AstroCab - A Space Taxi for Two People Launch and Return - Blue Team

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***Abstract*—What with Axiom Space Station, Russian Orbital Space Station and Orbital Reef, the plans for future space stations in Low-Earth Orbit are myriad, which generate a thriving market for vehicles to shuttle people to and from these stations. This report presents a concept of a two-person space taxi, called AstroCab. Several subgroups provided a collaborative work in order to design a small, efficient and reusable vehicle aimed to be fully operational by 2035. Some of the challenges inherent to such a project include the launch and return processes, which is what is covered in this report. Therefore, considerations about the launch site, the launcher and the approach to the target station, including far-range rendezvous and close-range docking, are reflected upon. Also, the re-entry in the atmosphere entails the need to deal with various issues such as the heating and the loads the crew will be exposed to. Eventually, the choice of the landing site and the recovery procedures are of paramount importance for turn-around time of the spacecraft which is crucial from an economical point of view.**

***Index Terms*—Human Spaceflight, ISS, Transfer Vehicle, LEO, Rendezvous, Docking, Reusable vehicle**

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I. INTRODUCTION

A. Context

The International Space Station is not only a fantastic research laboratory in outer space, but also one of the most groundbreaking human achievements both from a scientific and an international cooperation perspective. However, its retirement is close but projects of future space stations are myriad, be it with Axiom Space's station, Orbital Reef or even Russia's Orbital Station. Therefore, the number of humans going to space, and especially to Low Earth Orbit may be expected to skyrocket in the coming decades, which implies a wide market of vehicles to carry them to and from these stations.

B. Description of the project

This context gives birth to the idea of designing a 2-person space taxi. Such an undertaking entails dealing with several challenges, what with the architecture of the vehicle, the life support system and development cost, to mention a few.

Therefore, the work has been distributed among the blue team in smaller sub-teams, between Overall Coordination, Vehicle Design, Launch and Return, and Human Aspects. Regular meetings have been organized to discuss the general strategy of the mission as well as the inter-dependencies between the teams' scope. One of the outcomes of these meetings has been the name of the project: AstroCab.

This paper focuses on the launch and return, which includes the launch, rendezvous, docking operations, reentry, landing and recovery phases.

II. PRE-LAUNCH

Much of the pre-launch work was done in coordination with the coordination team. Since the pre-launch confines the entire mission to certain parameters due to the choice of launch site, procedure etc., it was necessary to have a back-and-forth between the two teams.

A. Launch and Landing

The choice of launch site is very crucial to the overall operation. The difference between a good and bad launch and landing site is the difference between a sustainable operation and financial insolvency.

First and foremost, it was decided that the launch and landing site would be located as close to each other as possible, if not within the same complex. This was of importance since this would allow the operation to have a shorter turnaround time between recovery and re-launch, thus saving time and money on transportation and allowing more launches in a shorter time frame.

The chosen site also had to give access to a range of different orbital inclinations that could house future space stations and thus are a target for this project. A launch site at a high latitude would make it impossible to reach an orbital inclination lesser than its latitude without a major plane-change manoeuvre. On the other hand, a launch from an equatorial launch site would be able to reach essentially every orbital inclination. However, most launch sites have strict launch azimuth restrictions that constrain the achievable orbital inclinations.

Thirdly, the launch site has to have available ground infrastructure without the need of many major construction works to make it a feasible choice.

Lastly, weather would have to be at least a manageable issue that would not jeopardize launches or landings at such a high rate that the venture would become unprofitable.

These requirements narrowed the field down to three alternatives: Kennedy Space Center in Cape Canaveral, Guiana Space Center in Kourou, and Satish Dhawan Space Center in Andhra Pradesh, India. While the last two lack a proper landing runway, a crucial need for the planned space plane vehicle, they make up for it in some of the other areas, as well as having major international and/or military airports nearby that could satisfy that need. However, at the end of the day Kennedy Space center was picked as launch and landing sites.

KSC is already an established launch site with tons of infrastructure in place, as well as having its runways 15 and 33 already used as landing runways for the space shuttle missions. KSC also has favorable launch azimuths that allow its launches to reach orbital inclinations of around 28.4°- 57°, as shown in Figure 1. This would allow it to reach the orbits of the ISS and Tianggong station, as well as future stations launched to commercial low-earth orbit destinations (CLDs). Another thing that sets KSC apart from the other two main alternatives is the weather. While Cape Canaveral has some of the highest frequencies of lightning strikes in the continental US, both Kourou and Satish Dhawan have much higher rates of precipitation due to their (comparatively) tropical climate. Satish Dhawan also has the monsoon season to contend with every year. These were some of the considerations that led to picking KSC.

