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Trajectory optimization of semi-reusable launchers

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Abstract

Since first commercial flights of semi-reusable launch vehicles, a worldwide race for reusable and semi-reusable launch vehicles has started.
The trajectory optimization complexity of a reusable or semi-reusable launch vehicle increases significantly with respect to expendable launcher trajectory optimization.
In order to improve the convergence of semi-reusable launcher trajectory optimization and limit the risk of sub-optimal solutions, new optimization methods have been developed. These methods also allows to reduce the optimization duration.
This paper defines this optimization problem and provides examples of optimizations using these new methods.

1. Introduction

Reusable launch vehicles allow to push the limits of expendable launch vehicles by reducing launch cost (assuming refurbishment is cheaper than a new production), increasing launch cadence (by reusing parts, less production lines are needed) and decreasing environmental impact (more propellant is used during launch, counterbalanced by the lower impact of reused parts).
Hence, the next generations of European launchers will certainly use reusable stage. In this sense, the European Space Agency shown interest in this scope by financing several studies on reusable launchers and launcher fleets including reusable stages.

In order to define efficiently these launchers and to assess their performances, the development of new optimization methods is needed. Indeed, the trajectory optimization of reusable launchers (or semi-reusable launchers) is significantly harder than for expandable ones.

This is mainly the consequence of the several coupled arcs: the ascent arc and the return arcs. When maximizing the payload mass, each arc should be optimized to provide the maximal performance to the ascent arc. The optimization complexity is increased by the introduction of new optimization parameters to manage the additional arcs. Moreover, the coupled paths increase significantly the risk to get stuck on sub-optimal solutions with classic optimization methods.

ArianeGroup has developed new optimization methods to optimize more easily the semi-reusable launchers trajectories. The aim of these methods is to improve the optimization convergence to the optimal solution and to decrease the optimization duration.

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2. Assumptions

This paper is focused on the trajectory optimization of semi-reusable launchers. The following assumptions are taken on the launch vehicle, landing site and command law:

- The launcher is semi-reusable with the return of the first stage or of its boosters.
- The return is performed with a toss-back trajectory made of one to third boosts: an optional return boost to target the return site, an optional braking boost to reduce aerothermal constraints (dynamic pressure, thermal flux…) and a mandatory landing boost.
- The landing site can be a barge or a site around the launchpad
- The braking boost and landing boost of the return stage are performed in the opposite side of the relative velocity (180° angle of attack)

The two managed return strategies are illustrated here:

