vehicle. A 3 stage solution is more reliable and provides a GLOW 25% lower. The current trend in the launcher market is to use less stages, but the small mass of the payload is a critical factor in this situation. Using 2 stages, the ratio between the payload and the total mass that reaches orbit is only 7%. With 3 stages the ratio is between 12% and 44% depending on the controllability of the upper stage.

Considering the propellant type, a first selection includes solid, hybrid, storable and cryogenic liquid ones. The hybrid has been discarded due to the low performance and low technology readiness level (TRL). Additionally toxic propellant (e.g. N2O4-hydrazine) has been discarded. A comparison has been performed between solid propellant, LOX-kerosene, LOX-methane, LOX-LH2 and H2O2(HTP)-kerosene.

As expected the lowest GLOW is provided by the LOX-LH2 concept, but the low density of the fuel requires a huge tank in comparison to the other propellant types. Considering the small dimension and the consequent low ratio between volume and surface; the GLOW advantage of this concept is only in the order of 5%. The disadvantages instead are clear when considering the additional costs for ground operation of cryogenic fuel. Similar results are found for the methane concept with the higher efficiency of the propulsion balanced by the need of bigger tanks, thus higher diameter and longer vehicle. These lead to have the full cryogenic concepts to be discarded.

The three remaining concepts are listed below with their main disadvantage:

- Solid propellant has high level of accelerations.
- LOX-kerosene requires a cryogenic tank for LOX.
- H2O2-kerosene has no European heritage.

The use of a spin stabilized solid third stage has clear advantages in term of GLOW: the avionics mass can be moved to the second stage with a very small mass that reaches orbit. This solution presents some disadvantages in term of injection accuracy, so additional analysis should be performed in later phases of the project to access the viability of this solution.

3.3 Structural material

The use of aluminum of composite material has a clear impact on the GLOW of the vehicle with the CFK one 20% lighter. However, the price difference between these two materials could compensate it. Therefore, in the current phase of the project the material selection is not finalized.

4. ECONOMIC CONCEPTS EVALUATION

The potential configurations are then rated based on the economic aspects, but considering only the recurring costs. These are the production costs, the operational costs and the insurance costs. They are estimated using two independent approaches: TRANSCOST and a bottom-up method developed in-house.

TRASNCOST rates the solid propellant concept as the cheapest one, followed by the H202-kerosene (+30%) and the LOX-kerosene (+50%). The bottom-up approach instead identifies the liquid concepts cheaper than the solid one due to the higher cost associated to the ground segment in case of solid propellant. A more detailed cost estimation model has to be developed in the later phases of the project in order to validate the business plan.

5. MDO ON SELECTED CONCEPT

The most promising concept is identified in the HTP-kerosene one. This is used as starting point for a dedicated analysis implementing the Multi-Disciplinary Optimization (MDO) capabilities of ASTOS: this approach is more time demanding but it ensures a higher level of precision in the results.

Common bulkhead tanks are used for the first and second stage, both with 70 cm diameter whereas the upper stage and fairing have smaller diameter, 30 cm. The first stage implement 4 identical engines with low expansion ratio in order to reduce the backward pressure; a fifth identical engine with higher expansion ratio is present in the second stage. This will reduce the required costs for the development of the engine; a solution implemented in several new launchers: Falcon 9, Electron.

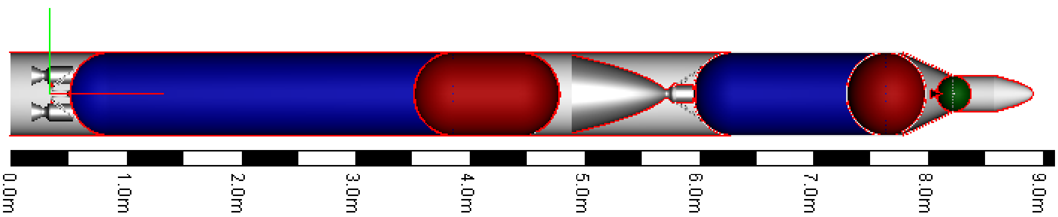

Figure 4. ASTOS model of selected concept

The fuel tank is presented in red, the oxidizer in blue; the green upper stage is using solid propellant. The payload is not shown, but dimensions of the fairing are sufficient for a

3U CubeSat. The resulting vehicle has successful passed the DLR Mission Definition Review (MDR).

5.1 Payload mass

The complete analysis is considering a payload mass of 6 kg, 3U CubeSat. As already mentioned this small mass has a negative effect on the efficiency of the system and therefore the cost of this launcher is higher than the price of comparable solutions (e.g. Nanoracks).

A potential solution is the increase of the payload mass. The mass selected is 24 kg, 12U CubeSat. The other aspects (material, propellant, etc.) are the same as the solution with 6 kg payload. The optimal design with 24 kg payload has a GLOW that is only 30% more than with 6 kg payload. Economically speaking, a very interesting solution with a cost in the order of 40 k€/kg.

6. ACKNOWLEDGEMENT

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