Ariane 5 Performance Optimization Using Dual Bell Nozzle Extension

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ABSTRACT

In order to evaluate the impact of dual bell nozzles on the payload mass delivered into geostationary transfer orbit, detailed studies were conducted. Here, the main stage of the standard Ariane 5 ECA configuration was adapted using a redesigned Vulcain 2 rocket engine with dual bell nozzle extension. For this reason a multitude of potential dual bell nozzle contours were designed. As the most upstream starting point of the dual bell nozzle extension the position of the turbine exhaust gas injection was chosen. Restrictions for nozzle expansion ratio and nozzle length were given by the launch pad geometry ELA 3 of Centre Spatial Guyanais (CSG) launch site in French Guiana. The two main variation parameters in this study were the starting point and the inflection angle of the dual bell nozzle extension. For each geometry, characteristic parameters e.g. specific impulse in sea-level and in altitude mode were evaluated. Considering this parameters an analytical and a numerical method were applied to predict the impact of the dual bell nozzle on the payload mass gain. The analytical approach derives the velocity increment, Δv for a standard Ariane 5 ECA ascent, based on the Tsiolkovsky rocket equation. The obtained Δv was compared with the Δv of the modified Ariane 5 ECA including the designed dual bell nozzles. Assuming a constant velocity increment for all configurations, the payload mass gain was determined. A simple correlation for the estimation of payload mass gain was found. The numerical approach was conducted applying DLRs trajectory simulation code TOSCA-TS. To include the additional structure mass due to the new nozzle extension in the calculations, the mass of all configurations was estimated. Both procedures yield good agreement for the calculated payload mass increase. The payload gain was evaluated to approximately 450 kg into geostationary transfer orbit.

1 INTRODUCTION

Due to the development of reusable space transportation systems, the configuration of modern launch vehicles changed from serial to parallel staging. To ensure the ignition of the main stage engine before lift-off, it has to be ignited prior to the booster stage. Thus, the main stage engine operates over a wide range of altitude from sea-level up to vacuum conditions. Due to high ambient pressure the application of a nozzle with large expansion ratio leads under sea-level conditions to a separation of the highly over-expanded nozzle flow. The asymmetric flow separation inside the nozzle induces undesirable strong side loads, which can amount several percent points of the instantaneous engine thrust [1]. To avoid flow separation at low altitude the expansion ratio of the nozzle has to be limited, thus flow separation only occurs during start-up and shutdown of the engine. At altitudes of lower ambient pressure a higher expansion ratio is desirable as it leads to a higher specific impulse and therefore allows an increase of payload mass. The European launcher Ariane 5 ECA with its main stage engine Vulcain 2 is an example for the limitation of the main stage engines nozzle expansion ratio. For a better engine performance an altitude adaptive nozzle concept with a small expansion ratio under sea-level conditions and a high expansion ratio under altitude conditions is desirable. The dual bell nozzle is such an altitude adaptive nozzle concept [2].

To evaluate the impact of dual bell nozzles on the payload mass delivered into a given target orbit, a modified Vulcain 2 nozzle including a dual bell nozzle extension in the main stage (Ariane 5 ECA DB) was used. To determine the optimum of a Vulcain 2 DB concept, the optimization process included several dual bell nozzle configurations. First, an analytical method (see Sec. 4) was applied to evaluate the effect of different dual bell designs (see Sect. 3.2) on the launch vehicle performance. For a realistic evaluation of payload mass gain, the structure mass increase due to the added dual bell nozzle extension was considered (see Sec. 3.3). Thus an optimization between specific impulse gain due to the increased exit velocity of the engine and the additional structure mass of the nozzle was performed. During the design process of the different dual bell nozzle extensions the restrictions of the launch pad at Centre Spatial Guyanais (CSG) launch site in French Guiana were taken into account. After determination of the payload mass gain of Ariane 5 ECA DB using a analytical approach, a detailed launch trajectory simulation was performed to validate the former results.

2 Ariane 5 ECA

The Ariane 5 ECA is part of the Ariane 5 family and designed for missions into GTO. It has the capability to deliver two satellites of an overall mass of approximately 10.1 t into geostationary transfer orbit. With around eight satellites per year the Ariane 5 ECA is the most common launch vehicle for commercial communication satellites and has a market share of around 40 %. The launcher consists of a cryogenic main and a cryogenic upper stage. During the launch the Ariane 5 ECA is powered by two solid rocket boosters, which provide more than 85 % of the thrust during the start.