Fig. 1: Launch azimuth restrictions for KSC. Launch azimuth of 35° results in an inclined orbit at around 57°

B. Procedure

As will be discussed in Section VII, the launch vehicle will be re-used from a previous launch. Due to this, a series of checks and procedures need to be performed prior to the launch in order to ensure a safe trip. However, these will also be discussed in the aforementioned section.

When the launch vehicle has been deemed safe and viable, then the launch is timed in such a way as to minimize the needed delta-V, as well as minimizing the time spent in orbit. This is done in two ways. Firstly, by timing the launch window to intersect with the orbital plane of the target station and launching in the appropriate azimuth, the amount of fuel saved is in the order of 400 m/s - quite a substantial amount. Secondly, if possible, let the launch occur so that the vehicle ends up as close to the target station as possible after the circularization burn. This timing depends on the target orbit, so it is hard to give a general launch window. However, as a rule of thumb, one should launch roughly 5-10 minutes before the target station is right above the launch site. A phasing orbit, as discussed in Section IV, will be used when a perfect timing is not possible. Also, the first condition described here is the more important one of the two. So, this one will be the constraining condition.

In addition to the orbital timing, the weather has to be taken into account. The launch commit criteria used in this project is the same as that of the space shuttle. These criteria include, but are not limited to [1]:

- 24-hour average temperature has been above 5 degrees centigrade
- The temperature has not fallen below 0 degrees centigrade during the past 24 hours
- The temperature has not exceeded 37 degrees centigrade during the past 24 hours
- The wind has not exceeded 22 m/s the last 3-hour period
- The launch cannot commence if the wind at 20 meters height has exceeded 10-18 m/s, depending on the wind direction
- No precipitation is present on the launch pad or in the flight path
- No reasonable possibility of lightning strike on the launch pad or within the flight path
- Direct visibility not hampered by cloud cover up to 2.4 kilometers

C. Off-nominal Case

The off-nominal in this case is obvious, namely poor weather. In this case, it is better to not tempt fate, so we simply cancel the launch. At AstroCab, we always put safety first! The potential cost of delays and loss of goodwill pales in comparison to the potential loss of human life, and it is simply not a worthy risk. Poor weather also comes into consideration for landing. In this case, there is more of a focus on the wind and visibility conditions at the landing site, since the vehicle will function like an airplane in this case. The decision point for landing is made 70-90 minutes before the expected landing will take place. If the weather conditions are not met at this point in time, then an alternate landing site is needed. The chosen alternate landing site is, as discussed in VI, is Spaceport America in New Mexico, USA.

The weather conditions include, but are not limited to [1]:

- Less than medium cloud cover below 2.4 kilometers and direct visibility of 5 kilometers or more
- Peak cross-wind cannot exceed 8 m/s, 6 m/s at night
- Head-wind cannot exceed 13 m/s
- Tail-wind average cannot exceed 5 m/s, 8 m/s peak
- No thunderstorm, lightning or precipitation activity within 55 kilometers of the landing site
- Less than or equal to moderate turbulence
- There is a possibility of giving a GO for landing, if there is a clear pattern of improving weather at the landing site and in the flight path

The weather report will come from the United States Space Force's Space Launch Delta 45, who have operational command over KSC, as well as managing the weather reports.

III. LAUNCH

The scope of the project was rather to define the launcher capacities appropriate for the AstroCab rather than actually designing a rocket for it.

A. Preliminary constraints

First, the launch trajectory starts from the ground and reaches the Low Earth orbit and therefore goes through the atmosphere. The consequences of this are twofold. On the one hand, environmental issues and pollution are of paramount importance. This excludes the launchers using solid fuel propellant and hydrazine, both known to be very toxic and harmful for the environment. Moreover, even though thermal nuclear propulsion system has been tested, for political, safety and environmental reasons, it can not be considered for such a mission. On the other hand, the rocket must be able to provide a high thrust and a ΔV of 10 km/s, accounting for escaping the Earth's gravity and countering the atmospheric and gravity drag, to reach LEO's orbital velocity. This constraint makes it impossible to use electric propulsion.

Eventually, all the previous considerations result in using a classical chemical rocket that has to meet several requirements.

B. Launch Requirements

Secondly, the requirements imposed on the launcher have been put forward after a continuous collaboration with the Vehicle Design team. Indeed, one of the most important criterion about the rocket is the mass it must bring to LEO which hinges on the vehicle dry mass and the propellant needed for all the maneuvers. Hence a back-and-forth exchange between the two teams. Eventually, the launcher must be able to put in Low Earth Orbit a payload of, at least, 6.5 t corresponding to the total mass of the vehicle. Moreover, the diameter of the latter, including the wings, won't restrain the launcher choice. Effectively, the different abort modes designed for the vehicle imply that it does not have to fit into an imposed fairing, instead it will sit on top of the rocket. Besides, in order to avoid exposing the crew to tremendously high levels of acceleration, the engines of the rocket must be throttleable.

