Originally presented at Houston Annual Technical Symposium (May 17, 2013)

Updated on August 17, 2014

An Improved Economic Model for Asteroid Mining

Shen Ge, Experimental Center for Applied Physical Systems LLC
Neha Satak, Experimental Center for Applied Physical Systems LLC

Abstract

Asteroid mining is drawing increasing interest with the establishment of two space companies in 2012 publicly declaring their intention of mining asteroids. However, the economics model necessary to analyze the feasibility of asteroid mining initiatives has not advanced in the last decade which presents a significant challenge for these companies and future startups to attract significant investment for such capital projects. Specifically, no significant additions have been added to Mark Sonter's net present value equation for asteroid mining since his thesis was published in 1997. This paper serves to address both the technical and economic factors required to determine a future asteroid mining mission's feasibility. Building upon the Sonter equation, the Ge-Satak equation introduces new variables to cover the gaps and resolves uncertainties in the previous equation.

Acronyms

GEO	Geostationary Earth Orbit
HEEO	Highly Eccentric Earth Orbit
LEO	Low Earth Orbit
NEA	Near-Earth Asteroid
NPV	Net Present Value

1. Introduction

The present perception of limited resources and resource wars stemming from resource shortages in basic commodities including volatiles such as oil or water and metals such as rare earth metals or platinum group metals have taken headlines. Likewise, space commercialization is held back by the high entry cost due to the exorbitant cost of launch vehicles. A price drop in launch vehicles originating from the developments of private space companies initially fueled by the market of space tourism and small satellites can lead to affordable access to low earth orbit and beyond.

Due to the growing demand for resources as the world economy grows as well as the increasingly affordable access to space, the current "Limits of Growth" paradigm in the public's mind can be replaced by a more optimistic view of near infinite resources obtainable in the next two decades in space. Considerations of long-term prosperity of humanity point toward space colonization, focusing on the plentiful and diverse material resources in the asteroids, the most easily accessible and resource-varied celestial bodies in the solar system (Sonter, 1997).

This paper first provides an overview of both the technical and economic factors required for an asteroid mining project to be financially feasible. Building upon Sonter's seminal thesis, a new economic equation is presented which includes a more comprehensive scenario than Sonter analyzed. Finally, a scenario for a robotic mission to travel to the asteroid 1996 FG3, the baseline for ESA's asteroid sample return mission MarcoPolo-R, is analyzed for the net return of mining those asteroids.

2. Economic and Technical Factors

To justify this optimism requires an integration and analysis of detailed technical and economic factors. These economic and technical factors include (Campbell, 2009):

a) The **demand** of the market in both space and Earth in the next two decades for products produced and delivered.
b) The **supply** in both material composition and extractable volume from the asteroids which can be characterized by both spacecrafts and telescopes.
c) The **orbital parameters** of particular asteroids that can provide accessible trajectories within a sufficient budget and time.
d) Feasible **mining and processing technologies** to allow successful drilling, mining, and any necessary space refining developable in the next two decades.
e) A **positive net present value** in investment that can be derived from these factors.

Present and future markets can be divided into a space-based market and an Earth-based market (Ross, 2001). In space, there is a growing interest in research and manufacturing of high value pharmaceuticals, semiconductors, ultra-pure crystals, etc. which requires large-scale material purity. Space tourism is also growing with market studies by Futron showing that as many as 80% of people younger than 40 are interested in commercial space travel. Many are willing to pay up to three months of salary to do so while 10% are willing to pay a year's salary. Space hotels by Bigelow Aerospace or Shimizu Corporation will require on-orbit manufacturing and assembly that may be conveniently and affordably served by raw materials from asteroids.

On Earth, precious metals and fossil fuels are becoming increasingly depleted. New terrestrial sources are obtained at increasing economic and environmental cost (Ross, 2001). Higher prices for manufactured goods, undeveloped technologies due to lack of raw materials, global and regional conflicts due to commodity competition, and environmental damage from less accessible deposits are all growing concerns.

Space mined materials used in LEO can include metals for construction, unprocessed mass as cosmic radiation shields, and volatiles. Volatiles including water, oxygen, and nitrogen for humans and carbon dioxide and nitrogen for agriculture are needed for permanently manned space habitats (Nichols, 1994). They can also be used as propellants for satellites and spacecrafts. Many asteroids are abundant in water which can be broken down into hydrogen and oxygen for rocket fuel and oxidizer. Lastly, volatiles are useful in metal processing. For instance, carbon monoxide is essential to the carbonyl process for low-temperature purification and the deposition of iron and nickel.

The useful products obtainable from asteroids are shown in Table 1 which highlights both volatiles and metals. Taking a look at platinum group metals (PGMs), there is increasing demand on Earth. Platinum, rhodium, iridium, palladium and gold have the primary dual markets of industrial uses and precious metals (Blair, 2000). Primary industry uses of PGMs include emissions-control catalysts, chemical refinery components, and manufacturing of electronics and hard disks. Precious metal uses include jewelry and investment products.

Table 1: Volatiles and metals found in asteroids are categorized by primary use (Ross, 2001).

