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EURASTROS ascent trajectory and abort analysis

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Abstract

The EURASTROS study [1] was a joint study between Ariane Group GmbH and the German Aerospace Center (DLR), exploring astronautic transport capabilities of Ariane 6. The study included the preliminary design of a crew module (CM) [2], a service module (SM) [3], a performance analysis of possible Launch Abort System (LAS) concepts and a cost analysis [4]. This paper presents the work performed with the purpose to define the general ascent strategy and to design suitable end-to-end abort strategies compatible with the mission and system requirements. It shows the selected reference ascent trajectory and covers detailed preliminary analyses of the exo- and endo-atmospheric abort scenarios regarded within the EURASTROS project.

All analyses were closely tied to continuous optimization of the Ariane 6 ascent trajectory and corresponding iteration of achievable payload performances, using astronautic transport to an ISS orbit as reference study case. The conducted analyses explored multiple possibilities for performance adjustment in agreement with human rated mission requirements, while also respecting space debris mitigation standards. Eventually these investigations concluded in the proposal of 11 Mg propellant un-loading of the Upper Liquid Propulsion Module (ULPM) of the Ariane 64 (A64) with respect to standard GTO upper stage fuel, yielding a trajectory enabling for maximum performance and also sufficient safety.

The crew module, envisioned for a total crew of up to three astronauts, was designed with close resemblance to the Apollo CM, with a Service Module (SM) for exo-atmospheric flight at the rear and a Launch Abort System (LAS) for endo-atmospheric abort at the front, but with volume reduced by 28 %. For the LAS design, the most promising configurations were designed towards minimum thrust allowing to reach a minimum safety distance of 200 m to the launch vehicle within 3.5 seconds after separation and to fulfill further safety requirements in case of an abort from launch pad. Simulations conducted at DLR concluded that the bare minimum thrust should exceed 950 kN for both concepts in order to meet imposed safety requirements. Based on these results a subsequent mass budget estimation yielded a total mass estimate between 4700 – 5400 kg for the LAS.

The SM is based on the ASTRIS kick stage and utilizes the engine BERTA running on storable fuel. This module is dimensioned to provide continuous exo-atmospheric launch abort capabilities while preventing any potential impact on populated areas on European and Eurasian soil. For such an abort scenario, the Last Direct Re-entry Point (LDR) after which an abort-to-orbit would be executed, has been defined. Influences of the corresponding maneuver pitching angles on ballistic downrange as well as on required time for abort-to-orbit are explored and the SM minimum thrust was adjusted to yield sufficient performance capabilities. Eventually, six abort modes for exo-atmospheric flight are proposed and discussed.

1. Introduction

Astronautical transportation is a significant challenge for any space fairing nation, as it demands immense technical, organizational and financial efforts and experience. It is however also a rewarding key capability, opening up huge scientific, strategical and also commercial potentials. Europe however, is still lacking a dedicated astronautical transport capability, instead being fully dependent on American or Russian launch vehicles to transport its astronauts. Against this background, the EURASTROS study, a joined study between Ariane Group GmbH and several institutes of the German Aerospace Center (DLR) was conducted in 2021, investigating the potentials of the new Ariane 6 launcher family for astronautical transportation. Its main goals include the identification of the technological [1][2][3] and financial means [4] required to execute an European astronautical mission prior to 2030. Since every astronautical transportation system has to respect crew safety above all else, continuous possibilities for launch abort and crew escape are required during all flight phases, either via abort-to-ground or abort-to-orbit.

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The investigations presented in this paper include initial performance assessments of the new Ariane 6 launchers (A62 and A64) against the background of a generic astronautical mission from Centre Spatial Guyanais in Kourou (CSG) to the ISS (see chapter 2). Further, engineers at Ariane Group GmbH synthesized two possible concepts for a launch abort system (LAS) for endo-atmospheric abort [3], which were cross evaluated and iterated by DLR (see chapter 3). For exo-atmospheric abort scenarios the usage of the service module (SM), usually used for in-space-propulsion, is envisioned. The corresponding analyses and findings are addressed in chapter 4.

2. Nominal Ascent Analysis

2.1 Reference Mission

For the performance analyses on the Ariane 6 a generic mission into an ISS orbit was selected as reference application case. The target orbit for the spacecraft (SC), consisting out of the CM and SM, is assumed to be circular with an altitude of 400 km at an inclination of 51.6°.

The launch shall occur from the current Ariane 6 launch pad (ELA 4) at the CSG in Kourou in order to use a maximum of synergy of already existing hardware and ground installations. A modification of the launchpad, for instance to ensure access to the crew compartment or escape from the launch tower in case of an emergency was beyond the scope of the study and remains to be investigated.

In a nominal scenario, the LAS will become obsolete once the launch vehicle (LV) reaches sufficient altitude to render atmospheric influences negligible. This is usually the case once an altitude of 90-110 km is surpassed, after which the SM will provide sufficient propulsive capabilities for any escape scenario so that the LAS can be jettisoned from the LV. This occurs approximately 180 seconds after lift-off and 50 seconds after separation of the main P120-boosters. A minimum delay of 25 s between ejection of the LAS and separation of the P120-boosters of Ariane 6 is imposed in order to offer sufficient time to the attitude control system to compensate for any attitude perturbation induced by booster separation.

It is decided to pursue a mono-boost strategy for the upper stage during ascent up to the release of the SC. While the upper stage of Ariane 6 is capable of multiple reignitions and a bi-boost strategy would noticeably increase launcher performance there is a nonzero risk that the second engine ignition may fail, leaving the astronauts in an unstable orbit. There might be mitigating measures such as using the SM to compensate for the lack of ΔV and still reach a stable orbit, but these were not investigated at this stage.

Initially, the orbit altitude targeted by Ariane 6 was limited to 300 km maximum in order to keep loads during an exo-atmospheric abort within sustainable limits. This limit was used for the initial performance assessment. An extended analysis of abort trajectories concluded however that a more severe limit was necessary in order to keep the G-loads encountered during an exo-atmospheric abort within acceptable limits (see chapter 4 for further details). This limit imposes an injection into a 200 km orbit and afterward use the SM to reach the final ISS orbit. In compliance with safety and debris mitigation regulations, it is required that the Upper Liquid Propulsion Module (ULPM), the upper stage of the Ariane 6, is actively de-orbited for a splash-down in the sea after release of the SC into the injection orbit. This requires a retrograde burn producing between 60 and 90 m/s of ΔV.

2.1 Performance of Ariane 6

In order to gain a first glimpse of attainable performances for the Ariane 6 launchers, the DLR’s in-house launcher models of Ariane 62 and Ariane 64 [5] were used for a parametric study sweeping through a range of circular orbit altitudes for release of the SC. Due to abort case considerations (see chapter 4) during the initial study phase, the orbit to be attained at the end of the upper stage burn shall not exceed 300 km. Instead of the conventional fairing mass of approximately 2600 kg, a mass of the LAS of roughly 5100 kg was considered. This corresponds to the initially assumed mass of the abort tower LAS-configuration plus one ton of margin for the LAS-systems iteration described in chapter 3. As mentioned before, this component will be jettisoned upon leaving the atmosphere. The nominal ejection logic of the LAS is similar to that of the standard Ariane fairing, meaning that it will only be separated once the heat flux rate drops below 1135 W/m², which is because the fairing also conveys some protection to the upper side of the CM. It shall be noted that obviously the limit of 1135 W/m² is a placeholder for a limitation tailored to the needs of this mission. This heat flux rate limit is anyhow never active due to the relative steepness of the ascent trajectory. Furthermore, LAS jettisoning may not occur earlier than 25 s after booster separation.