Eventually, the project strives to a high launch frequency thus, the main criteria concern the cost and availability of the launcher, the safety of the crew, as well as the payload mass to LEO.

C. Launch Vehicle

Once all the criteria inherent to the launcher have been listed, a final question raised about the choice between government and private rockets, as the private sector keeps proving that it can substantially decrease the costs of the launches to space. As a consequence, both origin of rockets have been regarded.

Then, a wide list of launchers have been considered and their capacities have been compared to these criteria, as shown in Table I.

Although the cost of the launch is one of the most crucial criterion for the choice of the rocket, the idea is to try to find

TABLE I: Rockets considered for the AstroCab project

Launcher	Mass to LEO	Cost per launch	Status
Starship	150-200 t	10 M$	Operating
Vulcan Centaur	19 t	110 M$	Operating
Antares 230	8 t	80 M$	Retired
Falcon 9	17 - 23 t	50 M$	Operating
Ariane 6 A62	10 t	75 M€	First flight 2024

the rocket that would best fit the requirements, especially the mass of the AstroCab. To that extent, even though Starship reaches remarkably low cost per launch, its capacity is so high compared to what is needed that it would be unlikely to manage to sign such a contract with SpaceX for its Starship. Eventually, considerations about the payload mass, the reusability of its first stage and the expected decrease of the cost in the coming years as announced by SpaceX for the Falcon 9, result in choosing the latter. The outstanding reliability of the Falcon 9 over the last decade has been a plus to deem this launcher to be the most appropriate rocket for the AstroCab project.

D. Launch Sequence

The launch will follow the stages of a typical Falcon 9 launch, with the recovery of the first stage, with the only difference being that the vehicle will not be put into a fairing but instead it will lay on top of the rocket.

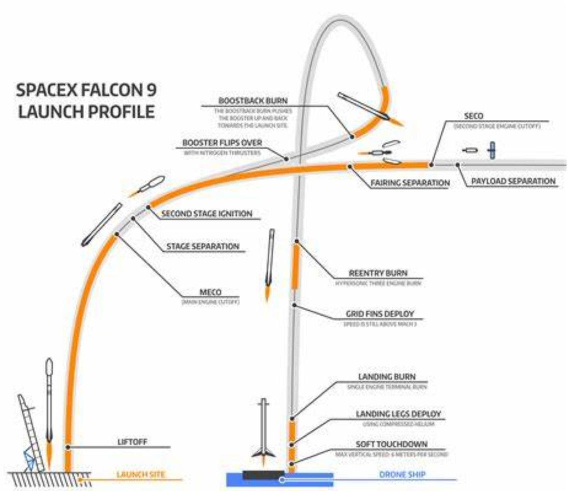

Fig. 2: Typical steps of a Falcon 9 launch

The launcher ensures the orbital insertion strategy, which will basically follow the one of the Space Shuttle [2]. In the case of AstroCab, it consists in cutting off the second stage of the rocket, and therefore separating the vehicle from the second stage, at the apogee of 148 km of altitude, of an elliptical orbit whose perigee is within the atmosphere. The benefits of such an operation are myriad. On the one hand, the rocket and the vehicle remain far enough from possible future space stations so that it avoid any interference or collision with a maneuvering vehicle around one of them. On the other hand, and more importantly, it enables the vehicle to abort the rendezvous and re-enter the atmosphere and land safely if necessary *i.e.* if something went wrong among the crew or if, for any reason, the thrusters appear not to work anymore. Still, in the nominal case, the vehicle will rapidly start the rendezvous as the atmospheric drag is still preponderant at this low altitude.

IV. Rendezvous

A. Phasing

Since AstroCab is placed into a co-planar orbit compared to the target space station there is no need for big burns to change planes. There might be some need for adjustments to line up with the exact plane of the station orbit but this margin is included into the station keeping.