2.1 Main stage

The Vulcain 2 engine of the main stage provides approximately 1350 kN thrust and has a burning time of around 540 s. The engines nozzle has an expansion ratio of $\varepsilon_e = 58$. The typical main stage parameters are listed in Table 1. Starting from an expansion ratio of $\varepsilon_e = 32$, turbine gas is injected for film cooling of the nozzle wall. Thus the overall mixture ratio of 7.1 in the nozzle flow is a combination of the combustion chamber mixture ratio of 6.7, the turbine gas injection (TEG) and the dump coolant injection at $\varepsilon = 29.2$.

Parameter	Symbol	Value
lift-off mass	m_{tot}	186 t
propellant mass	m_{pro}	171 t
fuel type	LH2/LOX	
engine	Vulcain 2	
mixture ratio	ROF (TCA)	6.7
sea level spec. impulse	$I_{\text{sp, sl}}$	312 s
vacuum spec. impulse	$I_{\text{sp, vac}}$	429 s
total engine mass flow	$\dot{m}$	320 kg/s
engine mass	m_{eng}	2100 kg
nozzle extension mass	m_{noz}	461 kg
nozzle expansion ratio	ε_e	58
burning time	t_{brn}	540 s

Table 1: *Parameters of redesigned Ariane 5 ECA main stage*

2.2 Upper stage

The injection of the payload into the required orbit is performed by the cryogenic upper stage of Ariane 5 ECA. The upper stage has total mass of 19.2 t including 14.6 t of liquid oxygen and hydrogen. The upper stage engine HM7B provides a total vacuum thrust of 64.6 kN. Its typical burning time is around 970 s. The characteristic parameters of the upper stage of Ariane 5 ECA are listed in Table 2.

Parameter	Symbol	Value
total mass	m_{tot}	19.2 t
propellant mass	m_{pro}	14.6 t
fuel type	LH2/LOX	
engine	HM7B	
mixture ratio	ROF	5
vacuum spec. impulse	$I_{\text{sp, vac}}$	446 s
total engine mass flow	$\dot{m}$	14.8 kg/s
nozzle expansion ratio	ε_e	83.1
burning time	t_{brn}	970 s

Table 2: *Parameters of redesigned Ariane 5 ECA upper stage*

2.3 Solid rocket booster

During lift-off the two solid rocket boosters provide more than 85 % of the overall thrust of the launcher. The lift-off mass is 278 t including 240 t of propellant. With the 140 s of buring time the booster develops an average lift-off thrust of 5060 kN. Table 3 summarizes the typical booster parameters.

Parameter	Symbol	Value
lift-off mass	m_{tot}	278.0 t
propellant mass	m_{pro}	240.0 t
fuel type	Al/HTPB/AP	
engine	EAP P241	
sea level spec. impulse	$I_{\text{sp,sl}}$	250 s
vacuum spec. impulse	$I_{\text{sp,vac}}$	275 s
burning time	t_{brn}	140 s

Table 3: *Parameters of redesigned Ariane 5 ECA booster stage*

3 DESIGN OF DUAL BELL NOZZLE EXTENSIONS

3.1 Dual bell concept

The dual bell nozzle is an altitude adaptive nozzle concept [3]. The idea of a dual bell nozzle is to combine a small expansion ratio at low altitude with a large expansion ratio at high altitude. The nozzle is constituted in a base nozzle and a nozzle extension, linked by an abrupt wall angle change at the contour inflection. Figure 1 illustrates the concept of the dual bell nozzle. The contour inflection forces the flow to a controlled and symmetrical flow separation under high ambient pressure conditions, the so called sea-level mode. During ascent of the launcher the ambient pressure decreases and the nozzle pressure ratio NPR (ratio of total pressure over ambient pressure) increases [2]. After reaching a certain point of altitude, the flow suddenly attaches to the exit plane of the nozzle extension and the transition to altitude mode takes place. Due to the further expansion of the nozzle flow, the vacuum performance of the engine with full flowing dual bell nozzle extension is increased compared to a conventional engine. Figure 2 illustrates the comparison of the engine thrust over altitude between the investigated Vulcain 2 like engine and an engine with dual bell nozzle extension. The advantage of using a small expansion ratio at low altitude and a large expansion ratio at high altitude is clearly visible [4]. Here the transition from sea-level to altitude mode occurs at an altitude of around 8 km.

