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ANALYZING THE INFLUENCE OF AN ADDITIONAL KICK-STAGE ON PERFORMANCE AND FLIGHT PROFILE OF A MINILAUNCHER

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Abstract

While the performance proposed by European microlaunchers does not reach the same values as the heavy launchers (F9, Ariane 6), there is a constant fight to increase their payload capacity. There are direct solutions: reducing masses, more efficient engines, or some more sophisticated options to be explored.

Among the latter is adding an additional stage, usually ridiculously small in term of size compared to the original launcher, but nevertheless always offers a significant boost of performance. This solution is currently developed at MaiaSpace, with the kickstage Colibri, allowing a payload capacity increase of 1000 kg[1], which, for certain missions, is equivalent to more than doubling the initial performance.

While the performance boost can be seen as a direct consequence of the laws of physics, adding a kickstage introduces new constraints to the launcher architecture. We conducted several studies revolving around the performance boost of Colibri and what it means for the flight profiles.

Notably on the upper stage, for which the lowered duty in term of participation of the mission has several impacts, such as the staging and the propulsion needs. Also, the flight performance reserves calculation model had to be adapted to be coherent of the new launcher's architecture and new flight safety concerns emerged.
Additionally, Colibri's design had to be incrementally optimized to fit the performance needs required to be competitive in the very competitive mini launcher market.

The results indicated contrasted performance gains for some missions and significative impact on the launcher. These findings contributed to the development of the launcher and the global optimization of the launcher architecture.

1. Introduction

In the early days of ArianeWorks, established in 2019 as a collaborative innovation platform between ArianeGroup and CNES, the idea of a kickstage was already alive, but its purpose was originally to unlock innovation in the space mobility domain. ArianeWorks initiative led to the creation of MaiaSpace in 2022, as a fully owned subsidiary of ArianeGroup, tasked with developing Europe's first reusable and eco-responsible mini-launcher Maia[2].

Mounted on a less energetic launcher than the current Maia vehicle, it would bring the capacity to finish the injection mission of a payload and to deorbit a stage left in orbit by a previous launch of a heavy launcher, following the "One up one down" philosophy.
It was also aimed that the kickstage would be transparent to the performance, since it brings as much performance as it decreases it with its own mass. Colibri also does not increase drastically the cost of the launcher while bringing more value to the launch due to the additional performance and services possibilities.

The convergence between the performance enhancement, the need of mobility in orbit, the access to space, the opportunities to reach the IOS (In Orbit Services) markets and the vision of durability that is a core value of MaiaSpace brought Colibri concept and spirit to MaiaSpace.

As the first commercial flights would arrive before the maturation of the IOS market, the focus was primarily put on the performance enhancement side of Colibri in the first months of its development. The mission of Colibri was oriented first on the performance enhancement functionality. During this phase, one could catch the numerous impacts Colibri has on the launcher flight profile, and by consequence its whole architecture.

This paper reports the results on designing a tri-stages launcher from a bi-stages constitution while minimizing the repercussions on the overall architecture, and on adapting the flight profile to overcome the constraints introduces by the kickstage.

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Glossary	
IOS	In Orbit Services
g0	Earth gravity constant: 9.8065m/s²
Isp	Specific impulse: measure of efficiency of a launcher engine
kc	kickstage
us	Upper stage
ls	Lower stage
FSOA	French Space Operation Act
LOS	Loi sur les Opérations Spatiales
ELV	Expendable Launch Vehicle
RLV	Reusable Launch Vehicle
LEO	Low Earth Orbit
SSO	Sun Synchronous Orbit
REAT	Re-entry Emission Assessment Tool
DRAMA	Debris Risk Assessment and Mitigation Analysis

2. Performance improvement

To understand the benefit of adding a kickstage to a bi-stages mini launcher, it is possible to directly calculate performance via trajectory optimisation tools, and this is what is recommended to do to take precisely into account the numerous parameters that influence the trajectory of a launcher. But we can also go through the theory of rocket staging. Let’s assume the optimization criterion is the ratio between the payload mass and the mass at lift-off:

$$C = \frac{M_{Payload}}{M_{Lift-off}} \tag{1}$$

The ΔV given by each stage is given by Tsiolkovsky[3]:

$$\Delta V = g_0 . Isp . \ln\left(\frac{M_i}{M_f}\right) \leftrightarrow M_i = M_f . \exp\left(\frac{\Delta V}{g_0 . isp}\right) \tag{2}$$

With M_i the initial mass of the stage, M_f the final mass.
For every stage, the initial mass can be decomposed, as well as the final mass:

$$M_i = M_e + M_s + M_{sup} \tag{3}$$

$$M_f = M_s + M_{sup} \tag{4}$$

M_{sup} being the total mass of what is above the stage, M_e the mass of propellant, M_s the dry mass.
We introduce the structural index:

$$k = \frac{M_s}{M_e} \tag{5}$$

We can express the ratio between M_{sup} and M_i as such:

$$M_i = M_e . (1 + k) + M_{sup} \leftrightarrow M_e = \frac{M_i - M_{sup}}{1 + k} \tag{6}$$

$$\frac{M_f}{M_i} = \frac{M_i - M_e}{M_i} = \frac{1}{M_i} . \left(M_i - \frac{M_i - M_{sup}}{1 + k}\right) \leftrightarrow \frac{M_{sup}}{M_i} = (1 + k) . e^{-\frac{\Delta V}{g_0 . isp}} - k \tag{7}$$

We can express the C criterion in function of the number of stages n, given that all stages have the same structural index k and that they deliver the same velocity increment:

$$C_{n-stages} = \left((1 + k) . e^{-\frac{\Delta V_{total}}{n . g_0 . isp}} - k\right)^n \tag{8}$$

We can trace the results for several values of k, and validate the fact that adding a stage will theoretically increase the performance of a launcher:

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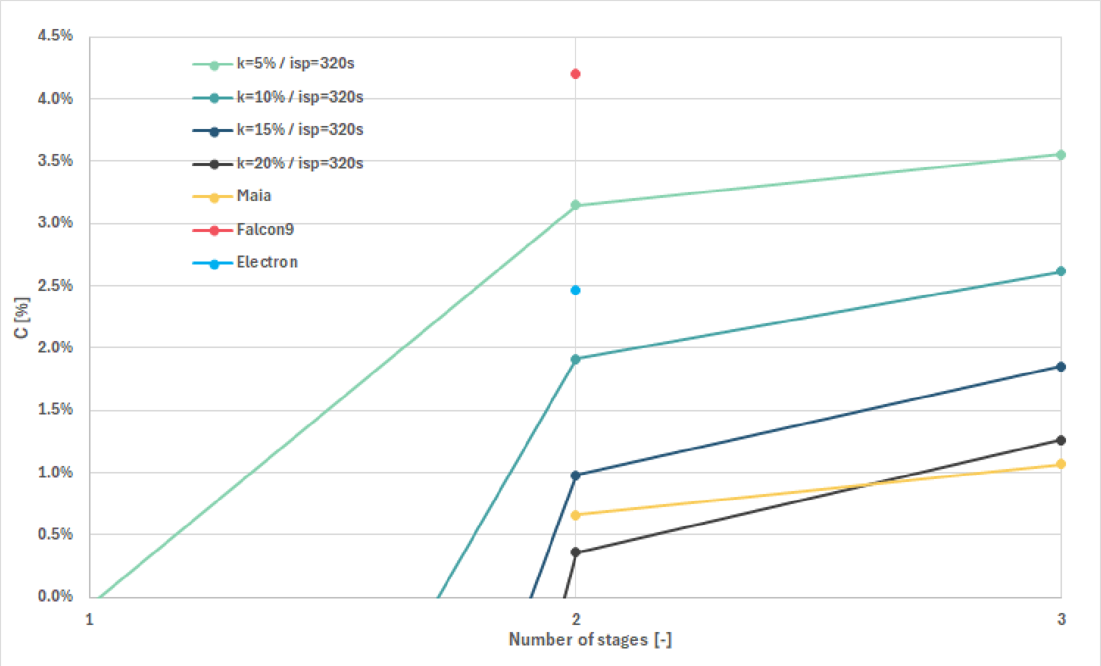

Figure 1 : C criterion in function of the number of stages

To confirm this evaluation on the case of a mini launcher, we can consider the real case, where all stages do not have the same structural index, isp and does not give the same ΔV increment. With values close to the Maia launcher, we can evaluate C thanks to the equation (8) and find the same conclusion on the benefit of the tri-stages with regards to the bi-stages configuration.

As a comparison, on low orbit, Electron has a ratio between the payload mass and the mass at lift-off of 2.5%[4], Falcon 9 4.2%[5].

We can also observe that with higher structural index, the bonus of having a kickstage is higher. There is however a threshold in term of structural index and isp, when both are too degraded, where the C criterion starts to decrease.

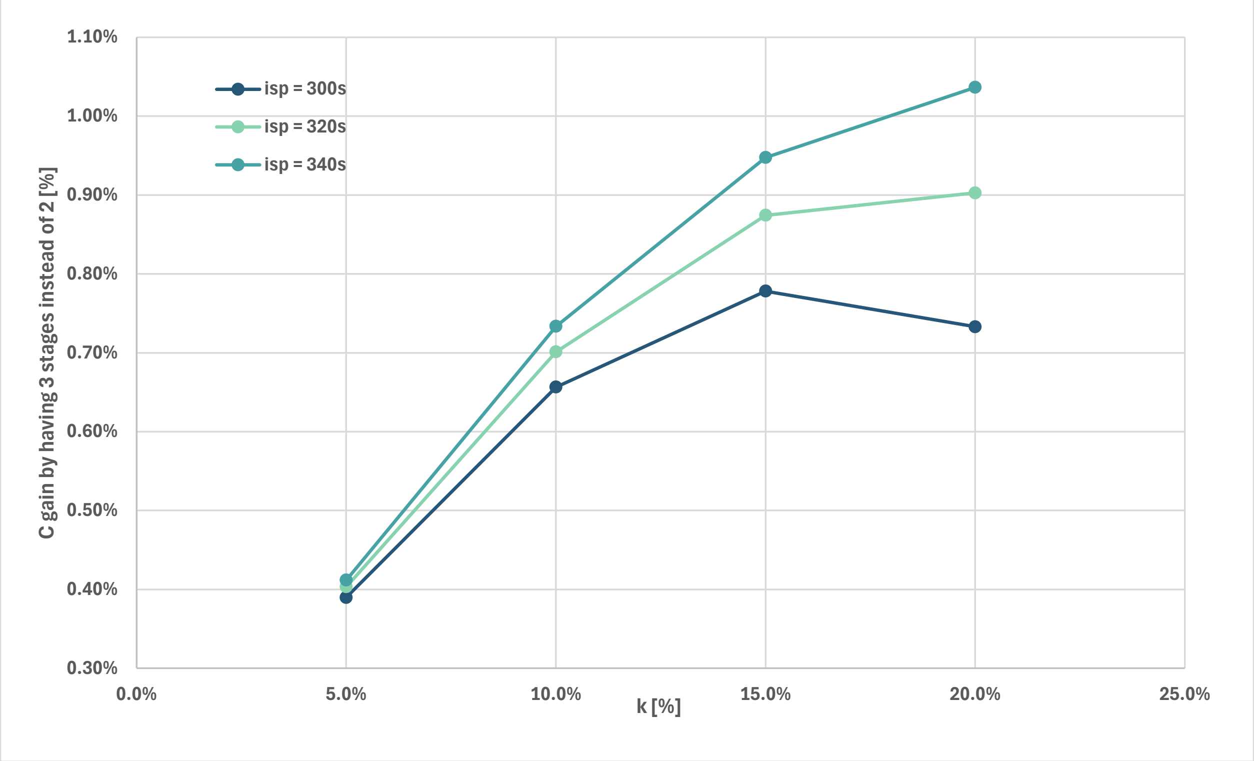

Figure 2 : Evolution of the gain in the C criterion in function of the structural index of the stage