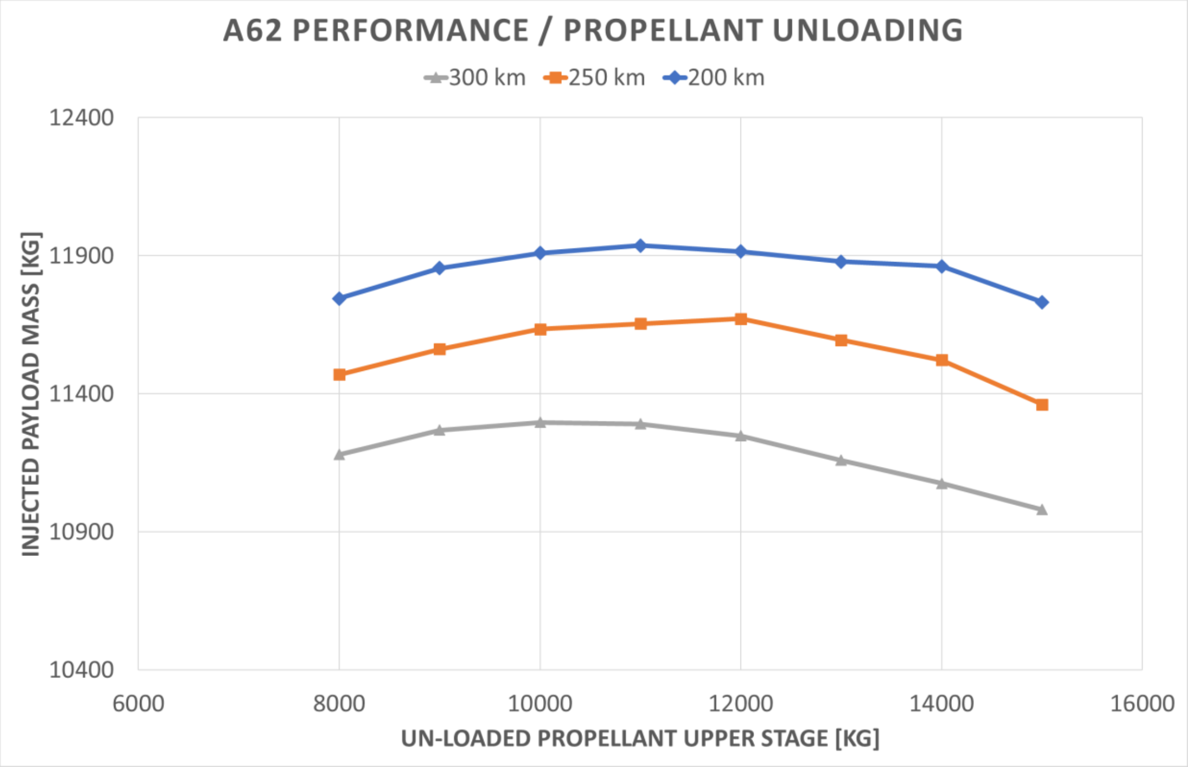

Figure 1: Performance of Ariane 62 standard configuration for varying orbit altitudes and fuel loading

In order to avoid it becoming space debris, the ULPM will be de-orbited after delivering the SC. Therefore, 548.6 kg of fuel are reserved, enough to reduce the perigee of the ULPM's orbit to zero km altitude. This fuel mass is composed of 247.1 kg fuel for re-ignition preparation and 301.5 kg of fuel consumption for the de-orbit maneuver itself.

A range of propellant fill levels for the ULPM were investigated. This is motivated by the fact that the launcher performance significantly benefits from reducing the loaded upper stage propellant by a certain amount. It is assumed that the tank mixture ratio is unaltered by any un-loading level. Though it is clear that significant fuel un-loadings require further investigations and additional qualification effort, this study focused only on the feasibility aspects and as such any further investigations were beyond the scope of this study.

Figure 1 shows the performance range obtained for Ariane 62 standard configuration. It shall be noted that the amount of fuel un-loading refers to the maximum load level as realized for an Ariane 64 GTO launch, irrespective of the investigated LV configuration. Furthermore, it shall be highlighted that the small deviations from a notional smooth evolution of the payload mass with respect to the fuel un-loading is a numerical artifact of the trajectory optimizing tool. These deviations do not exceed 50 kg and are thus negligible.

The calculated performance is required to exceed the combined masses of the CM and the SM plus any necessary interfaces in order to represent a feasible solution. In an initial assessment, the mass of this compound was assumed to be 12 Mg, approximately 6400 kg of which were attributed to the SM. Furthermore, it is recommended to maintain a sufficient margin between the required and the obtainable performance in order to account for potential evolutions of the CM or SM but also for potential performance assessment evolutions of Ariane 6.

The performance maximum for Ariane 62 is achieved by un-loading 11 to 13 Mg and ranges from 10.3 to 11.9 Mg of mass released in the indicated orbit, resulting in negative payload margins of at least 100 kg, which is why it was decided to discard Ariane 62 from further considerations and instead continue with Ariane 64 as the baseline launch system for a European astronautical mission.

The two additional solid boosters of Ariane 64 confer an additional performance gain of approximately 10 Mg. The obtained results are shown in Figure 2. The maximum performance ranges between 21.3 and 22.0 Mg, thus allowing sufficient payload margins and is obtained for an un-loading of 9 to 11 Mg propellant.

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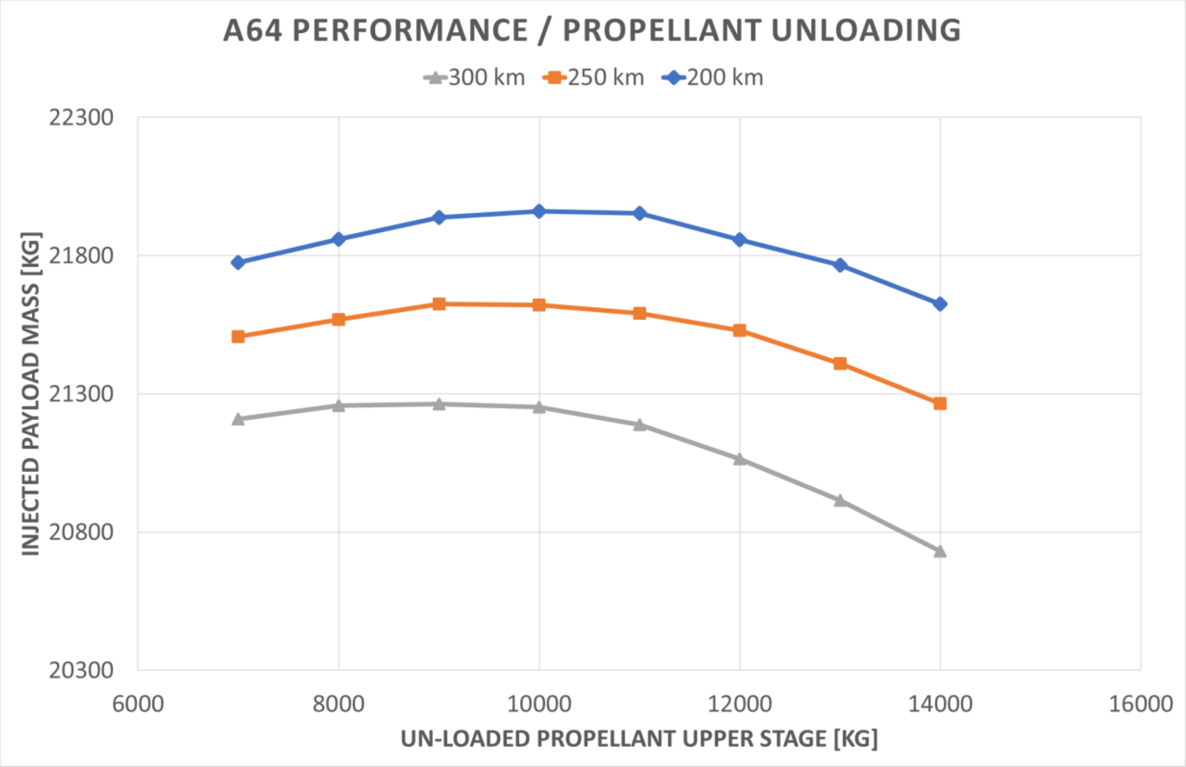

Figure 2: Performance of Ariane 64 standard configuration for varying orbit altitudes and fuel loading

2.2 Reference Ascent Trajectory

This section describes the reference ascent trajectory for EURASTROS that is later used as basis for further investigations of other project partners. The latest derived trajectory, which was also used for the endo- and exo-atmospheric abort analyses is illustrated in Figure 3. This trajectory assumes using the Ariane 64 as LV, with propellant un-loading of 11 Mg in the ULPM-stage and an injection of the SC into a 200 km circular orbit at an inclination of 51.6°. As mentioned above, the injection orbit is finally fixed to 200 km out of abort G-load considerations as laid out by chapter 4. The fuel required for de-orbiting of the ULPM after its primary mission was set to nearly 550 kg, including fuel for ignition preparation alongside the fuel for the boost itself. While an optimization of the ULPM's fuel loading of Ariane 64 is not strictly necessary performance-wise, an un-loading of 11 Mg proved to be advantageous with respect to ground safety, as this reduction in acceleration time during ULPM flight leads to an earlier injection into a stable orbit. This in turn moves the earliest point at which an abort-to-orbit can be performed with the SM farther West so that an abort-to-ground prior to this point leads to a splash-down off the coast of France and thus avoids a landing on hard ground over a densely populated area.

Figure 3 shows selected parameters of the reference ascent trajectory. As can be seen the angle of attack (AoA) is significant as soon as the LV leaves the denser atmospheric layer when the dynamic pressure and hence the aerodynamic forces drop down significantly, with a zero angle of attack being enforced before in order to minimize side loads and moments on the launcher. The axial accelerations (n_x) during ascent are at maximum immediately before the burnout of the boosters, exceeding 4 G for approximately 50 seconds, whereas lateral accelerations (n_z) are found insignificant during the whole ascent. As NASA standards for astronautical transportation allow axial accelerations up to 7.5 G for a total of 300 seconds [6], the accelerations of the presented reference trajectory are found unproblematic.

