Asteroid Mining
Overall Coordination Report
Red Team

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***Abstract*—Interplanetary space is still little explored but is known to be very rich in natural resources. The depletion of resources on Earth and the acceleration of human colonization could make the exploitation of space resources interesting. A mission to return minerals from an asteroid may be envisaged in the near future. The objective of this project is to study a concept for a resource mining mission to a near-Earth asteroid. The scope of this study is conceptual and focuses on the identification of the means required to carry out such a mission. This paper, which constitutes a part of the complete study, briefly introduces asteroid mining, its context, and worth, followed by a short overview of the mission description, which includes the objectives, assumptions and requirements. Next, a preliminary communication strategy is discussed, followed by estimation for the mission cost, a brief idea of the funding resources, the economy and legal aspect of asteroid mining, and finally, the project management architecture has been presented.**

***Index Terms*—Space, exploration, mining, minerals, asteroid, business**

I. Introduction

The demand for Earth's natural resources is only increasing with the growing population and the development of new technologies that require high-performance materials. Access to these resources is not yet compromised but could be in the next decades [1]. Some are already beginning to turn their eyes to space to find resources that might soon be nowhere to be found —or simply profitable to sell —back on Earth [2] [3]. Resources like water or metals are also looked at because harvesting them from space could be easier than sending them in space from Earth. Indeed, many celestial bodies populate our solar system and constitute an important reservoir of untapped materials. Space resources can replace terrestrial resources and can also facilitate space exploration by reducing current limitations on sending materials into space. The Moon is the most obvious target for this, but there is also a large number of asteroids relatively close to the Earth. Nearby asteroids have a negligible field of gravity, making them easier to approach and escape.

This study explores the exploitation of an asteroid to harvest and sell the natural resources found there. The target is asteroid *469219 Kamo'oalewa* which is a quasi-satellite of the Earth. Its orbit is stable and its distance from the Earth varies between 40 times and 100 times the Earth-Moon distance. The scope of this study is limited to a conceptual design of a mission to the target, to make a profit by selling the mined resources. The use of a crew is planned for the installation of the necessary machinery on site. The mission must be ready to be launched before the year 2030.

Members of the Red Team worked collaboratively on this study. The work was divided into four sub-sections, carried out by four sub-groups of the team.

A first sub-group, called *Logistics*, worked on the planning aspects of operations, in particular asteroid operations. They identified the resources of interest present on-site and produced a concept for a mining station to extract and purify these resources [4].

A second sub-group, called *Human Aspect*, looked at the constraints associated with the presence of a crew. They identified the necessary systems on-board the spacecraft and took care to take into account possible failures that may occur during the mission to ensure the survival of the crew [5].

A third sub-group, called *Space Vehicle*, was responsible for the design of the spaceships needed to carry out the mission. They determined the trajectories, launch windows, and propulsion system of the spacecraft. Atmospheric re-entry and on-board power generation were also studied [6].

A fourth group, called *Overall Coordination*, worked on the general aspects of the mission. They also ensured that the other groups progressed well and checked the inter-compatibility of the designs during the development of the concept and resolved conflicts between different solutions.

This report addresses the work of the *Overall Coordination* sub-group. Reference is made to the work of the other sub-groups where appropriate.

II. Context

A. Asteroid mining: why ? what ?

Asteroid mining can be an advantage for mankind in many ways. It can supply resources for life on Earth as well as for the development of future in-orbit or interplanetary infrastructure. Further knowledge can be gained about bodies which may be on a collision course with planet Earth. There are two main types of asteroids. Ones that are rich in water, called chondrites and ones that are rich in precious metals, called achondrites [7].

Water is a key aspect when it comes to spaceflight. First of all humans in space need it to drink, prepare food and for hygiene. Thus it would be convenient for example on the lunar gateway or space hotels, which are in various stages of development [7], to have water close such that it is not necessary to bring it from Earth. Besides the human needs in water, it can also be used as a propellant. Electrolysing water produces hydrogen and oxygen. Low orbit fuel stations can provide fuel for spacecraft targeting deep space missions meaning that they do not have the need anymore to bring all their fuel from Earth and with that saving a lot of mass at launch.

Solid resources from asteroids that are useful for humans are silicate minerals and platinum group metals [8]. Silicon can be processed from silicate minerals, which are needed in semiconductor applications. Those are the heart of all electronic devices and always needed nowadays. Platinum group metals are very good catalysts and therefore an important component of fuel cells which are currently of high interest for example in the automotive industry in terms of CO_2 reduction.

The advantage to use resources from asteroids for infrastructure in space is obvious: They don't have to be launched from Earth which is energy intensive and costly. When it comes to precious metals on planets, they are located deep towards the center and therefore hard to reach [7]. Some achondrites have been formed from colliding planets, bringing the material closer to the surface. A second benefit is that asteroids are very rich in precious metals compared to mines on Earth. Some estimates put the concentration of precious metals on asteroids up to 20 times higher than in mines on Earth [8].

Besides getting resources from asteroids, the knowledge one can get out of asteroid mining missions is tremendous. As many such bodies can be on a collision course with Earth, it is important to study their composition in order to plan deflection missions which gives us the ability to protect our planet.

III. Mission description

The general description of the mission was defined in collaboration with the other sub-groups involved and then refined to arrive at a precise scope. This description was updated as the other sub-groups progressed with their designs. The mission design is limited to space segments and in-situ mining operations. Launch elements are selected from those available on the market today or are assumed to exist before 2030.

A. Mission objectives

The mission is structured around two primary objectives :

1) Establish a mining station on the asteroid with the help of a human crew
2) Bring extracted material from the asteroid back to Earth for selling

Materials that could be sold in space but whose return to Earth is not profitable are excluded from the study. Elements designed for this mission are assumed to be used only for this mission. The possible use of the same elements for a second mission to another target is not considered here.

A secondary objective has also been identified for the studied mission :

1) Extract water from the asteroid for propellant production or to support mining operations

This would reduce costs and increase the carrying capacity of spacecraft travelling back and forth between the Earth and the asteroid. The crew does not rely on propellant produced in-situ for their return to Earth. Non-crewed vehicles use this extra propellant for their return to Earth.

B. Assumptions

The target is assumed to rotate at a rate low enough to allow a spacecraft to attach to it automatically and safely. The day-night cycle caused by this rotation is considered in the design. The loss of line of sight for communication between the asteroid's surface and the Earth is also considered.