Volatiles	
Primary Use	**Molecules**
Life Support	H_2O, N_2, O_2
Propellant	H_2, O_2, CH_4, CH_3OH
Agriculture	CO_2, NH_4OH, NH_3
Oxidizer	H_2O_2
Refrigerant	SO_2
Metallurgy	CO, H_2S, $Ni(CO)_4$, $Fe(CO)_5$, H_2SO_4, SO_3
Metals	
Primary Use	
Construction	Fe, Ni
Jewelry	Au, Pt, Rh
Catalytic converters	Rh, Pd, Pt
Fuel cells	Pd, Pt
Radioisotope thermal generators	Ir
Jet and rocket engines	Re
Petroleum refining	Re
Special uses	Os, Ir, Ru, Rh
Electronics	Si, Al, Ge, P, Ga, Cd, Cu, As, Se, In, Sb, Te
Construction	Al, Si
Fiber optics	Ge
Transportation	Al
Household items	Al

2.1 Asteroid Geology

The compositions of asteroids are deduced from laboratory studies of meteorites and from spectral reflectivity studies of asteroids at ultraviolet, visible, and near-infrared wavelengths (Ross, 2001). Though there are many classes of taxonomies for asteroid types, Ross suggests a rough spectral taxonomy of three categories:

- C-type (carbonaceous): water-bearing with very high contents of opaque carbonaceous material
- S-type (stony): anhydrous rocky material of silicates, sulfides, and metals
- M-type (metallic): mostly metals

Near-earth asteroids (NEA), asteroids close to Earth with a perihelion less than or equal to 1.3 AU, are very diverse in composition and easily accessible. About half of the kilometer-sized NEA population is believed to be carbonaceous, and hence carbon-rich and water-rich. Carbonaceous asteroids are subdivided into five categories but only the first two categories are of interest due to their high water and volatile content. The estimated relative compositions of the asteroid types are shown in Table 2 based on four meteorites. For particular asteroids, the relative percentages of composition will differ.

Table 2: The four types of asteroids are shown here. Note that meteorites vary in composition and these are only representative of the four categories (Ross, 2001).

	Mineral	**C2-type**	**C1-type**	**S-type**	**M-type**
Free metals	Fe	10.7%	0.1%	6-19%	88%
	Ni	1.4%	--	1-2%	10%
	Co	0.11%	--	0.1%	0.5%
Volatiles	C	1.4%	1.9 – 3.0%	3%	--
	H_2O	5.7%	12%	0.15%	--
	S	1.3%	2%	1.5%	--
Mineral oxides	FeO	15.4%	22%	10%	--
	SiO_2	33.8%	28%	38%	--
	MgO	23.8%	20%	24%	--
	Al_2O_3	2.4%	2.1%	2.1%	--
	Na_2O	0.55%	0.3%	0.9%	--
	K_2O	0.04%	0.04%	0.1%	--
	P_2O_5	0.28%	0.23%	0.28%	--
Physical	Density (g/cm^3)	3.3	2.0 – 2.8	3.5 – 3.8	7.0 – 7.8

2.2 Orbital Parameters

The trajectory required to reach an asteroid is highly dependent on the asteroid's orbital parameters. In space, delivering mass from one orbit to another does not depend on distance but rather on the required velocity change, delta-v. Table 3 shows a list of delta-v requirements for various transfers. Here, the delta-v for a near earth asteroid is assumed to be the minimum for known NEAs.

Table 3: Delta-v requirements for various orbital transfers are shown (Ross, 2001).

Transfer	**Delta-v (km/s)**
Earth surface to LEO	8.5
Earth surface to escape velocity	11.2
Earth surface to GEO	11.8
LEO to escape velocity	3.2
LEO to Mars or Venus transfer orbit	3.7
LEO to GEO	3.5
LEO to HEEO	2.5
LEO to Moon landing	6.3
LEO to minimum delta-v Near Earth Asteroid	4.0
Lunar surface to LEO (aerobraking)	2.4
NEA to Earth transfer orbit	1.0
Phobos or Deimos to LEO	8.0

Considering the low delta-v required in traveling to NEAs as opposed to asteroids in the main belt between Mars and Jupiter or the Jupiter Trojans at the Jupiter stable Lagrangian points, mission trajectories to NEAs are considered most feasible. The NEAs are classified into Apollos, Amors, Atens, and Arjunas with orbital parameters shown in Table 4.

Table 4: NEAs are divided into four groups based on their orbital elements perihelion distance (q), aphelion distance (Q), and semi-major axis (a).

	Apollos	Amors	Atens	Arjunas
Perihelion (q)	q < 1.017 AU	q > 1.017 AU	q < 1.0 AU	q ~ 1.0 AU
Aphelion (Q)	Unconstrained	Unconstrained	Q > 1.0 AU	Q ~ 1.0 AU
Semi-major axis (a)	a > 1.0 AU	a > 1.0 AU	a < 1.0 AU	a ~ 1.0 AU
Eccentricity (e)	Unconstrained	Unconstrained	Unconstrained	e ~ 0
Inclination (i)	Unconstrained	Unconstrained	Unconstrained	Unconstrained

2.3 Mining Technology

The mining system model follows four stages of exploration, rock breaking, excavating, and processing. For mining water, only the exploration and excavating stages are necessary. Exploration approaches depend on the material but in all cases, the mining machinery must be firmly anchored to the asteroid surface to prevent drifting off due to low gravity (Sonter, 1997). A typical low gravity body such as the asteroid 1999 JU3, the target of JAXA’s Hayabusa 2, with an estimated radius of 460 m and a density of 1300 kg/m^3 will have a gravitational attraction of only $1.672 * 10^{-4}$ m/s^2 at the surface, about 0.001% times less that of Earth’s (Herrman et al., 2011). The escape velocity from such an asteroid with spherical approximation is estimated to be ~0.392 m/s.