The achieved performance of the trajectory of approximately 21.9 Mg exceeds the strict minimum requirements for this mission and hence offers a comfortable margin with respect to possible future mass evolutions. In case these mass evolutions do not materialize the over-performance could be used to increase payloads delivered to the ISS.

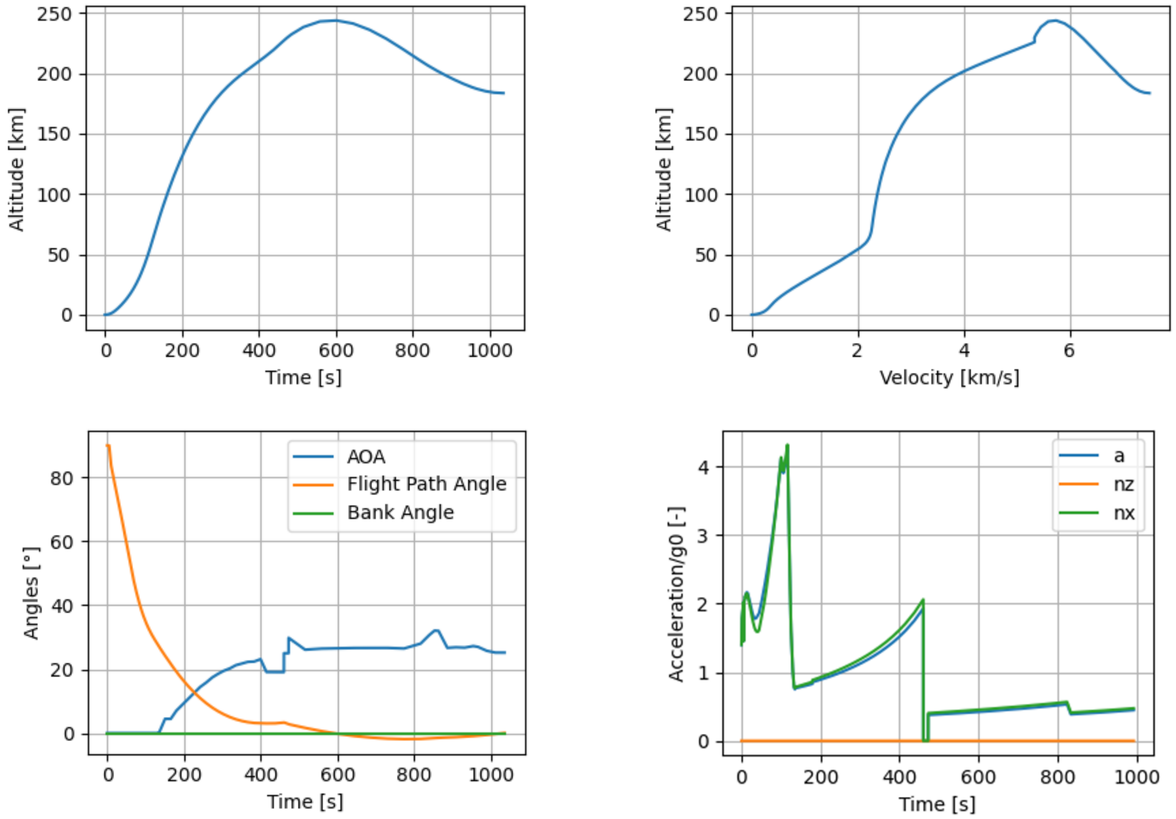

Figure 3: Ariane 64 reference ascent trajectory, orbit 200 km x 51.6°, 11 Mg un-loading from ULPM

3. Endo-Atmospheric Abort Analyses

One of the most critical phases with regards to astronautical transportation is the early launch phase inside Earth's atmosphere, due to close proximity to the ground and correspondingly short reaction times. During this phase abort capability is realized via the LAS, an additional autonomous motor or set of motors able to propel the CM away from the LV and onto a safe escape trajectory. To aid the EURASTROS study DLR iterated the minimum required thrust of the LAS motors required for a successful escape from a failing Ariane 64 under all circumstances. Furthermore, the preliminary mass budget of the LAS was updated based on the results of these investigations and a short assessment on crew combability was performed.

3.1 Regarded Launch Abort Systems

Within the EURASTROS-study, two possible architectures for the LAS are seen as most promising and are htus subjected to a preliminary assessment of their escape performance capabilities.

Both concepts, developed by Ariane Group [3], utilize solid rocket motors (SRMs) for propulsion and are mounted in front of the SM, encapsulating the CM in a protective fairing, together forming a propelled escape body (PEB).

Figure 4 illustrates both these concepts and Table 1 provides an overview over their preliminary mass budget at the beginning of DLR's investigation. One of the concepts ('Tower') uses a classical abort-tower configuration with a large single SRM in front of the CM, known from e.g. NASA's Apollo-program, whereas the other concept ('Hot') utilizes eight small SRMs mounted close to the CM's aft section, in order to maintain the original Ariane 6 fairing shape. For controllability, both concepts are equipped with an attitude control system (ACS) in their nose section.

Since the 'Hot'-concept's lever between the ACS and center of gravity is significantly smaller compared to the 'Tower'-concept, it requires a heavier ACS thus showing an increased initial mass.

It has to be noted, that a more detailed mass breakdown of the LAS was not part of the presented study and that only propulsive and non-propulsive masses were distinguished. More detailed information on the LAS-concepts and their development can be found in [3].

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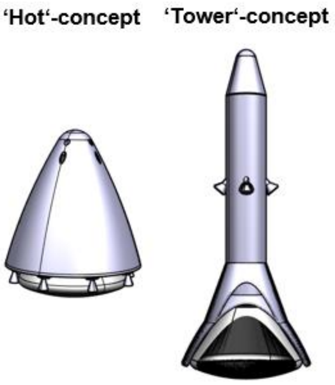

Figure 4: Graphical illustration of both investigated LAS concepts [4]

Table 1: Initial mass budget of both investigated LAS concepts

Concept	'Hot'	'Tower'
m_{prop} [kg]	1348	
m_{struct} [kg]	3477	2753
m_{LAS} [kg]	4825	4101
SI_{LAS} [−]	2.58	2.042
m_{CM} [kg]	5635	
m_{PEB} [kg]	10460	9736

3.2 Simulating Launch Abort

Analyzing and iterating engine performance is performed by using the tool 'Trajectory Optimization and Simulation of Conventional and Advanced Spacecraft' (TOSCA) developed by DLR, which uses a Runge-Kutta integration method. In TOSCA, LV are regarded as point-mass-models within a calm, windless atmosphere, influenced only by gravitational, propulsive and aerodynamic forces, the latter being introduced by an aerodynamic database (AEDB) of the PEB, also developed by DLR. This simplified approach allows for fast but still accurate computations and trajectory optimizations. The AEDB was generated by blending the aerodynamic coefficients of 3D Reynolds-averaged Navier-Stokes (RANS) simulations at Ma=1.2 for AoA between 0 and 45° with coefficients from 2D, axisymmetric RANS simulations with AoA=0 ° over an increased Mach number range (0.6 <= Ma <= 3). For Ma>=3, approximative coefficients were derived by using the modified Newton method.
It is to note, that in TOSCA full controllability and trim ability of the investigated bodies is assumed, as well as that the body is able to immediately assume every given attitude without significant delay.

Table 2: Main events of launch escape maneuver

Time until LV-failure [s]	Event(s)
T - 1.0	Failure detection, Initiating abort chain
T - 0.75	Start LAS-motor ignition
T - 0.5 = t_{sep}	LAS motors at full thrust, PEB separation, Start escape along straight trajectory with 0 ° AoA
T ± 0.0	LV-failure, Initiate constant AoA-change ($\dot{\alpha}$) of PEB
T + t_{pitch}	Maximum AoA reached, Continued escape with constant AoA
T + 3.0	Motors start to burn out, PEB begins attitude change towards 0 ° AoA
T + 3.2	Motors completely burned out, Continued ballistic escape with 0 ° AoA

In the current design iteration of the LAS, it is assumed that the system can anticipate an imminent LV-failure at the time T with one second warning time, upon which it automatically triggers the abort chain illustrated in Table 2. Thus, separation of the PEB from the LV is assumed simultaneously to the abort motors reaching maximum thrust, which is 0.5 seconds prior to the actual LV demise, marking the starting point for each abort simulation. Afterwards the PEB is propelled away in flight-direction, in an attempt to establish a minimum clearance to the pursuing LV. Subsequent to this initial clearing phase the PEB enters a phase with constant AoA-change ('pitching phase', t_{pitch}) which continues until the pre-defined maximum AoA is reached. Afterwards, this AoA is maintained constant until the LAS's motors burn out, which is not prior to 3.5 seconds after separation, in order to achieve a completely powered escape.