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It has its importance during the first flights, where the launcher is still in its ramp-up period and the performance increases incrementally following the growth in maturity of the launcher operation: reduction of dispersions, margins, improvement and optimisation of the industrialisation / manufacturing, acquisition of enhanced knowledge on the launcher behaviour in flight etc. **It can be anticipated that the structural index of the two first stages will be unoptimized for the first commercial flights, hence the opportunity to compensate for the conservative approach and provide a consistent performance from the firsts launches.**

Other factors can explain the advantage of having a kickstage in particular the propellant cost of the final manoeuvres before and after the payload injection, less demanding in term of ΔV, which are the circularization boost and the deorbitation boost.
In bi-stages the final reignitions can appear to be costly in term of consumption, due to propellant settling and subsequently performance. We can estimate this consumption to several hundreds of kilos.

$$M_e = M_i.\left(1 - \exp\left(\frac{-\Delta V}{g_0.isp}\right)\right) \quad (9)$$

With a kickstage, this consumption is less than a hundred kilos, thanks to its reduced weight and functional constraints. Since this consumption is directly retrieved from the performance, this is a direct observation that a kickstage is a solution to realize those final manoeuvres at a lower performance cost.
Auxiliary performance gains can be found on the upper stage, since it realized only one boost. As instance in the reduction of the pressurization system that bring a reduction of the stage dry mass (see §2).

3. Impacts on the flight profile

We previously saw that, given the right parameters, a kickstage can increase the performance of a launcher. Before going further into the dimensioning of the kickstage, and because it will help to understand what the needs in term of ΔV capacity are, we should comprehensively analyse the impacts of having a kickstage on the flight profile.
Most of the missions that a mini launcher will realize are to LEO (Low Earth Orbit). The common flight profile with a bi-stages configuration is:

1. Atmospheric flight realized by the lower stage.
2. First exo-atmospheric boost realized by the upper stage to reach an intermediate orbit with the apoapsis altitude being the same as the targeted orbit.
3. Second boost of the upper stage at the apoapsis to circularize the orbit.
4. A final boost to deorbit the second stage if necessary.

In rare cases, if the altitude aimed is low enough and the boost of the second stage not too short in term of duration, it’s possible to combine the steps 2 & 3 into one boost.

Adding a kickstage opens the spectre of possibilities on flight profiles.

The first scenario, which yields maximum performance, corresponds to the case where the ΔV required from the kickstage is highest. The second stage is then no longer on a stable orbit.

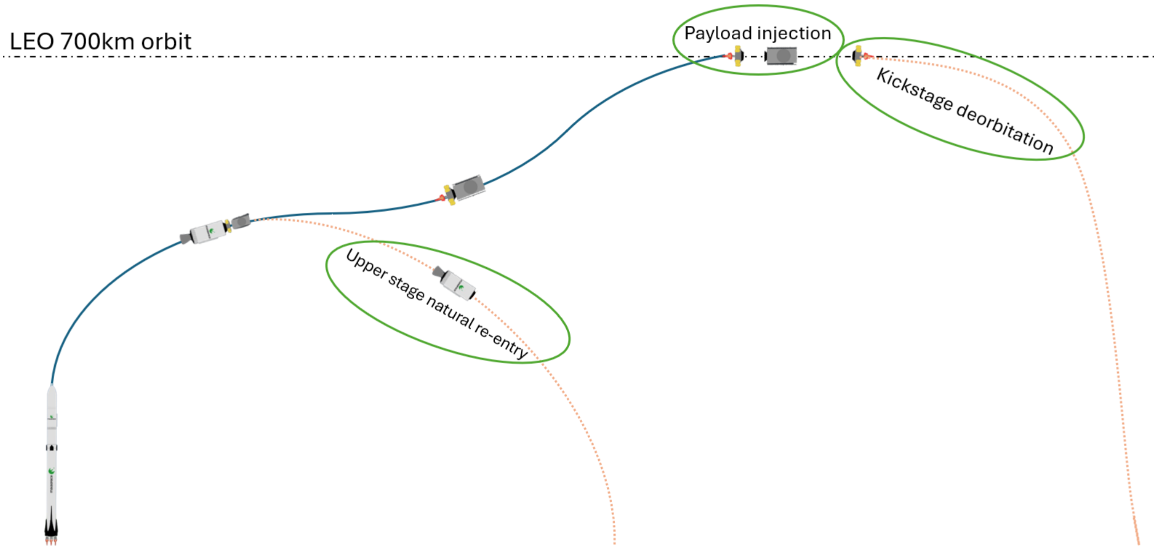

Figure 3 : Flight profile with a suborbital upper stage: scenario 1

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Therefore, several new constraints appear.

- The kickstage must be able to sustain the orbit fast enough (i.e. increasing the periapsis altitude above 140km) to reach a stable orbit before reentry. This constraint transcribes as a minimum thrust constraint for the kickstage propulsive system, which for the MaiaSpace case study yields in 500N-1kN of minimal thrust.
- As per the FSOA[6], the nominal re-entry of the upper stage should happen in an empty maritime area. When the upper stage footprint following reentry does not respect this constraint naturally, the trajectory must be modified to verify this criterion.