The launchers currently on the market are supposed to still be available around the 2030s. An equivalent launcher with a similar cost is assumed to be available otherwise.

The assembly of part of the mining equipment is supposed to require the presence of a crew carrying out extra-vehicular activities.

In-orbit refueling of cryogenic fuel is assumed to be commonplace in the 2030s.

C. Requirements

The mission must meet a set of requirements. These requirements have been defined and refined in collaboration with the sub-groups involved in the project.

1) Functional requirements:

- *The mining equipment shall be safely bound to the surface or interior of the asteroid*. To avoid losing equipment in space and avoid creating hazardous conditions around the asteroid
- *The mining process shall ensure that no material from the asteroid is ejected into space*. To avoid creating hazardous conditions around the asteroid
- *The equipment on the asteroid shall include a docking interface for crew and cargo vehicles*. To facilitate approach and anchoring and reduce the risk of failed tethering to the asteroid.
- *A communication link shall be operational at all times between Earth and the crew vehicle*. To receive ground support in case of onboard failure
- *A communication link shall be operational at all times between Earth and the mining station*. To communicate with the crew during asteroid operations

2) Operational requirements:

- *A human crew should assemble the mining equipment on site*
- *The human crew should stay on the asteroid at least 100 days*. To assemble the mining equipment, this duration is the result of a trade-off between a trajectory analysis and the logistics needs
- *The mining station should tether itself without the help of an in-situ crew*. To be able to launch the mining station independently of the crew

3) Constraints:

- *The mission shall be ready to fly before the year 2030*
- *The mission should be profitable*
- *The crew mission time shall be below 300 days*. To limit radiation effects and life consumables mass
- *The crew shall rely only on their vehicle for their safety*. Rescue missions cannot be easily planned and the number of launch windows is limited.

D. Mission elements

Multiple vehicles are used at different moments in the mission. Each vehicle is designed for a specific purpose.

1) Mining station: The mining station is at the heart of the mission. It serves as a vehicle to transport all mining equipment from Earth to *469219 Kamoʻoalewa*. All the necessary mining equipment is contained inside the mining station during the transit. The mining equipment includes all machinery needed to actually mine the asteroid and gather valuable material as well as the refinement machines used to purify the extracted material and keep only the most valuable parts of it.

At the asteroid, the mining station is emptied of the mining equipment and serves as a docking interface for the crew vehicle and the cargo vehicles. The mining station stays at the asteroid.

2) Crew vehicle: The crew vehicle is used to transport the crew to the asteroid and back to Earth. It is sized for a crew of 3 and a main mission duration of 304 days. Everything needed to keep the crew safe and healthy (life support systems, backup systems, consumables) is included in the crew vehicle.

An airlock is mounted on the crew vehicle and is used by the crew to perform Extra-Vehicular Activities on the asteroid.

3) Cargo vehicle: The cargo vehicles bring the mined and refined material back to Earth. Two identical vehicles are used to return all the mined material to Earth. Each cargo vehicle has a payload capacity of 50×10^3 kg.

E. Mission profile

The mission is broken down into several phases. Each phase involves different technologies. The phases are sequential. Although a phase may begin (e.g. launch from Earth) before the previous one is completed, the cores of each phase are not active simultaneously.

The three phases identified for the mission are: transporting the necessary mining equipment to the asteroid (referred to as Phase I); assembling the mining equipment on the asteroid with the help of a human crew (referred to as Phase II); automatic mining operations and returning of the materials to Earth (referred to as Phase III). The three main mission phases are summarized in Appendix A (Figure 2).

A preliminary phase, referred to as Phase 0, is assumed to have already been carried out before the design of the mission in question in this study. It is a reconnaissance flyby of the target with a small probe. The data acquired by this probe include accurate measurement of the shape; dimensions and mass of the target; a characterization of its surface; details of the elements present in the asteroid and their abundance. The mission design is made from the results of this hypothetical mission.

The mission is fully completed in 7 years from the first launch to the collection of all mined material on Earth. Phase I is the longest phase due to the low thrust transfer. Phase II is the shortest. The mission timeline is shown in Figure 1.

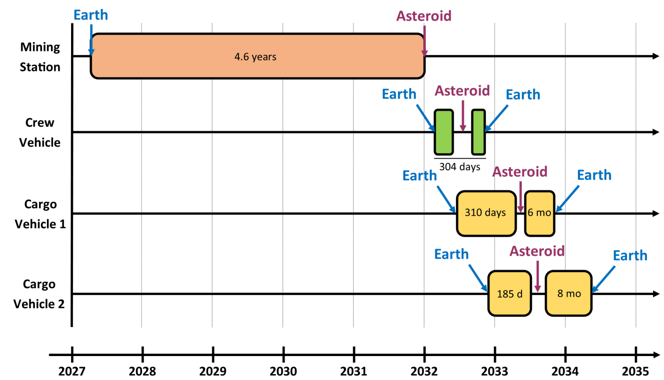

Figure 1. Mission timeline. Phase I is about moving the mining station from Earth to the asteroid. Phase II is the assembly of the mining equipment by the crew. Phase III is the mining of the asteroid and the return of mined material to Earth with the cargo vehicles

1) Phase I: The first phase consists in sending all the equipment necessary for the mining operation to the target asteroid. All the equipment is contained in a single ship.

The mining station is first launched with a *Falcon Heavy* launcher (*Space X*) into Low Earth Orbit. A second launch is operated, using a *Falcon 9* (*Space X*). This launcher brings extra propellant to the mining station. The refueling vehicle is not designed in this study. It is assumed that such vehicles are commonly used in the 2030s. Once the mining station is refueled, the onboard propulsion system brings it to *469219 Kamoʻoalewa*. The transfer starts on 2027-04-12 and lasts 4.6 years [6].

The mining station reaches the asteroid on 2031-12-31 and tethers automatically to its surface [4]. Antennas are automatically dispatched on the surface of the asteroid to make sure at least one of them has a line of sight to Earth. This ensures that the crew can always communicate with Earth when the crew vehicle is docked to the mining station.

2) Phase II: Phase II starts after the mining station is securely tethered to the asteroid. It is the manned phase and is the heart of the mission.

