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ANALYSIS OF AN ASTEROID MINING ARCHITECTURE UTILIZING SMALL SPACECRAFT

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Abstract
Asteroid mining offers the possibility to revolutionize supply and availability of many resources vital for human civilization. Recent analysis suggests that Near-Earth Asteroids (NEA) contain enough volatile and high value minerals to make the mining process economically feasible .Considering possible applications, the importance of mining water in space specifically has become a major focus for near-term options. Most proposed projects for asteroid mining, however, involve spacecraft based on traditional designs resulting in large, monolithic and expensive systems.
An alternative approach is presented in this paper, basing the asteroid mining process on multiple small spacecraft, i.e. a de-centralized architecture. Nonetheless, to the best knowledge of the authors, so far limited thorough analysis of the asteroid mining capability of small spacecraft has been conducted. Therefore, this paper explored the lower limit of spacecraft size for asteroid mining operations. This provides the foundation to establish a feasible miniaturized spacecraft design capable of extracting water from asteroids and transporting it to an appropriate orbit for further processing, as is presented in this work.

KEYWORDS
ASTEROID MINING, WATER EXTRACTION, ARCHITECTURE, SMALL SPACECRAFT

1. Introduction

Asteroids are celestial bodies that are of fundamental scientific importance for uncovering the formation, composition and evolution of the solar system. Particularly, Near-Earth Asteroids (NEA) are the main goal for any future enterprise. They may contain reservoirs of useful minerals and composites including water, metals and semiconductors [1].
Furthermore, several concepts for extraction and supply of water were developed recently considering not only refueling purposes for spacecraft but also other uses such as radiation shielding and potable water for life support systems in outer space. Near Earth Asteroids (NEA) have gained popularity due to their access opportunities, as they are the easiest celestial bodies to reach from Earth [2]. Recent advances in the miniaturization of spacecraft components may allow for a more cost effective and reliable approach to mine NEAs. Thus, a mission architecture focusing on the utilization of small spacecraft is proposed and analyzed.

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2. Methodology

The project addresses the asteroid water mining venture. First, a survey of relevant technologies and past missions was performed and also a survey on water mining techniques. For the next step, a trade-off analysis was made in order to select a suitable technique for small spacecraft concept. Top level requirements are identified with respect to the selected extraction techniques, to establish major constraints. As a conclusion, a road map describing the steps required for the venture is presented, highlighting the main topics discussed throughout the document.

2.1. *Survey of Relevant Technologies*

In the last twenty years, a vast amount of data and results from dedicated space missions on asteroids have been collected. Spacecraft observations were mainly used to complement, improve and generate theories and findings derived from ground based asteroid data.[3]. Exploitation of asteroid resources, hasn't been reached yet, although some minimal asteroid samples have been retrieved.

Space missions to asteroids provide an accurate description of their composition, but more prospection missions are required to determine individual candidates for mineral exploitation. Besides exploration, mining techniques have also been developed but not yet tested in space. There are several mining approaches that vary in function of the asteroid size, as for small asteroids, whole asteroid capturing is a more feasible option, rather than for larger objects, in which extracting chunks of material is more reliable [4].

2.1.1. Current Technology: Sample Retrieval

Recently, there is significant interest in sample retrieval missions having in mind that their characterization not only provides a deeper insight into the Solar System, but also represents a technological challenge for space exploration. Various space macro-engineering projects have as a primary objective to capture an asteroid or part of it and return to a useful orbit for its processing. [3]

The "Keck Institute of Space Studies" [5] mentioned that there are five categories of benefits from the return of an asteroid sample or a full asteroid retrieval, which are:

- Synergy with near-term human exploration.
- Expansion of international cooperation in space.
- Synergy with planetary defense.
- Exploitation of asteroid resources.
- Public engagement.

The following past and present missions were surveyed:

- Hayabusa 1,2.
- Stardust.
- Osiris-Rex.

Sample return mission from asteroids were successful in the past as proven by the Hayabusa and the Stardust missions. It is possible to return a very small amount of material from outer space in order to be studied, however no approach has been made to try to test a technique in which a higher amount of material can be extracted. Therefore, the space mining venture requires the testing of mining techniques in space. Both the techniques considered in the past missions use collectors that cannot be expanded for extracting and processing purposes. What is more, contemporary missions focus heavily on the science aspect of exploring asteroids. Osiris-Rex techniques for sample retrieval are not scalable and depend on the amount of nitrogen the mission needs to carry for the retrieval itself limiting its functionality. This concept is not feasible for the asteroid mining venture. Successful rendezvous has been proven and also the attempt to do a soft landing. No other means for attachment were tested, which is a critical step in the asteroid mining architectures that considers extracting a determined component.

Figure 1. Artistic impression of Hayabusa 1. NASA Planetary Science Division, NASA JPL.