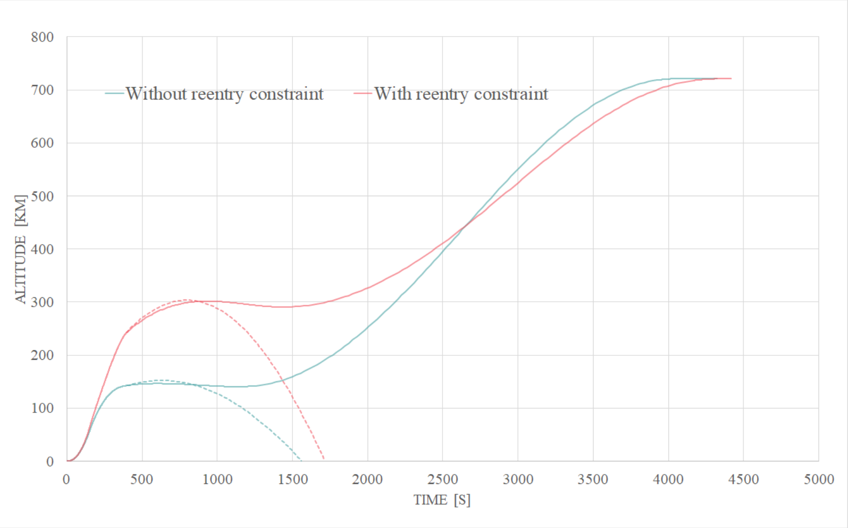

Figure 4 : Evolution of altitude with and without reentry constraint to verify a safe impact of the upper stage

To assess the feasibility, the area of the natural impact point is observed, and if necessary constrained to aim for an acceptable maritime area. Secondly, we must ensure that even with a dispersed flight, the probability for the upper stage to re-enter 25km away from a coastline is still under 10E-5. This can be equivalent to a maximum flightpath angle at re-entry constraint. These two constraints merged can have a significant impact on performance if not naturally respected.

This may also affect the available orbit inclinations the launcher can reach, when no acceptable maritime area is available nowhere near the natural re-entry impact point.

For the two conditions showed above, that are linked to safety constraints and the LOS, we must analyse the injection of the upper stage via dispersed trajectories and estimations of footprint re-entry areas.

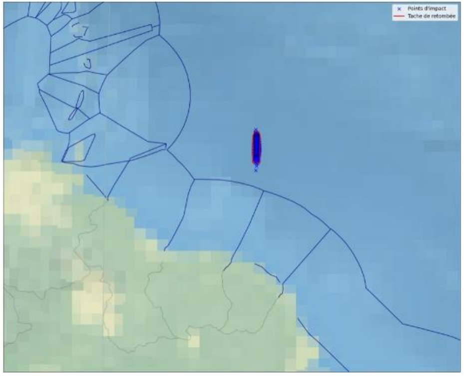

Figure 5 : Lower stage footprint impact area

This kind of methodology is already developed for the re-entry of all the launcher components (lower stage, fairing, upper stage after deorbitation) but it should be adapted. Indeed, even if the upper stage re-entry is already evaluated and known in the case of the deorbitation, the injection conditions, the guidance, thrust levels at the end of the upper stage boost are not the same that when it’s being deorbited. Additionally, the orbital parameters that the guidance should aim for could be defined differently.

We can also think of cases where the launcher is over-propulsive and the upper stage might reach a more energetic orbit, allowing the kickstage to finish the mission in a more comfortable state and consecutively the payload to get a

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higher lifespan in orbit / better injection precision, but must shut down to ensure a re-entry inside of a safe maritime area.

A second flight profile that can be considered, is when the upper stage is orbited at a low altitude orbit (between 150km and 300km). The kickstage must deliver a lower ΔV to reach the desired orbit but can still increase the overall performance if the targeted orbit is high enough to make this scenario worth it.

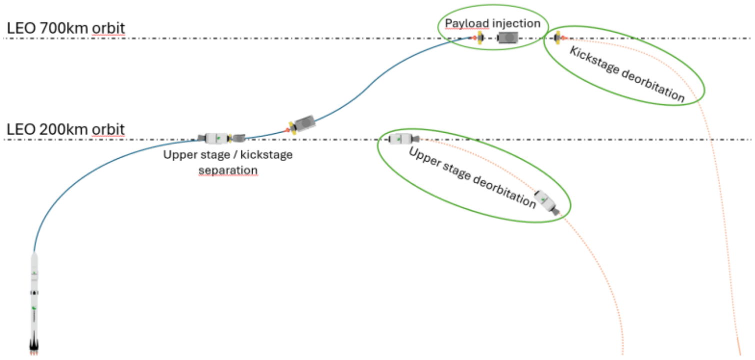


Figure 6 : Flight profile with an orbited upper stage: scenario 2

The real benefit indeed comes with higher orbit altitude, of at least 500km, and we can see in the figure below that the performance cannot be higher than with the first scenario. These performances were calculated via exhaustive trajectories calculations.

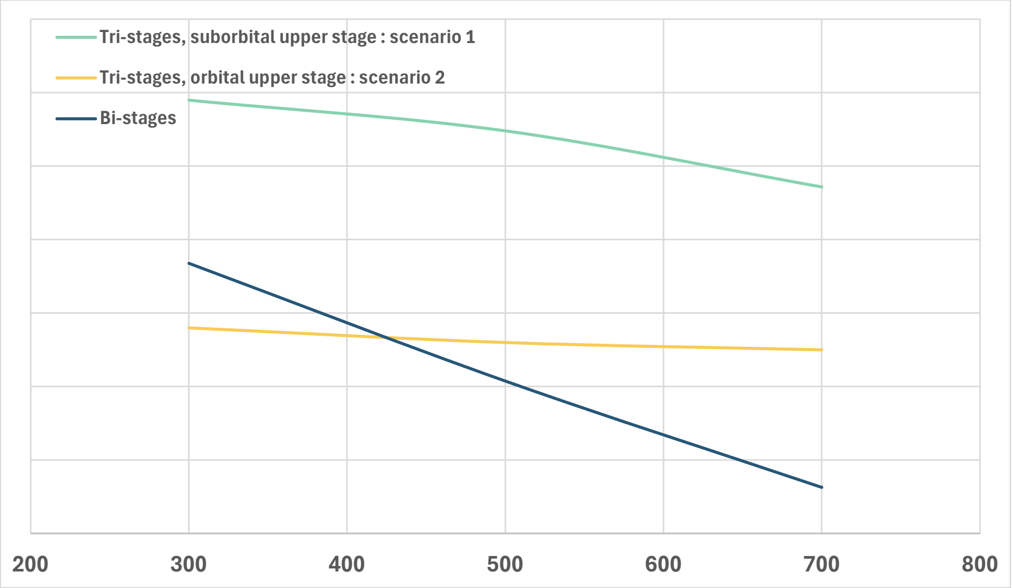


Figure 7 : Performance in function of the altitude and the flight scenario

In this case, both the kickstage and the upper stage must realize two additional boosts, which can constrain the propulsive systems, cancel the overall performance gain of such scenario.