A strategy similar to the one used to launch the mining station is used. The crew is sent into orbit aboard the crew vehicle with a *Falcon Heavy* (*Space X*) and then the crew vehicle is refuelled in orbit by a *Falcon 9* (*Space X*) [6].

The crew vehicle then departs from Earth on 2032-01-09 and heads to the target. The transfer lasts 120 days. After docking the crew vehicle to the mining station, the crew assists the assembly of the mining equipment and the beginning of the mining operations [4]. The stay time on the asteroid is 120 days and cannot be shortened. If for some reason the crew cannot leave the asteroid during the departure window, they can use a backup launch window a month later. Redundancy on-board the crew vehicle is sized for this eventuality [5].

The return to Earth takes 80 days. The crew vehicle performs a reentry in Earth's atmosphere and lands on the ground on 2032-11-08 in a desert in the United States (Utah).

The total mission duration for the crew is 304 days. The delay between the launch from the ground and departure from Earth is neglected.

3) Phase III: Phase III starts before the end of phase II. The first cargo vehicle is launched from Earth before the mining station is fully assembled. The cargo vehicles are launched with a *Falcon 9* launcher (*Space X*). There is no in-orbit refueling.

The first cargo vehicle leaves Earth on 2032-06-06 and cruises for 310 days to the asteroid. It docks to the mining station and stays there for 30 days to be filled with mined material. The return to Earth takes 6 months.

The second cargo vehicle leaves Earth on 2032-11-28 and cruises for 185 days to the asteroid. It docks to the mining station and stays there for 100 days to be filled with mined material. The return to Earth takes 8 months.

Both cargo vehicles are separated into two parts before reentry to lower the thermal constraints [6] and then land on the ground.

F. Mining process

The mining process used on the asteroid is similar to that used on Earth. A main shaft is dug in the direction of the length of the asteroid. Once this shaft is completed, smaller galleries are dug perpendicular to it. The transition between these two operations is done while the crew is on site. Mining operations continue autonomously after the crew has departed the asteroid.

The excavated material is safely stored on the surface of the asteroid to avoid spreading particles around the asteroid. This material is refined using the machinery in the mining station and the purified minerals are stored near the mining station and transferred to cargo spacecraft when they are docked to the mining station [4].

IV. Communication strategy

The communication strategy between the Earth and the different space vehicle during all phases of the mission is briefly discussed in this section. It is to be noted that for the link budget calculations, approximate figures have been considered. Also, details regarding the communication hardware is not covered in this study. An estimation to present briefly the idea for the communication system has been discussed.

A. Architecture

A *communication architecture* is the arrangement or configuration of satellites and ground stations, in a space system for transfer of information between them [9].

In order to specify the communication architecture, the first step is to define the mission objectives and requirements. For the asteroid mining mission, an important requirement with respect to communication link is that the crew should be able to communicate with Earth under all situations. Video communication would be preferred. Also, the mining station and the cargo vehicle should be able to continuously share its telemetry and housekeeping data.

1) Data Rate: Having answered the essential question regarding what information needs to transferred over the communication link, a preliminary decision on the data rate can be reached. Video transmission usually requires a data rate of 10s of Mbps [10]. For the calculations of the link budgets, a data rate of $10\ \mathrm{Mbps}$ has been considered for the communication link of the crew vehicle. The data rate for the housekeeping and telemetry has been taken as $8000\ \mathrm{bps}$ (approximates obtained from [10]). For all the communication links, a Bit Error Rate (BER) of about 10^{-5} has been targeted so that reliable communication is achieved [10]. In order to minimize the E_b/N_o ratio, a concatenated convolution, and Reed Solomon modulation scheme has been considered for the data transfer.

2) Frequency Bands: In order to achieve the desired data rate for the crew vehicle, a high-frequency transmission band will be required, given the fact that the transmission distance would range between $14 \times 10^6\,\mathrm{km}$ to $40 \times 10^6\,\mathrm{km}$. Therefore, the crew vehicle would communicate in the Ka frequency band. This will not only ensure high bandwidth but also support beyond line of sight requirements [11]. Since the housekeeping and telemetry requires a much lower data rate, communication in X band would suffice for the mining and cargo vehicle. Lower frequencies for this have been ruled out, due to the high transmission distance.

For the link budget calculations, approximate figures for the frequencies in Ka and X band have been considered. The exact value would be decided through the approval of the International Telecommunications Union (ITU).

3) Link Design: Keeping in mind the above requirements, a rough downlink budget has been designed with the below data.

Transmission Distance: $3.5 \times 10^{10}\,\mathrm{m}$

Frequency: $1.8 \times 10^{10}\,\mathrm{Hz}$ (Ka-downlink), $8.4 \times 10^9\,\mathrm{Hz}$ (X-downlink) [11]

Data rate: $10\,\mathrm{Mbps}$ (video), $8000\,\mathrm{bps}$ (telemetry and housekeeping)

Ground Station gain: $74.16\,\mathrm{dB}$ (See Section IV-B2)

Tx Antenna efficiency: 0.7 (assumed)

T_s (Noise temp): $338\,\mathrm{K}$ (assumed)

Other losses: $3\,\mathrm{dB}$ (approx. [10])

Minimum E_b/N_o: $2.4\,\mathrm{dB}$ (for the required BER, with the given modulation scheme, see Appendix B, Figure 3)

Link Margin: $3\,\mathrm{dB}$ (considered)

With the above parameters, the link is designed and the antenna diameters and transmission power is obtained as shown in Table I. The first column regarding the different types of antenna is explained in detail in Section IV-B1.

Table I
Antenna Characteristics

Antenna	Frequency Band	Diameter [m]	Tx Power [W]
HGA	Ka	3	100
MGA	X	0.25	30
LGA	X	0.10	15

B. Antenna & ground segment choice

1) Antenna: Three types of antenna has been proposed for the mission.

- High Gain Antenna (HGA): 1 HGA of Cassegrain type as the primary communication antenna with Earth. The HGA on the crew vehicle would be communicating in the Ka band and on the others in the X band.
- Medium Gain Antenna (MGA): 2 MGAs, either Horn or Patch, to be used in the safe mode as a fallback option, in case the HGA is not available. They would be communicating in the X band.
- Low Gain Antenna (LGA): 3 dipole antennas to be used as an LGA in case of emergencies. Since the LGA would be transmitting in a broad beam, it would still be able to communicate with the Earth, in case the spacecraft fails to point itself or for any other such emergencies. They would be communicating in the X band.