Herrman et al.’s studies have shown that for a rover, the disturbance from the rover wheels moving across a rock or gap can lead to a lift-off of one or more wheels. The rover cannot continue until the wheels land back on the surface. Simulations conducted by the team show that at 1% of Earth’s gravity, locomotion is complicated and at 0.001% of Earth’s gravity, locomotion is impossible. Hence, traditional rovers such as those used in the exploration of the moon or Mars would not work. Instead, a hopper which uses rocket engines to jump from one site to another is a more feasible option.

Another option is the use of a cliff hanger or rocket climber under development by Yoshida et al. which can grasp onto the rocks (Yoshida et al., 2002). The robot has three sets of limbs with a sticker at the end and walks over the surface with these limbs. Like a laparoscopic forceps, the end of the limb has jaws to hold to the surface of the asteroid. It can also pick up rock fragments and scoop soft regolith if it exists.

Basic construction and resource recovery activities on asteroids can be on the surface, underground, or a combination of both (Chamberlain et al., 1994). Methods must be matched with deposit characteristics. Early space mining and excavation activities likely will feature small, simple machines suitable for excavating and for doing other construction activities. Design criteria for surface mining and construction equipment are frequently in conflict. According to Chamberlain et al., the key factors in designing this equipment include

1. Simplicity
2. Ruggedness and robustness
3. Flexibility
4. Availability of technology
5. Low energy requirements
6. Low mass
7. Automation
8. Tribology (bearings and seals)
9. Availability of fabrication materials

If the material is surface regolith, a scooper or scraper with a container will be needed. The second stage, rock breaking, may be necessary for hard rocks. If hard rock mining is to be done, rocks will need to be broken into smaller pieces and collected into a closed container. There are various methods of achieving this currently under development by the South African mining industry as shown in Table 5. The South African Space Resources Association believes that while their country develops robotic technologies for mining narrow gold mines, South Africa also simultaneously develops technology for space mining (Neale, 2011).

Table 5: Four techniques of rock breaking for hard rock mining are shown.

Technique	**Output (m^3/min)**	**Specific Energy (J/cc)**	**Power (W)**	**Mass (kg)**
Controlled Foam Injection (CFI)	10.19	2.49	0	2000
Electric Rock-breaking	0.075	15.8	40000	TBD
Microwave Drilling	.000314	TBD	600	1
Diamond Wire Sawing	.036	TBD	TBD	TBD

Controlled Foam Injection (CFI) as shown in Figure 1 is a method based upon the use of high pressure foam as the fracturing medium (Harper, 2008). Foam, a two-phase mixture of a liquid and a gas, is made with a viscosity several orders of magnitude higher than a gas or even water, and will provide pressures for efficient controlled fracturing without really high pressures needed by other methods such as explosives, propellants, water cannons, or electrical discharges.

Figure 1: Controlled Foam Injection method of rock excavation developed by CFI Technologies, Inc. (Harper, 2008).

Tetra Corporation has developed a technology called the Electric Discharge Drilling (EDD) which can remove rocks at a rate of 0.5 to 2.5 cc per pulse with frequencies of 20 to 200 pulses per second (Harper, 2008). An electric discharge produced plasma in surrounding water which results in a high pressure shock wave which then breaks the rock.

Microwave drilling is in the research phase at the University of Tel Aviv and has been demonstrated an ability to drill in South African host rocks (Harper, 2008). Microwaves are guided along a metal pin to produce localized heating and melting ahead of the pin; the advancing pin displaces the molten material.

Diamond sawing is a wire which consists of diamond-impregnated cutting elements threaded onto a steel cable (Harper, 2008). The wire then rotates at high speed and pulls through the rock across the face to be cut. The diamond wire rope has been used on the Nederburg Miner for the removal of coral reefs.

Two categories of underground mining systems used on Earth are drill-blast-muck mining and mechanical mining (Chamberlain et al., 1994). For space applications, the latter is more applicable. The four general types of mechanical mining systems available on Earth which can be used in space are tunnel boring machines, drum-type continuous miners, roadheaders, and rock splitters. Table 6 highlights the advantages and disadvantages of each mechanical mining system.

Table 6: The four types of mechanical mining systems with advantages and disadvantages of use in space are shown here (Chamberlain et al., 1994).

Mechanical Mining Systems	**Advantages**	**Disadvantages**
Tunnel boring machine (TBM)	--	Massive size Inflexible
Drum-type continuous miner	Moderately flexible	Massive size High-power requirements
Roadheader	Versatile	Limited to small- to medium-scale operations
Rock splitter	Can be modified for space-use	--

The extraction of volatiles requires a different set of systems from that of extracting rock. For instance, extracting water ice from icy soils can be achieved by a system currently being developed by Honeybee. The Mars In-situ Water Extractor (MISWE) currently under development there consists of the Icy-Soil Acquisition and Delivery System (ISADS) and the Volatiles Extraction and Capture System (VECS) (Zacny and Paulsen et al., 2012). The ISADS is a deep fluted auger which drills into the ice. When enough material is extracted, the ISADS is retracted into the VECS and sealed. The VECS has a cylindrical heat exchanger and volatile transfer system.

