Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration*

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Abstract

NASA and US Government-sponsored research established the baseline working knowledge and systems for space exploration and continue to make important contributions to US National and to worldwide space exploration activities. We are in a transition period now, where private commercial interests and public-private partnerships are assuming more of the leadership in space activities and in research to support all aspects of space business. It is important to recognize the historically critical importance of NASA and US sponsored research, but the expansion of private activities following NASA initiatives is becoming more important. As an example, the support of the International Space Station by private supply missions illustrates the expansion of private industry into this once exclusively government task. How has private industry leveraged this activity to expand their capabilities, and how will this opportunity be leveraged by private industry to create a broader-based commercial space sector? We examine, from a qualitative standpoint, the various activities that are being driven by actual and planned commercial space activities, and then provide an initial quantitative assessment of returns for private businesses. The scope of this assessment begins with publicly announced efforts to return commercial quantities of rare earth elements and precious metals from metallic asteroids, and then focuses on the “found” value of supporting materials, such as ice, building materials, such as iron, and regolith, such as dust that can be used as shielding and formed into bricks for walls or mass for shielding. Incidental to the high-valued opportunities related to metallic asteroids, our initial conclusions indicate that ice acquisition and use in situ for life-supporting atmosphere, fuel supply and production of energy from uninterruptable solar energy collectors may be as important as focusing on capturing metallic asteroids. As a comparison with historical precedent, consider the businesses that supplied the gold mining efforts in California during the 1800s; more consistent and long-lived businesses were established from providing supplies to the miners than were made by the miners.

Selected References


**Website**

Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

Making Space Exploration Affordable

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Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

We know ISRU is practical, when and where is it profitable?

1. In Orbit;
   1. Fuel Depot, using residual fuel from other launches
   2. Fuel Depot, using manufactured fuel from Lunar or Asteroid sources; ice as primary resource
   3. Solar-Power Satellites, manufactured from space-based materials
   4. Communications, Satellite Maintenance, monitoring and reporting

2. Lunar
   1. Ice-derived $H_2$, $O_2$, LOX
   2. Minerals and Metals, KREP, REE, Ti, Thorium
   3. Power Generation, H-3 and H-3 export to earth
   4. Monitoring, maintenance and observation

3. Near-earth Asteroids and / or Mars
   1. High-value REE
   2. Water-Ice and other volatiles
   3. Kerogen-based materials
   4. Aluminum, iron, nickel, cadmium and other building materials
Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

**Worldwide Capacity and Demand for Launch Services**

(Number of launch vehicles)

- **Total Launch Capacity Worldwide**
- **Commercial Demand Worldwide**
- **Governmental Demand Worldwide**

Source: Congressional Budget Office based on data provided by the Federal Aviation Administration and the Futron Corporation.
Orbital Altitudes of many significant satellites of earth

- 0 km - Sea Level
- 37.7 km / 23.4 mi - Sea Propelled Jet Aircraft Flight Ceiling (recorded in 1977)
- 225 km / 139.6 mi - Sputnik 1 - The very first artificial satellite of earth
- 340 km / 211.3 mi - International Space Station
- 390 km / 242.3 mi - Former Russian Space Station Mir
- 595 km / 369.7 mi - Hubble Space Telescope
- [700 km - 1700 km] - Polar Orbiting Satellites
- (435 mi - 1056 mi)

Map of Cislunar Space

- HEO
- LEO
- GEO
- MEO
- L1
- L2
- Moon

Scale: 1 Pixel = 10 Km / 6.2 mi
Opportunities in Orbit, Earth Lagrange Points, and Cis-Lunar Space

Commercial Communications Satellites
Geosynchronous Orbit

Boeing 67
Others 236*

* Includes Eutelsat-owned S/C:
Sinosat-3 (Eutelsat 3A) and AM 22 (Sesat 2)

Note: @ inclined orbit
Based on best public information available at the time.