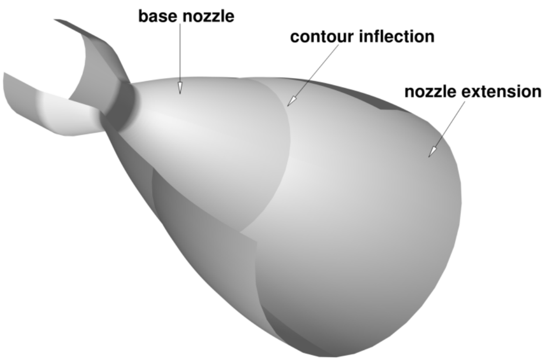

Figure 1: *Principle of a dual bell nozzle.*

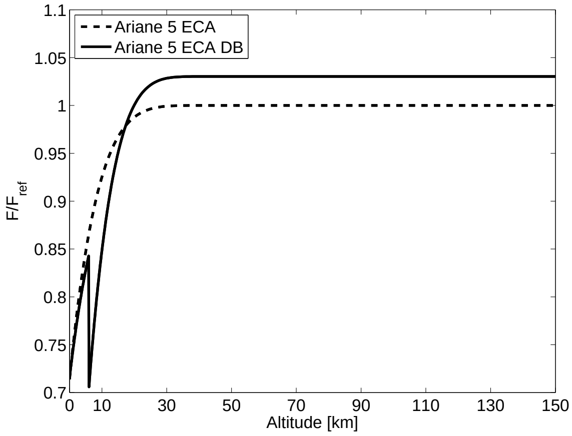

Figure 2: *Comparison of redesigned Vulcain 2 with and without dual bell nozzle extension*

3.2 Dual bell nozzles design

Based on a Vulcain 2 like contour numerous dual bell contours were designed. As base nozzle a shortened Vulcain 2 like nozzle was considered. Five different wall inflection positions, corresponding to expansion ratios of 33, 38, 45, 50 and 58 were chosen. The shortest configuration ε_b = 33 corresponds to the position directly downstream of the TEG injection manifold (see Sec. 2.1). Varying the inflection angle α_{inf} five extensions for each base nozzle configuration were designed, beginning at the last point of the shortened Vulcain 2 like contour. Figure 3 displays the variation of the inflection angle for an ε_b = 50 base nozzle. The extension contour design was realized using a DLR in-house code based on the method of characteristics (MOC) [5]. The last point of the base nozzle corresponds to the inflection point of the dual bell contour. Starting from the last right-running characteristic a Prandtl-Meyer expansion of the supersonic nozzle flow occurs. As the chosen wall inflection angle is reached, an isobar is build on the free jet contour leaving the base nozzle. The resulting contour is a so called CP extension, yielding a constant pressure along the nozzle extension length. This type of dual bell nozzle extension has proven to ensure a fast and defined transition from one operation mode to the other [2]. Restrictions for the nozzle length and diameter are given by the Ariane 5 ECA launch pad of Centre Spatial Guyanais launch site in French Guiana. An additional constraint on the length of the dual bell nozzle extension was based on the wall angle, i.e., the angle between the isobaric contour extension and the horizontal line. The isobaric contour extension was stopped as soon as this angle reached zero degrees. The flow conditions in the generated contours, e.g.

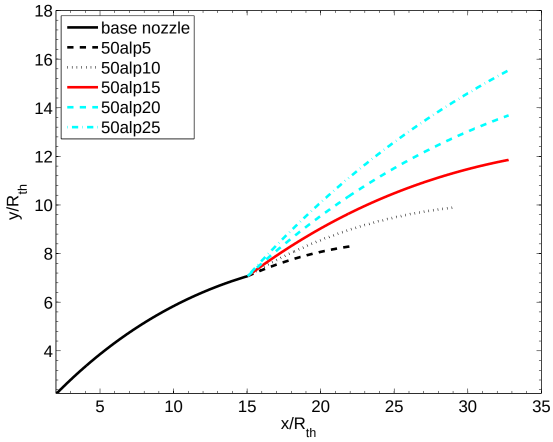

Figure 3: *Studied dual bell nozzle contours of a base nozzle with an expansion ratio of 50.*

the specific impulses for sea-level and altitude conditions were calculated applying a similar method based on MOC. The transition pressure ratio NPR_{tr} and the transition altitude were defined by the wall pressure along the nozzle extension. The characteristic parameters of the designed dual bell nozzles are listed in Table 4. The notation of the different nozzles is a combination of the expansion ratio at the contour inflection ε_{b} and the inflection angle α_{inf}. For example 50alp15 means a dual bell nozzle extension with an inflection angle of $\alpha_{\mathrm{inf}} = 15°$ beginning at an expansion ratio of $\varepsilon = 50$.

