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System design of EURASTROS reference configurations and mission

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Abstract

Is Europe technologically ready for an independent astronautical access to space?

The EURASTROS study has been carried out following the high level objectives to investigate cost-efficient, robust and relatively short-term accessible astronautical space transportation services based on European assets and technologies [1]. To meet the high level objectives and to maximize the benefit from European heritage on previous spacecrafts and demonstrations, a service module – capsule spacecraft concept was baselined.

Based on the HLR an incremental system sizing workflow has been initiated, comparable to a condensed Phase 0 system study. First, A6 performance data was elaborated to provide inputs for nominal and degraded mission scenarios & respective crew safety related operations [2]. Following that, critical principal sizing of the crew module subsystems as of the TPS, propulsion system & ECLSS were carried out in usage of engineering methods and numerical tools [3]. The resulting crew module mass and the determined A6 trajectory data enabled the technological trade-off analysis on and sizing of the atmospheric abort system. Here, some particularities of the European setting needed to be mastered. In the final step the service module vehicle conceptual design has been elaborated. Due to the end-to-end abort capability and the focus on application of European technology, no easy-fit solution has been identified. Instead, an adaptation of the currently under ESA contract developed ASTRIS kick-stage including its baselined BERTA storable engine was performed. The computed needs of such a service vehicle resulted to be well in line to ASTRIS system boundaries.

Abbreviations

A62:	Ariane 62 with two solid boosters
A64:	Ariane 64 with four solid boosters
ACM	Attitude Control Motor
AGG:	Ariane Group GmbH
ARD	Advanced Reentry Demonstrator
ATV:	Automated Transfer Vehicle (of Ariane 5)
BERT	“Bemannter Europäischer Raumtransport” study on European Human Spaceflight
CAD:	Computer Aided Design
CM:	Crew Module
DOF:	Degree of Freedom
DRL:	Down-Range Landing site
ELA-4:	Launch complex for Ariane 6 in Kourou
ELV:	Expendable Launch Vehicle
ECLSS	Environemtal Control and Life Support System
ISS:	International Space Station
LAS:	Launch Abort System
LEO:	Low Earth Orbit
LLC:	Launch Control Centre
LLPM:	Lower Liquid Propulsion Module
LPE:	Launch Pad Escapen
LV:	Launch Vehicle
Ma:	Mach number
NCR:	Non-recurring costs
RC:	Recurring costs

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RLV:	Reusable Launch Vehicle
RTLS:	Return To Launch Site
SM:	Service module
TPS:	Thermal Protection System
TRL:	Technology Readiness Level
TVC:	Thrust Vector Control
ULPM:	Upper Liquid Propulsion Module (of Ariane 6)
Za/Zp	Orbital apogee/perigee

1 Introduction

The European Astronautical Space Transportation (EURASTROS) study was carried out in 2021 as a joint project in-between several leading DLR institutes and Ariane Group GmbH. The main objective of this study was to understand the principal challenges of the design and operations of a human rated spacecraft to be launched on an Ariane 6 launcher from Guyana Space Centre towards the International Space Station.

The EURASTROS spacecraft system design attempts to achieve a purely European system focusing on LEO centric operations. It features a classic Capsule/Service Module spacecraft design for the transport of three astronauts. This paper provides an overview on the reference mission and the references system configuration. Particularly main finding during the work on the Launch Abort System (LAS) and the Service Module (SM) are summarized. The overall concept depiction including the overall mass budget of the system is provided and proposals on the recommended continuation of the activity are stated.

2 Principle HLR and Reference Mission

2.1 HLR

The EURASTROS system study follows the objective to find the most time and budget efficient approach for European-made astronautic spaceflight.

To support this goal a development logic has been established to streamline development activities and optimize in terms of duration and costs. This logic follows the hereafter listed main assumptions in terms of system principal requirements and the development assumptions.