4. Sizing the kickstage

To maximize the performance boost given by the kickstage, it was crucial to find its optimal functioning point in term of sizing. To be adaptable, the kickstage should also be able to perform the two scenarios described in §3.

Since Colibri main design parameters where the last to be frozen in the development of the launcher and are less constraining to modify with regards to the other stages, we could adapt its capacity to better fit the needs of the Maia launcher.

With the equation (8) we can observe that an optimum exists. Several parameters can vary in this equation:

- Isp is a major contributor of performance and usually is maximized by the engine manufacturer.
- Structural index: it is always optimal to minimize it to increase the performance, but only a certain range of structural index is reachable, depending on the functioning of the stages: motorization, composition of the

tanks (aluminum or steel), fluid pressurization system etc. So usually those are fixed, leaving a very short to no margin for optimization.

- The repartition of the ΔV between the stages.

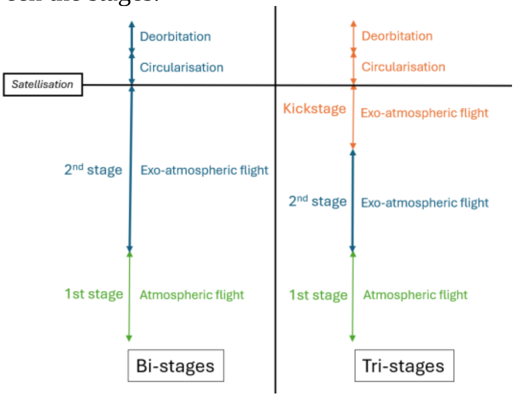


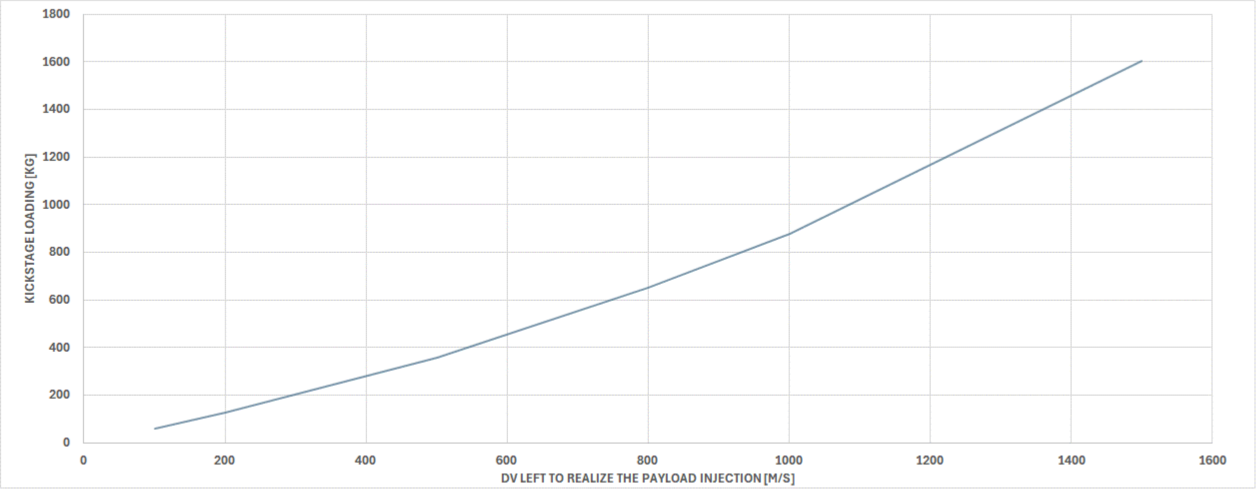
Figure 8 : Example of decomposition of increment of velocity for bi-stages and tri-stages launchers

In a three stages configuration, as we saw in §3, with the optimal flight profile, the satellisation occurs during the kickstage flight, resulting in a suborbital upper stage. However, this does not mean that the upper stage generates less propulsive ΔV than in a bi-stages configuration, in fact, the upper stage must inject a surplus of payload (which is a consequence of the propulsive ΔV given by the kickstage) and a fully loaded kickstage. As a result, the orbit reached is degraded compared with a bi-stages configuration and is suborbital.

Considering that the upper stage does not finish the payload injection, but instead injects the payload attached to the kickstage to an orbit less energetic than the final orbit, we can detect several functioning points for the kickstage. By assuming an isp of 300 seconds, that is a typical value of isp the engine can reach considering the fuel used by Colibri (H202 and ethanol), and a modelling of the structural mass ratio using a derived law— showed below, based on calculated dry masses for various configurations and loading conditions—we can establish a relationship between the required propellant mass and the ΔV achievable by the kickstage.

$$k = (3643.4 * \frac{Loading^{-0.593}}{100}) + 0.11$$

This allowed us to estimate the necessary loading as a function of the kickstage's ΔV performance.



We can detect several functioning points:

- 100 kg kickstage, that would realize only the circularization and desorbitation boosts.
- 1 000 kg kickstage that would, in addition of the two final boosts as above, participate to the exo-atmospheric flight.
- 1 500 kg kickstage. Its participation to the exo-atmospheric flight would then be quite subsequent.

For the Maia launcher there is two use cases, when the first stage is recovered versus when it is expendable. In these two scenarios, the structural index and the ΔV repartition is quite different for the two first stages. When it is reusable, the lower stage structural index is degraded because of the devices allowing the reusability (landing legs, flight control bay, fins), and it participate less to the ΔV needed for the ascent phase since a part of its propellant is saved for the reentry boosts. Also, the payload range is lower, so the kickstage has less mass to carry into orbit. In expendable version, the lower stage is lighter and participate at its maximum to the ascent phase. However, the payload range is higher, the kickstage can have up to several tons on its top.