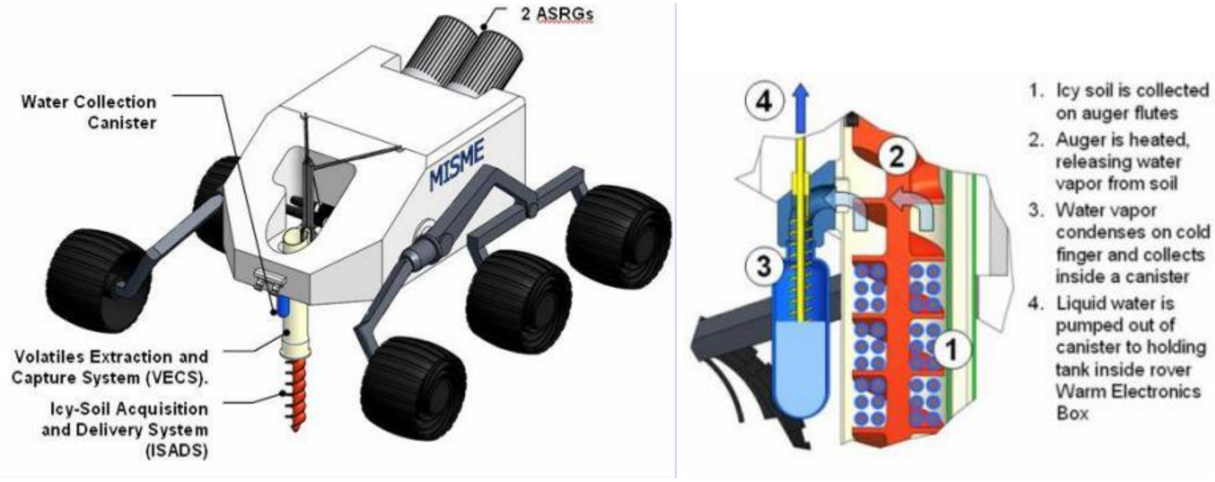


Figure 2: Mars In-situ Water Extractor (MISWE) (Zacny and Paulsen, et al., 2012).

MISWE as shown in Figure 2 is designed to be deployed from a mid-size rover or a lander. The ISADS auger is 10 cm in diameter and drills up to 50 cm deep. The volume of sample per single operation is ~3500 cc with a mass of ~5 kg at 1.5 g/cc material density, a representative sample of ice and soil. The proof of concept's drilling power was ~100 watts and the penetration rate was 1 m/hr. Preliminary tests recovered more than 50% of water in the soil. The sequence of operations is as follows (Zacny and Chu et al., 2012),

1. The MISWE lowers and preloads the VECS sleeve onto the rock-free surface.
2. ISADS auger starts drilling and acquires icy-soil.
3. Upon reaching the target depth, ISADS auger retracts from the hole back into the VECS sleeve.
4. MISWE moves into a new location and preloads the VECS sleeve against a fresh surface creating a seal.
5. ISADS starts heating up the icy-soil.
6. Pump liquid water into a storage tank within the Warm Electronics Box.
7. VECS moves up exposing the ISADS auger.
8. ISADS auger spins ejecting dry soil.
9. ISADS auger moves into the stowed position.
10. Rover moves onto next location.

The water heating method uses conductive heating. Conductive heating can be achieved with a simple resistive heater, which can be embedded within the auger or mounted to the auger surfaces. To generate electricity for heating, two ASRGs need to charge batteries for at least four hours. Hence, the MISWE water extraction process would take a 4-hour break after every cycle to recharge its batteries.

The last stage of processing depends on the type of metal or volatile. For hard rocks or a volatile such as water, bringing it back to Earth for processing may be the most economically feasible option.

3. Net Present Value

3.1 Sonter's Model

Sonter in his seminal thesis and subsequent papers on economics of asteroid mining has repeatedly stressed the use of net present value (NPV) as an accurate measure of project merit over a project time period (Sonter, 1997). Presently, large ventures on Earth including mining companies use NPVs to determine whether a project is financially feasible so as to determine which projects to invest resources in.

The NPV calculates the present value of receipts of money to be received years in the future, including the effects of interest that the invested money could have been earning. In the NPV calculation, the factors to be minimized and maximized are as shown in Table 7.

Table 7: Factors to minimize and maximize for NPV calculation are indicated (Sonter, 1997).

Minimize	**Maximize**
Capital required	Revenue
Time before income stream	Number of products
Technical innovations required	Number of customers
Market fluctuation sensitivity	Market size

Sonter formulated a NPV based on the rocket equation and mining principles. Starting from the base formula of a NPV for a single payback receipt,

$$\text{NPV} = \text{R}(1+\text{i})^{-\text{n}} - \text{C, where}$$

n = time from capital-raising to launch + T_x (transfer orbit time) + time from Earth-capture to sale

i = discount rate (rate of return that can be earned on an investment in financial markets with similar risk)

$T_x = a^{3/2}$ where a is the semi-major axis of the transfer orbit from the asteroid back to Earth

R = C_{orbit} (unit value of mass in orbit) * $M_{returned}$ (mass of volatiles returned for sale)

$M_{returned} = M_{produced} * \exp(-\Delta v/v_e)$

$M_{produced} = M_{mined}$ * r (% recoverable of valuable material)

$M_{mined} = M_{mpe}$ (mass of mining and processing equipment in kg) * f (throughput factor in kg/day per kg of equipment) * t (mining period in days)

v_e = exhaust velocity of the rocket engine in km/s

$\Delta v = \sqrt{\Delta v^2_{ecliptic-transfer} + \Delta v^2_{inclination-change}}$ in km/s if the line of nodes is coincident with the line of apsides

$\Delta v_{inclination\text{-}change} = 0.5 * i$ (inclination change in degrees) in km/s

C = C_1 (capital costs) + B (annual budget) * n (years until return)

$C_1 = C_{manuf}$ (specific cost of manufacture of miner in \$/kg) * ($M_{mpe} + M_{ps} + M_{ic}$) where M_{ps} is the mass of the power source and M_{ic} is the mass of the instrumentation and controls

Combined, this equation becomes

$$NPV = C_{orbit} M_{mpe} f t r e^{-\frac{\Delta v}{v_e}} (1+i)^{-a^{3/2}} - [C_{manuf}(M_{mpe} + M_{ps} + M_{ic}) + Bn]$$

There are several limitations to the Sonter equation which needs to be highlighted. First, since Sonter only considers on-orbit usage of material, for the receipt (R), he assumes that the upper limit on selling the resources is the $/kg launch cost. In other words, if a launch vehicle costs $10,000 to deliver 1 kg of material up to LEO, the asteroid mining company must sell 1 kg of material it mined at less than $10,000. Sonter does not consider lower market caps due to an existing space manufacturing market.