2.1.2. *Current Technology: Remote Sensing*

"The goal is to find ore, not merely a concentration of some minable resource" [3]. Ore refers to material that is commercially profitable and it can be precious metals, helium -3, water, organics or others. Prospecting is the first step to establish if the material abundance in an asteroid is potentially profitable, this is done by analyzing the data coming from observed asteroids, which provide information that can be interpreted to gain knowledge on the spin rate, size, shape, albedo reflection and to determine the type of asteroid. The techniques of prospecting or remote sensing are the same technology as the remote sensing satellites used on Earth. [6]

The following past and present missions were surveyed:

- Deep Space 1.
- NEAR Shoemaker.
- Rosetta.
- WISE.
- Dawn

There have been several missions related to studying the characteristics of asteroids in the past years and also in the present. Many of the characteristics have been identified by ground observations and the missions complemented the data by close observation of some bodies. Although many asteroids have been identified, there is little detailed information about their composition. The missions sent had primary targets either in deep space or in the asteroid belt. Near Earth asteroids have not been analyzed deeply by any of these past missions. In order to pursue a space mining venture, the information about the bodies that are closer (NEAs) is critical to identify potential candidates for certain resource exploitation.

2.1.3. *Current Technology: Future Missions*

In this venture, it is also important to look into future mission designs in order to understand the challenges to face and consider the technology options that are available, as well as the purpose of these missions.

The following future missions were surveyed:

- Asteroid redirect mission (NASA)
- Prospector 1 (DSI)
- Arkyd Prospectors (Planetary Resources)
- Hedgehog (NASA)
- Robotic Asteroid Prospector
- Asteroid Provided In-Situ Supplies

The future mission concepts from the two companies involved (DSI and Planetary Resources) with the asteroid mining venture propose prospecting spacecraft only. Other approaches assessing the asteroid mining venture involve capturing mechanisms aiming at very small asteroids of 20m or less. These consider a relatively big spacecraft with the capturing capability and the sufficient energy needed to deorbit the asteroid and return it to a lunar or Earth orbit. There are a few small spacecraft concepts proposed for asteroid mining, but these consider a mother (bigger) spacecraft that carries them.

Although the feasibility analysis in several papers state that the asteroid mining venture is economically feasible, the technology is not mature enough as the process of anchoring and extracting is still a challenge which needs to be tested. Besides, the venture will be highly benefited from prospection missions as they would bring information and possible first targets to begin with.

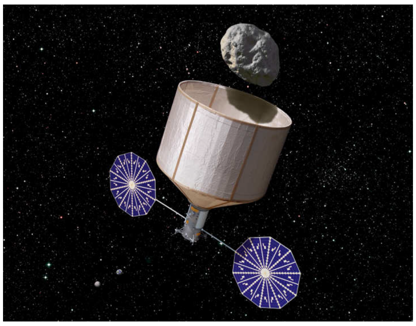


Figure 2. Concept of an asteroid retrieval spacecraft. (Image Credit: Rick Sternbach / KISS)

2.2. *Survey of Water Mining Techniques*

The concept of water extraction involves finding the reservoirs of water in NEA's, extracting, processing and transporting them to a location of value where a fuel depot is available. Water can be found as ice, and this can be refined into fuel, water for life support systems, air (with extra additions) and radiation shielding. According to Dula & Zhang [7] the main customers that would consider water to be valuable in space will include all explorers who would prefer to buy less expensive fuel instead of its transport from Earth.

2.2.1. *Asteroid water*

The first step is to identify the water reservoirs in asteroids. As an analogy of what it is expected to be found in asteroids, the celestial bodies' composition is compared to the results found on Earth in terms of the elements they may contain and their water holding capacity.

If hydrated carbonaceous asteroids in the Near Earth Asteroids population are considered (around 10% population) as the only water carrying objects and assuming that these objects carry around 8.5% water, the water available in near Earth space can be estimated. Sanchez & McInnes [2] estimations are shown in figure 3.

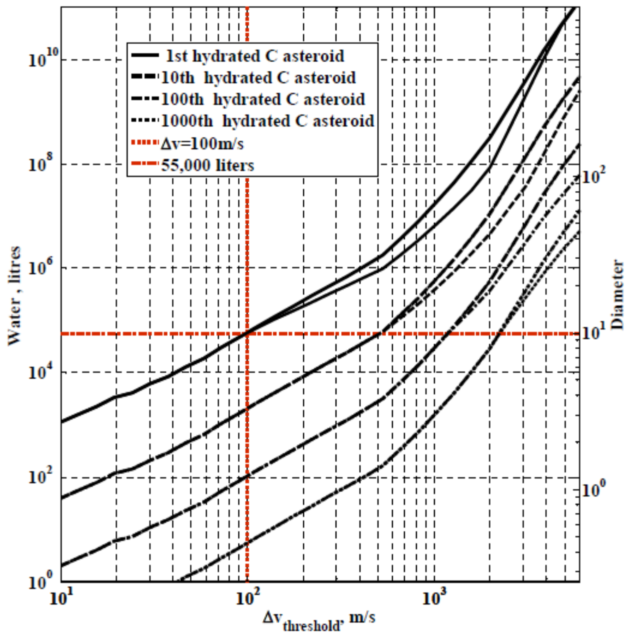


Figure 3. Water resource pool. (Sanchez & McInnes, 2011)[2]

All the estimations were made based on study results of asteroid composition determined by observing C –class asteroids for many years through an absorption band in their reflectance spectra, near 3 um. The importance of asteroid prospectors to have an accurate estimation is highlighted as important before initiating an extraction process.