Principal HLR	description
Time to market	The European Astronautical Transportation System shall have the first mission within 4 years.
Mission to LEO	The European Astronautical Transportation System shall be able to take up to 3 astronauts to LEO and back to Earth. The first mission shall be headed to the ISS
Non Recurring Costs	The European Astronautical Transportation Launch System shall be developed so as to minimise non-recurring costs as far as possible and shall not in any case cost more than 5000 M€, including, but not limited to, development, qualification, procurement of jigs and tools, adaptation of facilities and ground segment
Recurring Cost	The European Astronautical Transportation System shall have recurring costs comparable to actual market prices for transport to ISS and back
Adaptation of existing A6 launcher	The European Astronautical Transportation Launch System shall be based on the Ariane 6 launcher. It shall complement the existing A6 launch system, limiting its modifications as far as possible. As such, the maximum mass of the upper part (all structures above the upper stage) shall be: a. 10 metric tons for an A62 configuration b. 20 metric tons for an A64 configuration For placing the upper part on the following orbit:

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	Za = 250 km, Zp = 250 km, inclination = 51.6
Docking with ISS	The European Astronautical Transportation System shall provide for a docking/berthing capability with the ISS, allowing astronauts pass into the ISS through the docking hatch
Abort and rescue system	The spacecraft shall provide continuous autonomous launch abort capability from lift-off through orbital insertion in the event of a loss of thrust or loss of attitude control
Landing system	The European Astronautical Transportation System shall use a new deceleration/landing system, which allows keeping the maximum loads of the ground impact within human tolerable limits. The landing shall be performed on water

– **Table 2-1 - principal HLRs from development logic and cost perspective**

To answer the set of HLR an aggressive development logic and respectively an effective system design need to be established. Principal top level considerations of the development are listed in Table 2-2.

Development Logic - principal assumptions

- Exclusively European technology shall be applied (particularly no ITAR restricted technology shall be baselined)
- Preferably high TRL technology shall be utilized, in best case re-used from previous/existing programs
- An iterative demonstration approach shall be integrated into the development logic for early critical technology demonstration
- To assure a fast development cycle the development iterations on subsystem/ component level shall be minimized and compensated by system tests
- Since development costs are critical to the timeline, development activities shall be parallelized accepting inherent risks
- The development logic is focusing on the space segment of EURASTROS since it is expected to be driving the schedule and costs of the program
- For full system qualification purposes an orbital A64 flight accomplishes the development process
- The two baselined A64 ISS flights (one cargo flight and one crewed flight) at the end of the development shall be commercial flights

– **Table 2-2 - top level development logic assumptions**

2.2 Reference Mission

The EURASTROS system shall fulfil a LEO based operational scenarios. The reference mission for the system was based on an Ariane64 launcher from Guyana Space Centre to the International Space Station ISS. This reference mission drives the propellant budget dimensioning.

Consequently, the following target orbits were baselined:

- Capsule injection orbit: 200 km x 200 km x 51.6°
- Target orbit for crew capsule: 400 km x 400 km x 51.6°

The Ariane 64 configuration was chosen since the additional recurring costs of the A64 in comparison to a potential A62 configuration were considered minor in contrast to the induced constraints of the A62 performance. Additionally, the A64 offers huge growth potential to the EURASTROS system in terms of passengers and capabilities. Nevertheless, as shown in Figure 4-1, the baselined EURASTROS configuration might also be launched by an Ariane 62 increment. This potentially opens additional opportunities within the European spaceflight eco-system.

The following major mission constraints (C) were taken into account:

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C1. the system must allow for mission abort on any point on the launcher trajectory
C2. Landing over inhabited area is to be excluded also in abort scenarios
C3. Even in case of a ballistic re-entry of the crew module within an exo-atmospheric abort scenario the g-loads shall not exceed NASA human body limit specifications [3]
C4. The pad abort scenario requires water splashdown of the crew module

In addition to the HLR those derived mission constraints were major drivers for the system design.

2.3 Baselined A64 trajectory

A detailed description of the launcher trajectory is provided in [5]. To understand the principal constraints that the selected trajectory induces on the spacecraft design a condensed description is given.

Ariane 6 features a low thrust to weight ratio of its ULPM. Consequently the performance optimized launcher trajectory towards LEO tends to overshoot its instantaneous apogee before approaching its final orbit. Such an overshoot is critical for the end-to-end abort capability of the system. Due to the resulting high instantaneous apogee with relatively low speed, a critical situation occurs in the case of a launch abort on this point of the trajectory. The strong de-acceleration from the steep re-entry angle would result into strong g-loading on the astronauts and exceeding the acceptable range over time. The Service Module might be fired to increase velocity and consequently reduce the re-entry angle. However, only in a very limited range. To mitigate this critical trajectory overshoot and also to increase performance to LEO, within the EURASTROS study an ULPM propellant de-loading strategy was introduced. This de-loading strategy reduced the overshoot to an acceptable range of around 230km as depicted in Figure 2-1. The de-loading strategy is described in [5]. The resulting re-entry in abort case is described in [4].