Given several loadings for the kickstage, we can assess analytically the performance gain associated, in two scenarios:

- Maximal performance gain: without considering any constraint on the trajectory to respect an acceptable upper stage safe re-entry. In this case, we considered the ΔV given by {lower stage + upper stage} to be constant for every loading of the kickstage considered.
- Corrected performance gain: in the case where the natural upper stage reentry area is not be acceptable, the flight profile must be constrained, thus degrading the ΔV contribution from the upper stage. Here we considered a degradation of 100m/s.

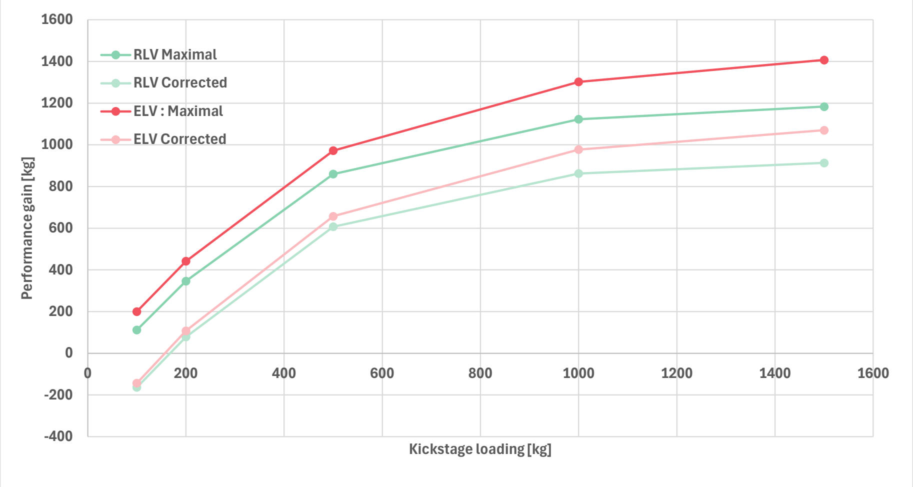


Figure 9 : Performance gain in function of the kickstage loading for the two launchers configurations

It was originally anticipated that since the first stage contributes less to the payload injection in RLV case, the influence of the kickstage would increase, however, this is not what we found. It is interesting to notice that, with these hypotheses, the performance gain is higher with an expendable vehicle.

These performance gains could be corrected for the highest loading, indeed, with the range of thrust considered for the kickstage, increasing the loading too much will come with heavier losses (gravity, incidence), and thus lower performance gain than imagined. Also, the assumption of instantaneous boosts implied by the Tsiolkovsky equation is more incorrect with the growth of the kickstage’s loading.

Again, this result is impacted in the first degree by the natural upper stage area, which is different if you consider a reusable or expendable vehicle: the upper stage is injected on a more energetic orbit in an expendable configuration. This conclusion can be reversed in the case where the upper stage re-entry is naturally valid with the reusable configuration and not with the expendable one.

The performance gain seems to converge to 1 ton of performance with 1 ton of loading. This is a result we confirmed by several performance and trajectories studies, with exhaustive trajectory optimizations, modelling the entire injection mission of the launcher, and the upper stage re-entry. This also allowed us to also assess the optimal thrust level, that is not caught by the Tsiolkovsky equations. We could generate these performance abacuses to find the most efficient kickstage configuration for each mission and configuration. Each pane represents a value of isp that we swept.

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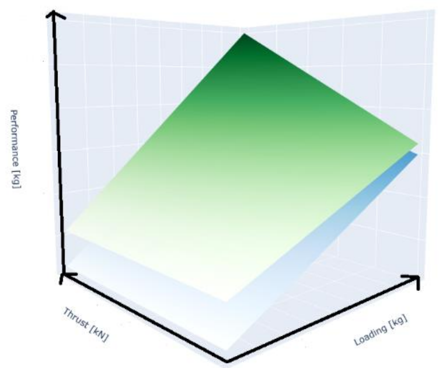

Figure 10 : Performance abacus in ELV configuration

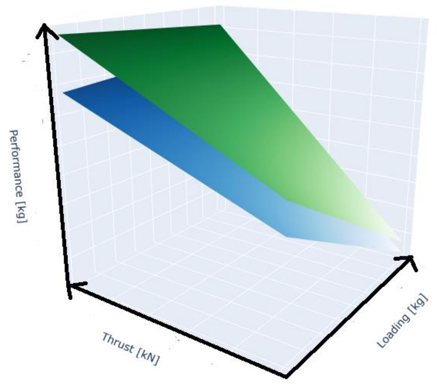

Figure 11 : Performance abacus in RLV configuration

In this mission, we can see that the upper stage re-entry constraint implies different behaviours on the performance evolution regarding the kickstage loading. The ELV configuration follows the previous conclusion of the analytical study, but in RLV, the performance is higher for lower loading. Also, in this configuration, the performance is sensible to the thrust of the kickstage, which is not the case in ELV.
The decision of the optimal loading becomes not trivial. Even if unloading the kickstage is a possibility bringing less constraints than on the lower or upper stage (sloshing issues), there will always be a slight performance loss associated as the kickstage will have unfilled tanks and a degraded structural index. In the end, a configuration, RLV or ELV, will be moderately sacrificed in term of performance.

Additional factors were considered in the choice of the optimal solution, such as the structure architecture that was explored by bottom-up calculations with mass, cost and propulsion estimations and the long-term roadmap of the kickstage, that includes the future market of space mobility and in orbit services, where higher loading will come in handy to permit more range of activity.

This result affirms the need of trajectories optimization to find the precise optimal functioning point for the kickstage, and that can’t be replaced by an analytical study that allows only a fast glance at potential optimal sizes.

5. Impacts on flight performance reserves

The flight performance reserves are a quantity of propellant that is not used by the engines in the nominal trajectory to ensure a certain probability of non-exhaustion of the launcher before reaching the targeted orbit. We consider flight performance reserves to cope with the dispersions (atmosphere, engines, masses etc.) that can occur during the flight and that can’t be predicted precisely before a flight.
They can be calculated analytically or statistically with Monte Carlo method.