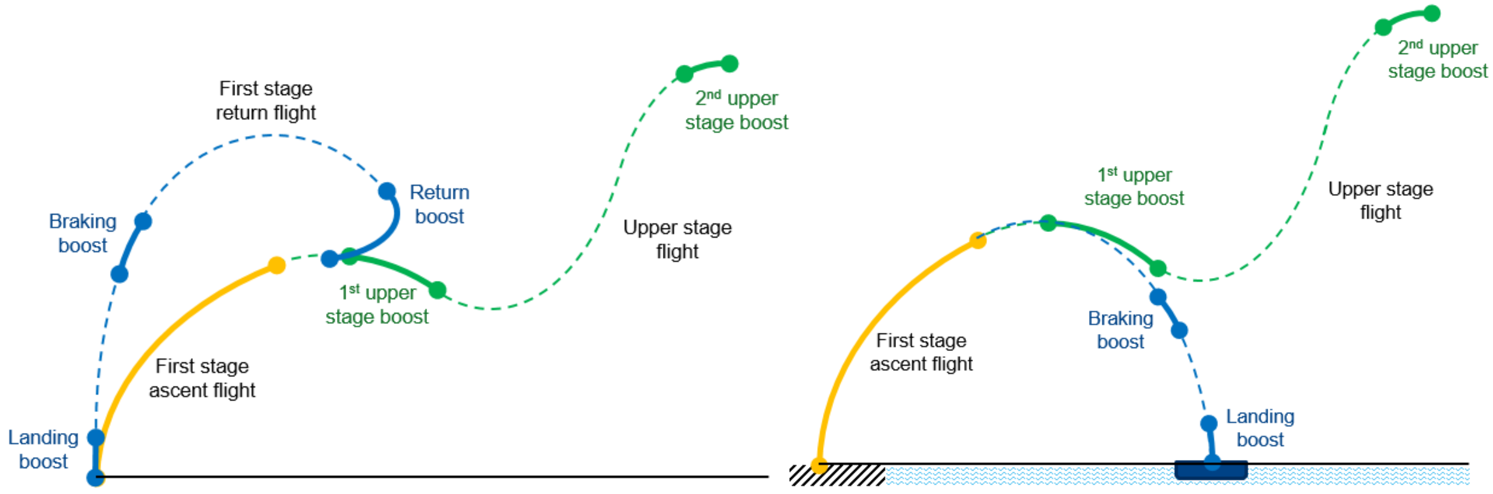

Figure 1: First stage return strategies

3. Trajectory optimization of semi-reusable launchers

The main parameters to optimize the semi-reusable launch vehicle trajectory in the aim of maximizing the payload mass are detailed below:

- On the ascent path:
  - The first pitch over amplitude, which results in a given zero angle of attack ascent atmospheric flight
  - First pitch over azimuth
  - The instant of the reusable stage separation (first stage or boosters)
  - The exo-atmospheric command law (attitude) of the remaining stages
  - The instant of upper-stage cut-off. And for some missions, the duration of the ballistic phase and instants of upper-stage re-ignition and second cut-off.
  - The payload mass
- On the return path:
  - Duration and orientation of the 1st return boost in order to target the landing site. In the case of a barge landing non-constrained in terms of distance, this boost can be skipped. This boost is supposed performed shortly after the stage separation (couples to tens of seconds).
  - Instant and duration of the braking boost, used to reduce either the dynamic pressure or the thermal flux on the return stage. On some missions this boost is not required because constraints are naturally respected.
  - Instant and duration of the landing boost. At the end of this boost the launcher should have a null relative velocity and altitude.

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In the other side, the main constraints of the optimization problem are:

- Maximal dynamic pressure at the stage separation
- Maximal dynamic pressure on the ascent path
- Maximal thermal flux at fairing separation and after
- P/L injection orbit, for example expressed as apogee altitude, perigee altitude, inclination and optionally perigee argument
- Maximal dynamic pressure and thermal flux on the return path
- Landing site to be reached (if constrained)

The optimization problem has an important number of optimization variables. This can result in long optimization duration and in risks to get stuck on a sub-optimal solution. To manage this risk and reduce the computation time, a set of methods has been developed at ArianeGroup.

4. Examples

The new developed methods have been applied on several semi-reusable launch vehicles. In this section, some examples of trajectories with hypothetical vehicles launched from Kourou (French Guiana) are presented. The launch vehicles presented use LOX/CH4 propellants.

In these examples, all the available propellant of the upper stage and the lower stage has been consumed. This is a clue of the optimality of the solution. We can also see on the charts the saturation of the maximal return dynamic pressure at 100kPa (the threshold of the constraint).

The following charts show the trajectory of a two-stage launcher performing a GTO mission. The first stage is recovered on a sea barge. The position of the sea barge is unconstrained, as a result there is no need of a return boost. There is a 22s braking boost which limits the return dynamic pressure. We can observe a double dynamic pressure peak close to the end of the braking boost. The braking boost provides about 680m/s of propulsive ΔV. For the landing boost, about 430m/s is provided by the engine.