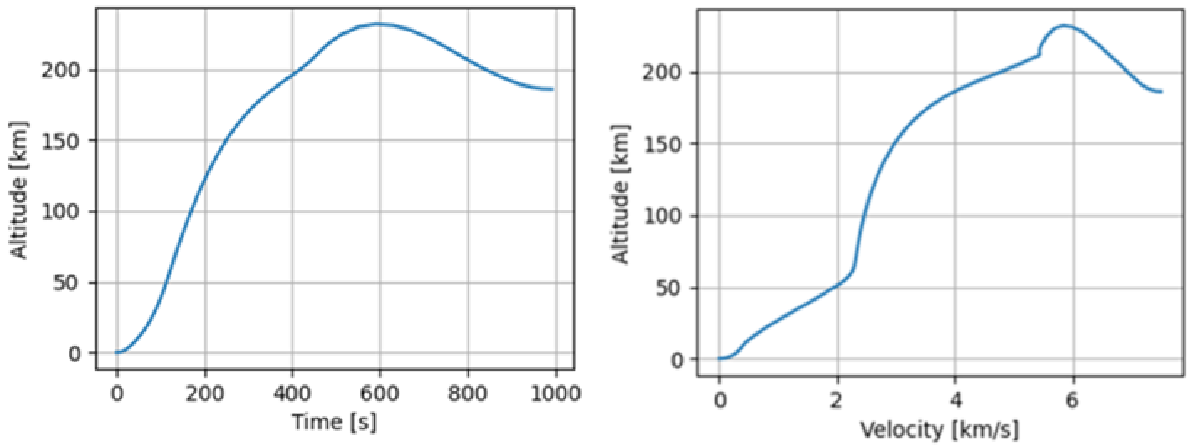

Figure 2-1 EURASTROS Ariane A64 trajectory with ULPM deloading

Due to the resulting azimuth of the A64 trajectory towards ISS inclination, the ground track of the mission crosses the European and Asian continents before reaching orbital velocity. This results into a potential hazard since a launch abort scenario could lead to a ground impact of the EURASTROS system with potential catastrophic consequences. There is no effective strategy to mitigate this risk by launcher trajectory variations. Consequently, the EURASTROS system needed to be dimensioned in a way that the Last Direct Re-entry point (LDR) of the system was matching the point where the spacecraft could reach orbital velocity with its own main propulsion system. This scenario is the driver for the Service Module dimensioning and is described in [4].

3 EURASTROS System Design

In the following a principal summary on system design is provided.

3.1 Crew Module

The shape of the astronaut capsule is derived from the Apollo capsule, i.e., it has a spherical nose and a truncated conical back shell. To accommodate at least two astronauts, an outer diameter of $d = 3.5$ m is chosen which results in

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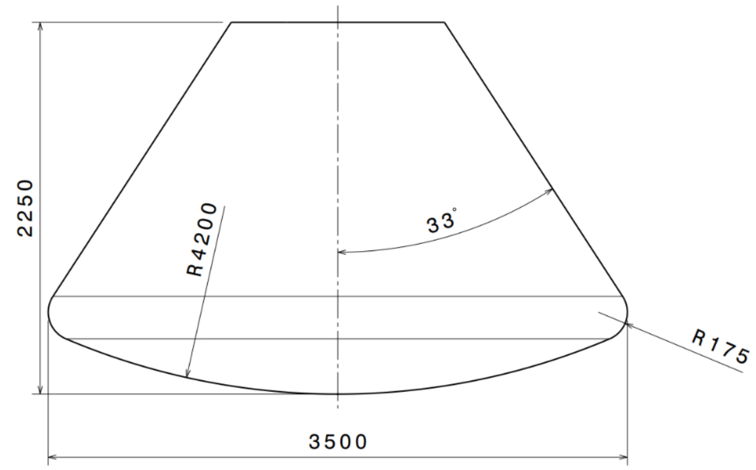
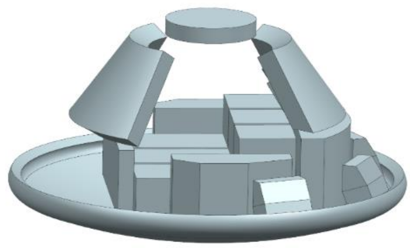
a volume of 11.6 m³ or about 72% of the Apollo capsule volume. A third astronaut can be accommodated as an option. The choice of the Apollo shape is beneficial for a fast and cost-efficient development of the capsule due to the heritage of the Atmospheric Reentry Demonstrator (ARD), that successfully flew in 1998 [8]. The outer shape of the capsule with its major dimensions are shown in Figure 3-1.
An engineering concept was drawn up with regard to the distribution of the internal masses in terms of crew seating and equipment. The objective was to determine the possibility to adjust the center of gravity to comply with the system requirements. The masses are calculated either via sizing effort, such as for the TPS, or via comparison with previous work (e.g. BERT study). The resulting top-level mass table is presented in Figure 3-1.