Second, though Sonter takes into account the delta-v required for the return trip since he makes the assumption some of the asteroid material mined will be used as propellant for the return trip, he does not take into account the delta-v required to reach the asteroid at all. The delta-v to the asteroid (and the delta-v back to Earth as well to be more detailed) need to be taken into account to model the total spacecraft mass including propellant which directly affects the spacecraft's cost and the launch cost.

3.2 New Model of NPV

The new model of net present value developed by Ge and Satak takes into account parameters which Sonter's NPV neglected. The Ge-Satak equation takes the form,

$$NPV = P - C_M - C_L - C_R - C_E, \text{ where}$$

P = returned profit ($)

C_M = Manufacturing cost ($)

C_L = Launch cost ($) is equal to $m_{s/c}$ (mass of spacecraft) * u_{LV} (unit mass cost based on the performance of the cheapest launch vehicle capable of launching the spacecraft mass). Note that the mass of spacecraft is calculated based on the payload fraction and the spacecraft payload.

C_R = Recurring cost ($) is equal to B (annual operational expense) * T (total time)

C_E = Reentry cost ($) is equal to $M_{returned}$ (mass returned) * f_e (fraction of material sold on Earth) * u_{RV} (unit mass cost based on the performance of the cheapest return vehicle capable of returning the mass to Earth)

The returned profit and the manufacturing cost can be expressed in its own respective equations. The returned profit can be expressed as such,

$$P = \frac{[V_s(1 - f_e) + V_e f_e] M_{returned}}{(1 + i)^T}$$

where,

Vs = Value in space ($)

Ve = Value on Earth ($)

f_e = Fraction of material sold on Earth

$M_{returned} = M_{produced} * \exp(-\Delta v_r/v_e)$

$M_{produced} = M_{mined} * r$ (percentage recoverable of valuable material)

$M_{mined} = M_{mpe}$ (mass of mining and processing equipment in kg) * f (throughput factor in kg/day per kg of equipment) * t (mining period in days)

v_e = exhaust velocity of the rocket engine in km/s

$\Delta v_r = \sqrt{\Delta v^2_{r,ecliptic-transfer} + \Delta v^2_{r,inclination-change}}$ in km/s is delta-v for asteroid to Earth return trip (assume line of nodes is coincident with the line of apsides)

$\Delta v_{r,inclination-change} = 0.5 * i$ (inclination change in degrees) in km/s

i = discount rate (rate of return that can be earned on an investment in financial markets with similar risk)

T = total time which is $a_1^{3/2} + a_2^{3/2} + t/365$ where a_1 is the semimajor axis of the trajectory from Earth to the asteroid in AUs, a_2 is the semimajor axis of the trajectory from the asteroid to Earth in AUs, and t is the mining period in days

The manufacturing cost can be expressed as such,

$$C_M = C_{miner} + C_{spacecraft}$$

where,

C_{miner} = cost of miner ($)

$C_{s/c}$ = cost of spacecraft ($)

Though there are many ways to estimate the cost of a miner and a spacecraft, a basic estimate based on the mass of the miner and the spacecraft respectively is a good first order estimate. The cost of the miner is assumed to be linearly dependent on the mass of the miner whereas the cost of the spacecraft is assumed to be dependent on the payload mass, i.e. mass of the miner, and the payload fraction, i.e. the fraction of mass that is the payload.

$$C_{miner} = M_{mpe}u$$

$$C_{s/c} = 10^6(225 + \frac{M_{mpe}p_f}{8})$$

where,

u = unit cost of miner ($/kg)

p_f = payload fraction defined as

$$p_f = \frac{e^{-\Delta v_t/v_e} - s_f}{1 - s_f}$$

where,

s_f = structural fraction defined as the structure mass over the structure and propellant mass

$\Delta v_t = \sqrt{\Delta v_{t,ecliptic-transfer}^2 + \Delta v_{t,inclination-change}^2}$ in km/s is delta-v for Earth to asteroid trip (assume line of nodes is coincident with the line of apsides)

$\Delta v_{t,inclination\text{-}change}$ =0.5 * i (inclination change in degrees) in km/s

Note that the payload fraction is assumed to be dependent on the delta-v for the Earth to asteroid trip.

4. Results

Before doing any calculations on future real asteroid missions, parameters for constants must be assumed as shown in Table 8. These parameters will remain constant regardless of which asteroid is the target for mining. For simplicity's sake, the resource to be extracted is assumed to be water. Defining a demand and supply curve to find the cost of water is beyond the current scope of this paper but a simple analysis can be done assuming that if there is insufficient supply (demand > supply), the cost of the water will be exorbitantly high and cheaper if there is sufficient supply (supply > demand).