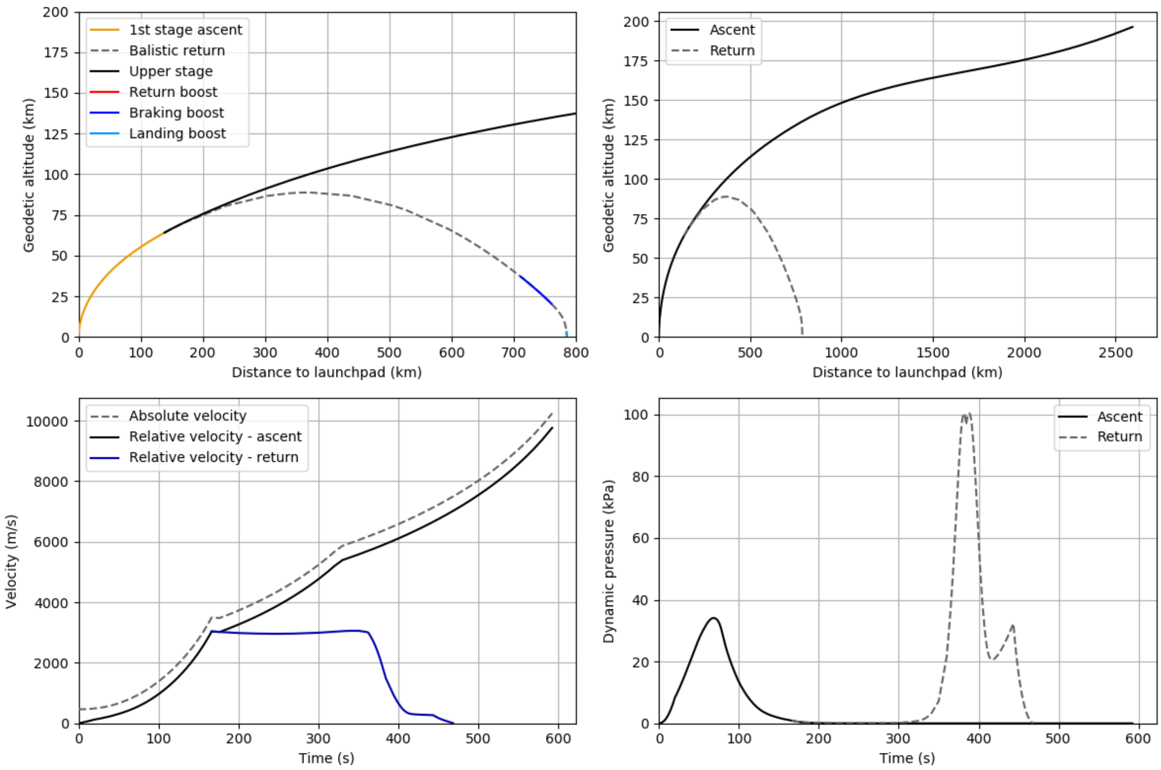

Figure 2: Two-stage launcher GTO mission with downrange recovery

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The following charts show the trajectory of a two-stage launcher performing a SSO mission (800km) with two upper stage boosts. The first stage is recovered on a landing site close to the launch site.
The optimal transfer orbit is automatically computed, as well as the coasting phase duration and the second upper stage boost, at the apogee of the transfer orbit. On this mission, the return boost provides about 2400m/s, the braking boost 180m/s and the landing boost 440m/s. Indeed, the braking boost is usually shorter on launch site recovery missions than on sea barge missions.