The aerodynamics of the capsule, resulting aerothermal loads and consequent TPS and structural dimensioning is provided in [4].





Component	Mass / kg
Structure	792
TPS	673
Equipment	2731
Crew (seats)	820
Total	5016

Figure 3-1 EURASTROS capsule with its major attributes

3.2 Atmospheric Launch Abort System (LAS)

The Launch Abort System (LAS) refers, following the EURASTROS terminology, to a high-energetic propulsive system to accelerate the crew module out of a critical zone after critical events, as launcher failure detection, within the atmospheric mission phase.
The LAS operational perimeter begins with the arming of the system on launch pad after crew access and ends nominally with its jettisoning in high altitude flight phase. As the nominal fairing of non-crewed Ariane missions, the separation event of the LAS will be initiated at acceptable thermal fluxes around 1100 W/m2. After jettisoning, the safety chain is continued by the exo-atmospheric abort system. The EURASTROS LAS is not designed for re-usability and will drop into the Atlantic Ocean.
The conceptual design phase of the EURASTROS LAS is summarized in Figure 3-2. A first collection of information and pre-selection phase is followed by an iterative design & analyses phase. Finally, detailed work is performed on two remaining concepts, resulting into a development & cost logic activity and the selection of a preferred concept.

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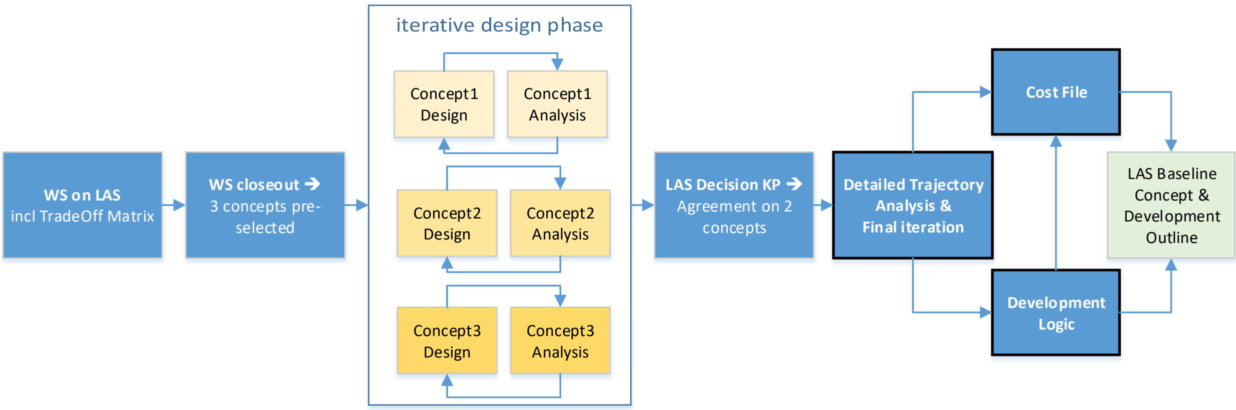

Figure 3-2 EURASTROS Launch Abort System conceptual design workflow

A full set of potential LAS concepts with solid and liquid propellants was considered for the initial trade-off studies as depicted in Table 3-1.

Table 3-1: LAS concepts for trade off study.

Potential concepts				
Escape Tower	Capsule-integrated	Escape Ring below Capsule	Service Module Integrated	Ejection Seat

Main driving parameters for the conceptual pre-selections were:

- Compliance to end-to-end abort chain
- risk mitigation – for example solid motor technology was only selected for jettisoned systems to avoid solid motors in orbit
- Motor availability in Europe[1] and consequently development risk mitigation
- Assumed system complexity

This resulted into three main concepts as summarized in Figure 3-3. All initial concepts were designed for 800 kN average thrust for around 4 s burn time with thrust build up and decay assumptions. Two of the concepts were based on solid motor technology, one on hybrid propulsion technology.