Once the AstroCab is in the insertion orbit it is made sure that the systems are operating as intended. When this is done it is moved into a higher phasing orbit in order to reduce the drag on the AstroCab with a Hohmann transfer. Increasing the altitude of the orbit from 150 km to 250 km increases orbital lifetime and will require less thrust for remaining in the same orbit. This maneuver is illustrated in Figure 3

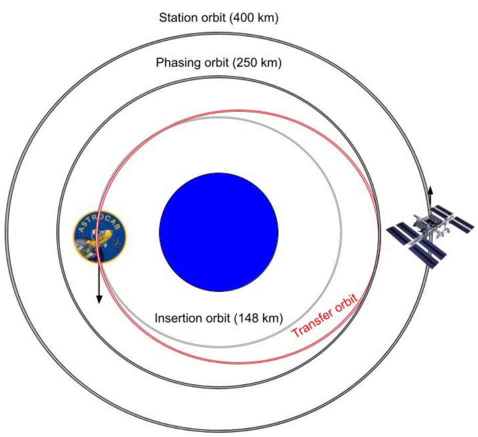

Fig. 3: Transfer to phasing orbit from insertion orbit.

This phasing orbit is used to get to the right transfer window for the transfer to the space station in its orbit. At 250 km this enables the spacecraft to catch up to the space station with 3 minutes per orbit. This means that if the launch of the AstroCab is completely out of sync with the space station, which is launch so that when it arrives in the phasing orbit it is just in front of it it will take 45 hours to get into the next transfer window. This is on the higher side but still under two days as per the requirements. To lower travel time a better launch window can be selected.

After the phasing has been done the next step is to get to basically the same orbit as the target space station. It is not a good idea to intercept the station on a collision trajectory but aim for a point that is near the station and when AstroCab gets close and more accurate predictions on trajectory can be made thrust to get into the rendezvous sphere of the space station. In this way the target station is never in any danger of colliding with AstroCab if there were to be a malfunction of the thrusting system. The framework of the operations near the target station is laid out in a document called International Rendezvous System Interoperability Standards which will be explained further in the following section. The Hohmann transfer to near space station orbit can be seen in Figure 4.

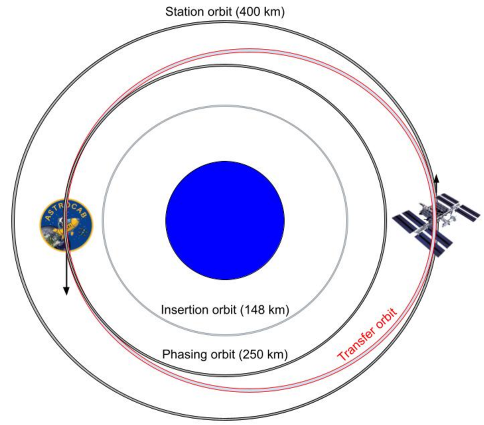

Fig. 4: Transfer to station orbit from phasing orbit.

The ΔV for the big orbital maneuvers during the rendezvous phase is described in Table II.

TABLE II: ΔV for rendezvous burns

Maneuver	$\Delta V(m/s)$
Hohmann to phasing	60
Hohmann to station	86

B. International Rendezvous System Interoperability Standards

During the operations of rendezvous and docking, safety is important. One way of making sure that this is done is to follow standards. One of those standards is called International Rendezvous System Interoperability Standards or IRSIS. IRSIS establishes the baseline framework for an interoperability interface, terminology and techniques to enable collaboration in space when it comes to rendezvous and docking. [3]

It is also in our own good interest to make sure that AstroCab acts professionally and follows guidelines and recommendations. A failure to do so will affect the company negatively.

V. Docking

A. System

A critical component ensuring the success and safety of these missions is the autonomous docking system that is used. Following collaborative discussions and coordination with the Vehicle Design team, an autonomous Light Detection and Ranging (LiDAR) docking system is implemented as the optimal solution, providing precision and reliability in the docking operations.

LiDAR technology operates on the principle of emitting laser pulses and measuring the time it takes for these pulses to be reflected back from a target, in this case being the space station. This time measurement is then converted into distance, allowing for precise positioning and navigation. In the context of the AstroCab, the LiDAR docking system uses this technology to autonomously guide the vehicle to a docking port located on the space station. It consists of an assembly of laser emitters, sensors, and computational units that process spatial data in real-time.

The docking process initiated by the LiDAR system begins as the vehicle enters a predetermined proximity to the space station. At this juncture, the system activates, projecting laser pulses toward the docking port. The reflection of these pulses is captured by onboard sensors, facilitating the calculation of distance and the generation of a three-dimensional representation of the docking trajectory. This real-time mapping is crucial for navigating the space taxi through the complexities of space, taking into account the relative movement of both the taxi and the station, as well as the influence of orbital dynamics.

Autonomy in the docking process is paramount, given the precision required and the potential for human error. The LiDAR system autonomously adjusts the vehicle's speed, orientation, and trajectory, ensuring optimal alignment with the docking port. This guidance is carefully calculated, allowing for adjustments down to the millimeter, a testament to the system's precision. The autonomous nature of the LiDAR system significantly reduces the crew's workload, and enhances the safety of the docking process by minimizing reliance on manual controls [4].