2) Ground Segment Choice: In order to communicate over video (high data rate) with the asteroid (high transmission distance), powerful ground stations would be required. Keeping in mind this requirement, the use of European Space Agency (ESA)'s European Space Tracking (ESTRACK) network has been proposed.

Further information on the chosen ground station facilities is shown in Table II. The ground stations are chosen in such a manner that they are 120° apart around the Earth, thus ensuring constant sky coverage. Also, National Aeronautics and Space Administration (NASA)'s Deep Space Network(DSN) and Swedish Space Corporation (SSC)'s Satellite Ground Network services have been suggested as alternate/back-up options. Another option which has been briefly discussed is to own ground stations to be used for this mission solely. Since, constant contact might be an issue if a shared service is used, having dedicated ground stations for this mission could be an option that can be explored.

Table II
PROPOSED GROUND STATIONS AND THEIR FACILITIES. [12]

Station	Cebreros	Malargue	New Norcia
Country	Spain	Argentina	Australia
Diameter [m]	35	35	35
Efficiency	0.6	0.6	0.6
Gain [dB]	74.16	74.16	74.16
Tx Power [dBW]	40	40	40

V. ECONOMICAL & POLITICAL ASPECT

A. Asteroid value estimation

According to the current observational data, the asteroid *469219 Kamo'oalewa* has been classified as an S-type asteroid which is a sub-group of achondrites. It has a mean diameter of $41\,\mathrm{m}$ [13]. As small asteroids are rarely spherical, the calculations were based on the asteroid being in a cylindrical shape with a length of $50\,\mathrm{m}$ and a $30\,\mathrm{m}$ diameter. Furthermore, the data from asteroid surveys suggest that the density of S-type asteroids is between 2 to 3 $\mathrm{t/m^3}$ [14].

Based on these data points, the following assumptions were made regarding the composition of the asteroid:

- 10% of the asteroid's total volume consists of Nickel-iron group metals, of which 75% is iron, 20% is nickel and 5% is cobalt.
- 1% of the total volume consists of precious metals, of which 70% is gold, 5% is platinum and 25% is palladium.
- 89% of the total volume consists of rock and regolith.

The asteroid has a volume of $35.3 \times 10^3\,\mathrm{m}^3$, a mass of $97.8 \times 10^3\,\mathrm{t}$ and a density of $2.77\,\mathrm{t/m}^3$. Based on these assumptions and current market prices, there are $28.7 \times 10^3\,\mathrm{t}$ of Nickel-iron group metals on the asteroid worth $129M, and $6.2 \times 10^3\,\mathrm{t}$ of precious metals worth $335B. See Appendix C for a detailed breakdown of the calculations.

Because of the mass limit of the cargo vehicle and the shaft and tunnels mining method, only $434\,\mathrm{m}^3$ containing $1201\,\mathrm{t}$ of materials will be mined in this mission. This is roughly $1\,\%$ of the whole asteroid, and almost all of the monetary value resides in the $76\,\mathrm{t}$ of precious metals worth $4B. The $352\,\mathrm{t}$ of Nickel-iron group metals mined would only be worth $1.5M if they were brought back to Earth, which definitely would not be worth the effort. These metals could conceivably be used in space as building materials. In this case, on top of the market value, an additional value of $3000\,\$/\mathrm{t}$, which is the launch cost if the materials were launched from Earth, can be assigned to them. This would bring the value of the Nickel-iron group metals to about $1B, but they are still way less mass efficient to transport than the precious metals. This mission would therefore mainly be focused on bringing back the precious metals mined on the asteroid back to Earth.

B. Mission cost estimation

The cost of the mission mainly consists of three parts:

1) Design Development Test and Evaluation (DDT&E): This is the cost to design, develop and manufacture the spacecraft and mining equipment required for the mission. In order to arrive at a rough estimation of the costs, the Advanced Missions Cost Model (AMCM) developed by NASA was used [15]. This model is a top-down estimate based on past space missions. Different parameters can be adjusted in relation to similar hardware, and the mathematical formula will calculate an estimate. The AMCM formula for DDT&E cost in millions of dollars is:

$$\text{DDT\&E cost} = \alpha Q^{\beta} M^{\Xi} \delta^{S} \Sigma^{\frac{1}{(IOC-1900)}} B^{\phi} \gamma^{D}$$

The Greek letter constants are:
$\alpha = 9.51 \times 10^{-4}$
$\beta = 0.5941$
$\Xi = 0.6604$
$\delta = 80.599$
$\Sigma = 3.8085 \times 10^{-55}$
$\phi = -0.3553$
$\gamma = 1.5691$

The parameters are:

- *Q, Quantity* is the total number of units to be produced, this includes flight hardware and also ground-test articles. For each incremental increase of this number, the total cost will increase more slowly, resulting in decreasing per unit cost when the number increases.

- *M, Mass* is the dry mass of the system in kg. Similar to *Quantity*, with each incremental increase of the dry mass, the per unit mass cost decreases.
- *S, Specification* is a value that designates what type of mission is to be flown. This number reflects the general difficulty of the mission type, a higher number will result in a higher cost, and due to it being in the exponent, this number has a significant effect on the overall cost. See below for a selection of relevant *Specifications* and their values.

Crewed planetary lander	2.47
Crewed planetary	2.40
Crewed reentry	2.28
Lunar rover	2.15
Human habitat	2.14
Un-crewed reentry	1.92
Upper stage	2.08

- *IOC, Initial Operational Capability* is the system's first year of operations, the cost increases the later in the future it is accounting for the fact that cost of programs increases with time, although the difference is marginal compared to the other parameters.
- *B, Block* is the system's block number, it reflects the level of design inheritance and the maturity of the technology. For a brand new design, the block number is 1. If the system is based on an existing design, the block number may be 2 or more. For example, block 4 means it's the 4th iteration of an existing system. The cost decreases rapidly in the beginning from block 1 to block 5 reflecting the learning curve for a new design, but tapers off after block 10 as few improvements on cost can be made at that level of maturity.
- *D, Difficulty* is a number that assesses the technical difficulty and complexity compared to other missions of the same type. It ranges from -2.5 "extremely easy" to 2.5 "extremely difficult" in 0.5 increments, with 0 meaning "average". This assessment can be somewhat subjective and arbitrary. This number is also in the exponent and together with *Specification* are the two dominating factors in estimating the cost of the system.