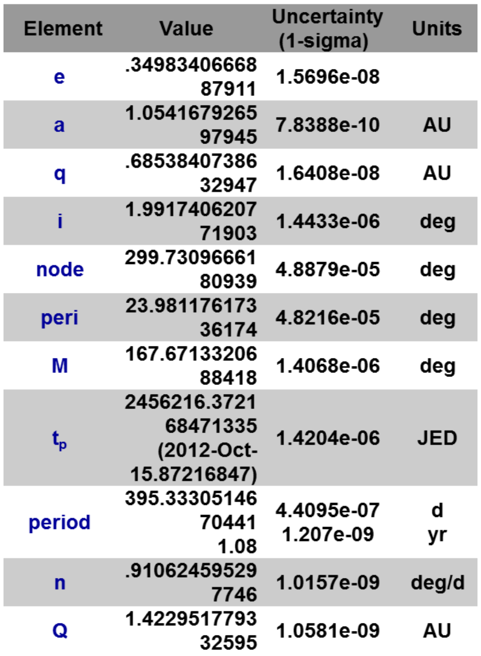
On Earth, the most expensive place for water is currently in Europe where it can reach ~$8.00 per meter cubed (1000 liters). In space, this will still be considered extraordinarily cheap and hence a rough estimate is that even with asteroid-mined water, water prices will remain high at ~$10.00 per liter.

Table 8: Shown here are for the constants of any mission to mine a water-based asteroid.

Parameter	Definition	Value
V_s	Value of material in space	\$200.00/L if demand > supply \$10.00/L if supply > demand
V_e	Value of material on Earth	0 USD (for water)
f_e	Fraction of material sold on Earth	0% (for water)
U	Unit cost of miner	10^6 \$/kg
s_f	Structural fraction	0.3
M_{mpe}	Mining equipment mass for water	30 kg (based on guess from 3500 N water extractor)
r	Percentage recoverable material	12% (assuming water on a carbonaceous asteroid)
f	Throughput factor	0.8333 kg mined/kg equipment/day (assuming water extraction)
B	Recurring expense	10^6 \$/year
i	Discount rate	10%
isp	Specific impulse of the rocket engine. Multiply by 9.8 m/s^2 to find the exhaust velocity	410 seconds

The example case uses the asteroid 1996 FG3 which is the baseline of ESA's MarcoPolo-R mission. Its orbital parameters are obtained from NASA JPL's NEA database and are depicted in Table 9. Using a two-impulse ballistic interplanetary trajectory optimization solver with the NASA JPL ephemeris and the SNOPT NLP algorithm, several optimal dates required for the initial departure from Earth and the departure from the asteroid are found. The travel time, mining time, and the total time is then factored into the Ge-Satak NPV equation and the NPV with respect to the total time and the mining time calculated. Results indicate that selling ~1500 kilograms of mined water at \$200.00 per liter (kg) yields the highest positive NPV, that of \$763,370,000. As shown in Figure 3 and Figure 4, this is neither the greatest mining time nor the least total time which indicates that a tradeoff exists between balancing the quantity of resources mined and the time it takes for the resources to return to Earth. The ultimate mission times start from an Earth departure on June 14, 2019, followed by an asteroid rendezvous on February 19, 2021. A mining period of two and a half years then ensues. The spacecraft with the extracted water departs on September 28, 2023 and arrives back at Earth orbit on March 22, 2014. The flight path with coordinates is depicted in Figure 5.

Table 9: The orbital parameters of near earth asteroid 1996 FG3 gathered from the NEA database at NASA JPL are shown here.



Element	Value	Uncertainty (1-sigma)	Units
e	.3498340666887911	1.5696e-08	
a	1.054167926597945	7.8388e-10	AU
q	.6853840738632947	1.6408e-08	AU
i	1.991740620771903	1.4433e-06	deg
node	299.7309666180939	4.8879e-05	deg
peri	23.98117617336174	4.8216e-05	deg
M	167.6713320688418	1.4068e-06	deg
t_p	2456216.372168471335 (2012-Oct-15.87216847)	1.4204e-06	JED
period	395.3330514670441 1.08	4.4095e-07 1.207e-09	d yr
n	.910624595297746	1.0157e-09	deg/d
Q	1.422951779332595	1.0581e-09	AU

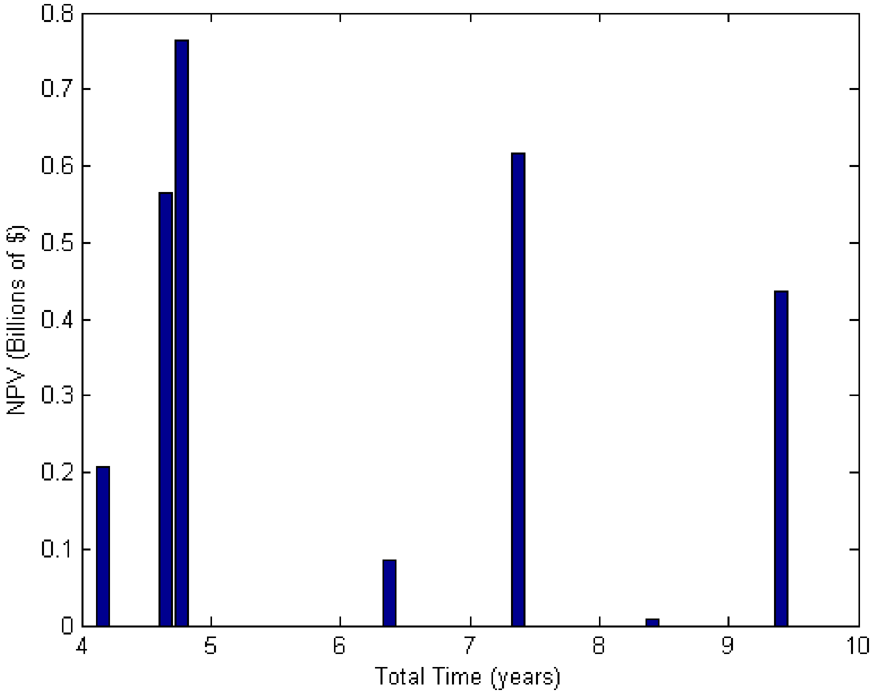


Figure 3: As can be seen, selling water at $200.00 per liter (kilogram) yields a NPV of $763,370,000.

