KTH Royal Institute of Technology
SD2905 Human Spaceflight

HeRMeS: Human Repair Missions to GEO Satellites

Overall Coordination Report

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Abstract

This report studies the feasibility of human services and repair missions to satellites in geostationary orbit. The Human Repair Missions to GEO Satellites (HeRMeS) project includes a manned space station 500km above geostationary orbit and an autonomous retriever spacecraft attached to the space station for satellite servicing. The mission timeline estimates the first test launches to begin in 2027 and the first launch for a service mission in 2030. Cost budget for the project development is divided into design, development, testing and evaluation, wrap costs, operations, product management and systems engineering. The total estimated project cost is approximately $11 billion dollars with the expectation to break even in 2037 and accumulate $1.8 billion of profit in 2057. Overall mass budget includes facility construction, crew, and operations, totalling 82.1 tons of mass to be launched.

A proper feasibility analysis for HeRMeS needs to cover political, legal and economic considerations, and therefore this report presents a summary thereof. The Outer Space Treaty is an international agreement that provides relevant principles to enforce security and liability. The United Nations Office for Outer Space Affairs (UNOOSA) requires registration for all objects to be launched into space according to the requirements of the launching state. As the privatization of space quickly grows, many countries may decide to impose fewer regulations to encourage economic growth. Initial company funding would channel from government contracts and partnerships such as ESA's ARTES 33 program, which covers up to 50% of the eligible costs. Another method of acquiring funding is seeking private investors, or so-called "space angels" for high risk investments. In order to be eligible for ESA partnership and stay close to prospective customer base, HeRMeS will establish its headquarters in Paris and Luxembourg with an additional office in Washington, D.C. As an off-nominal case for future expansion of the business model, HeRMeS could consider providing additional services, such as salvaging, research, and CubeSat launching. Lastly, this report presents some motivations for human involvement in satellite servicing, focusing on technological development, research and space exploration. Humans provide better services to field studies, especially in off-nominal situations, wherein humans are able to make snap decisions to resolve difficult emergencies. Development of technologies and expertise for further lunar missions and Mars explorations makes human involvement in Earth orbit operations invaluable.

1 Introduction

Exploring beyond the Earth and expanding the territory of human kind has long been a drive and motivation for space exploration. By the end of the latter half of the 20th century, humans had developed rockets powerful enough to overcome the force of gravity and reach orbital velocities. This paved way for space exploration to become a reality many had dreamt of for a long time. Today, the space industry has expanded tremendously: launching rocket, spacecrafts and satellites is fairly easy, although still rather expensive [1]. Our dependency on satellites has increased as rapidly as new technologies have developed. Satellites are necessary for the functioning of many technologies, which people around the world use on a daily basis. Despite this, satellites are the only infrastructure not being repaired, serviced, or upgraded [2].

1.1 Background

During the Space Race after World War II, communication and navigation satellites were launched in rapid succession to serve for everyday use. In the 1980s, the usage of communication satellites expanded to be able to carry television programs, which made it possible for ordinary people to pick up satellite signals from their TV at home. The applicability of satellites has continued to develop over the years. A satellite orbiting the Earth at the specific path called the geostationary arc (GEO) will follow Earth's equator, orbiting at the same rate as the Earth. This allows the satellite to face the same point on the ground at all times, making it ideal for communications services like television, radio, GPS and internet [2].

Satellites nowadays are mostly used for communications, Earth observations and weather measurements. They have made discoveries such as the ozone holes over Antarctica, monitored phenomena such as forest fires and delivered photographs of the Chernobyl nuclear power plant disaster in 1986 [2]. They are essential elements of science, defense and telecommunication industries for both private companies and governments across the world. Currently, there are approximately 2000 active operative satellites in space, with almost a third of them in GEO. The maximum lifetime of a new satellite is twelve years [3]. When the satellite is considered inoperative or dead, it is, by an international agreement, put into a graveyard orbit above the initial orbital altitude. Hence, satellites are never fixed, refueled, repaired, serviced, or upgraded, save for rare exceptions.