See Appendix III for details on the parameters chosen for each system and the estimated DDT&E costs. Note that one additional unit for each system on top of the fight hardware has to be built for ground support and testing purposes. The mining equipment will be launched together with the mining station as its payload. But they serve very different purposes and the costs were estimated separately.

Table III
PARAMETERS AND ESTIMATED DDT&E COST FOR EACH SYSTEM.

Parameter	Mining Station	Mining Equipment	Human S/C	Cargo	costs in M$
Quantity (Q)	2	2	2	3	
Mass (M)	30 139	33 576	31 544	12 418	
Mission Type (S)	Upper stage	Lunar rover	Human habitat	Upper stage	
	2.08	2.15	2.14	2.08	
IOC	2027	2027	2032	2032	
Block (B)	3	10	3	4	
Difficulty (D)	Average	Low	Average	Low	
	0.0	-1.0	0.0	-1.0	DDT&E Total
Cost	3030	1838	4223	1282	10 373

The mining station is essentially a huge transport vehicle with the ability to rendezvous and tether itself to the asteroid and it doesn't have life support. The *Specification* of "Upper stage" was the best fit for this vehicle. It is also assumed that by the time of development of this vehicle, the lunar gateway or some equivalent would already be operational. The mining station would thus be the third iteration of a cargo spacecraft. The first being in low Earth orbit, the second being the lunar gateway. *Difficulty* was chosen to be the default "average". The main challenges are the sheer mass of the spacecraft and the tethering mechanism. The mass is already reflected in the *Mass* parameter and the development of the tethering mechanism could not justify the increased cost of 57% or $1.7B if *Difficulty* was set to "high". With these parameters, the cost estimate arrived at $3B. Comparing this to the development cost of ESA's ATV at $1.8B [16], this number seemed reasonable.

The mining equipment consists mainly of drills, tanks, processing units, and a rover system. The *Specification* best fit for this was "Lunar rover". Most equipment would be adapted from very mature technologies already in use on Earth, *Block* 10 was chosen for this reason. Compared to past lunar rover missions mainly in the Apollo era, with the rapid development of commercial lunar landers and small satellites today, and off the shelf parts being cheaper and more readily available, together with the increasing expertise and capability of designing and building rovers to the Moon and Mars by space agencies, *Difficulty* for the mining equipment was set to "low". This resulted in an estimated cost of $1.8B.

The human spacecraft would provide life support and suitable living conditions for 3 astronauts for 300 days, it would also contain an airlock and have docking capabilities. Note that the *Mass* quoted is excluding the humans and consumables. The *Specification* most appropriate for this vehicle was obviously "Human habitat". Similarly to the mining station, this would be the third iteration of this technology. The *Difficulty* was set to "average" as the mission duration is in line with current systems. The estimated cost for the human spacecraft was $4.2B. Compared to similar systems, for example the Columbus module which had a cost of $1.8B [17], this number also seemed reasonable.

The cargo spacecraft is essentially a stripped down version of the mining station. The same *Specification* of "Upper stage" was used. The *Block* number increased by 1 as it's based on the mining station and the *Difficulty* was set to "low" as it's less complex than the mining station. The estimated cost for both cargo spacecraft was $1.3B.

2) Launch and Refueling Costs: For the mining station with the mining equipment as its payload, one Falcon Heavy launch is required. The human spacecraft will also be launched on a Falcon Heavy. In both instances, the expendable version of the Falcon Heavy, with a cost of $150M per launch [18], is used to maximize performance. The two cargo ships can be launched on Falcon 9s with a cost of $62M per launch [19]. The mining station and the human spacecraft will also require orbital refueling. This technology has not been tested as of today, but it is an essential part of deep space exploration and its development is already ongoing [20]. For this reason, it is assumed that there will be commercial services available to serve this need and the cost is estimated to be \$200M including launch cost each time. The total cost of launch and refueling is estimated to be \$824M. See Table IV for the launch and refueling costs of each system.

Table IV
ESTIMATED LAUNCH AND REFUELING COSTS FOR EACH SYSTEM.

Item	Mining Station	Mining Equipment	Human S/C	Cargo	costs in M$
Launch Vehicle	Falcon Heavy (Exp)		Falcon Heavy (Exp)	Falcon 9	
Number	1		1	2	
Launch Cost	150		150	124	
Refueling Cost	200		200	-	Total
Cost Per System	350		350	124	824

3) Operations Cost: The operations cost includes ground support, mission control and planning, and telemetry monitoring and analysis. It can be estimated as an additional percentage of the system DDT&E cost every year.

For the human spacecraft, it's estimated to be $10\,\%$ per year which is in line with the the cost of the operations of the ISS excluding launches [15]. The mission duration of the human spacecraft, from launch to reentry back on Earth is 304 days resulting in an estimated operations cost of \$352M.

The mining station and the cargo spacecraft are much simpler in their operation, and the the cost of the operations is estimated to be $2\,\%$ per year. The mission duration of the mining station is from launch until the last cargo spacecraft leaves the asteroid lasting 6.1 years, resulting in an estimated operations cost of \$370M. From launch to reentry back on Earth, each cargo spacecraft on average has a mission duration of approximately 1.4 years, resulting in an estimated operations cost of \$37M.

The operation of the mining equipment is more complex as it contains a number of robots performing various mining tasks on the asteroid, but it's still estimated to be less costly than operating the human spacecraft, at $5\,\%$ per year. From arriving at the asteroid until the last cargo spacecraft leaves the asteroid for Earth, the mining equipment will operate for 1.5 years, resulting in an operations cost of \$138M.

In total, from the first launch to the last cargo spacecraft comes back to Earth, the cost of the operations of the entire mission amounts to \$896M spanning 7.1 years. See Table V for the cost of the operations of each system.

Table V
ESTIMATED OPERATIONS COST OF EACH SYSTEM.

Item	Mining Station	Mining Equipment	Human S/C	Cargo	costs in M$
DDT&E Cost	3030	1838	4223	1282	
% Per Year	2%	5%	10%	2%	
# Years	6.1	1.5	0.8	1.4	Total
Cost Per System	370	138	352	37	896

In summary, the total estimated cost of the mining station and the mining equipment was \$5.7B, the human spacecraft was \$4.9B and both the cargo spacecraft was \$1.4B. The grand total cost for the entire mission was an estimated \$12.1B, see Table VI for a breakdown of the total estimated costs for each system.