2.2.2. *Techniques applicable in space*

Unfortunately, no mining techniques have been developed in the space environment, however, many concepts have been studied and some solutions considered such as heating techniques.

Extracting water on barren planets such as Mars has also gained interest as a defining factor for human settlements. Given the fact that a few missions have landed on Mars, some concepts for water extraction were proposed. These concepts can also be applied to other celestial bodies such as NEA asteroids.

According to Wiens et al.[8] , potential designs for water extraction by heating include:

- **Inclined Pipes.** Electrical heating elements heat the soil in a rotating inclined pipe. The released vapor would rise from the soil, travel the inside surface of the pipe and exit on top. The dehydrated soil would pass out the bottom of the pipe.
- **Kettles/Pots.** Soil is placed in an electrical heater inside a kettle releasing vapor. Then, vapor is condensed and collected as liquid water.
- **Sifters.** Soil passes through a sifting screen releasing vapor. The screen is heated by an electrical heater.
- **Funnels.** A funnel and a conveyor belt are used to heat the soil and release vapor.
- **Focused Light.** Focus sunlight to concentrate energy heating a portion of the soil to release water vapor.
- **Microwaves.** Heat the water contained in the soil by high power radio waves. The microwaves apply energy to the water directly and do not require heating the soil unlike conventional methods.

For any of these techniques, a cold trap needs to be attached in order to condense the vapor and collect liquid water. A concept diagram of a microwave system is shown in figure 4.

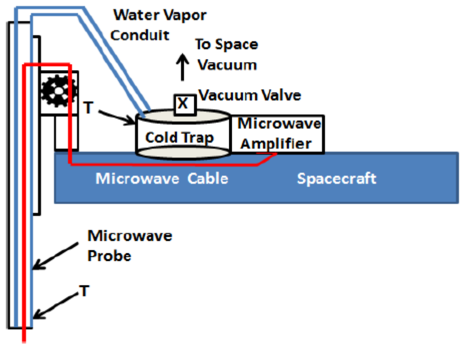


Figure 4. Schematic diagram of the microwave extraction system. (Ethridge, 2016)[9]

3. Results and Discussion

The water mining technique needs to be defined considering the technological feasibility. A decision matrix is a helpful tool to select an appropriate technique for this endeavor.

The matrix shall provide the result from a quantitative analysis allowing the identification of the most suitable water extraction technique applicable to small spacecraft. Table 1 presents the water extraction techniques evaluated.

Water extraction technique	Advantages	Disadvantages
Vacuum drying (Pneumatic System)	Very Reliable. Few moving parts.	Need to carry compressed air and other instruments. Hard to implement. Hardly scalable. Complex.
Hot air or steam drying	Very reliable Few moving parts. Simple.	Need to carry compressed air and other instruments. Hard to implement.
Solar drying (focused light)	Very Reliable High temperature in small area. Feasible.	Sunlight dependent. No night operation. Alignment required.
Inclined pipes heating	Few moving parts. Continuous operation. Easy to collect vapor.	High energy High mass.
Kettle/Pot heating	Simple. Few moving parts. Amount vs time.	Insulation requirement High energy required. High mass.
Sifter heating	Simple. No moving parts.	Gravity Dependent. High clogging risk. High energy Fast heating, less efficient.
Funnel heating	Simple. No moving parts. Small amount of soil required	Gravity Dependent Clogging risk High energy
Conveyor Belt (drum drying)	Continuous Operation. Very efficient. Very reliable.	Gravity Dependent. Several moving parts. High energy High mass
Microwave drying	Compact. Good efficiency. Few moving parts. Reliable	relative high energy demand. Relative high mass.
Capturing and heating	very efficient. Continuous Operation.	Sunlight dependent. Hardly scalable. Alignment requried. Very hard to implement

Table 1. Extracting water technologies comparison.

The parameters considered to be evaluated are:

- Scalability. The water technique needs to be scalable as it needs to be suitable for a small spacecraft. Higher score if it can be scalable.
- Complexity. The method's complexity adds a relative risk to the mission. The higher the complexity, the higher the risk of failure. For the calculation, high score means that the method is simple.
- Technological Feasibility. Evaluation whether a technology is currently fea-

sible to work in the asteroid environment. High score if it was proven in similar conditions.
- Durability. The technique needs to be robust enough to work properly and repeatedly in a non- ideal scenario that could be encountered in an asteroid. High score if it is most likely durable.

The evaluation criteria will consider a scale from 1 to 10 for each parameter and the weighting of each one of them is as follows:

- Scalability. Weight = 1.5
- Complexity. Weight = 1.2
- Technological Feasibility. Weight = 1.5
- Durability. Weight = 1.3

Table 2 contains the values assigned to each technique and the total score obtained. The highest score is the technique selected for the architecture proposal.

Water extraction technique	**Scalability**	**Complexity**	**T. Feasibility**	**Durability**	**TOTAL SCORE**
Vacuum drying (Pneumatic System)	3	3	7	7	27.7
Hot air or steam drying	5	5	8	5	32
Solar drying (focused light)	3	6	10	9	38.4
Inclined pipes heating	7	6	8	4	34.9
Kettle/Pot heating	6	8	3	8	33.5
Sifter heating	7	8	4	5	32.6
Funnel heating	7	7	4	5	31.4
Conveyor Belt (drum drying)	4	5	3	5	23
Microwave drying	8	6	9	7	41.8
Capturing and heating	1	2	10	9	30.6

Table 2. Decision Matrix for the water extraction technology.