The satellite industry is the only technical business where you build something worth half a billion dollars, and never look at it again. [1]. If any other infrastructure were to break, it would be repaired. The space industry has one exception for space repairs: the Hubble Space Telescope. Ever since it was launched in the beginning of the 1990s, the spacecraft has been serviced on a regular basis, making it the most productive scientific apparatus humans have ever built [2]. Building, developing and launching a new satellite can cost a fortune [1]. As it stands today, companies and governments that own satellites have little to no options when it comes to inoperative satellites.

1.2 Purpose

The general purpose of this project is to present a feasibility study of human service and repair missions to satellites in geostationary orbit. The first mission is meant to be launched within ten years from the beginning of the project. A set of project reports will present a study focused on the overall aspects of the mission, servicing of the client satellites, logistics from start to end, human aspects of sending humans to space and the space vehicle and habitat; the present report is concerned with the overall mission and management of the team.

2 Mission overview

The chosen mission title is HeRMeS: Human Repair Missions to GEO Satellites. The project begins with identifying sources of funding, but focuses on the development of the necessary systems for the mission. Following a detailed iterative analysis, the overall mission consists on a temporarily manned station above geostationary orbit, where astronauts stay for the duration of their mission, typically around two months. A small, autonomous retriever spacecraft detaches from the station, lowers its orbit to rendezvous with a target client satellite, and carries it back to the station. Once there, the astronauts perform the necessary servicing operations during multiple extravehicular activities (EVAs). Once the work is finished, the retriever returns the satellite to its original orbit, and moves on to the next target. The expected yearly service demand is twelve satellites: seven that require only lifetime extension, and five to be upgraded with new parts — overall, this means between two and four crews per year. Further details and arguments for this design are given later in the relevant reports.

The design and verification of the station will consume a big part of the total development budget. As can be seen in the mission timeline (Figure 2 in the appendix), the first test launches are estimated to begin in 2027 and expected to be completed by 2029, thus paving the way for launching the first service mission in 2030.

2.1 Cost budget

A cost estimation for the mission has been performed following a top-down approach. This method was selected rather than a more accurate bottom-up approach owing to the difficulty of finding enough relevant data, which was deemed to be beyond the scope of the present project. Nonetheless, a more detailed and complete financial analysis will be presented in the Services group report. The breakdown of costs is illustrated in Table 1, and includes design, development, testing and evaluation (DDT & E), wrap or overall costs, operations and management, and product management and systems engineering (PM & SE). The total estimated project cost amounts to eleven billion dollars.

Figure 1 illustrates the cash flow for the first 20 years of the project, starting in 2019. Naturally, until the execution of the first servicing mission, the cash flow will be negative due to the costs of development and manufacturing the vehicle systems, as well as management costs and other expenses such as astronaut training. From year 2031 on, the debts column

Table 1: Total cost budget of the mission according to the top-down approach

Cost component	**Cost [M$ FY 2019]**	**Percentages [%]**
DDT&E and production	2181	21
Wrap costs	2155	21
Operations (10 years)	5299	50
PM & SE	963	9
Total	10598	100

diminishes due to the payments received from customers for servicing satellites. With these calculations, the break-even point of the project will be reached in 2037, generating a total profit of approximately $1.8 billion 20 years after the start of the project.