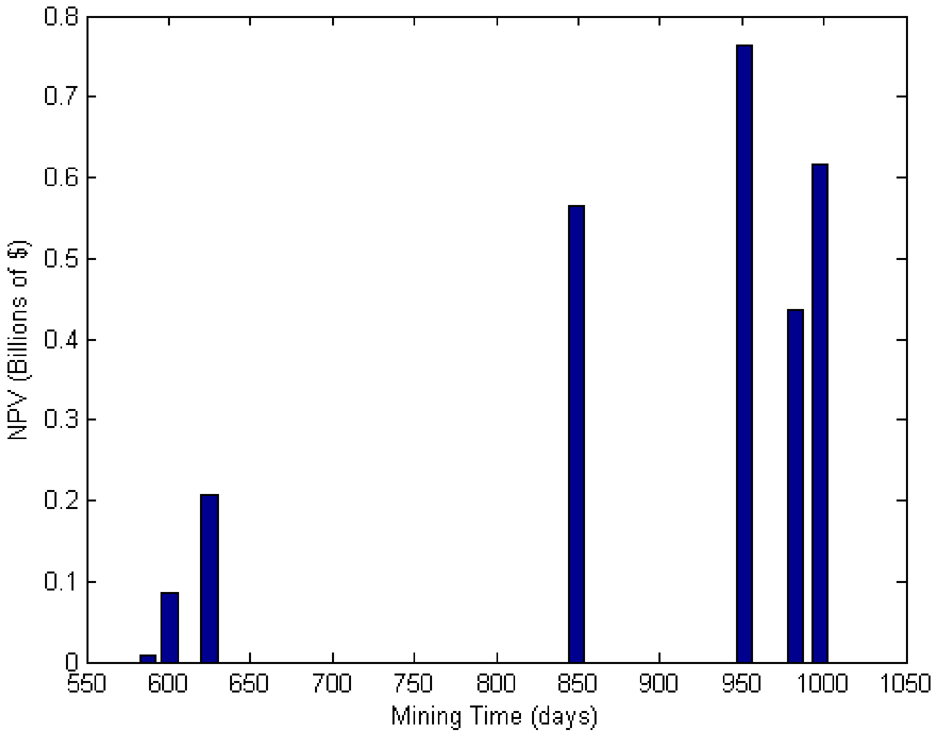


Figure 4: Both the mining time and the total time need to be optimized for maximum returns.

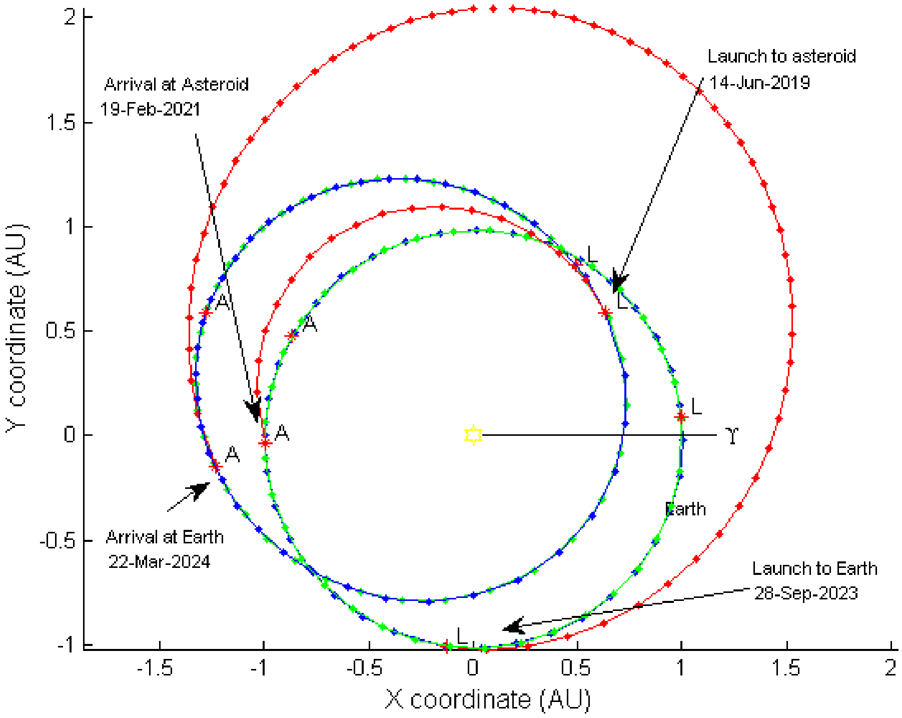


Figure 5: The trajectory to 1996 FG3 and back to Earth is shown by the colored lines.