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[4] Image with courtesy of Ariane Group GmbH

It is assumed that the PEB returns towards an AoA of zero degrees within 0.2 seconds after SRM burnout, continuing on a ballistic trajectory afterwards. In reality, additional maneuvers like turning around the CM and jettisoning of the LAS prior to landing would have to be executed, but due to the preliminary nature of this cross evaluation, such maneuvers were not regarded here and should instead be investigated in future studies.

Table 3: Abort scenarios and -requirements used to size LAS

Scenario	**'LPE'**	**'maxQ'**	**'maxA'**
t_{sep} [s]	0.0	49.2	113.5
H_{sep} [km]	0.0	10.5	51.5
L_{sep} [km]	0.0	3.7	53.0
v_{sep} [m/s]	0.0	425	1910
γ_{sep} [°]	90.0	59.9	31.4
q_{sep} [kPa]	0.0	35.7	1.7
a_{sep}^{LV} [m/s^2]	16.7 (P120)	19.6 (A64)	39.2 (A64)
Escape requirements	**A1**) Distance to P120 exceeds 200 m after 3.0 sec	**A2**) Distance to LV exceeds 200 m after 3.0 sec	
	B) Apogee altitude of escape trajectory exceeds 1.5 km **C**) Downrange of landing site resulting from ballistic flight to separation location exceeds 3.0 km		

Benchmarking of both LAS-concepts was done against the background of three reference escape scenarios, for each of which initial conditions are listed in Table 3. These initial conditions refer to the state during separation, defined by time (t_{sep}), altitude (H_{sep}), downrange from separation point (L_{sep}), velocity (v_{sep}), flight path angle (γ_{sep}), aerodynamic pressure (q_{sep}) and acceleration of the regarded LV (a_{sep}^{LV}). The scenarios correspond to critical phases during ascent, starting with a ground-launched launch pad escape (LPE) from the ELA-4 launch pad in the Kourou CSG and two air-borne phases where the launch vehicle experiences maximum aerodynamic pressure (maxQ) and maximum acceleration (maxA) prior to burnout of the A64-SRMs.

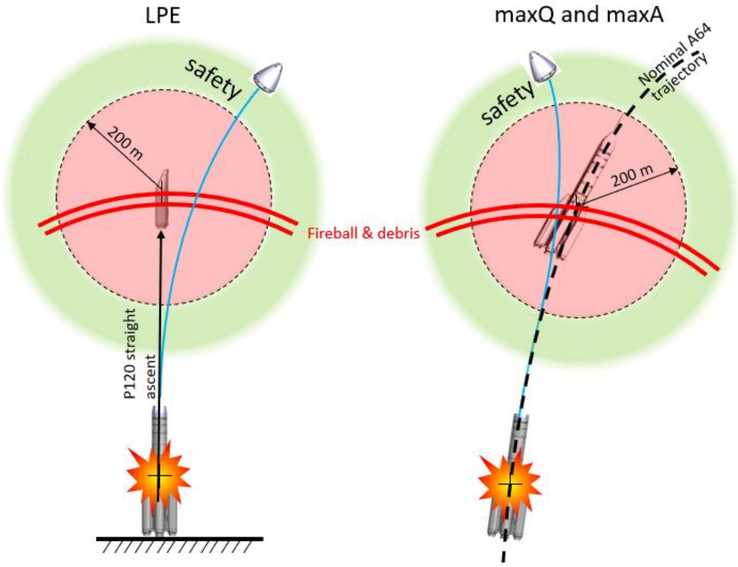

Figure 5: Illustration of safety distance requirements of all regarded scenarios

In all these scenarios the LAS has to propel the CM away from flames and debris resulting from an explosion of the A64. Within the EURASTROS-study, the LAS was considered able to fulfill this requirement (req. A1 or A2), if it could propel the CM at least 200 m away from the A64 within 3.5 seconds after separation (t_{sep}). In a conservative approach, this safety distance was measured against the nominal A64-reference-trajectory, meaning that in DLR's simulations the nominal ascending A64 is surrounded by a hazard sphere with a radius of 200 m which the LAS has to exit within the given time (illustrated in Figure 5). Since in the LPE-scenario the A64 is still resting on the launch pad, it was instead assumed that one of the four P120-boosters would detach and ascent straight into the sky, serving as reference point the safety-distance-requirement (req. A1) is measured against.

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Additionally, each escape trajectory must allow for successful parachute deployment, thus necessitating a high enough apogee altitude, which was defined to be 1500 m. Furthermore, a minimum downrange between landing and launch site is necessary in order to avoid the CM crashing into infrastructure or landing in a hazardous debris field. As a first estimate for this downrange, a value of 3000 m was selected which is similar to the shortest distance between the ELA 4 launch pad and the nearby coastline.

For each given scenario, numerous exploratory abort simulations were executed during which the maximum AoA and AoA-change-rate ($\dot{\alpha}$) were variated for a given thrust level, starting from an initial guess of 800 kN axial thrust. Investigated AoA were limited to - 45 …+ 45 ° and assumed $\dot{\alpha}$ to 5 – 30 °/s since values exceeding these boundaries were seen as too ambitioned for the assumed ACS. In these regards, positive AoA refer to a nose-up attitude, whereas negative AoA refer to a nose-down attitude. The resulting trajectories were afterwards compared to the A64-reference ascent trajectory from chapter 2 or the trajectory of a straight ascending P120-SRM respectively, in order to obtain the Euclidean distance between the reference LV and the PEB 3.5 seconds after separation. If this distance did not exceed the required 200 m for any AoA-$\dot{\alpha}$-combination the thrust level was increased, accompanied by an iteration of the LAS's mass budget and a repeat of the simulation procedure. The propellant of the SRMs was always kept at a level, which allows for a continuously propelled escape.

Due to the preliminary nature of this study, further simplifications were put in place in order processing efforts and iteration efforts at bay. The first simplification was, that only ballistic trajectories were regarded, meaning that e.g. a deployment of parachutes and their corresponding influence on the trajectories and landing areas were not regarded. Additionally, it was assumed that all LAS-motors would maintain constant thrust and I_{SP} during the whole escape sequence regardless of separation altitude, and that the produced thrust vector is always axial. The latter is especially important regarding the 'Tower'-concept, because this means that the radial thrust components and possible interactions between the LAS's exhaust jet and the CM are disregarded and that only the axial thrust component (and the corresponding structural and propellant masses) were iterated.

The iteration of the non-propulsive masses was conducted in close cooperation with representatives of Ariane Group. The resulting iterated mass budgets for both concepts are displayed in Table 4. As can be see, the LAS's masses differ from the masses used in chapter 2, with the 'Tower'-concept being around 400 kg lighter and the 'Hot'-concept being 300 kg heavier, but regarding the total payload capacity of 22.1 Mg, these differences are in the order of magnitude of approx. 1.8 %, thus no significant impact on the reference trajectory is anticipated.

Table 4: Updated preliminary mass budget of regarded LAS

Concept	**'Hot'**	**'Tower'**
F_{min} [kN]	950	950
m_{prop} [kg]	1558 (+15.6 %)	1558 (+15.6 %)
m_{struct} [kg]	3865 (+11.2 %)	3141 (+14.1 %)
m_{LAS} [kg]	5423 (+12.4 %)	4699 (+14.6 %)
SI_{LAS} [$-$]	2.481	2.016
m_{CM} [kg]	5635	
m_{PEB} [kg]	11054 (+5.7 %)	10330 (+6.1 %)

3.3 Resulting escape trajectories and minimum thrust

The iterative process described in the previous chapter converges fastest when regarding the maxA-scenario and slowest when regarding the LPE-scenario. This is on the one hand, because the PEB has to overcome the lowest aerodynamic resistance and on the other hand, because two of the three escape requirements (B and C) are inherently fulfilled in the maxA-scenario. These two requirements are also inherently fulfilled in the maxQ-scenario. It is also found that a safe escape distance was easier to achieve if positive AoA were pursued in the maxA- and maxQ-cases, since this leads to the escape trajectory diverging from the reference LV's trajectory, which is following a gravity turn. The LPE scenario however is found to be the sizing case with regards to minimum thrust and most limiting with regards to the assumed AoA and $\dot{\alpha}$. In this case the minimum thrust level is iterated to be 950 kN for both regarded LAS-concepts. As can be seen from the established distance between P120 and PEB after 3.5 seconds (compare Table 5), the iterated concepts seem to be over-performant at first, however this thrust level is required mainly due to requirements B and C. This is also illustrated in Figure 6, which shows the derived escape trajectories in the LPE-scenario for both concepts and for the initial thrust level, which was actually able to establish the required safety distance (Req. A1), but unable to fulfill Req. B and Req. C at the same time and the eventually iterated thrust level. The depicted solutions for the increased-thrust case are the only sensible ones which could be achieved with the iterated thrust level – lower AoA would violate the altitude requirement (B) and higher AoA would violate the downrange criterion (C).