B. International Docking Procedures

The docking to the target space station marks the end of the first phase of the round trip in the AstroCab. Strictly speaking, the docking follows the far-range rendezvous and consists in the very last approach maneuvers to the target. These procedures are detailed in International standards [5] and notably with the Russian KURS system from which the operation sequence for the AstroCab has been based on [6].

Once the rendezvous, and especially the phasing succeeded, the close proximity maneuvers begin. First, to position itself along the target's docking axis for the final approach, the spacecraft performs a fly-around, depending on where the vehicle comes from with respect to the docking ports of the targeted station, at a relative distance between 200–400 m. During the fly-around, the navigation sensors on spacecraft tracks the target to obtain range, range-rate, line of sight, angle information and relative attitude of the two vehicles. After the fly-around, the spacecraft will hold a constant relative position about 200 m from the target while waiting for the go-ahead signal from the ground. Once approval is given, it begins the final approach following a straight line closed-loop controlled trajectory with an initial closing rate of 1 m/s. During the last 10 meters of closing between the chase and target vehicles, the relative velocity is about 0.1 m/s. Ultimately, the Soft Docking System of the International Berthing Docking Mechanism actively captures and dissipates the kinetic energy of the approaching vehicle while the Hard Docking System makes the structural pressurised connection between the station and the AstroCab.

Moreover, the international standards define the notion of Abort corridor, which is a cone envelope of the relative position and attitude of the approaching spacecraft with respect to the station in which it must remain to successfully operate the docking. As the docking has been chosen to be fully automatic, the relevant abort envelope is the Automatic Abort Corridor in Figure 6. If the vehicle exits it for any reason, the docking must be aborted, the vehicle must move away from the station and wait for a new go-ahead signal to reattempt the docking.

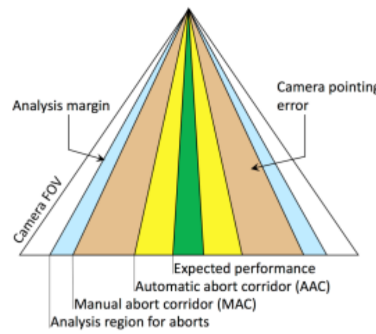

Fig. 5: Abort corridors definition

The accurate limits of this corridor are given in the main characteristics of the IBDM [7].

IBDM

Initial docking conditions:

Relative longitudinal closing velocity, m/s 0.05-0.10

Relative total lateral closing velocity, m/s < 0.02

Relative angular rate:

- pitch/yaw, relative angular rate, °/s < 0.15
- roll angular rate, °/s < 0.4

Angular misalignment of longitudinal axes:

- pitch/yaw misalignment, deg. < 5.0
- roll misalignment, deg. < 5.0

Lateral misalignment/eccentricity, m < 0.10

Fig. 6: IBDM abort corridor limits

VI. Reentry and Landing

To get back to the ground AstroCab will use a combination of a de-orbit burn and let the atmosphere slow it down, gliding to the ground as a glider and landing as an airplane. This is very similar to what the space shuttle did and vehicles such as the Dream Chaser will do. [8]

After undocking and backing away from the visited space station the AstroCab will use a retrograde burn to lower the perigee into the earth's atmosphere at 148 km. The total ΔV can be seen in Table III. This reentry burn does not immediately get AstroCab into the atmosphere but will use the increased drag by putting the maximum area which is the underside of the AstroCab towards the direction of travel. This saves on the fuel margin and enables a much more fuel efficient de-orbit than lowering the perigee directly into thicker parts of the atmosphere. More fuel could be used from the margin if there is need to de-orbit more quickly.

TABLE III: ΔV for reentry burn

Maneuver	$\Delta V (m/s)$
Reentry Burn to 148 km	73

From this point AstroCab will only use RCS-thrusters for stability and aerodynamics to guide itself back to the landing site.

Modelling the re-entry heating of AstroCab is quite a difficult task, due to the non-ballistic re-entry profile that will be used, something that really only has been used for the Space Shuttle, the X-37B, and the Buran. This means that both the cross-sectional area experiencing drag and the velocity will be changing based on the attitude of the spacecraft. Thus, the choice was made to base the spacecraft's re-entry profile on the space shuttle's. A typical shuttle re-entry profile, specifically the one for STS-5, is shown in Figure 7.