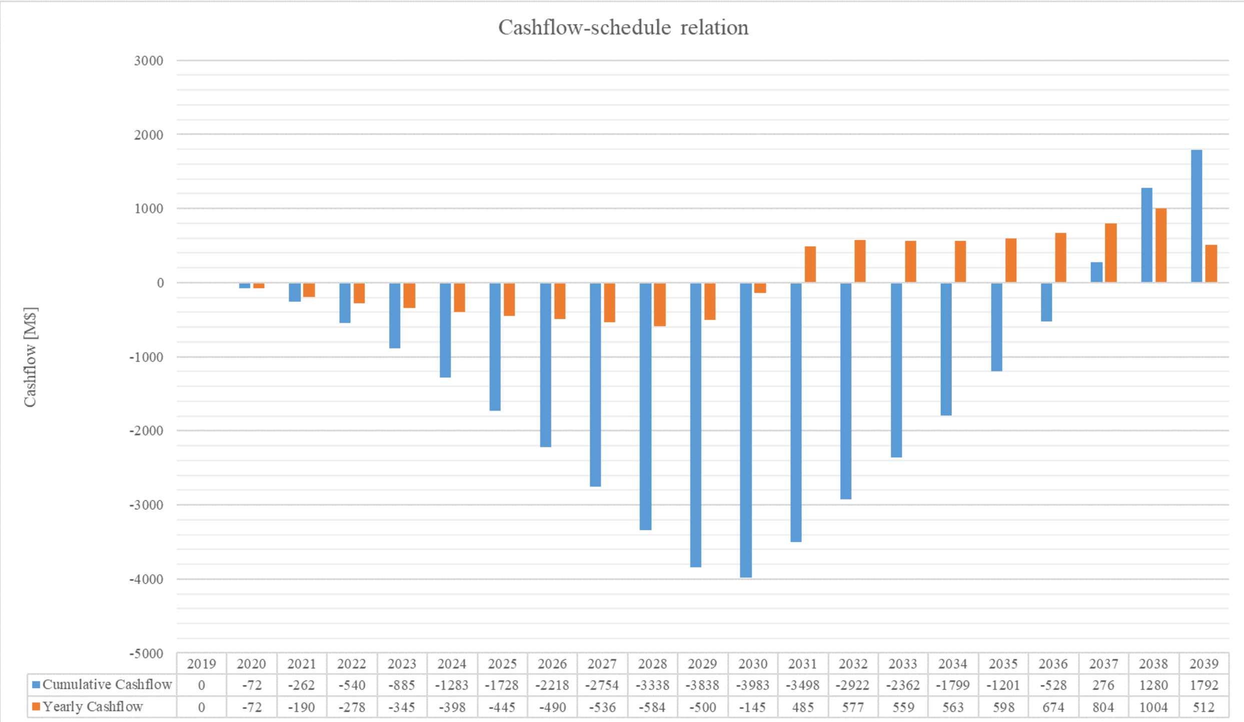

Figure 1: Yearly and accumulated cash flow diagram.

2.2 Overall mass budget

Table 2 gives an overview of the masses to be launched in three categories. First, the facility construction column summarizes the masses in metric tons required to build the station, including structural mass, power systems, thermal control, life support systems (LSS), storage space, etc., as well as the retriever. The second column shows the upmass required for each crewed launch, including the full extent of the Orion Multipurpose Crew Vehicle (MPCV), as well as the consumables and the astronauts' own mass. This mass needs only to reach low Earth orbit (LEO), since the Orion carries enough fuel and thrust capability to reach GEO on its own. Lastly, the operations column displays expected yearly requirements for servicing the client satellites.

Table 2: Overview of mass budgets (in metric tons) related to Station facility, Crew and Operations.

Facility Construction	mass	**Crew**	mass	**Operations**	mass
Station structure (excl. LSS)	31	Orion MPCV	30	Retriever Fuel	1.2
Station LSS	3	Human Needs	1.2	Fuel (MMH/N_2O_4)	3.5
Escape Capsule	9.4	Astronauts	0.32	Fuel (Xenon)	0.73
Retriever	0.5			Tools	0.12
				Solar Arrays	0.8
				Other Upgrades	0.3
Total	**43.9**	**Total**	**31.5**	**Total**	**6.7**

Notably, the masses of MMH/N_2O_4 and xenon are as required to refuel 7 satellites, as is the expected yearly demand. In all likelihood older satellites will use the former fuel (which is used in chemical propulsion), but more modern craft usually use electric propulsion, for which Xenon is an efficient and lightweight fuel. As the mission timeline progresses and services are contracted, better estimations can be made as to how much mass of each fuel is actually required.