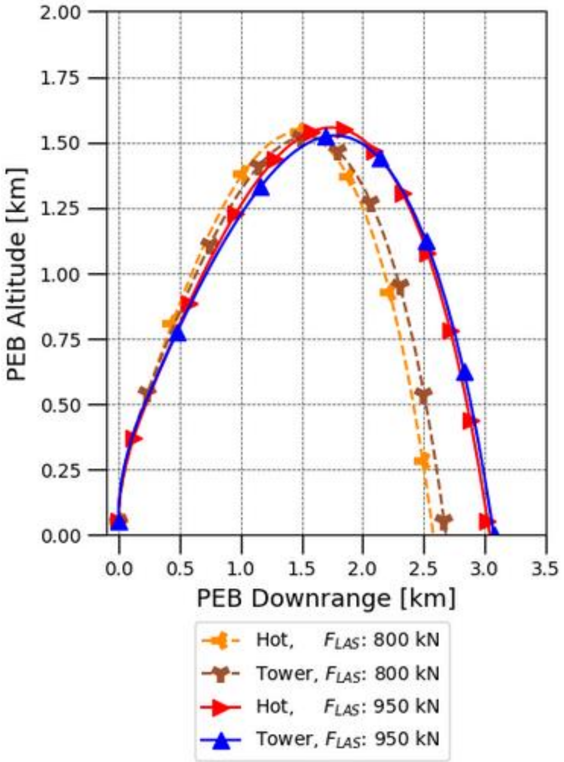

Figure 6: LPE-escape trajectories of both concepts for initial (dotted) and iterated (solid) thrust level

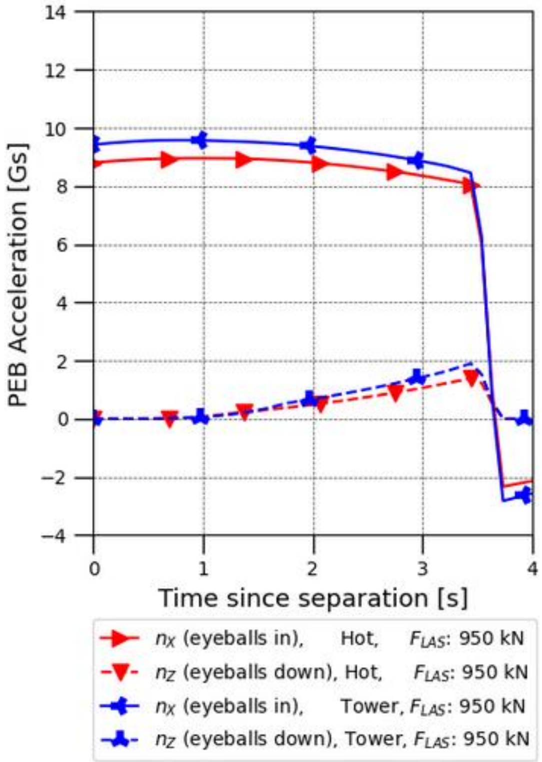

Figure 7: Axial (solid) and lateral (dotted) accelerations during powered phase of LPE for both LAS concepts

Table 5: Applicable escape trajectories for iterated thrust level ($F_{LAS} = 950\ kN$)

Concept	**Scenario**		AoA_{max} [°]	$\dot{\alpha}$ [°/s]	$n_{x,max}$ [Gs]	$n_{z,max}$ [Gs]	$\Delta R\ (t_{sep} + 3.5\ s)$ [m]
Hot	LPE		20.0	25.0	8.98	1.10	305
	maxQ	sharp	20.0	25.0	5.41	3.20	214
		relaxed	20.0	12.5	5.36	3.23	201
	maxA	sharp	20.0	25.0	10.25	0.11	250
		relaxed	20.0	12.5	10.25	0.11	236
Tower	LPE		25.0	20.0	9.58	1.47	328
	maxQ	sharp	25.0	20.0	5.64	2.89	224
		relaxed	12.5	10.0	5.40	1.79	201
	maxA	sharp	25.0	20.0	11.08	0.15	282
		relaxed	12.5	10.0	11.10	0.08	254

In order to verify the combability of these escape trajectories with the human tolerance towards accelerations, the axial (n_x, 'eyeballs in') and lateral (n_z, 'eyeballs down') G-loads during powered escape are also investigated. These approach 9-10 Gs during the powered escape flight, but drop back to moderate levels immediately after SRM burnout (compare Figure 7). According to [6], the upper limits for axial and lateral G-loads during an ascent abort are 20 and 12 Gs for a duration of 5 seconds, thus the detected accelerations are within tolerable limits.

When applying the thrust level and steering controls from the LEP-scenario onto the maxQ- and maxA-scenarios it can be found that maxQ and maxA are the cases with the highest lateral (maxQ) and axial (maxA) G-loads (compare Table 5). These are more pronounced in case of the 'Tower'-configuration, due to the lower total PEB-mass, but still within tolerable levels, remaining below 12 Gs as illustrated in Figure 9. Furthermore, the corresponding safety distances achieved 3.5 seconds after separation from the LV indicate that the abort maneuver sequence from the LPE-scenario actually produces a sharper-than-necessary turn ('sharp' cases in Table 5).

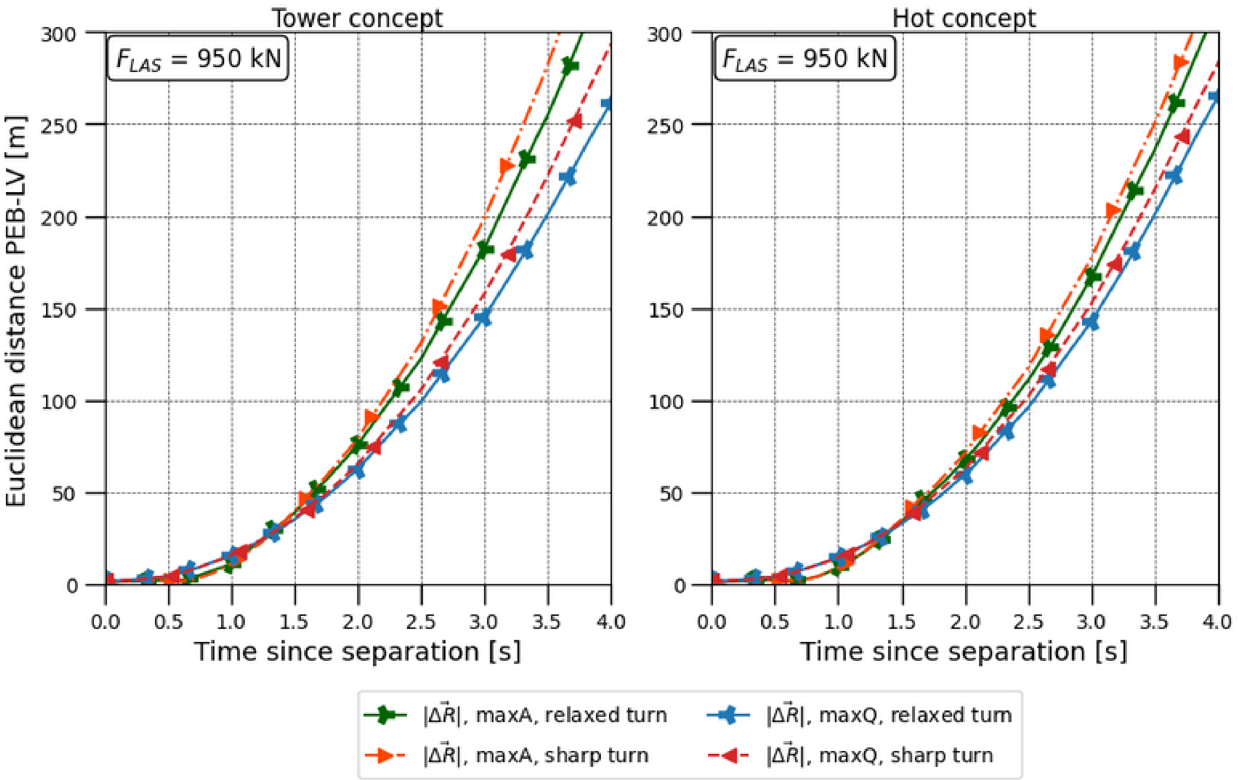

Figure 8: Euclidean distances yielded for iterated ‘Tower’ (left) and ‘Hot’ (right) LAS for maxQ and maxA-cases