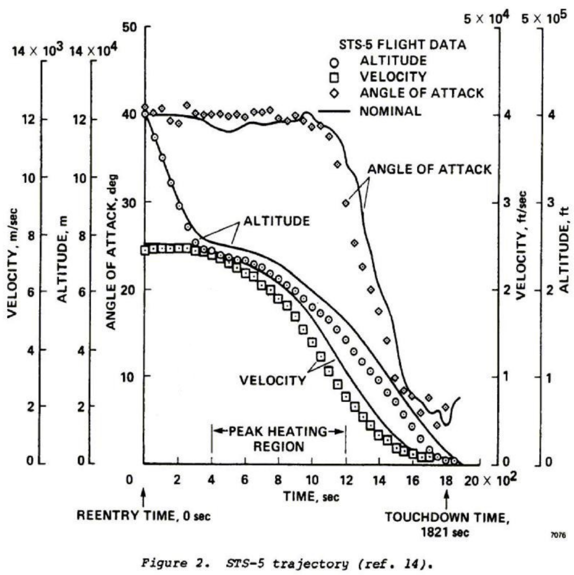

Fig. 7: Re-entry data for STS-5

Given that the Dream Chaser model of AstroCab is more aerodynamically capable than the space shuttle, high angle-of-attack maneuvers at high altitudes would allow more speed to be bled off earlier during re-entry, thus minimizing both the heat and G-forces experienced in the thicker parts of the atmosphere. Since the space shuttle usually reached temperatures at ∼1500 degrees centigrade [9], we can assume that the temperatures that AstroCab will experience will be in this ballpark, but slightly lower. Exactly how much lower is hard to say. Again, this re-entry profile is complicated and accurate thermal calculations for this would be outside the scope of this project and is definitely something that can be improved. Also, since more of the speed will be bled off in the thinner parts of the atmosphere, the G-forces experienced at maximum deceleration by the crew will be less than that of the space shuttle, i.e., roughly 3G.

During the descent AstroCab must be capable of at least 216 km of cross range capabilities. This means that AstroCab must aerodynamically be able to land 216 km away from the orbital path. This is explained in Fig 8.

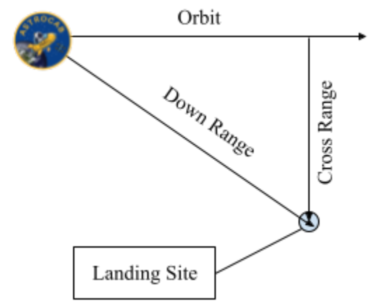

Fig. 8: Definition of cross range

This value is decided such that AstroCab can always return once every day when the orbit is at its closest to the landing site. The ability to reach this capability should not be an issue since cross range capabilities like this have easily been achieved before by the space shuttle [10].

The final touchdown will nominally be made onto the shuttle landing facility in Florida. This is a 4600 m long runway that was previously used as the main landing facility for the space shuttle. [11] A big advantage with this landing site is the long runway length but most importantly the short distance to the launch site that enables quick refurbishment on site. An overview of this landing site can be seen in Figure 9.

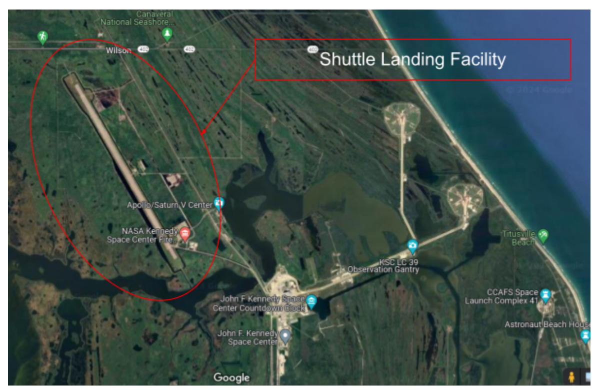

Fig. 9: Main landing site: Shuttle Landing Facility

As mentioned previously the weather in Florida can sometimes be unstable, especially during hurricane season. Therefore the backup landing site is selected to be Spaceport America in New Mexico. This runway is seen in Figure 10.

The backup runway is around 3.8 km long which is not as long as the runway in the shuttle landing facility. This should not be a problem however as AstroCab is much smaller than the space shuttle.

VII. Recovery and Re-use

A. Ground Logistics

Upon successful return of the AstroCab to Earth, a comprehensive and carefully planned ground logistics operation will commence immediately to ensure readiness for its next mission. This operation begins with the initial recovery phase

Fig. 10: Backup landing site: Spaceport America

where the spaceplane is secured and transported from the landing site to a dedicated processing facility. This phase involves specialized ground support equipment designed to operate safely and efficiently.