3.3 Estimation of the nozzle mass

For the mass estimation of the Vulcain 2 nozzle extension, it was divided in five sections:

- Interface ring
- Dump cooled base nozzle
- TEG manifold
- Upper part of film cooled extension
- Lower part of film cooled extension

For the nozzle base, the upper and lower part of the film cooled extension the mass per nozzle surface area was evaluated. The mass of the interface ring and the TEG

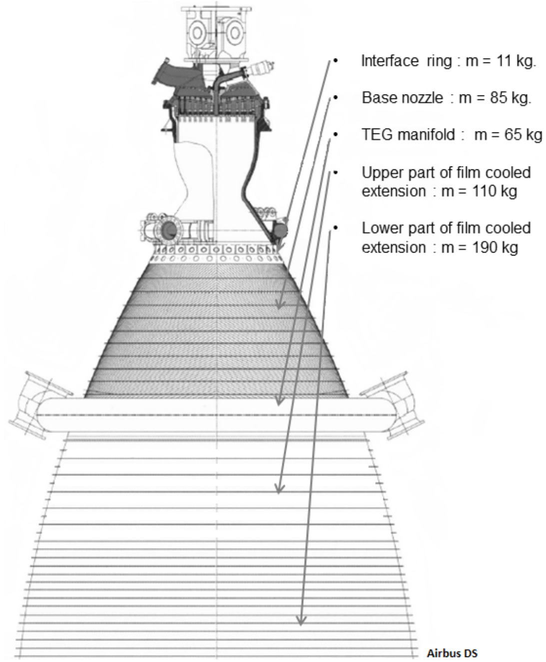

Figure 4: *Estimated mass distribution of the Vulcain 2 like engine. Picture taken from: "Vulcain 2: Thrust Chamber", product sheet by Airbus DS*

manifold were considered as constant values. In order to obtain a mass estimate, Inconel 600 with a density, $\rho = 8490\,\mathrm{kg/m^3}$ was chosen as nozzle material. The different segments of a Vulcain 2 nozzle together with their mass estimates are presented in Figure 4. The overall mass was determined to 461 kg. For calculations of the added dual bell nozzle extensions the same method and material was applied.

4 Estimation of Δv

Each point of an orbit can be assigned to a defined velocity that results from its kinetic and potential energy. If the change of a bodies trajectory is desired, its velocity vector has to be adapted. The difference between start and target velocity is the so-called Δv requirement. Thus a launcher has to provide a defined minimum Δv capacity to deliver a payload to a given orbit. Within this Δv capacity losses caused for example by drag or gravity have to be considered. For this reason the effective Δv capacity of a launcher is always bigger than the Δv requirement requested by simple trajectory considerations. The Δv capacity of a launch vehicle can be estimated using the

Name	$\alpha_{\text{inf}}[deg]$	ε_{ext}	L_{tot} [mm]	$I_{\text{sp, sl}}$	$I_{\text{sp, vac}}$	$I_{\text{sp},+}$ [%]	m_{noz} [kg]	Payload gain [kg]
Reference	-	58	2590	305	425	-	456	-
33alp5	5.7	64	3030	324	426	0.37	622	34
33alp10	11.1	93	3990	324	433	1.89	1047	267
33alp15	16.6	141	4500	324	437	2.96	1407	410
33alp20	24.2	150	3140	324	426	0.16	836	-91
33alp25	32	150	2680	324	416	-2.00	655	-569
33alp28	37.1	150	2510	324	413	-2.87	591	-764
38alp5	6.2	68	3030	319	428	0.78	623	136
38alp10	10.5	97	3995	319	434	2.13	1037	330
38alp15	15.3	146	4500	319	437	2.94	1374	415
38alp20	21	150	3300	319	426	0.38	863	-46
38alp25	27	150	2890	319	419	-1.42	701	-493
45alp5	5.7	70	3030	312	429	1.03	712	169
45alp10	10.2	99	3995	312	435	2.37	1009	400
45alp15	14.9	145	4500	312	438	3.02	1318	454
45alp20	20.2	150	3555	312	429	1.02	921	92
45alp25	25.9	150	3155	312	423	-0.42	758	-211
50alp5	5.2	69	3030	306	429	0.97	603	192
50alp10	10.4	98	3995	306	435	2.41	986	417
50alp15	15.7	141	4500	306	438	3.03	1277	471
50alp20	21.6	150	3745	306	431	1.53	971	202
50alp25	28.4	150	3335	306	426	0.29	803	-48
58alp5	6.6	66	3030	296	429	0.91	595	180
58alp10	9.5	93	4500	296	435	2.41	1217	366
58alp15	13.6	118	4500	296	436	2.54	1181	382
50alp20	18	146	4500	296	434	2.21	1226	284
58alp25	30.4	150	4090	296	430	1.33	1060	121