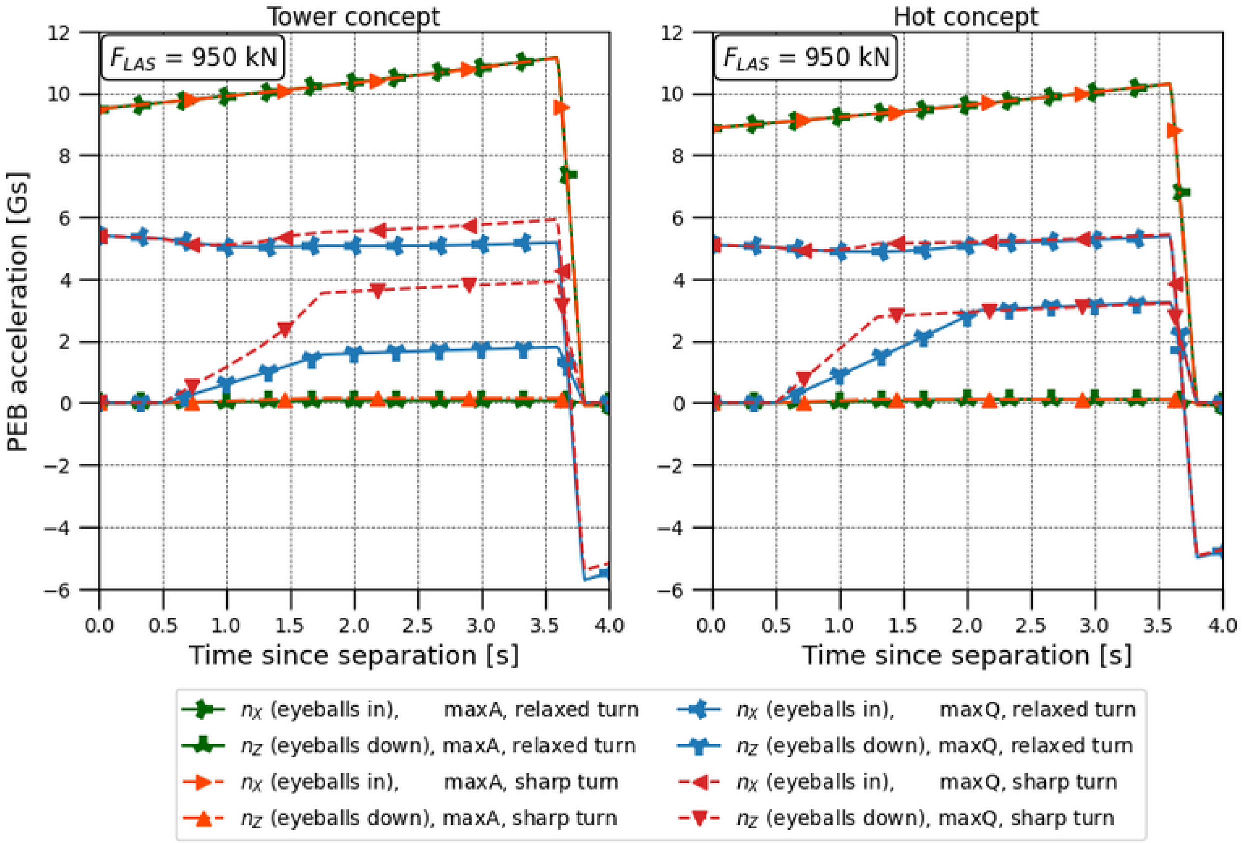

Figure 9: Accelerations of the iterated ‘Tower’ (left) and ‘Hot’ (right) LAS for maxQ and maxA-cases

In an attempt to explore if lateral accelerations could be mitigated by relaxing the steering controls during in-flight-abort, maximum AoA and $\dot{\alpha}$ were variated, this time aiming at combinations that lead to lower n_z and safety distances closer to 200 m (‘relaxed’ cases in Table 5, Figure 8 and Figure 9). It is found, that this possibility is limited by the maxQ-case, which allows for only slight relaxation of steering controls before failing to achieve the required safety distance. A marginal reduction in lateral accelerations is observable in this case.

4. Exo-Atmospheric Abort Analyses

If an LV-failure occurs at higher altitudes, i.e., above approx. 90 km and after the LAS was jettisoned, the SM will be used for the exo-atmospheric abort operations. This module is propelled by four BERTA engines, which use a storable fuel as propellant, producing about 4 kN thrust each with a specific impulse of $I_{sp} = 310$ s. The combined mass of the propelled SC, composed out of the CM and the SM, is 11405 kg including 1315 kg fuel.

In case of an exo-atmospheric abort, the LV-engine is cut off and the SM separates from the launcher and ignites its engines to carry the CM to a safe distance within a given timeframe. If needed, the SM engine can be further used to modify the flight path to reach a safe re-entry trajectory. Eventually, the CM and the SM separate and the CM re-enters the atmosphere to safely carry the astronauts to the ground. This is the default abort scenario.

Several requirements must be fulfilled to guarantee a successful rescue along this chain of events, as e.g. that an abort must be possible at any time without exceeding human tolerable G-loads during descent. This must be guaranteed for controlled re-entry as well as for uncontrolled/ballistic re-entry where the experienced loads are significantly higher.

4.1 Modeling exo-atmospheric abort

The exo-atmospheric launch abort is modeled in multiple phases, in all of which the SC is modelled as a point mass with three degrees of freedom. For phases at altitudes exceeding 90 km, i.e. escape from the launcher, course correction and coasting, only gravity and thrust are considered whereas aerodynamic forces are neglected. During the re-entry phase, starting once SC-altitude drops below 120 km, aerodynamic forces are simulated assuming the capsule to fly at its hypersonic design lift-to-drag ratio of $c_L/c_D = 0.383$ and a ballistic coefficient of $BC = 416.6\ \mathrm{kg/m^2}$. As for the endo-atmospheric abort scenarios, parachute deployment was not regarded. The time propagation is performed with an explicit fifth order Runge-Kutta scheme with adaptive time-stepping.

For a successful escape from the launcher, it is required that the SC reaches a distance of 250 m to the launcher within 30 s. It is assumed, that the launcher engines are shut down on separation, such that the launcher follows a ballistic trajectory during the escape phase. During the escape burn, the SM ignites two of its four 4 kN engines for 16.3 s while maintaining its initial attitude, i.e., the attitude of the launcher at the moment of separation. While the SC coasts to a safe distance, it eventually changes its attitude in preparation for a course correction burn which begins 30 s after separation from the LV. Before reentry, the SM is separated.

4.2 Results of exo-atmospheric abort

An exo-atmospheric abort approximately midway through the launch, where the launcher already gained significant altitude but the velocity is still relatively low, leads to a very steep re-entry. Furthermore, if this abort is performed uncontrolled/ballistic, the resulting steep re-entry causes G-loads that exceeding the human tolerable limits given by e.g. NASA [6].

During the A64 performance assessments (compare chapter 2), it was found that un-loading 11 Mg of propellant from the ULPM was a sufficient strategy to decrease G-loads, but a direct abort-to-ground still exceeded survivable limits, as is illustrated in Figure 10, where the worst case is during ballistic re-entry without any additional maneuver occurring for an abort 523 s after liftoff. This means that the default abort strategy cannot be used and that instead a mitigation maneuver with the SM engines is needed to decrease the re-entry flight path angle magnitude, thus mitigating the G-loads and making a ballistic re-entry possible. The SM is designed to supply the required thrust for this maneuver which is a 500 s burn with two engines at a pitch angle of 90° (nose-up). Note that this worst-case scenario only occurs in the rare event that, in addition to a LV-failure in a certain timespan, also the guidance and navigation system fails such that the ballistic fallback mode must be used.

In less critical cases, the SM would still perform a mitigation maneuver, but the CM would be able to steer its lift and fly a controlled re-entry, thus further mitigating G-loads (lifting re-entry). Figure 10 illustrates the predicted axial G-loads (eyeballs-in) during re-entry for the afore mentioned abort modes relative to limits defined by NASA for the commercial crew program [6]. While the peak G-load during a ballistic re-entry with mitigation maneuver of 19.5 G is still very high, the maximum G-load is present momentarily enough such that the re-entry can be considered acceptable in emergency situations.