20 Jun 2017 / 208259-001 w
Significant Hurdles:

- Launch Costs: Goal is to reduce costs to $1,000/kg to $100/kg
  - Chemically Fueled rockets are about at their limit
  - External propulsion has technological barriers, e.g., Laser, rail gun, space elevator.
  - Nuclear rockets have public perceptions to overcome, but represent the only viable option at this time.
Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

• Key issue: weight is dollars.
• Manned launch costs are 5 to 10 times greater than robotic-unmanned flights.
• Estimates for the Space Shuttle costs ranged from $15,000 to $25,000 per kilogram to low earth orbit.
• Airline freight rates are in the range of $5 to $15 dollars per kilogram.
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Launch Costs to Geosynchronous Transfer Orbit

Atlas V 401: $27,777 US$/kg GTO
Delta IV Heavy: $25,424 US$/kg GTO
Ariane 5 ECA: $24,079 US$/kg GTO
Ariane 5 ES: $30,249 US$/kg GTO
Proton-M: $16,620 US$/kg GTO
Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

First task is improvement in launch systems

“Nuclear DC-X [LANTR] has such far-reaching capabilities that it represents a new and vital way of realizing the benefits of space. This advanced propulsion concept can be implemented within 5 years to meet all manned and unmanned space mission requirements.” (Davis, 2004; pg. 54)

<table>
<thead>
<tr>
<th>Historical and Existing Launch Systems</th>
<th>Minimum Cost $/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockot</td>
<td>$10,000</td>
</tr>
<tr>
<td>Shuttle</td>
<td>$12,000</td>
</tr>
<tr>
<td>Athena 2</td>
<td>$12,000</td>
</tr>
<tr>
<td>Taurus</td>
<td>$20,000</td>
</tr>
<tr>
<td>ISS, Commercial</td>
<td>$22,000</td>
</tr>
<tr>
<td>Pegasus XL</td>
<td>$24,000</td>
</tr>
<tr>
<td>Long March CZ-2C</td>
<td>$30,000</td>
</tr>
<tr>
<td>Athena 1</td>
<td>$41,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Innovative, Near Term, Alternative Launch Systems</th>
<th>Projected Cost Range $/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Ablative Launch</td>
<td>$100 - $300</td>
</tr>
<tr>
<td>Nuclear Thermal Rocket</td>
<td>$150 - $500</td>
</tr>
<tr>
<td>Space Elevator</td>
<td>$50 - $150</td>
</tr>
<tr>
<td>Air Breathing Rockets</td>
<td>$200 - $500</td>
</tr>
<tr>
<td>Magnetic Levitation Launch Assist</td>
<td>$30 - $100</td>
</tr>
<tr>
<td>Pulse Detonation Engines</td>
<td>$500 - $1,000</td>
</tr>
</tbody>
</table>

### CAPABILITIES & SERVICES

SpaceX offers open and fixed pricing for its launch services. Modest discounts are available for contractually committed, multi-launch purchases. Prices shown below are paid in full standard launch prices for 2013. SpaceX can also offer crew transportation services to commercial customers seeking to transport astronauts to alternate LEO destinations. Please contact sales@spacex.com for details.

**FALCON 9**
- **Launch Cost**: $56,500,000
- **Mass (kg) to LEO**: 13,150
- **Cost per kg to LEO**: $4,297
- **Mass (kg) to GTO**: 4,850
- **Cost per kg to GTO**: $11,649

**FALCON HEAVY**
- **Launch Cost**: $77,100,000
- **Mass (kg) to LEO**: 53,000
- **Cost per kg to LEO**: $1,455
- **Mass (kg) to GTO**: 21,200
- **Cost per kg to GTO**: $6,368

### Illustration and text captured from SpaceX Website: www.spacex.com March 26th, 2104)
Space solar power systems. Latest assessments indicate power cost to be in the range of 12 to 18 cents per kilowatt hour. Average retail price of electricity for Texas during 2012 was 9.56 cents per kilowatt hour.
Japan Space Agency (JAXA) is aggressively working on Space-based Solar Power Stations and the potential of Helium-3 recovery from the Lunar Regolith.