The first step in the processing facility involves a thorough external inspection of the spaceplane to identify any immediate signs of structural stress or damage sustained during the mission. This inspection is critical for assessing the overall structural integrity of the spaceplane and for planning subsequent maintenance activities. Although a detailed inspection and potential repair of the heat shield is covered in the next section, it is important to mention that a preliminary assessment of the thermal protection system (TPS) is also conducted at this stage to identify any visible damage or wear. Following the external inspection, the spaceplane undergoes a series of post-flight operation, which includes the safe removal and disposal of any hazardous materials, such as residual propellants. These operations are conducted by trained personnel equipped with the necessary protective gear and tools, adhering to strict safety protocols to mitigate any risks associated with these materials [12].

Simultaneously, the spaceplane's main engine and other critical components undergo detailed inspections and maintenance. This involves the examination of mechanical and electrical components, software diagnostics, and the replacement of any parts that show signs of wear or damage. Special attention is given to the spacecraft's avionics, power systems, and life support systems to ensure they are operating within their specified parameters.

This approach to ground logistics, drawing inspiration from the Space Shuttle program, is designed to uphold the highest standards of safety and operational efficiency. By rigorously planning and executing each phase of the ground operations, the objective of achieving a rapid turnaround time, while maintaining the integrity and reliability of the spaceplane, is within reach.

B. Heat Shield Inspection

The heat shield inspection process is a critical component to the AstroCab's turnaround operations, ensuring the vehicle's safety and readiness for the subsequent flight. This process involves visual inspections and maintenance activities to the TPS due to the harsh conditions during atmospheric re-entry.

Upon re-entry of the space-plane the first step is in the heat shield inspection is a visual inspection and a photographic survey of the entire surface. Technicians and engineers use high resolution cameras and borescopes to inspect the heat shield tiles for any signs of damage. This includes looking for cracks, chips and other forms of wear and tear that might have occurred during the mission and re-entry.

Following the visual inspection, often a more detailed examination is required. Techniques such as ultrasonic testing which is a non-destructive evaluation technique is used to detect subsurface flaws in the panels which are not visible to the human eye. Similarly, thermography may be employed to identify any inconsistencies to the thermal properties of the TPS, indicating any potential hidden damages.

If any damages or wear is detected during the inspections, repairs and replacements are carried out of the affected tiles and panels. The AstroCab consists of many individually placed tiles, each of which is uniquely shaped and positioned. Hence, replacing these tiles is a high labor intensive process, requiring precise expertise to ensure that the overall integrity of the heat shield is maintained.

C. Turnaround Time

The goal is to complete the entire refurbishment process, which includes major engine maintenance, repairs to the Thermal Protection System (TPS), comprehensive safety evaluations, and detailed simulations, within a period of two weeks. This target is ambitious yet within reach. Before the Challenger incident, the Space Shuttle program managed to achieve its shortest turnaround time of 54 days. However, following the disaster, the minimum interval between missions increased to 88 days due to the introduction of stricter safety standards and more thorough inspections. The AstroCab's heat shield is significantly smaller than that of the Space Shuttle, which makes the objective of a two-week turnaround feasible. The smaller scale of the AstroCab simplifies certain aspects of the refurbishment process, rendering the two-week time frame not just optimistic but realistically attainable, with a strong emphasis on maintaining high safety and efficiency standards.

VIII. Conclusion and Discussion

The launch and return team has explored the requirements and limitations for those aspects for a two-person space taxi operation which will meet the future increase in commercial low-earth orbit destinations. This has been done in collaboration and coordination with the other sub-groups of the

Blue Team, something that has been rather fruitful and non-problematic.

The choice made by the Vehicle Design team to use a spaceplane both constrained and gave further opportunities to this sub-team. It constrained it in the fact that the landing site had to be able to accommodate a spaceplane of this size, something that only a few landing sites in the world could do. This finally led to the choice of KSC as the launch and landing site, with Spaceport America as backup landing site in the off-nominal case of bad weather rendering KSC runways 15 or 33 unavailable. This is both a good and a bad thing. KSC is a widely used spaceport that has been in use for decades, with proper infrastructure already available for use if needed. But also due to this, many other launchers use KSC. This could become a very crowded scene where many different companies all use the same spaceport, making it hard for any eventual enterprise to establish itself in this market. However, the choice of spaceplane also liberated the launch and return team from having to accurately calculating the re-entry heating and the recovery logistics, since the spacecraft would no longer land at the same place that it launched. This allowed further focus into other areas of the project.

With launch and landing site considered and chosen, the launcher specifications could be developed. Given the mass of the vehicle from the Vehicle Design team, i.e., 6.5 tons, a comparison between launcher masses to LEO could be made. Even though Starship offers the cheapest cost by far from the available options, it seemed overkill due to its incredibly high capacities. In the future, a potential ride-share program could be explored on the Starship, but for now the Falcon 9 is still an excellent choice, mainly due to its reliability and low costs per launch.