The first reason why a kickstage would increase the performance of the micro-launcher is directly related with what is presented in §3 and §2 with the repartition of velocity increments given by the stages. The kickstage flight is thriftier in term of propellant and would need less propellant to ensure the same probability of non-exhaustion as an upper stage in a bi-stages configuration.
For instance, ensuring a 99% probability of non-exhaustion in a bi-stages configuration result in several hundreds of kilos of propellant on the upper stage, which is as much, if more, of performance lost. In a tri-stages configurations, the number of reserves in the upper stage is reduced, and on the kick-stage they are counted in only several dozens of kilograms to respect the same exhaustion probability.

To comprehend the second effect that impact the flight performance reserves, it’s important to understand that every boost of the mission has a probability of non-exhaustion, and that the next boosts must ensure their own probabilities of non-exhaustion while catching-up the precedent boosts that may not have a 100% probability of non-exhaustion. This results of having the upper stage catching-up the lower stage flight and the kickstage catching-up the upper stage flight.

One could think that to maximise the performance, it could be optimal to let both the lower and upper stage go to exhaustion with a 50% probability and let the kickstage catch-up both the lower stage flight and the upper stage flight.

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However, as we saw above in §3 with a kickstage, we must ensure a safe re-entry of the upper stage in a maritime area. With no flight performance reserves on the upper stage, the injection of the upper stage would be very dispersed, and it would seem impossible to respect the safety constraint (i.e. having the 10^{-5} re-entry impact footprint out of any coastline). It's consecutively mandatory to ensure a higher probability of non-exhaustion on the upper stage and thus having a non-optimal repartition of the performance reserves among the stages.

Fortunately, the performance gain still exists in this case.

6. Environmental performance

As it was already observed, Colibri also has a positive impact in term of environmental performance of the launcher. Indeed, although the life circle of the production of the kickstage adds up to 2% of C02eq on the global environmental impact, the performance gain that Colibri bring reduces the relative environmental impact on climate change in term of C02eq per kilogram of payload injected in orbit.[1] Given that the impact of a single launch is too high to be compensated by any manner, this diagnosis become even more significant if we consider that additional bi-stages launches are necessary to reach the same total payload capacity reached with a tri-stages configuration.
We could estimate the evolution of this relative impact over the first years of commercialisation of MaiaSpace by evaluating the performance gain given by the kickstage during this period. **The impact is significantly reduced, by -110% in the first year, then by -40% in the second year. Finally, the impact converges to a value above -30% after the ramp-up period.**

Figure 12 : Performance relative impact on climate change of having a kickstage, for the first years of MaiaSpace commercialization

This evolution can be explained thanks to what we calculated in §2:

- During the ramp-up period, the launcher performance is less influenced by degraded structural index of the two first stages when a kickstage is used. That's why the usage of Colibri is a key to keep the competitiveness of MaiaSpace during its early commercial years.
- In established regime, even if the bi-stages configuration is competitive, the kickstage still increases the performance of the launcher, hence the positive impact of the Colibri.

Ultimately, as an explorative study, we estimated the impact of Colibri on the atmospheric pollution that occurs during the re-entry of the stages. As the stages goes back from space to Earth, either after deorbitation, or directly during the mission (like the upper stage in the scenario #1, see §3), the atmospheric re-entry can lead to fragmentation (dynamic pressure) and demise (atmospheric friction). The demise of the stages, depending on their material, can create deleterious particles for the atmosphere, such as NOx from the high temperatures experienced, or Al_2O_3 from metal oxidation, especially if these are generated in the upper layers of the atmosphere[7].

These calculations were realized by the tool REAT[8][9][10] that calculate particles emissions from the outputs of DRAMA, from the ESA's Space Debris Mitigation Guidelines Handbook[11], that assess the mitigation strategies, especially on the debris risks and the effectiveness of an end-of-life strategy.

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We could model the architecture of the kickstage with the corresponding materials of each system and sub-system. Combined with the right injection properties (velocity, flightpath angle), we could estimate the emissions.

The study of Colibri re-entry is particularly interesting as its structure is primarily made of aluminium, and we believe that this material creates Al_2O_3, a particle particularly harmful for the atmosphere. As the chemical processes of Al_2O_3 generation are yet to be fully determined, and that the exact aluminium alloy of the kickstage was not referenced in the tool, we will not focus on the absolute values of emissions of Al_2O_3. In addition, the DRAMA model of the kickstage is very simplified. Instead, we will analyse how injection orbit parameters impact its generation in the atmosphere.

In all these estimations, we considered a controlled deorbitation of the kickstage from a stable LEO orbit. The deorbitation manoeuvre aim for a -50km periapsis, so the flightpath angle at 120km vary between -3° and 2°, depending on where the deorbitation boost is realized.

We swept the altitudes and inclinations of the initial LEO orbit and estimated their impacts on the Al_2O_3emissions. Finally, we swept the flightpath angle, to simulate an uncontrolled re-entry with a flightpath angle close to 0°.

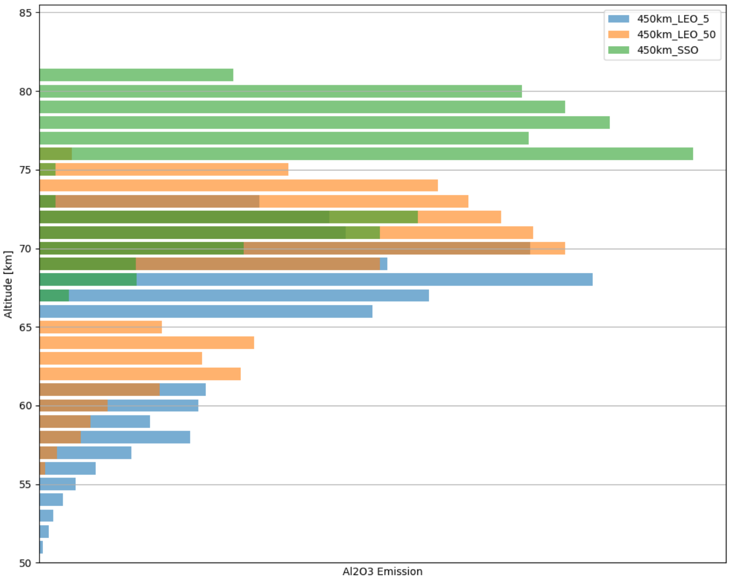

Figure 13 : Evolution of Al2O3 emission in function of the altitude, in the case of a controlled deorbitation of the kickstage, from several orbits with different inclinations

The two separated peaks represent, first, the demise of the primal structure (on the higher altitudes), then the demise of the sub-structures of the kickstage.