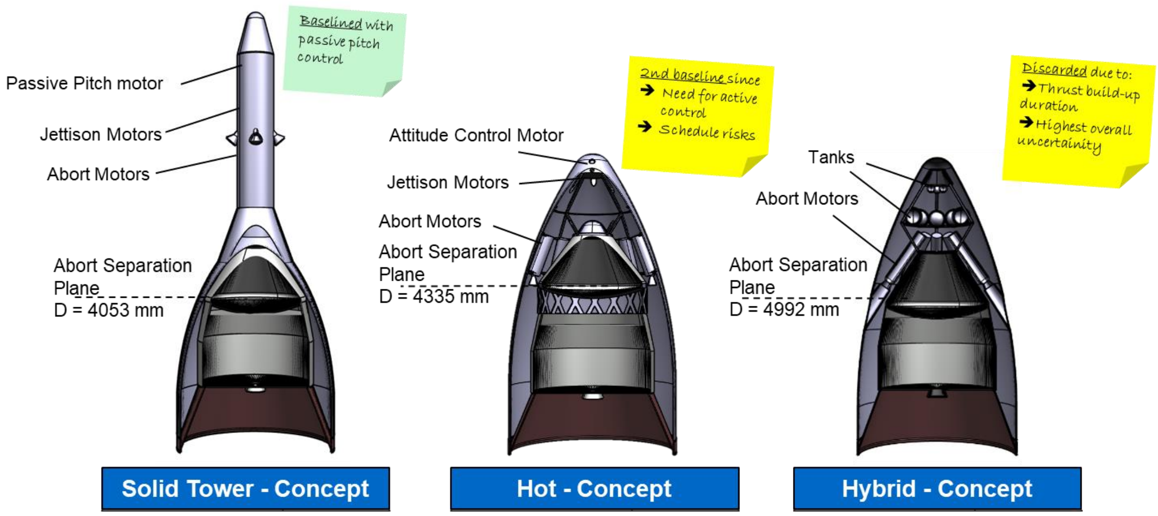

Figure 3-3: EURASTROS LAS Design concepts.

[1] Liquid storable motors were excluded due to non-availability of matching solutions in Europe (thrust level & reactivity)

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The hybrid concept was designed for pressure fed H_2O_2 / HTPB propulsion technology, consisting of 8 combustion chambers and respective tanks. The feed system is supplied by four high pressure Nitrogen tanks in the top of the system. A major advantage of this concept is the thrust vector control capability by thrust variations of the single motors. This allows for closed loop guidance without additional propulsion for pitch angle control. At the same time, jettisoning of the system can be performed by igniting e.g. four motors in throttled mode for short time. No additional jettisoning motor is required. This results into a promising conceptual mass despite the heavy main propulsion system, being only 6% above the referenced solid tower concept. The hybrid concept was discarded due to its overall uncertainty, in particular regarding the thrust reactivity, and the associated risk of impact on the very ambitious EURASTROS development schedule. Apart of this constraint the hybrid technology might become a viable solution.
The hot concept resulted from the attempt to not modify the Ariane 6 overall outer shape. This is expected to significantly simplify development work and coordination. Due to that, the hot concept might also be referred to as a "human payload", since the spacecraft is covered by nominal fairing geometry as any other satellite. The hot concept relies on an octa-cluster of solid engines. Its name "hot" concept is derived from the hot separation functionality. In the case of an abort scenario the solid motors will be ignited and blow the exhaust gases inside the fairing during the transient separation phase. Due to the position of the center of gravity and its aeroshape this concept is unstable and requires active control. The control is provided by an attitude control motor system (ACM) as demonstrated by US company ATK in the frame of the Artemis Orion spacecraft. Even if a principal ground firing on this technology has been demonstrated by Ariane Group, the development of such a technology is associated to high risks for the EURASTROS development timeframe and budget outline. Additionally, the mass of such a concept exceeds the mass of the reference concepts by 8%. Consequently, the hot concept is not the baselined concept for the Launch Abort system.
For several reasons, the baselined concept for the Launch Abort System is the Solid Tower concept. Its functionality is proven by heritage on previous applications as on the Apollo and Soyuz spacecrafts. Furthermore, the single solid engine is not concerned by imbalances in thrust and/or ignition reactivity. Due to its specific shape it features a beneficial location of center of gravity relative to the pressure point. Consequently, the escape system, consisting of the Launch Abort System and the crew capsule, is aerodynamically stable during the first flight phase. As can be derived from the low negative $C_{m\alpha}$ value, the vehicle is still controllable by moderate lateral thrust created by a pitch motor in the nose cone of the tower. This thrust is required to manipulate the pitch rate and the flight path respectively. During the flight duration the CoG of the system moves downwards in the direction of the capsule due to the mass exhaust of the main motor. To ensure aerodynamic stability and a stable position before capsule release, aerodynamic control surfaces in the rear of the vehicle are proposed. This might be grid fins as depicted Figure 3-6 or vanes or aerodynamic blades. A trade off on the preferred solution is recommended for follow-up activities. After the escape scenario or in nominal missions as soon as leaving the atmosphere, the launch abort system is separated from the capsule in the usage of the jettisoning motor.