The operations column also shows the yearly mass of tools and spare parts. An assumption here is that each refueled satellite will also need to have its solar arrays exchanged—typically, the arrays degrade over time, and while this is taken into account for the twelve years of expected lifetime, it is unlikely that they would last for twice that period. Other upgrades involve exchanging antennas or other parts for newer technologies.

3 Space law and political aspects

In order to perform an appropriate analysis for HeRMeS, it is appropriate to consider the politics and legal issues involved with handling and servicing satellites in orbit. Therefore, this section presents an overview of space law and of the most relevant political aspects related to the mission.

3.1 Outer Space Treaty

The Outer Space Treaty is an international agreement first signed in 1967 between the three main world powers at the time: the Russian Federation, the United Kingdom and the United States of America [4]. It provides the basic framework on international space law, and thus needs to be addressed before, during and after the project. The following principles from the treaty are relevant:

- the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind.
- outer space shall be free for exploration and use by all states.
- astronauts shall be regarded as the envoys of mankind.
- states shall be responsible for national space activities; whether carried out by governmental or non-governmental entities.
- states shall be liable for damage caused by their space objects.

3.2 Procedure before the launch

According to the United Nations Office for Outer Space Affairs (UNOOSA), whenever an object is to be launched into space the launching State shall register the space object by means of an entry in an appropriate registry which it shall maintain [5]. Each launching State shall inform the Secretary General of the United Nations of the establishment of such a registry. Each State of registry shall furnish to the Secretary-General of the United Nations, as soon as practicable, the following information concerning each space object carried on its registry:

- Name of launching State or States;
- An appropriate design of the space object or its registration number.
- Date and territory or location of launch.
- Orbital Parameters: Nodal period, Inclination, Apogee, Perigee.
- General function of the space object.

Each state of registry shall notify the Secretary-General of the United Nations, to the greatest extent feasible and as soon as practicable, of space objects concerning which it has previously transmitted information, and which have been but no longer are in Earth orbit.

The International Telecommunication Union (ITU) is an agency of the United Nations responsible for issues concerning information and communication technologies, including electromagnetic band allocations. The ITU ensures equitable access and efficiency in space technology related with information and telecommunication. Before initiating any action with respect to frequency assignments for a satellite network or system, an administration shall send the agency a general description of the network or system for advance publication in the International Frequency Information Circular no earlier than seven years and preferably no later than two years before the planned date of commencing utilization of the network or system [6].

3.3 Political aspects

As space may be considered a global resource, it is important to account for the political issues that may arise with its exploitation, especially related to this mission's purposes. In particular, the growth of services related to telecommunications, broadcasting and meteorology may cause some undesired political conflicts. For example, satellites orbiting above Earth owned by certain nations may accidentally (or otherwise) send restricted signals into other nations' territories, which may in turn desire to limit the information and communication access within them. This remains a global issue, and thus needs to be further discussed and addressed by the ITU and the Assembly of United Nations.

Another issue is that of flagging and each nation's regulations for space utilization, such as relating to human safety concerns. Each country retains jurisdiction and is responsible over its governmental and non-governmental spacecraft [8]. Private companies in space industry are growing quickly, and as a consequence each country will have to decide the level of regulation they want to impose. Accordingly, some states may decide to have less strict regimes regarding taxes and other operational costs in order to attract large private companies. This problem, known as "flag of convenience," may encourage space companies to be legally registered where they can enjoy these economic advantages and have fewer restrictions in term of law and regulations. Moreover, private companies might take advantage of the situation by allowing more safety hazards with respect to passengers and other space objects than would otherwise be acceptable.

4 Funding and economic aspects

After having set the regulatory framework, we introduce the economic aspects of the project, illustrating the funding strategy before introducing and reasoning the selected company structure. Finally, other relevant economic drivers are stated to ensure a complete analysis.