Sitting on top of the Falcon 9, the vehicle will first enter a sub-orbital trajectory with its apogee at 148 kilometers. This is to enable the performing of a systems check and leave the option of abort and re-entry open. If all systems are go, then an insertion to a phasing orbit can be commenced.

This phasing orbit is at 250 km, allowing the spacecraft to catch up with a station at 400 km at a rate of 3 minutes per orbit, while still not having too much drag affecting the spacecraft. After the phasing is complete, another insertion is made as to encounter the station at its orbit. This is done at a safe distance, so that if the thrusters suddenly stop working or any other mishap has occurred, the vehicle cannot collide with the station. There is an International Rendezvous System Interoperability Standard (IRSIS) that this vehicle will follow, as to facilitate the rendezvous and docking to as many stations as possible, at least those that also follow IRSIS.

The docking will mainly make use of a LiDAR system as the mainstay of the autonomous docking system. An autonomous docking system will cut down on time since human error would, ideally, no longer be a factor. It also shortens the training period of the astronauts since they don't need to be able to dependably and consistently perform docking, something that was requested by the Human Aspects team.

Approaching the station occurs in very tightly regulated phases and paths, according to an international standard. This approach is also done autonomously, and at incredibly slow speeds relative to the station in order to minimize potential damages in the case of malfunctioning thrusters. Following the procedures discussed in Section V, the vehicle gets captured by the soft docking system of the international berthing docking mechanism, which then leads into hard dock with the station.

After the mission on station is done, AstroCab will undock and drift away from the station until outside of the ”approach bubble” of said station. When at a safe distance, a de-orbit burn will lower the perigee down to 148 kilometers.

Based on the calculations of the procedures of AstroCab the a total summary of the ΔV-budget can be seen in Table IV.

TABLE IV: ΔV budget

Maneuver	$\Delta V (m/s)$
Hohmann to phasing	60
Hohmann to station	86
Close range	8
Reentry Burn to 158 km	73
Margin 20% on fuel mass	
Total ΔV	270

This de-orbit burn will not bring the spacecraft into the atmosphere, but the AstroCab can orient itself as to create a larger cross-sectional area, thus increasing drag and lowering fuel costs. The spaceplane vehicle also allows the team to base the re-entry trajectory and corresponding forces and heat effects on that of the Space Shuttle. Given the better aerodynamic capabilities of the AstroCab over those of the Space Shuttle, greater control authority would exist at thinner parts of the atmosphere, thus facilitating high-angle-of-attack maneuvers and thus bleeding off more energy at higher altitudes. This will in turn decrease the G-forces experienced by the crew as well as the heating on the spacecraft. The maximum temperature under nominal circumstances will then be lower than 1500 degrees centigrade.

After surviving re-entry, the AstroCab will use its more than 216 km cross-range capability to make its way preferably to KSC, otherwise Spaceport America. Recovering the AstroCab and re-using it for later missions imply a comprehensive ground logistics operation which will commence ASAP. After transporting the spacecraft to the processing facility, an inspection of any immediate damages is performed. After an external inspection, post-flight operations are performed, including the removal of residual propellants, etc. Also, the engines and other critical components undergo their own detailed inspections and maintenance. The heat shield inspection is critical to turnaround operations. This includes visual inspections and a photographic survey of the entire surface, looking for any signs of damage. Following the visual inspection, a more thorough search using ultrasonic testing is performed to find any subsurface flaws in the heat tiles. If any damages are found, repairs and replacements are performed on the affected tiles.

Using these methods, the AstroCab aims to reach a turnaround time of roughly two weeks, a number that is much smaller than the Space Shuttle's 88 days, since the AstroCab is a much smaller vehicle than the Space Shuttle. There are less tiles to inspect, and simplifies certain aspects of the refurbishment process.

The two largest uncertainties are the aerodynamic properties and the heating. The heating of the spacecraft is hard to model and varies on a lot of factors as it is in the very high hyper sonic region. The interactions between the air and the body of AstroCab leads to complex localized heating and will require a lot of modelling and testing before the final version of a heat protection system can be manufactured. Also the modelling of the heating is complex as it changes a lot based on the shape of AstroCab, with sharp edges usually attracting more intense heating than blunt surfaces. The analysis of the heating is a big part of further development of this vehicle.

The aerodynamic properties was an area which was not looked into in great detail from the Vehicle Design team as a limitation of the time scope of this project. A more detailed aerodynamic analysis should enable more accurate predictions of the final value of cross-range and verify it versus the requirements stated in this project.

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