Table 3-2 approximated mass ratios of selected LAS concepts

System	Escape Mass [kg]	LAS [kg]	capsule [kg]	Mass LAS/Escape	Mass LAS/capsule
EURASTROS	10200	5200	5000	0,510	1,040
Soyuz TMA	7600	3400	4200	0,447	0,810
Orion MPCV	16768	7062	9706	0,421	0,728
Apollo	9400	3600	5800	0,383	0,621
JAXA	8000	3000	5000	0,375	0,600

The overall launch abort system of EURASTROS, as depicted in Figure 4-1, features a generally high mass ratio. This is resulting from the Ariane 6 ELA4 launch pad distance to the ocean. To achieve ocean splashdown in case of launch pad abort, a distance of more then 3,5km kilometers needs to be overflown [5]. This results into high energy needs and consequent propulsive and overall mass upscale. A first thrust profile optimization was carried out within the EURASTROS study. Nevertheless, further improvement of the thrust profile (potentially also by stacking and sequencing of motors) would result into higher overall mass efficiency of the propulsive system.

3.3 Service Module

The Service Module (also payload module) is a critical element of the EURASTROS astronautical space transportation system. The principal functionalities of a Service Module can be described by the following top-level functional breakdown [6].

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- To provide structural continuity between the launcher & orbital system
- To provide thrust after upper stage/launch vehicle separation
- To provide electrical power
- To regulate heat for the life support & avionics equipment
- To store and provide other crew life relevant fluids (e.g. water, oxygen)

One core activity of the EURASTROS study is to carry out a conceptual design of such a service module according to the project High Level Requirements, mission constraints and the listed top-level functionalities.
The very first step of the conceptual work on the payload module was to collect and process information on the EUROPEAN heritage on such technology. The major previous or ongoing projects in this perimeter are:

- The Automated Transfer Vehicle (ATV)
  - ⇨ a European servicing vehicle for the ISS
- The European Service Module (ESM)
  - ⇨ a European contribution to NASA's Artemis program and Orion spacecraft

Both systems are designed in accordance to human rated design criteria and provide profound system-knowledge for servicing vehicles. Nevertheless, within the performed study it was decided not to baseline a solution based on one of those to vehicles for the following main reasons:

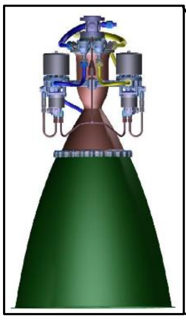
1. the ATV vehicle does not feature sufficient propulsive thrust to guarantee a continuous safety abort chain functionality which means a conflict with HLR. To make the vehicle compliant to this HLR means a fundamental manipulation of the vehicle's architecture
2. the ATV vehicle is out of service for several years with a high risk on the reconstruction of the supply chain
3. the ESM vehicle relies on main propulsion from the US STS program (OMS = Orbital Maneuvering System). Consequently, it is ITAR regulated and not applicable on the EURASTROS space transportation solution

Taking into account those criteria, no matching solution was identified within European perimeter. It was decided to approach the vehicle conception based on the ASTRIS Kick Stage and its main storable engine BERTA. Some information on ASTRIS and BERTA are summarized in Figure 3-4.