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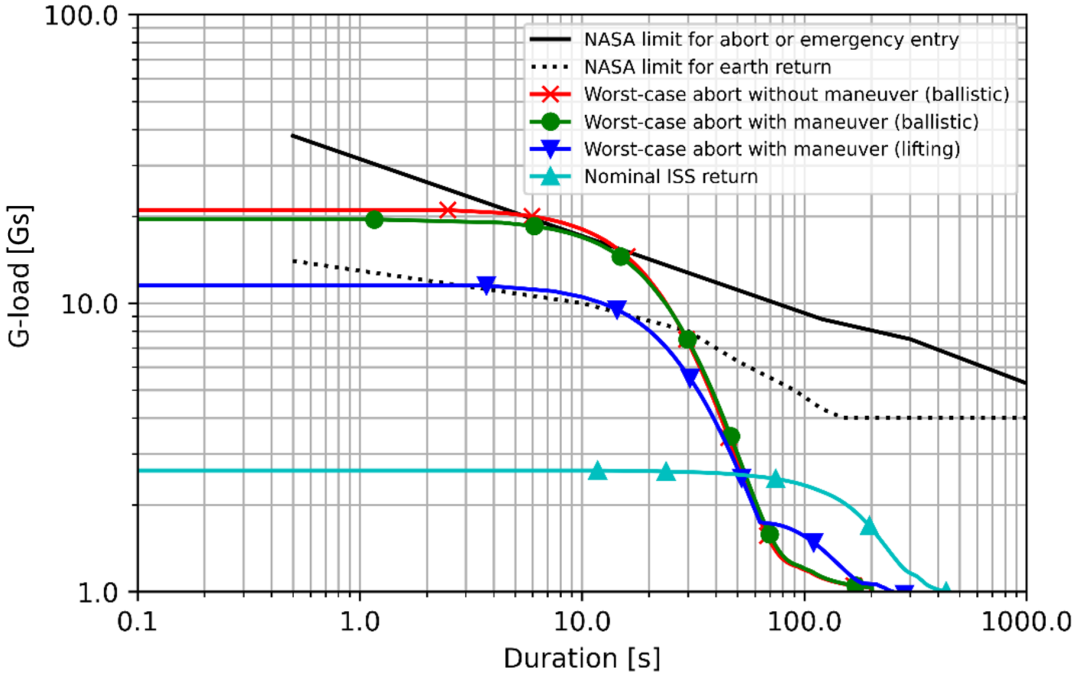

Figure 10: Worst-case G-loads and load duration for ballistic re-entry after abort with and without mitigation-maneuver, lifting re-entry with mitigation maneuver, and for nominal return from ISS

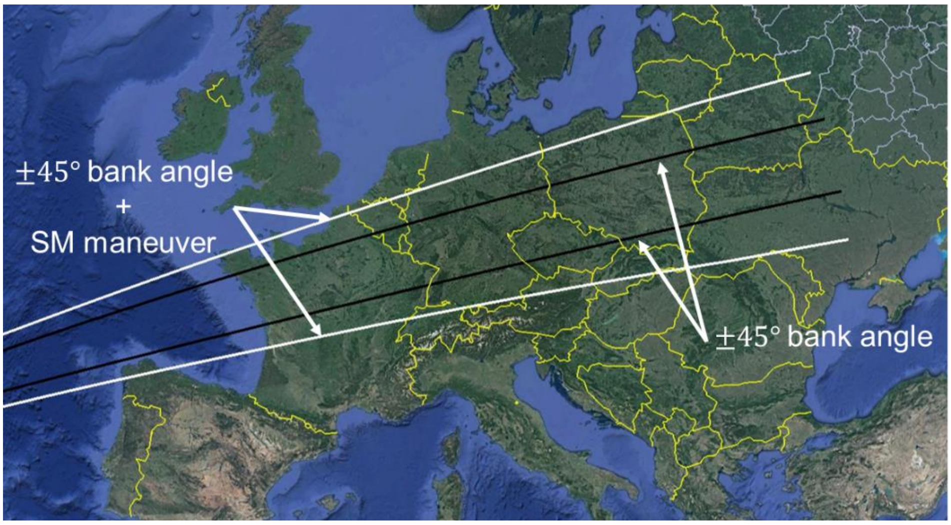

Figure 11: Impact locations of the capsule for aerodynamic steering (±45° bank angle) and aerodynamic steering assisted by a service module maneuver.

The G-loads present during a lifting re-entry also barely exceed the NASA limits for a nominal return from ISS and are thus acceptable for an emergency entry.

For all the afore-mentioned abort scenarios, a water-landing was targeted. Since the ULPM provides only relatively low acceleration, it travels a relatively long distance before commencing orbit insertion. As a consequence, an abort during the latest launch phase would result in the CM impact on densely populated European mainland. Figure 11 shows the impact locations of the CM, which are achievable when using aerodynamic steering during re-entry (black). Additionally, hypothetical landing locations reachable if steering would be assisted by a lateral SM maneuver prior to re-entry are shown (white), to illustrate that even with service module support, it is not possible to reach water for a safe water landing after aborts in the late phase of the launch. A change of the launch inclination to shift the ground track further north was analyzed but led to significant performance loss of the LV. Therefore, the spacecraft must be able to either shorten its downrange to land on water off the French coast or perform an abort-to-orbit maneuver to prevent impact on land.

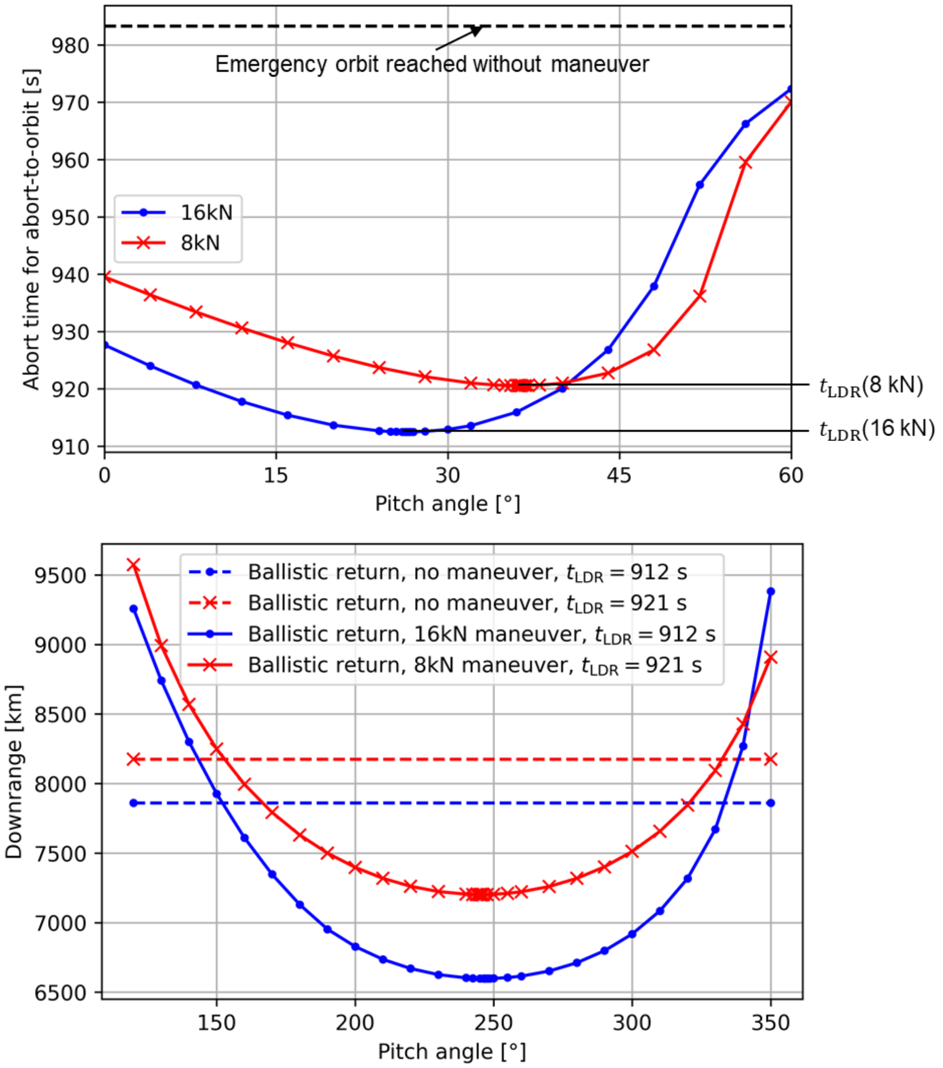

Figure 12: Earliest time for abort-to-orbit (top) for different SM thrust levels and optimization of SM maneuver pitch angles for minimal downrange (bottom).

The effects of both these maneuvers, the breaking maneuver to reduce the capsules downrange and the abort-to-orbit maneuver, were analyzed in detail. To maximize the effect of the SM maneuvers, an optimization was conducted in order to determine the most beneficial SM-attitudes for both maneuvers. First, it was determined at which pitch angle the abort-to-orbit maneuver is most effective. To do so, multiple abort trajectories, each one featuring an escape from the demising LV and an abort-to-orbit maneuver, where calculated for increasing times after lift-off along the nominal launch trajectory. In each case it was assumed that the SM maintains a constant pitch angle during the abort burn. The burn duration was limited to keep enough fuel for deorbiting from the emergency orbit including 20% margin. By numerical root finding, it was determined for which combination of abort time and pitch angle the spacecraft reaches a perigee of 120 km at engine cutoff. Because this earliest abort time with abort-to-orbit capability depends on the pitch angle of the burn, a minimization algorithm was employed to determine the exact pitch angle necessary to achieve the earliest overall abort time. The yielded abort time defines the point of last direct re-entry (LDR), prior to which an abort-to-ground would be executed. The analysis was carried out for SM configurations with 8 kN and 16 kN thrust. The resulting abort times for which a successful abort-to-orbit is possible as a function of the pitch angle is shown in Figure *12* (top) for both configurations. The LDR for each thrust level are located at the minimum of the corresponding curve. Pitch angles of 26° (16 kN) and 36° (8 kN) were found to be ideal for abort-to-orbit.