Considering the previous weighting for the analyzed water extraction techniques, the microwave drying technique is the most appropriate technique to be applied for small spacecraft. However, the focused light technique for heating also obtained a good score. This technique would not be entirely applicable for small spacecraft as it does not seem scalable to fit in the small spacecraft constraint. Therefore, a deeper insight to see whether this technology is applicable for small spacecraft is needed. Microwaves are scalable and feasible to work in a harsh environment besides the technology being relatively simple and durable. Therefore, this method was selected in the present project.

Some advantages of using the microwave techniques as described in Wiens et al.[8]:

- Greater efficiency than thermal energy sources.
- Directly heat the bound water while not wasting energy to heat the soil.
- Few moving parts.
- Reliable
- No warm up period, they produce instant heat.

3.1. *Mission Architecture*

After analyzing the asteroid mining proposed concepts and defining the most appropriate water extraction technique for the venture, it is important to make sure the system can fulfill the mission while avoiding over-design. The following requirements define in broad terms the functions and operations that the spacecraft should be able to perform. [10]

3.1.1. Top Level Requirements

The following top level requirements were identified:

T1. The spacecraft should have a small structure.

As it is the objective of the project, the spacecraft configuration should correspond to the parameters that define a small spacecraft for this application. According to NASA Ames documents, the definition for small spacecraft would include any spacecraft that has a mass under 500 kg.

T2. The spacecraft should be dimensioned in order to obtain around 100 kg of water.

To this point there is not an estimation of the demand of water in space to determine the necessary quantity returned per asteroid run for given operational cost. However, a value that makes calculations easier and that has been utilized for calculations in past projects is 100 kg. According to the analyzed general hydrated asteroids composition, this quantity is obtainable if the asteroid has at least 3 meters in diameter. [4]

T3. The spacecraft should be able to be refueled in-situ with the extracted water and be able to operate with a water based propulsion system.

For the mining operations to be successful, it is required to bring back the water extracted to a usable orbit. However, in order to make the spacecraft efficient and to reduce cost, the propellant loaded before launch must get the spacecraft to the rendezvous and be sufficient enough to approach a soft landing and provide a possible second attempt for water extracting if the first attempt fails. The spacecraft should be able to resupply itself. For this purpose, it should carry a water based propulsion system or a water compatible system.

T4. The spacecraft should carry imaging instruments in order to determine the best possible landing site.

The spacecraft should be able to determine the best possible landing site by estimating the spinning rate, the surface mineral content and the shape of the asteroid.

T5. The spacecraft should incorporate reusable anchoring, storage and extraction systems.

In order to be able to extract the amount of water established, the systems that are needed and support the mining operations involve anchoring, storage and the actual extraction and processing.

T6. The spacecraft should have a high degree of autonomy.

Since the spacecraft must perform distance mining operations, it needs to have a high degree of autonomy considering that communications will be very limited.

T7. The maximum travel distance of the spacecraft should be less than 0.1 AU from Earth.

Near Earth Objects (NEO's) are asteroids and comets with perihelion distance of less than 1.3 AU. However, there are a large number of close approaches that are accessible for rendezvous at 0.1 AU. Therefore this is selected as the limiting distance for rendezvous with an asteroid.

T8. The spacecraft should be capable of docking with a space station when it returns to an appropriate orbit.

Once the material has been extracted and departed from the asteroid, it should be able to arrive to the appropriate orbit and also capable of docking with a space station in order to deliver the product, be checked for maintenance and probably be sent to a new target.

T9. The spacecraft cost must be minimized to make the venture feasible.

One of the most important limits, the spacecraft should be relatively low in cost comparing the actual proposals for asteroid mining spacecraft in order to make it feasible.

T10. The spacecraft shall contain a backup propulsion system in order to be able to return to Earth if the water extraction is unsuccessful.

There is always the risk for the mission to fail, taking into account the conditions and circumstances that could possibly occur during any of the phases from accidents to system failures. The spacecraft shall be able to be return to Earth and in that case, it would need a propulsion backup, such as a basic electric propulsion system.

T11. The spacecraft shall be reliable enough and contain some redundancy units in order to repeat the trip several times.

During the lifetime of the mission, the spacecraft shall maintain its systems operating normally and if any failure occurs, some critical redundancy should be considered. The spacecraft needs to be able to realize the trip several times in order to satisfy the water requirements in near Earth orbit.