Propellant	MMH/MON
Engine Cycle	pressure fed
Qualification Target Date	end 2023

Parameter	Value
Mixture Ratio [-]	1,65
Total Mass-Flow Rate [kg/s]	1,297
Chamber Pressure [bar]	12,0
Specific Impulse [s]	318,0
Thrust [kN]	4,04
Mass [kg]	30,1

BERTA performance at reference point



Vehicle Type	Kick Stage
Payload capacity	~4500kg
Mission Type	multiday/ multiboost (up to 7x; growth)
Diameter	4,4m
Height	1,6m
Propulsive Mass	up to 2700kg (baseline ~1700kg)

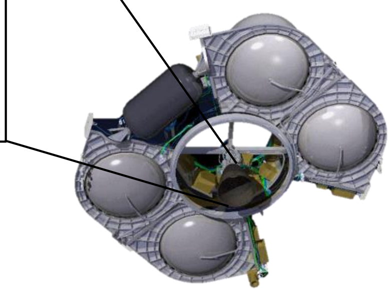


Figure 3-4: The ASTRIS Kick-stage and its respective BERTA engine.

The main reasons to base the conception of the Service Module on ASTRIS and BERTA are:

- both are currently in development under ESA contract with a timeline matching to the EURASTROS roadmap
- the BERTA engine thrust class of 4 kN allows for exo-atmospheric abort and escape scenarios with a reasonable engine clustering
- the systems implement state of the art technology including avionics and offer an existing supply chain
- the systems are core elements of the overall European space logistics eco-system strategy

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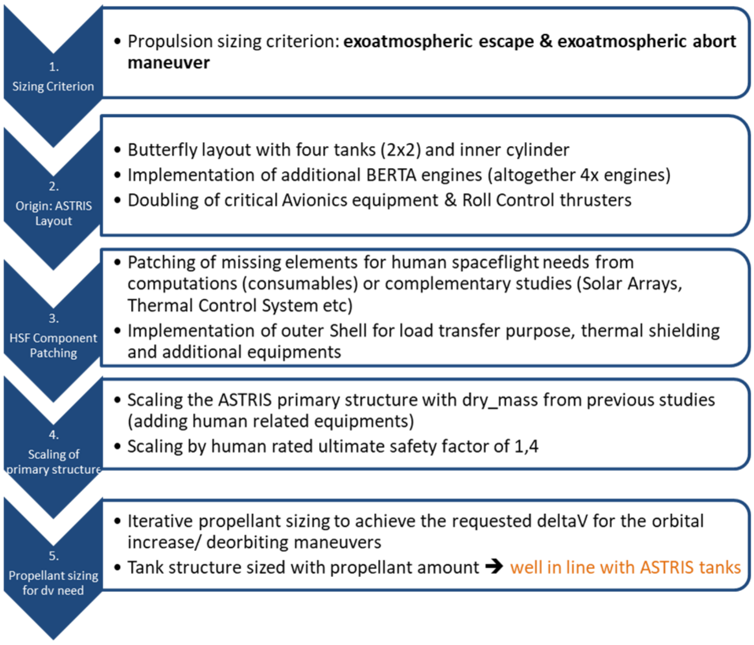
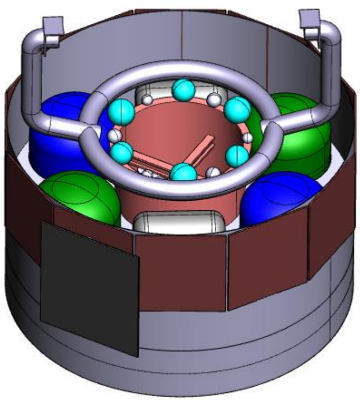


Figure 3-5: EURASTROS Service Module definition logic.

The service module conceptual work was structured iteratively according to the flowchart in Figure 3-5. The starting point for the conceptual design is the dimensioning of the maximal required thrust level based on preliminary mass data. Within the next step the available ASTRIS architecture is extended in terms of required thrust performance and some critical elements as avionics or attitude control. Furthermore, all specific human spaceflight related equipments are added and an additional outer shell for equipment packaging is implemented. To carry the additional equipment, the mass of the primary structures needs to be scaled up accordingly. On top, the typical human spaceflight safety factor of 1.4 is implemented into the mass scaling. Having fixed the principal dry mass, the propellant sizing to achieve the required deltaV including margins is performed. The resulting propellant mass is well in line to the ASTRIS propulsive mass spectrum. A concept depiction and the main Service Module vehicle parameters are presented in Figure 3-6