4.1 Company funding

Concerning the enormous financial volume and technological innovations, this project is a high risk, high revenue venture. The investors and partners need to be carefully selected and very reliable. The logical first step would be to start searching for governments or governmental organizations to support the development process, as they can provide the required means to deal with the risks in the long term. Naturally, the most suitable partner would be a space agency that has a common interest and is therefore willing to cooperate from the very start of the project. This partner can be found in the European Space Agency (ESA) since one of the aims is "to strengthen the competitiveness of European and Canadian industry in the global markets for satellite communications," as stated in the ESA Annual Report of 2016 [12]. This report also mentions public-private partnerships (PPP) between ESA and companies that "bring innovative products and systems into the marketplace" [13]. [14] provides more detailed information about the collaboration within the scope of the ARTES 33 program. ESA covers up to 50% of the eligible costs, that are related to "innovative Space and Ground Segment technology" or occur in the "early routine operation phase for testing and validation of function and performances" [14].

At this early stage in the project it is fundamental to look for other possible investors. One interesting financial services company that might we willing to invest in such a high risk project is the "Space Angels." They are internationally respected experts in the early phase investment of space ventures and are therefore perfectly suited to support this ambitious project in the first stage. This is usually only possible in exchange of equity stakes but also provides a useful network within space industry.

4.2 Company structure

The main constraint for the company structure is that it has to be registered in a country that is a member state of ESA since the aim is to have a PPP contract between the company and the agency. Taking into account the fact that the main customers, in this case big telecommunication operators Eutelsat or SES S.A. Holding, have their headquarters in Paris and Luxembourg, respectively, it would be advantageous to be located close to them. Additionally, ESA's headquarters are in Paris as well, which strengthens the choice of Paris as founding location of the company in order to keep the administrative work down.

Assuming that the main corporations will still be dominating the market in the year 2030 and beyond, it would be also necessary to keep close contact with companies from the US-market like Intelsat, and therefore have a second office set up in Washington D.C. Having representatives from the same country might be beneficial for negotiations with NASA or SpaceX as the spacecraft and the launch vehicle are acquired from these organizations.

4.3 Further economic drivers

Other key factors that have an impact on the business plan are insurance and future development strategies. Considering the first aspect, there are insurance plans that should be taken out in every phase of the project. Since there are no reliable sources on these kind of insurances available, it was necessary to roughly estimate the insurance rates. These are namely:

- Transit and pre-launch insurance (0.5 % of space station cost)
- Launch and place into orbit insurance (10 % of launch costs)
- Property insurance (loss of space station; 4 % of space station costs)
- Product liability insurance (in-orbit phase; 8 % of satellite value per service)
- Workers' compensation insurance (illness or death; 5 % of astronauts' salaries)

More advanced aspects to explore are expanding the business to conducting research on the space station by order of space agencies like ESA or NASA. In this case, the nearby location to these potential clients confirms the choice of the office locations.

4.4 Off-nominal opportunities

The off-nominal cases considered from the management perspective are to potentially expand our business model by including more services, which helps increase HeRMeS' market value and eliminates competition. The three most feasible and profitable options for additional services are salvaging, research, and CubeSat launching.

A large portion of the satellites in geostationary and geosynchronous orbit are transferred into the graveyard orbit, located a few hundred kilometers above, when they approach the end of their operation life. Though the decommissioned satellites are no longer functional, their components could potentially be salvaged. The U.S. Defense Advanced Research Project Agency (DARPA) has an ongoing project to develop a spacecraft equipped with dexterous robotic arms to salvage reusable parts in communication satellites [9]. With the technology soon to be available, HeRMeS could expand its business model by providing salvaging services in the graveyard orbit. Nevertheless, because of many retired satellites' foreign ownership, there is a gray area that such a satellite salvaging service would need to carefully navigate. No current space regulation forbids debris removal or salvaging and determining where exactly to obtain permission is complex.