3.1.2. Mission Architecture concept

After assessing past mission architectures and taking into account the top level requirements for the asteroid mining venture with small spacecraft, the following architecture is proposed and displayed in figure 5:

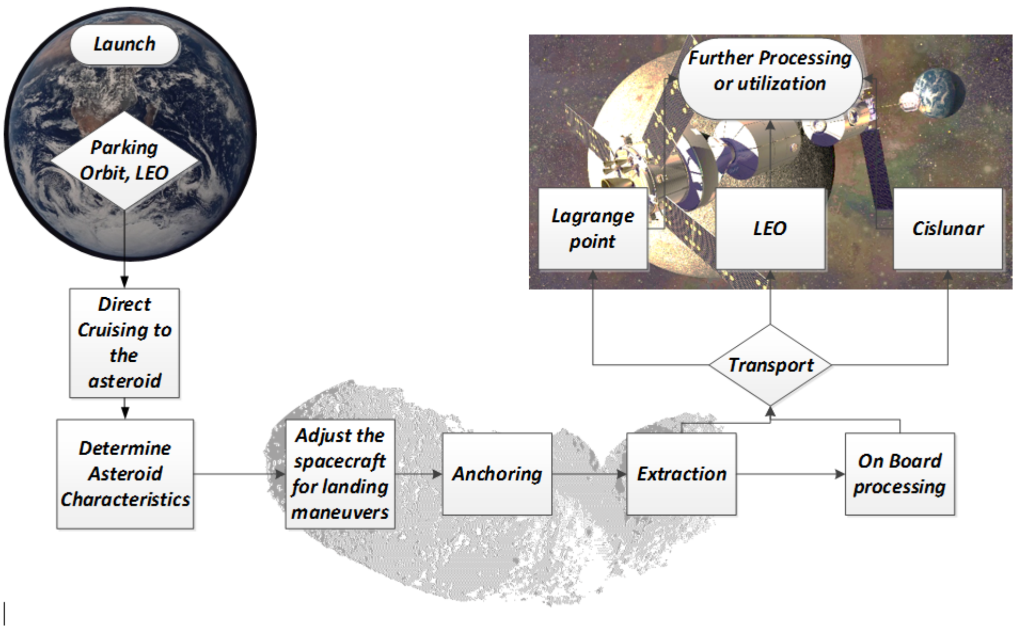


Figure 5. Proposed architecture for asteroid mining using small spacecraft.

After launch, the single or numerous spacecraft will be set in a parking orbit before entering a trajectory for rendezvous. The trajectory may consider a direct cruising to the asteroid. Once it arrives to the asteroid, it must determine the asteroid characteristics and adapt to that environment before the landing attempt. Maneuvers for landing are performed and an anchoring technique secures the spacecraft to the surface. Once fixed, the extraction is performed. The mineral extracted (water) will be processed insitu or only stored, according to later designs. Following the operations, detachment is performed and stabilization for the transportation to a cislunar or Earth orbit facility.

It is assumed that a potential asteroid containing a sufficient amount of water has been selected before the commencement of the mission.

3.2. *Mission Analysis*

The very first aspect that comes into play while analyzing the mission is the target selection. The asteroid target, besides having confirmed water in its composition, must be accessible from Earth in a relatively short time. Thus, a maximum time limit for the mission is defined. Water, as a resource, needs to be available in an Earth orbit and depends on the supply and demand that the venture could generate. In those terms, the longer the time of the mission, the less available resources accessible to potential customers.

The higher population of known asteroids are the Apollo type, covering 62% of the total number of discoveries until now. These asteroids would be suitable candidates for selection as their orbit crosses Earth's orbit and their semi major axis is slightly larger than Earth's. Due to these characteristics, it is possible to have very short round trip flights.

The concept of "rapid return missions" was applied previously to missions with the simple task of rendezvous and sample collection. These missions are considered "fast" because the time of the whole round trip of 1 year or less, but usually on the order of 6 to 9 months. The same concept can be applied for a low cost mining operation. Setting a maximum mission time of 1 year would boost asteroid science and the asteroid mining ventures [11]. Therefore, an appropriate maximum mission time of 1 year = 365 days, will be considered.

Barbee et al [11] also presents some estimations for asteroid trajectories and one of the examples shows a number of 160 days for a trip to a Near Earth Apollo asteroid. Considering the round trip, it leaves around 45 days for operations. From this, it can be dimensioned that an approximate time for real operations will be around 30 days, having 15 days for prospecting and landing site selection.

Following these concept and constraints, the trajectory schematic is presented in figure 6.

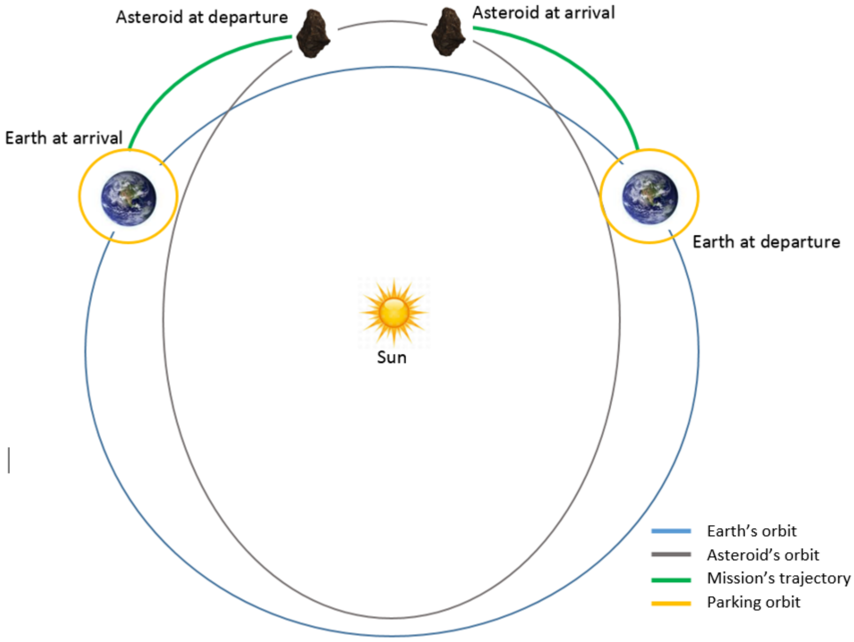


Figure 6. Mission Trajectory proposal.