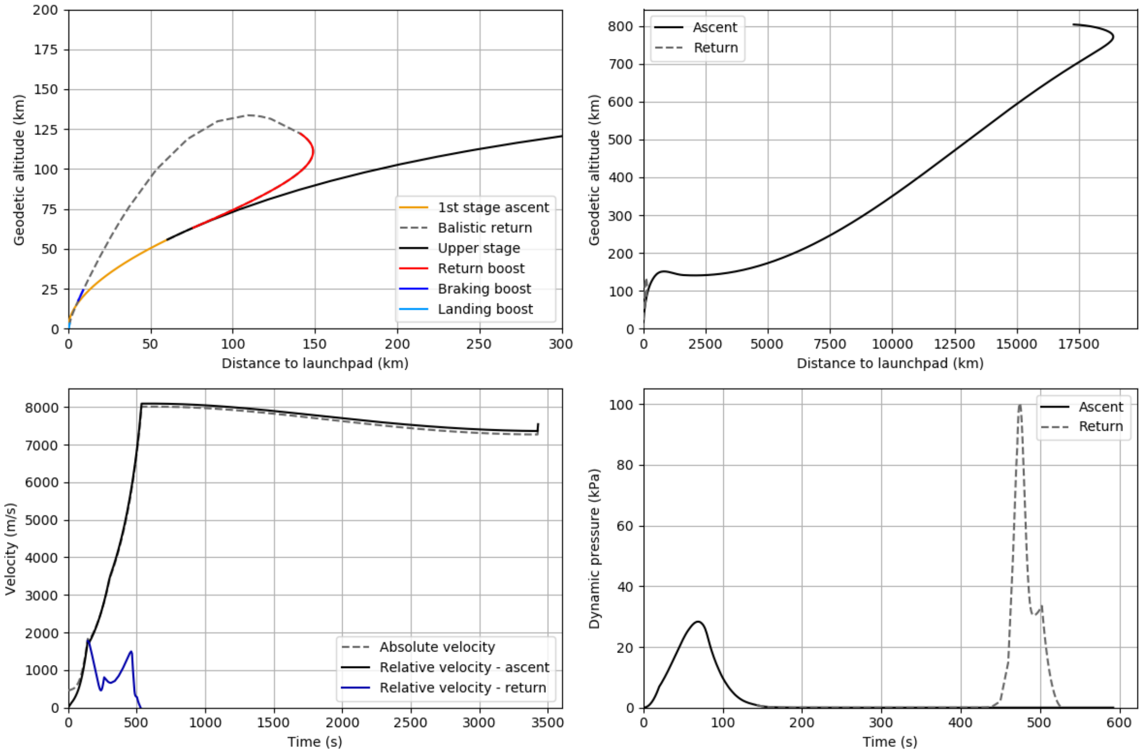

Figure 3: Two-stage launcher SSO mission with launch site recovery

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The following charts show the trajectory of a two-stage launcher performing a LEO mission (250km 50°). The mission is performed with only one upper-stage boost. The first stage is recovered on a landing site close to the launch site. On this mission, the return boost provides about 2000m/s, the braking boost 300m/s and the landing boost 440m/s.