Other than on-orbit servicing, HeRMes could also conduct space radiation and collision likelihood research in GEO. Active semiconductor components in satellites are sensitive to accumulated space radiation doses. To prolong the lifetime of an active satellite, space radiation dose research is essential. The research uses radiation-sensitive field-effect transistors (RADFETs) as sensors and is typically carried out over a long period of time to ensure accuracy, necessary due to the dynamic nature of the electron and proton fluxes from space radiation [10]. Therefore, RADFETs could be implemented into the space station for long term radiation research. Collision likelihood research is also vital to ensuring the lifetime of GEO satellites and the operation of active GEO spacecrafts [11]. There are currently between 1 036 – 3 060 tracked debris fragments greater than 10 cm, and 35 500 – 158 000 fragments greater than 1 cm. Statistic analysis results indicate that a collision is likely to occur every 4 years for one GEO satellite against a 1 cm debris, and every 50 years against a 20 cm debris. In addition to performing collision likelihood analysis, collision shielding technology and collision avoidance maneuver could be demonstrated on HeRMeS space station.

5 Motivation for human involvement

It is undeniable that sending humans to space is a great challenge, an expensive endeavour, one that would have been hard to fund even had Columbus discovered the riches of Atlantis. The difficulty of developing appropriate life support systems and human-rated space vehicles adds much to the cost, such that many argue that space exploration should be mostly automated and robotized. Indeed, robots are cheaper to build and implement, and require less complex structures to support them. Utilizing them for space operations instead of humans removes the risk to life from space-related accidents. Moreover, the recent trend of technological advances hint that robots should be capable of providing at least some of the services proposed in this mission.

If this becomes a reality by the time this project is to take place, it might seem nonsensical to go through all the trouble of designing a safe and productive yet costly environment for human activities. Accordingly, we present here some arguments to justify human involvement in space activities, including some general remarks as well as reasons why the HeRMeS project particularly benefits from it.

5.1 Human spaceflight

Technology development: space habitats & industry

Within the context of this type of mission and current project proposals such as the European GEOFarm, NASA's lunar Gateway, and even asteroid mining proposals, one can see a trend in space activities leaning towards space habitats and industry. In order to achieve these goals, more investment of time and resources is necessary to develop the required technology, and commercial enterprises such as HeRMeS represent a good framework to secure funding for development. Designing and testing human-rated space habitats in GEO provides a stepping stone for future, further exploration.

Research & exploration

While orbiters, rovers and probes can provide us a wealth of data from far-off worlds, they are limited to performing reconnaissance. Particularly considering the time delay involved with communicating with any planet or satellite farther than the Moon, robotized exploration suites need to either have their activities and protocols pre-programmed, or be extremely inefficient, as they need to wait for commands.

Humans, on the other hand, are better suited for proper field studies. The main difference between an experienced scientist and an automated rover as we know them is the ability to contextualize, be it their surroundings or the results of a given experiment. A well-trained geologist standing in a Martian gorge can have a quick overview of the landscape and draw conclusions from it, which then allow him or her to pick the best candidate rocks for study—in contrast, Curiosity can only drill into the ground and hope for the best.

In a similar fashion, humans are capable of making snap decisions and react to unforeseen situations, which makes them a valuable resource as overseers of industrial and repair operations. We are particularly well suited to handle sensitive or fragile equipment, which robots might be unable to manipulate delicately.

International and commercial cooperation

Since the historic end of the space race with the Apollo-Soyuz Test Project in 1975, international cooperation has been the norm for space activities. It led to a warming of relations between the two major world powers at the time, and to this day ISS-related activities serve as a means of contact and exchange between scientists and engineers around the world, which enriches the diversity of thought and allows for parallel development of science.

In addition, the recent rise of companies (both private and governmental) such as SpaceX, Thales Alenia and Arianespace show that there is plenty of room for commercial partnerships. Fostering relations between these companies as well as national agencies encourages competition and thus minimization of costs. In the current global economic system, this is the proven way to accomplish goals as ambitious as human spaceflight. In particular, providers of telecommunications with satellites in geostationary orbit will be keen to participate in the HeRMeS project, as they would be the main beneficiaries of our services.