C. Funding

As the estimated cost was in the \$10B range, most of the funding would likely be from investors such as venture capital

Table VI
TOTAL ESTIMATED COSTS FOR EACH SYSTEM IN M$.

Cost Category	Mining Station	Mining Equipment	Human S/C	Cargo	Total
DDT&E Cost	3030	1838	4223	1282	10 373
Launch & Refueling	350		350	124	824
Operations Cost	370	138	352	37	896
Cost Per System	5725		4925	1443	12 093

firms and high net worth individuals. The potential for asteroid mining is enormous, the monetary value of this asteroid alone is around \$300B, but more importantly the technologies developed for this mission will open the door for more affordable and profitable exploitation of deep space. But the risks are also high, space projects are known to be often delayed and/or over budget. This project would definitely need patient investors with deep pockets to potentially invest more money to cover the cost overruns.

Other revenue streams could also cover some of the costs. The company could seek government grants or contracts from space agencies or the military to develop and test new technologies. The company could also sign contracts with commercial partners to sponsor the project as it would surely be a high visibility event, or for jewellery and other high end item makers to secure exclusive rights to some of the precious metals mined in space for their novelty value.

D. Economy and legal aspect

Nobody has managed to mine an asteroid yet which is why a space economy has not been established. Deep Space Industries (now owned by Bradford Space) and Planetary Resources were the first companies with mission plans [21]. Furthermore, NASA's mission OSIRIS-REx is ongoing and with that, they will be the first ones to bring back material from an asteroid. The biggest problem in the asteroid mining business is the financing part. Asteroid mining companies need to make money on Earth before they can make it in space. Faithful investors need to be found which are most likely "Billionaires that want to become trillionaires", according to Andrew Glester [7]. Once someone with a lot of resources is convinced that the outcome will be very profitable, the first asteroid mining mission will begin and with that, the space economy will develop. How it is going to look like is written in the stars for now. But the next question that comes to mind once a mission is developed: Who owns what in space? First of all, it should be noted that space law is a grey area and should be considered skeptically. As of now, nobody can own an asteroid, as nobody can own the pacific ocean, but somebody can own the material on an asteroid as fishermen can own the fish they catch in the ocean. There are national laws to start with. The Space Act of 2015 of the United States declares that companies own the material that they mined from an asteroid [21]. Luxembourg also adopted that law and according to Von Der Dunk [21] it is possible that more countries will follow. The fact is that whichever country adopts laws that clarify ownership and makes it easy to do business in space, that country will be able to attract a potentially very lucrative industry and with that become richer since the money invested in space will be spent on Earth.

E. Off-nominal scenario

An off-nominal scenario that can arise for this mission is if another company lands on the asteroid before. As stated in Section V-D, currently there is no definite space law dedicated to asteroid mining. Hence, it is assumed that the materials of the asteroid will belong to the organization that gets there first. One of the main objectives of the mission is to sell the extracted material on Earth and make a profit out of it. However, if some other organization reaches this asteroid first, they can lay claim on the material, which in turn would make one of the objectives of this mission inapplicable. A couple of ideas in this regard has been floated as preventive measures against the above situation. It is to be noted that they have not been taken into account in this particular mission plan.

- An active object landing on the asteroid surface to lay claim on the asteroid and its materials.
- Identify an alternate asteroid with similar properties and explore it using the same technology and resources to make the mission fruitful.

VI. Project management

In this section, a summary of the work procedures and management of the project tasks are presented.

One of the main tasks of the *Overall Coordination* sub group, included managing of consistent information flow between all the four sub groups (as stated in Section I). To do this effectively, the below work methods were adopted.

As a team, the main tasks involved defining the mission requirements and concepts, identifying conflicts and maintaining consistency. In order to achieve this, effective use of the scheduled projects hours were made. During each meeting, the sub groups would update each other about their tasks; what they are doing and what they intend to do.

Each member of the *Overall Coordination* sub group was assigned to one of the other three sub groups in the team and followed the work of the respective group closely, throughout the project period. The *Overall Coordination* group members would then have a meeting amongst themselves, where they would update each other about the proceedings of their assigned sub groups. Based on the updates, the *Overall Coordination* sub group would work individually with each of the sub groups to remove impediments and blockers that arose due to inter-group dependencies.

Various online platforms were used in order to achieve ease in communication and maintain comprehensive documentation during the mission planning.

- Slack: a communication and collaboration platform, was used to communicate between the team members outside of work hours. Each sub group had separate channels for discussions pertaining to their group work. Also, there was a general channel for topics pertaining to the whole team. Finally, there was a decision log channel where every important decision made during the entire mission planning period was logged and available for later review.
- Google Drive: a cloud storage system, was used to documents all the findings and literature related to the project. Here too, each sub group had separate folders where they stored files and documents, providing an insight to their work. All the team members had access to each other's documents in case a reference or consultation was needed.

In this way, it was ensured, that there is consistency in the mission designs and concepts. After multiple discussions and iterative planning, the mission plan was eventually finalized.

VII. Conclusion

Asteroid mining will be of importance in the near future in order to harvest resources to supply our modern lives on Earth and to establish infrastructure in space, perhaps more importantly the human race needs to gain knowledge about asteroids to protect the planet. This study presents a concept of a mining mission to the asteroid *469219 Kamo'oalewa* with the goal of establishing a mining station on it, and return 76 t of precious metals worth $4B back to Earth as well as extracting water from it for propellant production.

The mission design is a collaboration between the sub groups *Logistics*, *Space Vehicle*, *Human Aspects* and *Overall Coordination* which together make up the *Red Team*.

The mission itself is broken down into three parts. In the first phase, the mining equipment is launched on a *Falcon Heavy* and transported to the asteroid, the trip takes 4.6 years. In the second phase a crew will travel to the asteroid in a crew vehicle launched on the *Falcon Heavy* and assist in the assembly of the mining station and the start of operations. The travel time to the asteroid as well as time spend on the asteroid is 112 days each, the trip back to Earth takes 80 days. Two cargo vehicles are launched from Earth in the third phase with the purpose of bringing back the mined materials to Earth. The first one will need 310 days to get to the asteroid, it will be filled within 30 days and travel back for 6 months. The second one will need 185 days to get to the asteroid, be filled for 100 days and then return to earth within 8 month.