A further analysis is conducted on the optimal price of the water. Though the initial assumption is selling water at $200 per kilogram for the space market, this price can be raised to $7000 per kilogram and still be competitive compared to launching water from Earth. Launching water from Earth is expensive due to the present price of launch costs. This price can be potentially raised even higher since delivering 1500 kilograms of water to orbit may require multiple launches depending on the type of launch vehicle used. The new price of $7000 per kilogram translates to a NPV of ~$9.3 billion, which is a significant difference from the ~$763 million based on original assumptions.

5. Future Work

In conclusion, Ge and Satak formulated a new net present value equation for asteroid mining which takes into consideration a wider range of variables to present a more rigorous and accurate economic model. Input variables such as the supply and demand curve, mining technologies, orbital trajectories, and propulsion methods can be further expanded and projected to provide an even more accurate economic model for determining the feasibility of future asteroid mining projects. Furthermore, each improved version of the economic model will assess a variety of target asteroids to provide a comprehensive picture of the opportunities available for asteroid mining.

References

Blair, Brad. "The Role of Near-earth Asteroids in Long-term Platinum Supply." *Space Resources Roundtable 2*. Golden, Colorado: Colorado School of Mines, 5 May 2000. Web. 1 Apr. 2013. < http://www.nss.org/settlement/asteroids/RoleOfNearEarthAsteroidsInLongTermPlatinumSupply.pdf>

Campbell, M., et al. "Developing Industrial Minerals, Nuclear Minerals & Commodities of Interest via Off-World Exploration and Mining." *AAPG EMD Annual Meeting.* Denver, Colorado: American Association of Petroleum Geologists, 9 Jun. 2009. Web. 20 Dec. 2012. < http://www.mdcampbell.com/spaceminingeconomics060909.pdf>

Chamberlain, P., Taylor, L., Podnieks, E., and Miller, R. "A Review of Possible Mining Applications in Space." *Resources of Near-Earth Space.* Ed. Lewis, J., Mildred, M., and Guerrieri, M. Tucson, Arizona: University of Arizona Press, 1994. 51-68. *University of Arizona Press.* Web. 8 Jan. 2013. < http://www.uapress.arizona.edu/onlinebks/ResourcesNearEarthSpace/resources03.pdf>

Faber, D., et al. "Prerequisites for New Mining Paradigms." *63rd International Astronautical Congress.* Naples, Italy: International Astronautical Federation, 2012. Print.

Harper, G. "Nederburg Miner." *Narrow Vein and Reef.* South Africa: South African Institute of Mining and Metallurgy, 2008. Web. 20 Jan. 2013. < http://www.saimm.co.za/Conferences/NarrowVein2008/08-Harper.pdf>

Hermann, F., Kuß, S., Schäfer, B. "Mobility Challenges and Possible Solutions for Low-gravity Planetary Body Exploration." ESA/ESTEC Report. 12-14 Apr. 2011. Web. 1 April 2013. < http://elib.dlr.de/69905/>

Neale, A. "Space Mining Applications for South African Mining Robotics." *4th Robotics and Mechatronics Conference of South Africa (RobMech 2011)*. Pretoria, South Africa: Advanced Robotic and Mechatronic Research Network, 23 - 25 Nov. 2011. Web. 1 Feb. 2013. < http://www.robmech.co.za/proceed/ROBMECH2011_Neale_Space%20Mining%20Application%20for%20South%20African%20Mining%20Robotics.pdf>

Nichols, Charles. "Volatile Products from Carbonaceous Asteroids." *Resources of Near-Earth Space.* Ed. Lewis, J., Mildred, M., and Guerrieri, M. Tucson, Arizona: University of Arizona Press, 1994. 543-563. *University of Arizona Press.* Web. 5 January 2013. < http://www.uapress.arizona.edu/onlinebks/ResourcesNearEarthSpace/resources21.pdf>

Ross, Shane. "Near-Earth Asteroid Mining." Space Industry Report. 14 Dec. 2001. Web. 10 Dec. 2012. < http://www2.esm.vt.edu/~sdross/papers/ross-asteroid-mining-2001.pdf>

Sonter, Mark. "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids." Diss. U of Wollongong, New South Wales, Australia, 1997. Web. 10 Dec. 2012. < http://www.nss.org/settlement/asteroids/MiningNearEarthAsteroids(Sonter).pdf>

Yoshida, K., Maruki, T., and Yano, H. “A Novel Strategy for Asteroid Exploration with a Surface Robot.” *34th COSPAR Scientific Assembly.* Houston, TX: Second World Space Congress, 10 – 19 Oct. 2002. Web. 1 Mar. 2013. < http://www.astro.mech.tohoku.ac.jp/~yoshida/paperlist/WSC02%20COSPAR%20B1,3-0033-02_old.pdf>

Zacny, K., Paulsen, G., Craft, J., Oryshchyn, L., Sanders, J., and Mueller, R. “Mars In-situ Water Extractor (MISWE).” *Concepts and Approaches for Mars Exploration.* Houston, TX: Lunar and Planetary Institute, 12 – 14 Jun. 2012. Web. 25 Mar. 2013. < http://www.lpi.usra.edu/meetings/marsconcepts2012/pdf/4268.pdf>

Zacny, K., Chu, P., Paulsen, G., Avanesyan, A., Craft, J., and Osborne, L. “Mobile In-situ Water Extractor (MISWE) for Mars, Moon, and Asteroids In Situ Resource Utilization.” *AIAA SPACE 2012 Conference & Exposition.* Pasadena, CA: AIAA, 11 – 13 Sep. 2012. Web. 25 Mar. 2013. < http://arc.aiaa.org/doi/abs/10.2514/6.2012-5168>