3.2.1. Mission Operations and phases

The mission shall be divided in the following phases:

- P0. Launch Phase. The launch phase corresponds to the spacecraft behavior at the beginning of the mission only. This stage is defined to start when the spacecraft is positioned in the launch vehicle and is disconnected from any physical connector for power supply or communications. In this stage, the spacecraft is powered by the batteries, and the main operations are reorientation to separation attitude once the spacecraft is separated from the launch vehicle and deployment operations. The phase ends when the solar arrays are totally deployed and the main subsystems tested in space. The spacecraft is then positioned in a stationary orbit.

- P1. Cruise Phase. The cruise phase starts with the engine firing to start the journey to the asteroid. Most of the equipment is just in stand-by during this stage, except for some key equipment such as power supply, communications and others.

- P2. Rendezvous Phase. The main operations during this phase are the prospection and characteristic determination of the asteroid, identifying possible landing sites. This phase shall last approximately 15 days. Communications with Earth are important to confirm the landing site and to attempt a soft landing operation. Spacecraft adaptation to the asteroid rotation is also necessary. Once the landing is successful and attached, the mining phase can start.

- P3. Mining Phase. During the mining phase, the level of autonomy of the spacecraft should be high as the communication with Earth will be limited. All operations related to mining shall be automatically performed in this stage, such as drilling, microwave heating, water collection and surface monitoring. The spacecraft shall be able to change landing site as well, after confirmation with ground control.

This will involve using some water as propulsion to depart and enter the rendezvous phase again.

- P4. Departure Phase. This phase will continue from the mining phase if either one of the two following criteria is true: The amount of water was extracted successfully or the maximum "stay" time in the asteroid was reached (value determined according to mission analysis). The "stay" time should be around 1 month (30 days) and this should be determined taking into consideration the cruising time and the available departure window to reach Earth with the extracted material. During this phase, the spacecraft shall departure the asteroid and reorient itself in order to enter cruise mode in return to Earth.

- P5. Docking Phase. The docking phase shall begin at the moment the spacecraft reaches the usable orbit. In this phase, most operations shall be monitored by the ground segment in order to have a successful docking with the corresponding station or spacecraft.

The phases' connection is also described in figure 7.

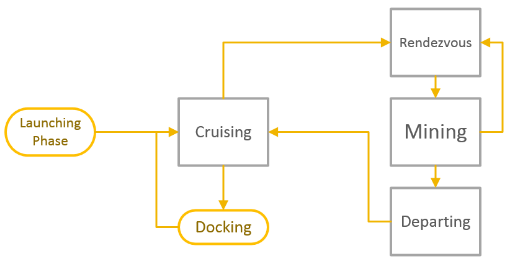


Figure 7. Mission Phases and connections

From the trajectory analysis and the other constraints, a set of time constraints can be specified:

- The mission time from parking orbit departure to the return to a usable orbit with the collected material shall be enclosed within a year (365 days) period.
- Real mining operations shall be performed in a 30 days period.
- Prospection, adaptation and landing shall be performed in a 15 days period.
- A mining path is defined for the round trip, once the water is extracted. The water extracted is divided into refueling water and deliverable water. The deliverable water adds automatically mass to the spacecraft that translates into dry mass as, "theoretically", it cannot be used as propellant. The spacecraft then transports the deliverable water to a usable orbit and travel back for another asteroid rendezvous where it can be refueled again. Therefore, the spacecraft needs to extract enough water for the whole journey described.

3.2.2. *Mining Path*

The mining path, as defined before, represents the round trip starting at the departure point from the asteroid until it reaches the next asteroid in which it can be refueled. The spacecraft is not supposed to be refueled in any other point during this journey. The propulsion water used for traveling must be enough for the venture and this limits the total water extracted in terms of power and the maximum distance or rendezvous. A schematic of the mining path is shown in figure 8.