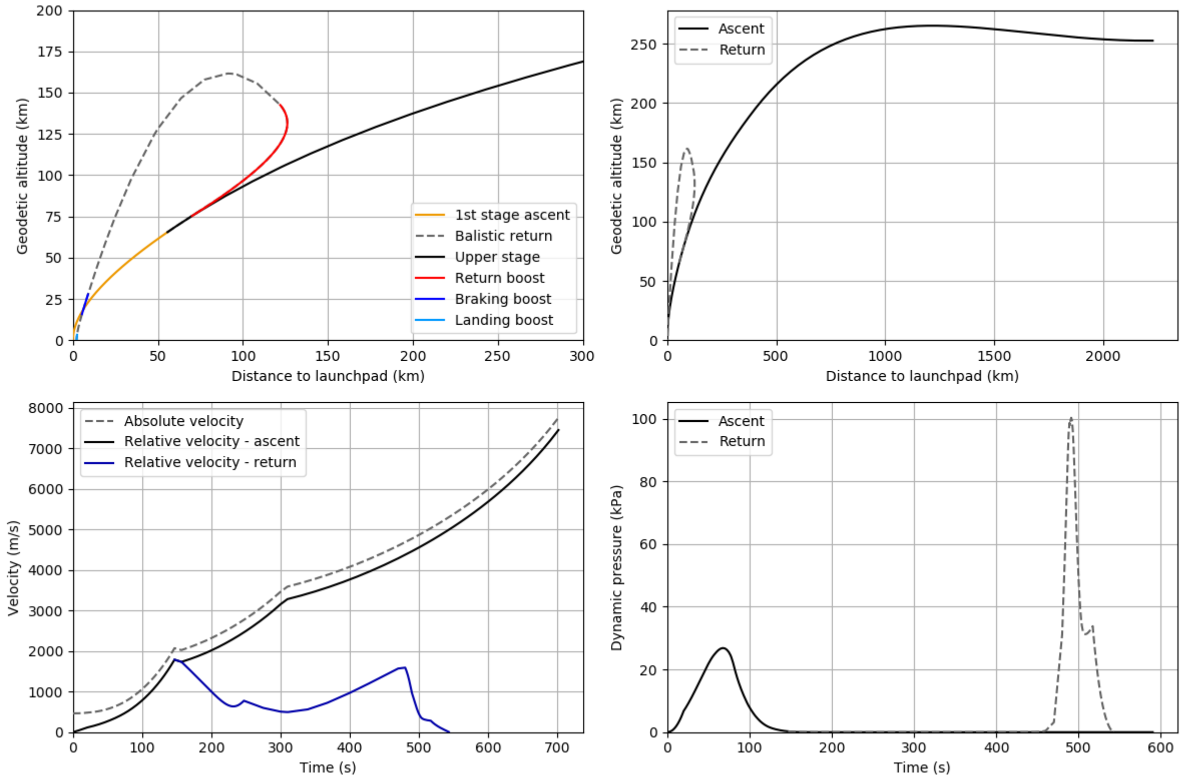

Figure 4: Two-stage launcher LEO mission with launch site recovery

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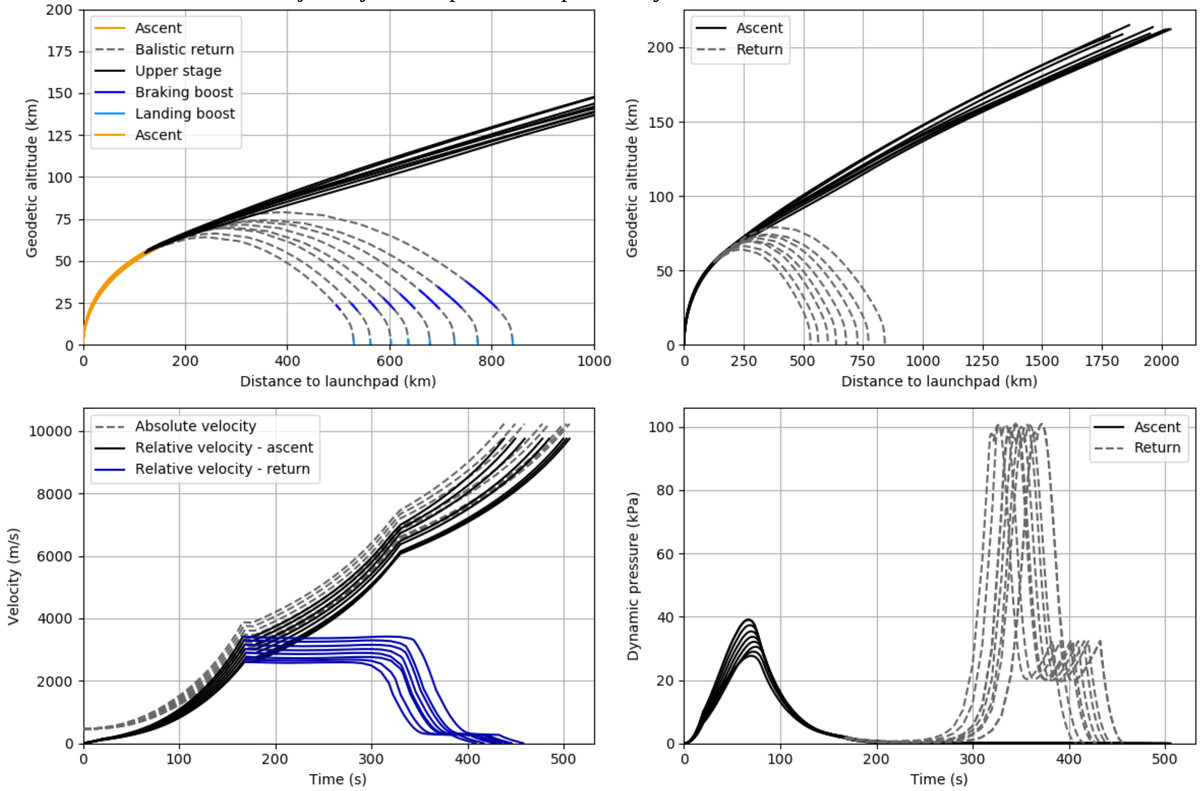
The next charts show the sensitivity of the first stage downrange to the size of the upper-stage. This sensitivity is performed on a two-stage launcher performing a GTO mission with the return of the first stage on an unconstrained sea barge.
The lower stage contains 500 tons of propellant (oxygen & methane) and the upper stage loading is scanned between 60 tons and 130 tons. Each trajectory is computed independently without initialization.



5. Conclusion

The new methods developed at ArianeGroup allows optimization robustness improvement (better convergence to the optimal solution) and reduced global computation time. Most semi-reusable launcher missions are optimized automatically without any initialization. This improvement enables scans on launcher characteristics and configurations in a day.

References

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