Prior to LDR, it must be guaranteed that the capsule reaches water for a safe splash down. This is only possible, if a course correction maneuver is performed to shorten the downrange of the capsule. The optimum attitude for this maneuver is found by determining the pitch angle that minimizes the CMs downrange for aborts with ballistic re-entry at LDR (illustrated in Figure 12, bottom). It is found that the earliest opportunity for abort-to-orbit (top) and the ballistic downrange of the capsule for aborts at LDR (bottom) are highly dependent of the maneuver pitch angle.

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Depending on this angle, the downrange of the capsule can be decreased by more than 1250 km. The maximum effect, i.e., the shortest downrange is obtained for pitch angles around 247°. The study showed, that the thrust requirement for the EURASTROS configuration is driven by the abort-to-orbit and downrange reduction maneuvers which require 16 kN to be able to always land on water or alternatively perform an abort-to-orbit.

The identified exo-atmospheric abort strategies can be summarized as listed in Table 6. At an altitude of 90 km, the LAS is jettisoned and the SM takes over the abort operation of carrying the CM to a safe distance to the LV. In the default abort mode, the re-entry G-loads are sufficiently low, such that no dedicated SM maneuver is needed, the SM is separated and the CM enters the atmosphere. In the timespan 442 seconds to 694 seconds after lift-off, it is necessary to perform a mitigation maneuver prior to re-entry, in order to reduce the G-loads on the capsule. 815 seconds after lift-off, a fully lifting re-entry would lead to impact on land. Hence, the capsule must gradually reduce its lift by performing bank reversals to reduce its effective lift and thus the downrange. From 861 seconds on, even a completely ballistic descent would not be sufficient anymore to achieve splashdown on water. Therefore, the SM engines must be used for a downrange-reduction-maneuver to limit the downrange and ensure a safe water landing. 912 seconds after lift-off, the SM can provide sufficient ΔV to reach an emergency orbit so that an abort-to-orbit maneuver will be executed instead. The analysis showed, that the abort-to-orbit scenario requires a minimum SM-thrust of 16 kN. All other considered cases, i.e. nominal mission, escape from launcher, mitigation maneuver, require less thrust.

In conclusion, the dimensioning of the emergency escape modes needs a careful consideration of the launch trajectory, the SM thrust and fuel, and the re-entry performance of the capsule. With the configuration of the present study a successful abort is possible from launch pad to orbit for safe transportation of astronauts to space.

Table 6: Launch abort modes for exo-atmospheric abort

$H > 90$ km	$t < 422$ s	Default abort
$442\text{ s} \leq t < 694\text{ s}$		Abort with mitigation maneuver
$694\text{ s} \leq t < 815\text{ s}$		Default abort
$815\text{ s} \leq t < 861\text{ s}$		Abort with active lift-reduction
$861\text{ s} \leq t < 912\text{ s}$		Abort with downrange-reduction-maneuver
$t \geq 912$ s	SECO	Abort-to-orbit

5. Open Points

Developing an astronautical transportation system is a complex task requiring several years of work. Against that background it is common, that not all points can be investigated with a satisfying level of detail.

One of these points is e.g. the debris footprint resulting from the LLPM during nominal operations. A critical assessment on whether this footprint covers Azores or Canary Islands or even frequented maritime routes would be necessary in the scope of a system qualification. An additional matter of qualification would be the un-loading of more than 3 Mg of propellant from the ULPM. While from a technical point of view, no blocking points are identified at this stage, the system impact needs to be further analyzed if humans are to be transported with this launcher. Eventually, it shall also be noted, that the obtained performance for Ariane 64 exceeds the required performance by at least 50 %, an excess that has to be compensated by appropriate means to avoid lowering economic viability.

Regarding the endo-atmospheric abort analyses, open points include wind and weather influences during launch, which can affect aerodynamic forces, thus resulting in different escape trajectories. Also, at the end of the escape phase, deployment of parachutes will lead to a higher susceptibility to wind influences, which have to be accounted if a specific landing location is desired.

Once the systems' designs have reached a higher level of detail, an assessment on trim ability should also be conducted to identify possible limitations with regards to flyable angles of attack and pitching rates. The same is to be said regarding the need for special maneuvers, like disposal of the LAS once the crew module has reached a save escape trajectory, the necessity to turn the capsule around in order allow for landing bottom-first and successful parachute deployment.

Some propulsive aspects should also be re-assessed once more detailed motor-data is available, like e.g. the altitude dependency on thrust and specific impulse. Eventually, it has to be pointed out that the minimum thrust of the 'Tower' concept was yielded by neglecting nozzle mounting angles and possible interactions between exhaust-jets and CM. Assuming an arbitrary nozzle mounting angle of e.g. 25 ° would mean that motor thrust has to be around 10 % higher than axial thrust, thus increasing propellant need and inert mass in the LAS. In this arbitrary example, minimum thrust need could be up to 1100 kN, raising the LAS mass up to 5360 kg, but without further detailed analyses this figure remains more of an estimate to be confirmed or denied by future studies.

Concerning the analysis of the exo-atmospheric abort, this study has limited on the parameters that are vital for a safe return, in particular re-entry G-loads and landing location. The abort modes might be further refined, e.g., to target splashdown zones in close proximity to rescue vessels. Furthermore, the analysis should be extended to a more detailed aerodynamic database that also includes uncertainties in the aerodynamic coefficients to assess dispersion in the projected trajectories.

6. Conclusions

The performance of both Ariane 62 and Ariane 64 configurations was analyzed for a mission to the International Space Station. One major result was that the performance of Ariane 62 was insufficient for the envisioned use as an astronautical carrier. It was hence decided to proceed with the Ariane 64 as it offers sufficient performance margin for the envisaged application. Un-loading of 11 Mg from the upper stage allows moving the earliest point at which an abort-to-orbit can be performed further west so that any abort prior to this point leads to a splash-down of the crew capsule off the French coast avoiding thus an abort-to-ground over densely populated areas and further boosts the payload performance. The obtained performance is nearly 22 Mg, largely sufficient for carrying the envisioned crew and service modules into the identified transfer orbit.

In a preliminary exploratory analysis, two concepts for a launch abort system have been investigated regarding their escape performance. Minimum thrust and flight controls have been iterated until they were sufficient to achieve safe escapes in three representative scenarios, covering the most important endo-atmospheric launch phases. It was found that the minimum thrust of both concepts is 950 kN, mainly necessitated through the requirements imposed by an escape from launch pad. The most extreme accelerations were found to be up to 11.1 Gs in flight direction and 3.2 Gs perpendicular to flight direction, which is compliant to astronautical space transportation standards. The initial mass budget of the launch abort system concepts has been iterated, still remaining within the payload capabilities of the Ariane 64. Respecting the applied simplifications, the ‘Tower’ concept offers a mass advantage of about 600 kg over the ‘Hot’ concept and is therefore used as baseline for future investigations. The preliminary assessment by DLR has identified no general show-stoppers regarding the endo-atmospheric abort capability.

The analysis of the exo-atmospheric abort shows that the final EURASTROS configuration is capable to provide enough thrust to always ensure either landing on water or alternatively perform an abort-to-orbit. However, the abort-to-orbit scenario requires a minimum thrust of the SM of 16 kN. A series of possible escape modes was derived and presented. Conclusively, with the configuration of the present study, a full end-to-end abort capability can be achieved for safe transportation of astronauts to space with the Ariane 64.

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References

[1] Ali Gülhan, Marco Wolf, et.al: ‘An Overview of the EURASTROS Study’, EUCASS-3AF CONFERENCE, LILLE, FRANCE, 2022.
[2] Pascal Marquardt, Markus Fertig, Thomas Reimer, Ali Gülhan: ‘EURASTROS capsule design and re-entry analysis’, EUCASS-3AF CONFERENCE, LILLE, FRANCE, 2022.
[3] Alex Plebuch, Pascal Marquart, Marco Wolf: ‘System design of EURASTROS reference configurations and mission’, EUCASS-3AF CONFERENCE, LILLE, FRANCE, 2022.
[4] Andy Braukhane, Alex Plebuch, Thomas Renk: ‘EURASTROS demonstration plan and cost analysis’, EUCASS-3AF CONFERENCE, LILLE, FRANCE, 2022.
[5] Valluchi, C., Dumont, E., Wilken, J. et al: ‘Status Ariane 6 & Vega-C und Ariane Next Konzept Konfiguration & Nutzlast‘, Herbst 2016. SART TN-02/2016, 2016
[6] NASA: ‘ISS Crew Transportation and Services Requirements Document’, CCT-REQ-1130 (Rev. E-1), 2016