Table 4: *Results for the dual bell nozzle design, the estimated additional structure mass and the calculated payload gain*

Tsiolkovsky rocket equation:

$$\Delta v = c_{\mathrm{e}} \cdot ln\left(\frac{m_{\mathrm{start}}}{m_{\mathrm{end}}}\right) \quad . \tag{1}$$

For the analytical approach the running boosters and the main stage engine were considered as one first rocket stage. Therefore, the Ariane 5 ECA ascent was divided in three flight phases:

- Phase 1: Solid rocket boosters and main stage engine running parallel
- Phase 2: Main stage engine running separately after jettison of boosters and payload fairing
- Phase 3: Upper stage engine running after main stage separation

Using the characteristic values presented in Section 3.2 the Δv capacity of Ariane 5 ECA was calculated as a reference state to be approx. 12.2 km/s. Considering an increased main stage engine exit velocity, due to a dual bell extension application, as well as an increased engine structural mass, an iteration concerning the payload mass was conducted in order to achieve the reference Δv capacity.

The payload gain was evaluated for a large range of specific impulse gain and additional engine mass. The calculations yield a linear correlation between additional engine mass, specific impulse increase and payload gain:

$$m_{\mathrm{PL+}}\,[kg] = -0.35 \cdot m_{\mathrm{V2+}}\,[kg] + 250 \cdot I_{\mathrm{sp+}}\,[\%]. \tag{2}$$

Applying this simple correlation the payload gain of every dual bell nozzle variation can be calculated. The result over a wide range is illustrated in Figure 5. The payload gain of all considered engine variations is listed within Table 4.

For every base nozzle length the maximum payload increase is reached for a wall inflection angle of 15°. The most promising configuration is the dual bell extension starting at an expansion ratio of $\varepsilon = 50$ and a wall inflection angle of $\alpha_{\mathrm{inf}} = 15°$. For this specific setup the calculations yield a payload gain of 471 kg into GTO. The dual bell geometry is illustrated in Figure 3 as the red line.

5 Numerical method of higher order

For the numerical approach the trajectory simulation code TOSCA-TS (Trajectory Optimization and Simulation

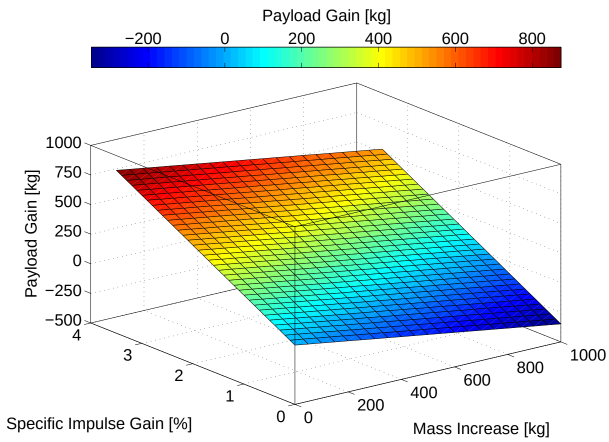

Figure 5: *Influence of increased specific impulse and the additional nozzle structure mass on the payload increase*

of Conventional and Advanced Transport Systems) was used. As long the nozzle pressure ratio was lower than the transition NPR, the thrust of the main stage engine was computed from the specific sea-level impulse of the base nozzle given by the MOC method (see Sec. 3). After reaching the transition altitude, the thrust was calculated using the characteristic values of the designed dual bell nozzle extensions. Furthermore, the change of lift-off mass and the stage mass due to the new added nozzle extension were taken into account.

5.1 TOSCA-TS

TOSCA computes the ascent trajectory for a given launch vehicle configuration into a target orbit. Therefore the launcher is treated as a point mass. The aerodynamic drag coefficient and the lift coefficient have to be provided as an input parameter. The launcher trajectory can be divided into several flight phases. The configuration of the launch vehicle considers the staging and the different types of engines (solid or liquid), applying their characteristic engine values (e.g. mixture ratio, specific impulse, etc.). The values of the different engines are given in Section 2. The calculated parameters for the main stage engine with a dual bell nozzle extension are listed in Table 4. For the simulation of the trajectory the equations of motions including the different stage characteristics and constrains are integrated using a Runge-Kutta algorithm of order 4/5 with adaptive step size. For the optimization of the predefined control parameters the Sequential Least SQuare Programming (SLSQP) algorithm is applied.