During the mission, communication needs to be assured between the crew and the ground station as well as between the mining station, cargo vehicle and the ground station. The crew vehicle will communicate on Ka band and the data rate is estimated to be $10\,\mathrm{Mbps}$. The mining and cargo vehicle transmit on X band and the data rate is $8000\,\mathrm{bps}$. Considering ground stations, the ESA ESTRACK network is used.

The total cost of the mission is divided into three parts: $10.4B for design development test and evaluation, $824M for launch and refuelling, and $896M for operations adding up to a total mission cost of $12.1B. Funding will mainly be supplied by venture capital firms and high net worth individuals. The study shows that for this first mining mission to an asteroid, the estimated costs exceeded the value of the material brought back to Earth. The costs needed to be brought down in order for the mission to be profitable from the get go, but the investments made for the development of new technologies will open up opportunities for the future.

Furthermore economical and legal aspects of asteroid mining were studied. As of now neither a space economy nor an international space law has been established. A space economy will most likely develop once the first companies managed to mine asteroids. In terms of the law there are some countries that have national laws i.e. the USA and Luxembourg and one hopes for other nations to follow and thus create an international law which covers the licensing for mining celestial bodies in deep space as well as defining the ownership of the mined materials. Lastly the overall coordination group was responsible for the project management of the Red Team which was performed with the help of *Slack* and *Google Drive*.

VIII. Acknowledgements

Trying to coordinate a team to plan an asteroid mining mission with different subgroups was a new challenge for the overall coordination group. Mentorship from academia as well as from the industry was offered, for which we are grateful. Therefore, we would like to extend our gratitude to the faculty for their valuable time to oversee this project and help us move forward. Thanks to our mentor Nils Pokrupa who guided us when we were stuck and also gave us his expert advice based on his experience in the space industry. Thanks to the Blue Team's mentor Erik Clacey who shared his time between his team and ours, when our mentor was not available. Thanks to our teaching assistant Anna Larsson who guided us throughout the project, sharing tips and suggestions and her experiences on working with this type of project previously, from a student's perspective. Thanks to our course teacher, Christer Fuglesang, who shared with us his personal experiences of human spaceflight and his vision of the future of space exploration.

Lastly, it would not have been possible without all the diligent members of the Red Team who worked with us on this project. We, the overall coordination group, humbly acknowledge their help and sincerely thank them for their time.

Working on a project of this kind was a novelty for us, and we are grateful to have been able to benefit from such good advice and assistance.

IX. Division of the work

The research on the different parts and writing of this report was divided as followed. Erwan Caffier introduced the work of this project as well as derived the mission objectives, assumptions, requirements, and profile in collaboration with the other groups involved in the project. The first part of the Context "Asteroid mining: why? what?" was Klara Anneliese Spiekers work, furthermore she is responsible for Economy and legal aspects. Kritee Mahanti designed the Communication strategy, introduced the project management of the Red Team and described the off-nominal scenario. The financial expert was Xiyao Song who estimated the asteroid value and the mission cost.

References

[1] David Cohen. 'Earth's natural wealth: an audit'. In: *New Scientist* (2007).

[2] *ESA Space Resources Strategy*. European Space Agency, 2019.

[3] Luxembourg Ministry of the Economy. 'Luxembourg and ispace, a Tokyo-Based Lunar Robotic Exploration Company, Sign MoU to Co-Operate within the Spaceresources.lu Initiative'. In: *Business Wire* (2017).

[4] Alexander Polidar, Marco Guerra, Florian Teilhard, Martina Rusconi and Harparan Dhindsa. 'Asteroid Mining - Logistics Report'. KTH, 2020.

[5] Adrien Bardou, Anthony Surivet, Gustav Burman and Ľuboš Jiroušek. 'Asteroid Mining - Human Aspect Report'. KTH, 2020.

[6] Adrien Engrand, Alberto Zorzetto, Antoine Bocquier, Sara Ghika and Maxime Perriquet. 'Asteroid Mining - Space Vehicle Report'. KTH, 2020.

[7] Andrew Glester. 'The asteroid trillionaires'. In: *Physics World* (2018).

[8] Mark Sonter. 'Asteroid Mining: Key to the Space Economy'. In: *adAstra* (2006).

[9] James R. Wertz Wiley J. Larson. *Space Mission Analysis and Design - Third Edition*. 1999, pp. 533–575.

[10] Wiley J. Larson and Linda K. Pranke. *Human Spaceflight: Mission Analysis and Design*. The McGraw-Hill Companies Inc., 2014.

[11] See Chuan Leong, Ru-Tian Sun and Peng Hon Yip. 'Ka Band Satellite Communications Design Analysis and Optimisation'. In: *DSTA Horizons* (2015).

[12] *ESA's Deep Space Tracking Network*. URL: https://download.esa.int/esoc/estrack/esa_estrack_brochure_2015_EN.pdf.

[13] *LCDB 469219 Kamo'oalewa*. Apr. 2017. URL: http://www.minorplanet.info/PHP/generateOneAsteroidInfo.php?AstInfo=469219%7C.

[14] Benoit Carry. 'Density of asteroids'. In: *Planetary and Space Science* 73.1 (2012), pp. 98–118.

[15] Harry W Jones. 'Estimating the life cycle cost of space systems'. In: 45th International Conference on Environmental Systems. 2015.

[16] W Ostrove. 'Space Systems Forecast - Launch Vehicles & Manned Platforms'. In: *Forecast International* (2014).

[17] Paul Rincon. 'Science/Nature — Columbus: Europe's orbital outpost'. In: *BBC News* (Dec. 2007). URL: http://news.bbc.co.uk/2/hi/science/nature/7125334.stm.

[18] Michael Sheetz. 'Elon Musk says the new SpaceX Falcon Heavy rocket crushes its competition on cost'. In: *CNBC* (Feb. 2018). URL: https://www.cnbc.com/2018/02/12/elon-musk-spacex-falcon-heavy-costs-150-million-at-most.html.

[19] SpaceX. *Capabilities & Services*. Nov. 2012. URL: https://www.spacex.com/about/capabilities.