In LEO, at the same altitude, the inertial velocity of the kickstage is nearly identical, however, the relative velocity depends on the orbit inclination, because of the Earth's rotation. On nearly equatorial orbits, where the benefit from the slingshot effect of the earth is higher, the relative velocity is lower, in orbit and consecutively during the reentry, than on polar/SSO orbits. Therefore, the kickstage will demise on lower layers of the atmosphere.

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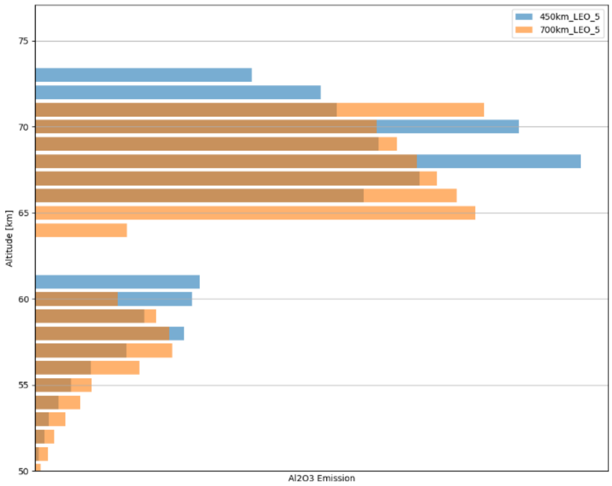

Figure 14 : Evolution of Al2O3 emission in function of the altitude, in the case of a controlled deorbitation of the kickstage, from several orbits with different altitudes

The effect of the initial orbit's altitude seems less significant than the effect of the inclination, but we can still observe a slight impact, given that the relative velocity in orbit is higher for lower altitude orbits (the necessary velocity to stay in orbit is higher, the lower your orbit is). The Al_2O_3 emissions are consecutively concentrated on higher layers of the atmosphere for lower LEO.

Finally, we observed the impact of the flightpath angle on the Al_2O_3 emissions.

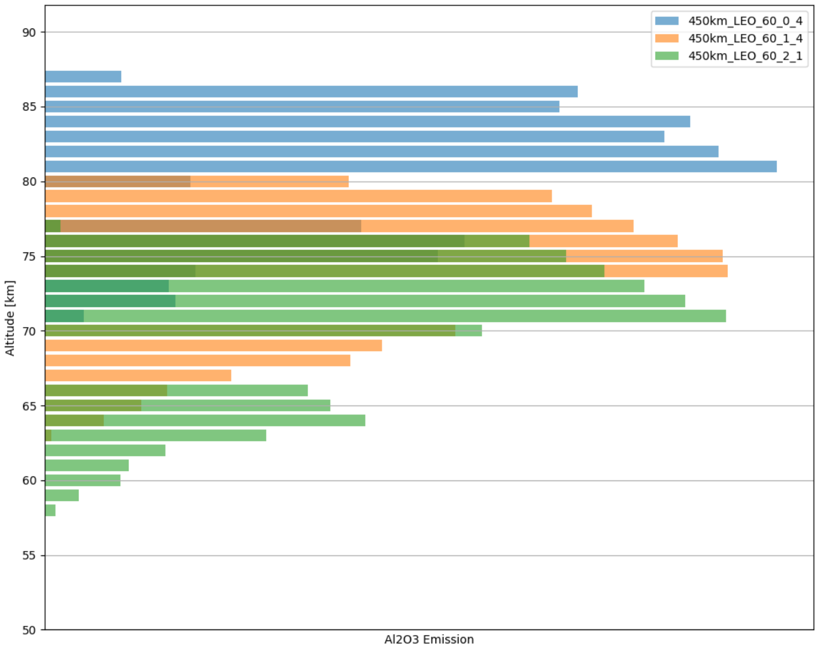

Figure 15 : Evolution of Al2O3 emission in function of the altitude, in the case of a controlled deorbitation of the kickstage, from several orbits with different flightpath angle at 120km

As anticipated, with a flightpath angle at 120km closer to 0°, the Al_2O_3 occurs on higher layers of the atmosphere, the delta in term of altitude can reach 10km for the demise of the primal structure.

These results are, given the current knowledge on atmosphere pollution at these altitudes, only observations, to take actions to reduce the pollution on the atmosphere we should first assess what layers of the atmosphere are the most harmed by such emissions and complete the analysis by estimating all the possible emitted particles by the vehicle during the re-entry. Another solution to reduce these emissions could be the design for non-demise[7], where we limit the demise of the vehicle, but this solution has many consequences, especially on the choice of the material of the kickstage that would potentially increase its dry mass, and reduce the performance gain.

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7. Conclusion

The integration of a kickstage into a mini-launcher architecture demonstrates significant potential to enhance payload capacity, optimize propellant efficiency, and address operational constraints such as re-entry safety and flight profile adaptability. By leveraging theoretical frameworks, accessible using very basic tools like the Tsiolkovsky equations and structural index analysis, the study provides a robust foundation for understanding the performance gains achievable through tri-stage configurations. The environmental benefits of the kickstage—particularly its role in reducing CO_2eq per kilogram of payload—further underscore its relevance in advancing sustainable spaceflight as soon as the early exploitation phase.

While the paper highlights the transformative potential of the kickstage, future work could explore its adaptability to evolving market demands, such as space mobility and in-orbit services, ensuring long-term competitiveness and sustainability in the mini-launcher industry.

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