5.2 *Calculation of payload gain*

To calculate the payload increase for a Ariane 5 ECA applying dual bell nozzle extensions, TOSCA -TS was used. As mentioned in Section 5 different flight phase were considered during ascent of the launcher. These flight phases are the vertical ascent, the gravity turn with constant nick rate, the separation of the solid rocket boosters, the main stage cut-off, a ballistic flight phase between the main stage separation and the ignition of the upper stage and the upper stage cut-off. Furthermore, the flight phase of the main engine with dual bell extension had to be divided into a first phase using the specific impulse for sea-level condition and a second phase using the specific impulse of the full flowing nozzle. The atmosphere was modeled using the US-standard atmosphere. The gravitational potential of the aspherical earth is modeled via Legendre-Polynomials of second order. This implies a gravitational acceleration depending on the distance to the center of the earth and the geographic latitude. Figure 6 illustrates the results for the conducted

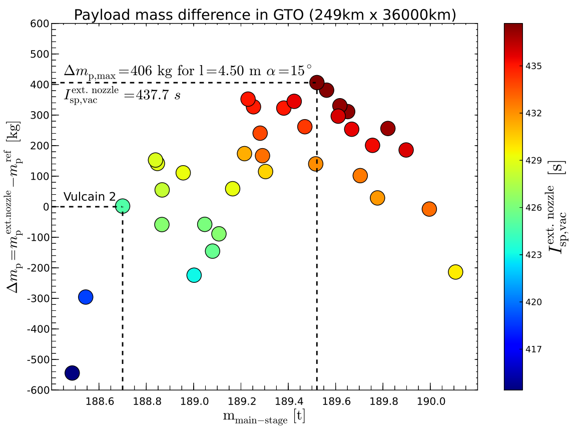

Figure 6: *Payload gain for different dual bell nozzle extension calculated with TOSCA-TS*

calculations. The plot shows the difference of payload mass delivered into GTO between Ariane 5 ECA DB and the reference configuration of Ariane 5 ECA versus the overall main stage mass for several TOSCA-TS calculations. The specific vacuum impulse is color coded. The simulations yielded a maximum payload mass gain of 406 kg for the configuration 50alp15. This configuration uses a dual bell bell nozzle extension beginning at $\varepsilon = 50$ of the original Vulcain 2 like nozzle contour and has a wall inflection angle of $\alpha_{\text{inf}} = 15°$, which is in good agreement with the analytical calculations of Section 4.

6 Conclusion

The impact of the dual bell nozzle extension for the Ariane 5 ECA on the delivered payload into a geostationary transfer orbit was studied. For the analysis, two different techniques, an analytical approach based on the rocket equation and a detailed launch vehicle trajectory simulation were used. The results of the two methods were in good agreement and at most an payload mass increase around 450 kg was found. Both methods yielded a maximum payload mass gain for a dual bell nozzle extension beginning at an expansion ratio of $\varepsilon_b = 50$ and a wall inflection angle of $\alpha_{\text{inf}} = 15°$. Concerning the capability of Ariane 5 ECA to deliver 10.1 t into GTO, 450 kg of more payload means a increase of around 4.5 %. Assuming a cost of approx. 16000 Euro per kg payload into GTO, this would lead to additional payload mass to the value of 7.2 million Euro per Ariane 5 ECA launch. Instead of increasing the payload mass of the Ariane 5 ECA a compensation of maybe too heavy future upper stage is possible using an main stage engine being enhanced by a dual bell application.

7 Outlook

The present work was based on a redesign of the Vulcain 2 engine with a dual bell nozzle extension applied downstream of the TEG injection. This yielded dual bell nozzles lengths up to 4.5 m. Hence the nozzle mass was increased up to 1407 kg. Furthermore, the produced side loads during transition from sea-level to altitude mode could be high, because of the large lever arm [6]. A complete redesign of the engines nozzle upstream of the nozzle throat would lead to shorter nozzle contours, yielding less structure mass and side load generation. During the analytical and the numerical calculations no mass optimization was performed. This would lead to additional payload mass gain. In addition, the TOSCA-TA simulations were not trajectory optimized. This will be part of following work.

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