[20] Eric Berger. 'NASA agrees to work with SpaceX on orbital refueling technology'. In: *Ars Technica* (July 2019). URL: https://arstechnica.com/science/2019/07/nasa-agrees-to-work-with-spacex-on-orbital-refueling-technology/.

[21] Jesse Dunietz. 'Floating Treasure: Space Law Needs to Catch Up with Asteroid Mining'. In: *Scientific American* (2017).

[22] Andrew O'Dea. 'DSN Telemetry System, Data Decoding'. In: (2013).

Appendix A
Mission Phases

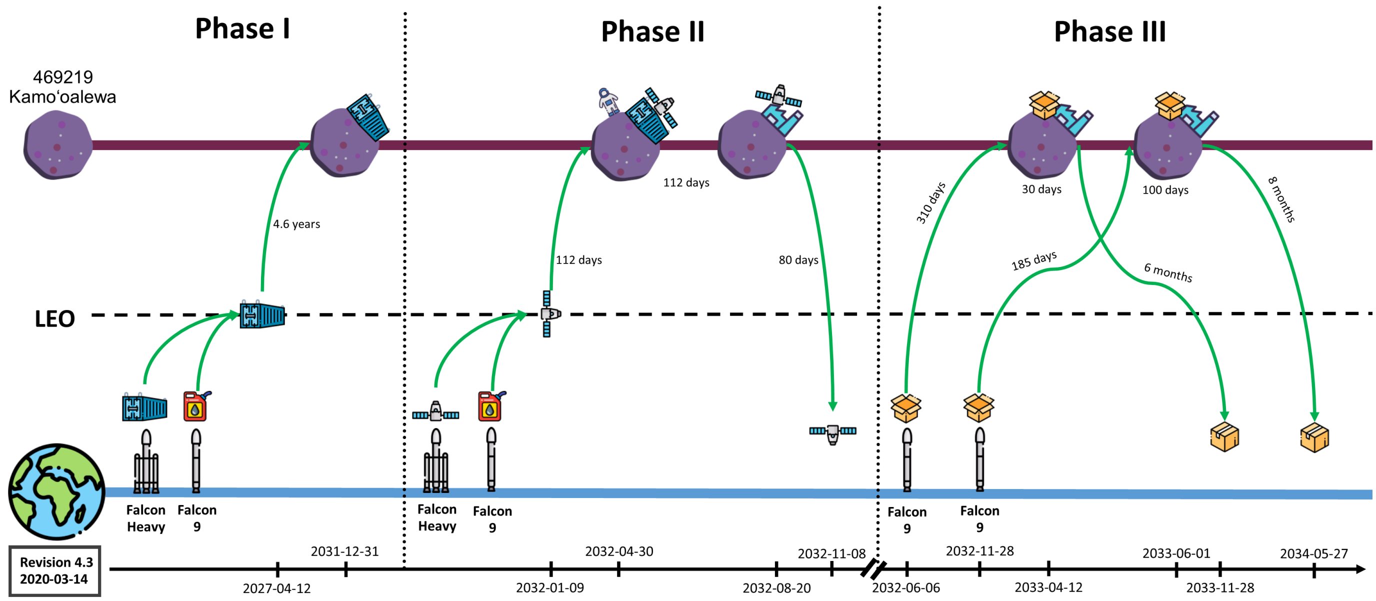

Figure 2. Summary of the main mission phases

Appendix B
Communication

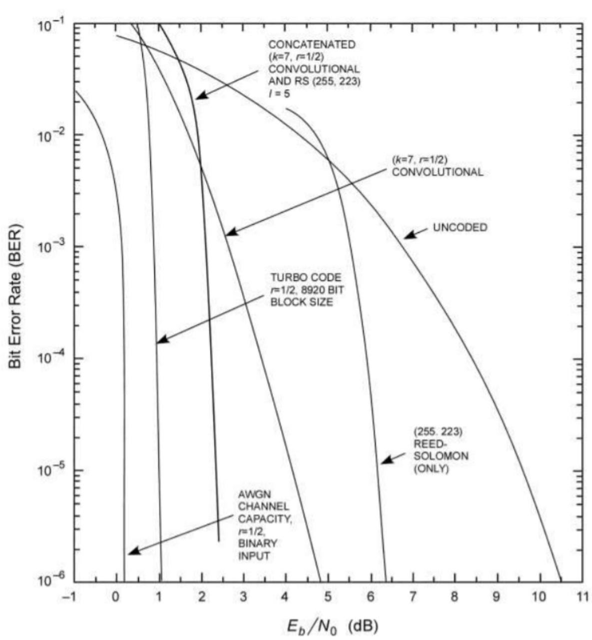

Figure 3. Relative performance of modulation schemes [22]

APPENDIX C
ASTEROID VALUE ESTIMATION

Table VII
DETAILED ESTIMATION OF THE VALUE OF THE ASTEROID.

Group	Volume [% of Total]	Volume [m^3]	Resource	Volume [% of Group]	Volume [m^3]	Density [kg/m^3]	Mass [kg]	USD/kg	Value [USD]	Mined Volume [m^3]	Mined Mass [kg]	Mined Value [USD]	Incl. Launch Cost
Nickel-iron group	10%	3534	Iron	75%	2651	7860	20 834 650	0.1	2 083 465	32.6	255 843	25 584	767 554 584
			Nickel	20%	707	8900	6 291 039	12.7	79 896 199	8.7	77 252	981 100	232 737 100
			Cobalt	5%	177	8860	1 565 691	30	46 970 737	2.2	19 226	576 786	58 255 386
			Total	100%	3534	-	28 691 380	-	128 950 401	43.4	352 321	1 583 471	1 058 547 071
Precious Metals	1%	353	Gold	70%	247	19 320	4 779 776	51 000	243 768 583 283	3.0	58 694	2 993 402 160	-
			Platinum	5%	18	21 450	379 053	31 000	11 750 636 447	0.2	4655	144 294 150	-
			Palladium	25%	88	12 020	1 062 055	75 000	79 654 099 984	1.1	13 042	978 127 500	-
			Total	100%	353	-	6 220 884	-	355 173 319 714	4.3	76 391	4 115 823 810	-
Rock & Regolith	89%	31 455	-	100%	31 455	2000	62 910 393	-	-	386.3	772 520	-	-
Total	100%	35 343	-	-	35 343	2768	97 822 657	-	335 302 270 115	434.0	1 201 232	4 117 407 281	5 174 370 881