Inspiration

Ultimately, the drive to explore is inherent to humanity. Even though robotized explorers such as Curiosity and New Horizons inspire adults and children alike (as seen by the many comics circulating the Internet), Neil Armstrong's legendary words and Chris Hadfield's witty cover of Space Oddity seem more tangible and approachable. They encourage people to become scientists and engineers, to discover what's out there. Citing Shelhamer [17],

> Human space flight might be dismissed as a meaningless and absurd romantic notion. But then so, to many people, is trying to identify the structure of the universe and its genesis. The selection by scientists of an area in which to perform their research is not as dispassionate as many would have us believe. What drives them to investigate one thing versus another is often hard to explain, and it is likely that most scientists are driven by the pure interest and joy of discovery than by any explicit cost-benefit analysis, and in this sense as well the biology of space flight is an interesting and valid scientific pursuit.

It can't be denied that exploration is a potential wellspring of knowledge. Putting humans in space wakes enthusiasm, and stimulates imagination and innovation to continue solving engineering problems. All in all, human spaceflight is a force that drives the future of research and humankind.

HeRMeS

As a service-oriented mission, HeRMeS reaches beyond research, setting a precedent for commercial activities in space. In order to provide the reliability and security that our services require, it is imperative that humans be involved in the project, at the very least during the early stages. There is certainly room for later development and automation, but any sort of complex assembly will likely necessitate human supervision. In the meantime, its focus on human activities will serve to open a global market and motivate new generations of engineers to further engage in space exploration

6 Conclusion

This feasibility study yields the conclusion that it is possible to construct a successful business model for human servicing and repair missions to geostationary satellites. Current aerospace technology as well as future projects in development guarantee technological feasibility to enable our satellite services in geostationary orbit. Growing demand for services and repairs and a soon possible future for entirely robotized missions grant a more than sufficient economic drive for the HeRMeS project to become a profitable reality. The funding required for HeRMeS is massive, but attainable. The estimated 10.6 billion needed to fund our initial missions would have a relatively slow time of profit return. It is predicted to break even in 2037 and receive profit amounting to 1.8 billion by 2057. HeRMeS will focus on both private and government funded projects at its intial stage. As satellite servicing becomes more stable, the company model is expected to expand into research and satellite launching business, and even assembly of larger structures as the in-orbit market grows.

This report shows that the challenges in GEO satellite servicing are entirely possible to overcome, and that having a GEO space station is an achievable future. The HeRMeS project is ambitious and ground-breaking. Should it be carried out to completion, it will become the pioneer in satellite servicing in geostationary orbit.

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Appendices

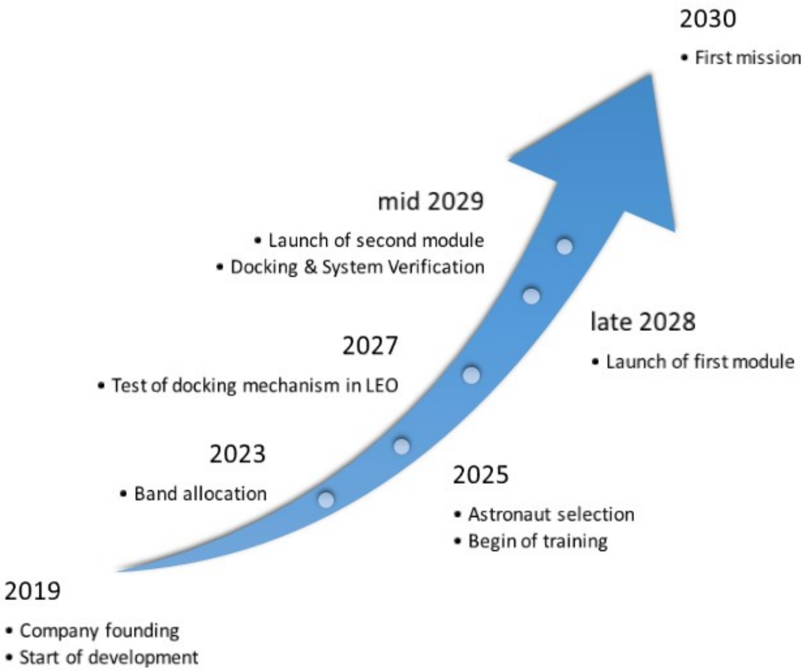

Figure 2: Mission timeline from 2019 to 2030