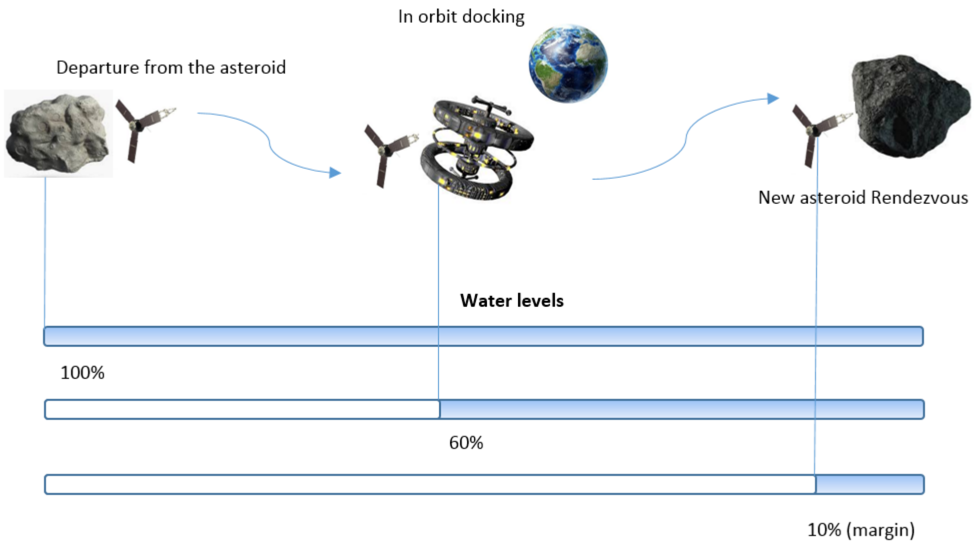


Figure 8. Schematic of the mission's mining path.

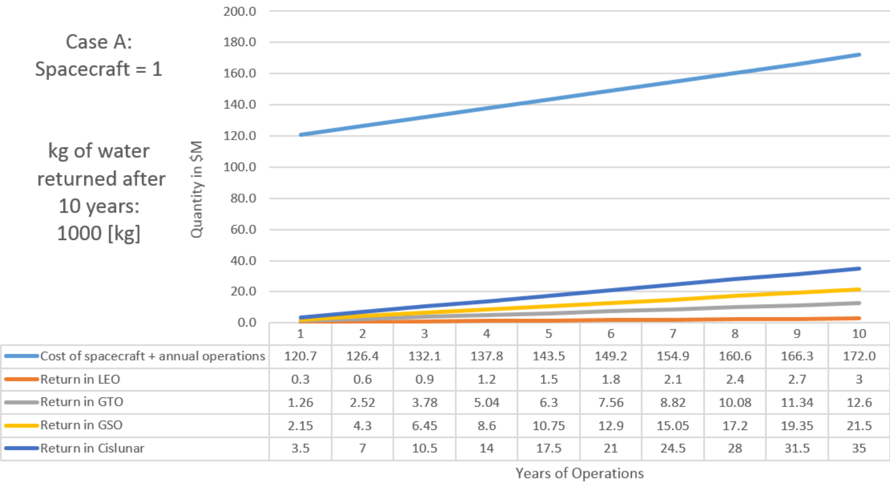
3.3. *Business Case Analysis*

The cost estimation leads to an economic return analysis. In this part, the mass production is spacecraft is assessed. For the calculations, the cheapest cost of putting 1 [kg] in an Earth orbit is considered. The improvement in the launch vehicles allow a lower price per [kg] and this price is assumed as the top price in which a kg of water returned from the mission can be sold. At the same time, the launchers provide with higher weight capacity for transport and it can be also assumed that a heavy launcher would be able to put in orbit several spacecraft in a single launch. The following parameters are considered and assumed for the calculations:

Cost of production of the first unit	**Cost of the launcher**	**Annual operations cost**	**Cost to put 1 [kg] to LEO**	**Cost to put 1 [kg] to GTO**	**Cost to put 1 [kg] to GSO**	**Cost to put 1 [kg] in Cislunar**
$65.5M (From SSCM total cost – launcher – Flight software cost(R&D))	$22M (Minotaur IV) $270M (Falcon Heavy estimated cost to send 53 tons to LEO)	$5.7M (average cost)	$3K (Price based on the Proton-M cost)	$12.6K (Price based on the Falcon-9 cost)	$21.5K (Price based on the Proton-M cost)	$35K (Estimated value)

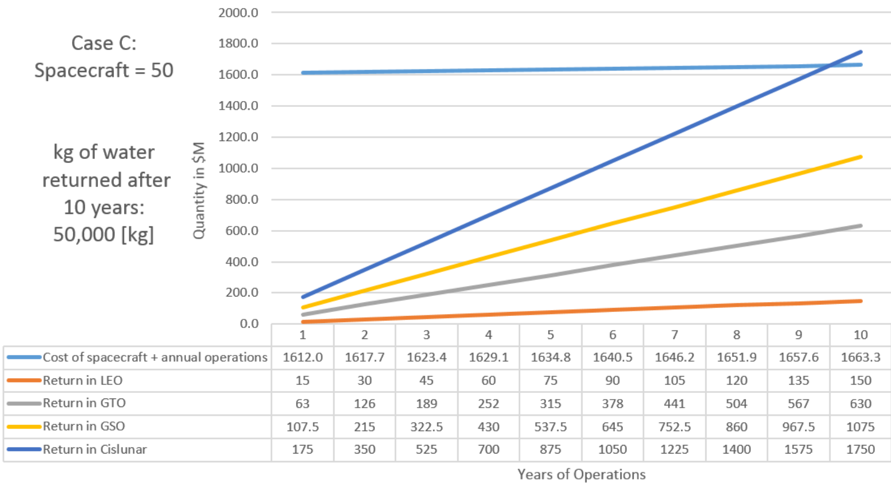
Table 7. Parameters and assumptions for the economic return analysis. [12]

With the defined parameters, and applying a learning curve, economic return graphs are generated. Some of the graphs are displayed in figures 9, 10 and 11.