Vehicle Type	Service Module
Mass incl CM adapter	6400kg
Mission Type	4 days free 210days docked
Diameter	4,4m
Height	3,4m
Propulsive Mass	1300kg
Dv_Budget	370m/s
Main Engine	4x4kN
RCS	24x10N

Figure 3-6 EURASTROS Service Module concept based on ASTRIS Kick-Stage and BERTA engine

4 EURASTROS Reference Configuration

Combining all single elements, a global picture of the EURASTROS system can be given in Figure 4-1. The overall orbital mass is easily within the nominal performance perimeter of an Ariane 64. Additionally, the performance of the Ariane 6 will be subject of continuous improvements and will exceed the values baselined today. Consequently, there are two potential approaches to maximize the benefit given by Ariane 6:

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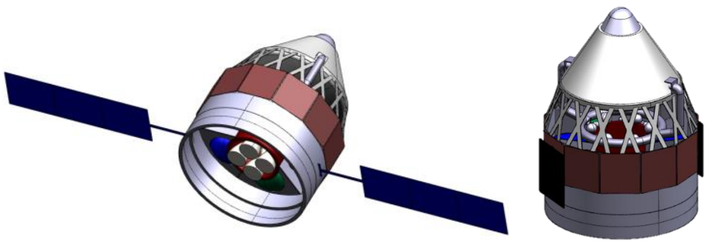
1. Apply the EURASTROS system on an evolution of the Ariane 62 configuration with increased payload performance to LEO
2. Maximize the crew and/or mission capabilities of EURASTROS to a level that justifies the Ariane 64 launch vehicle utilization

Both approaches seem interesting, dependent on the future setting of the European space eco-system and the related Human Spaceflight ambitions.



EURASTROS system (w/o ULPM adapter)		
CrewModule		5016kg
ServiceModule		6389kg
	Orbital Mass	**11405kg**
LaunchAbortSystem		5276kg
	Total Mass	**16681kg**

Opportunity for an A62 evolution

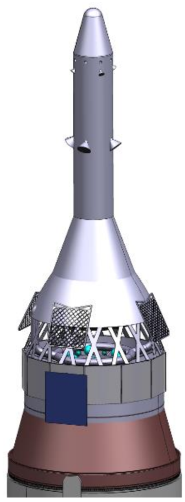


Figure 4-1: EURASTROS system global picture.

5 Conclusion and Recommendations

The EURASTROS study identified several challenges for European Human Spaceflight in usage of the Ariane 6 launcher from CSG, including the large lateral distance to the ocean, as well as the launch trajectory for abort cases, etc. However, the study shows that all pain points might be relieved by selecting suitable strategies and adapting the concept accordingly. Further, Europe offers a strong technological basis to realize the ambitious timeline of a first fully Europe-made crewed mission before 2030.

Due to its role in the future European space logistics eco-system, the evolution of the ASTRIS kickstage fulfilling the service vehicle functions seems smart and achievable. The overall platform sizing is confirmed to be well matching to the LEO centric operational scenario of EURASTROS.

A concept as EURASTROS can be the European entrance point into human spaceflight autonomy with lowest technological risks, development costs and earliest to time to market. No technical blocking points or major risks for such a concept could be identified within this study.

Keeping this promising result in mind, it is recommended to continue the activities on the European strategy towards human spaceflight and the overall space logistics eco-system vision. The use of knowledge achieved during projects as ARD, ASTRIS, BERTA, ATV, ESM and several others will strongly leverage the development lead time of such a concept.

<u>The focus for the recommended follow-on activities shall be on the following main corridors:</u>

<u>How to optimize the business concept and the commercial use?</u>
Within this corridor the main focus is expected to be on re-usability aspects and also on the maximization of the crew

<u>How to prepare for a future extension of the mission domain?</u>

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Smart technological choices and respective roadmaps need to be elaborated to ensure scalability of a European Human Spaceflight service, and to prepare it for future evolutions.

How to benefit most from the ASTRIS kickstage roadmap for European Human Spaceflight?
The ASTRIS kickstage provides a perfect basis for the service module functions, proving its strength in the European space logistics eco-system. Opportunities given by the re-use of the ASTRIS technological bricks need to be further analysed and quantified in terms of technical and commercial figures.

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