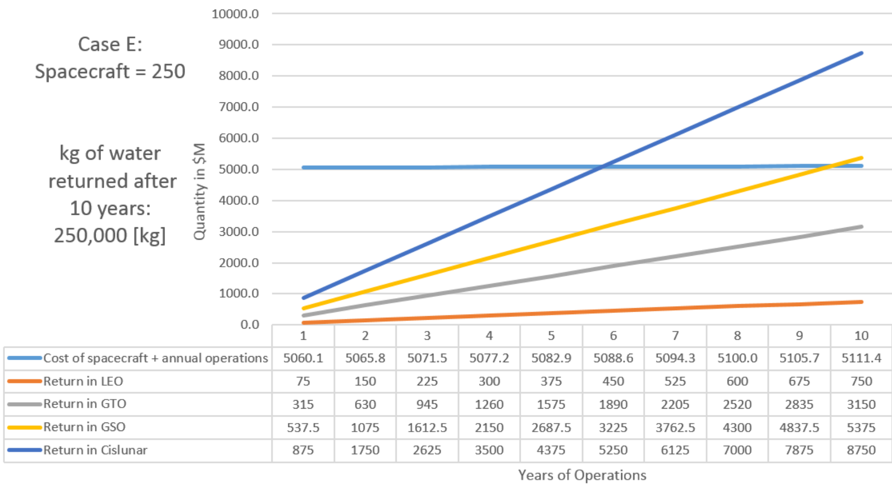
	1	2	3	4	5	6	7	8	9	10
Cost of spacecraft + annual operations	120.7	126.4	132.1	137.8	143.5	149.2	154.9	160.6	166.3	172.0
Return in LEO	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3
Return in GTO	1.26	2.52	3.78	5.04	6.3	7.56	8.82	10.08	11.34	12.6
Return in GSO	2.15	4.3	6.45	8.6	10.75	12.9	15.05	17.2	19.35	21.5
Return in Cislunar	3.5	7	10.5	14	17.5	21	24.5	28	31.5	35

Figure 9. Cost analysis and economic return for one spacecraft.



	1	2	3	4	5	6	7	8	9	10
Cost of spacecraft + annual operations	1612.0	1617.7	1623.4	1629.1	1634.8	1640.5	1646.2	1651.9	1657.6	1663.3
Return in LEO	15	30	45	60	75	90	105	120	135	150
Return in GTO	63	126	189	252	315	378	441	504	567	630
Return in GSO	107.5	215	322.5	430	537.5	645	752.5	860	967.5	1075
Return in Cislunar	175	350	525	700	875	1050	1225	1400	1575	1750

Figure 10. Cost analysis and economic return for fifty spacecraft.



	1	2	3	4	5	6	7	8	9	10
Cost of spacecraft + annual operations	5060.1	5065.8	5071.5	5077.2	5082.9	5088.6	5094.3	5100.0	5105.7	5111.4
Return in LEO	75	150	225	300	375	450	525	600	675	750
Return in GTO	315	630	945	1260	1575	1890	2205	2520	2835	3150
Return in GSO	537.5	1075	1612.5	2150	2687.5	3225	3762.5	4300	4837.5	5375
Return in Cislunar	875	1750	2625	3500	4375	5250	6125	7000	7875	8750

Figure 11. Cost analysis and economic return for two hundred and fifty spacecraft.

From the economic return graphs it is clearly noticeable that the only economic return scenario to make the venture feasible is the Cislunar orbit. To make the venture economically feasible, mass production of the spacecraft is essential. The first breakpoint is seen in "case C" which involves the production of fifty spacecraft for the venture in which their cost is reduced due to economies of scale. The return turns positive for the last year of the operations. It is important to highlight as well that several spacecraft can be launched by the use of only one launch vehicle such as the Falcon Heavy as it comes operational.

4. Conclusions

From the asteroid water mining architecture analysis, the following conclusions were reached:

- The venture is technologically feasible. With the current technology and development, such a venture is possible combining the appropriate components to assess each of the mission stages described.
- The use of lighter materials for the water extraction would directly reduce costs as the payload weight signifies more than half the dry weight of the spacecraft.
- The improvement on the technologies for water extraction using microwaves could highly impact the amount of water that can be extracted from a hydrated asteroid. The efficiency measured by w/gr of water is a determining factor for improving specifically the travel distance and the water deliverable capacity that can be transported to a usable orbit.
- Considering several spacecraft for the mission increases the reliability of the system reducing risks. The occurrence of a single point failure that ends with the loss of a spacecraft will not affect significantly the venture.
- Water based propulsion systems need to reach higher efficiency levels and establish itself as a reliable and mature technology.
- Software improvements for a higher degree of autonomy is also important. There is the need to program all the spacecraft operations and the development of integrated systems is also imperative for the venture.
- For the venture to be economically feasible, a series of factors need to be improved. The overall cost of the spacecraft should be reduced by using cheaper by equally reliable technology for the payload and bus. The spacecraft needs to be proved and then mass produced in order to have a positive economic return. It was also highlighted that the orbit in which there could be a positive economic return of investment is Cislunar orbit.

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