Transmission of energy via MASER, LASER or microwave transmission is an issue.
Installed Cost ≈ Range $1,000 to $2,700 /KW
Production (wholesale) Cost ≈ $0.05-0.07 /KWhr

(Glaser, P. 1993)
(Seboldt, W. 2004, Criswell, 2013)
Why return to the moon?

We need to live and work in space, the International Space Station has been a great experience, but by implication, our next stops are either or both the Asteroids or Mars. Both of these destinations have elements that have not been explored, evaluated or tested aboard the ISS. We need to learn how to live and work on the surface of a low-gravity body with limited to no atmosphere, and hostile radiation environments. The moon is still within range of an emergency supply mission, but it provides all of the test environments necessary to evaluate additional survival aspects.
Lunar Resources

*Clementine* Topographic Map of the Moon
Contour Interval - 500 m
The dark blue and purple areas at the moon’s poles indicate neutron emissions that are consistent with hydrogen-rich deposits covered by desiccated regolith. These hydrogen signatures are possible indications of water in the form of ice or hydrated minerals (Feldman et al., Science, 281, 1496, 1998).
<table>
<thead>
<tr>
<th>Resource</th>
<th>Use</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Helium-3</strong></td>
<td>Energy</td>
<td>Mature regolith</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td>Propellant, water</td>
<td>Mature regolith, poles</td>
</tr>
<tr>
<td><strong>Oxygen</strong></td>
<td>Propellant, air/water</td>
<td>Global</td>
</tr>
<tr>
<td><strong>Nitrogen, carbon</strong></td>
<td>Food and plastics</td>
<td>Breccias/regolith</td>
</tr>
<tr>
<td><strong>Metals/bulk regolith</strong></td>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Moon base, Shielding, Roads, Solar power facility</td>
<td>Regolith, mare</td>
</tr>
<tr>
<td>Titanium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rare Earth Elements, Helium-3 and Thorium Content of Lunar Regolith

Spudis, P. Ambrose, W.
Well-Developed Terrestrial Technology Gives Access to \( \sim 10^9 \) kg of Lunar \(^3\)He

- 33 kg \(^3\)He / year
- \( \sim 600 \) tonnes volatiles / year
- 556 km\(^2\) / year
- \( v = 23 \) m / h

- Bucket-wheel excavators
- Bulk heating
- Heat pipes
- Conveyor belt
Based on these assumptions, an IRR (internal rate of return) greater than 10% can be achieved with an installed capacity greater than 15 GWs. Using revised figures consistent with updated power costs and launch costs, an IRR of greater than 10% can be achieved with an installed capacity of 1,200MWs or greater. BLC
Space Solar Power Technology Demonstration For Lunar Polar Applications

Possible Ice Deposits
- Craters are COLD: -300F (-200C)
- Frost/Snow after Lunar Impacts
- Good for future human uses
- Good for rocket propellants
Permanent habitations will be efficient and comfortable. They will be the new permanent home for the explorationists in our societies.
“NEAs may be the most attractive source of shielding, propellants, metals and refractories in orbits around the Earth.” (Lewis et al., 1993)

“The purpose of In Situ Resource Utilization (ISRU) is to harness & utilize these [in situ] resources to create products & services which enable and significantly reduce the mass, cost, & risk of near and long-term space exploration.” (Sanders and Duke, 2005)

“The NEOs contain all the elements to make space exploration and resource development feasible, economically achievable, and profitable”. (Cutright, B. L., 2013)
Arguments for Near-Earth Objects: Economics

- Mass in orbit is worth 10-15 times equivalent Mass on the ground.
- If launch cost is $15,000 per Kilogram, then every kilogram in orbit is as valuable as 17 kilograms of Silver, a kilogram of Osmium or Iridium, 1/3 a kilogram of Gold or 1/5 of a kilogram of Platinum.
- From the perspective of being in space, a metric ton of water in space has a value of $15 Million Dollars. .......A one-kilometer-diameter C-type asteroid or dormant comet composed of 30 percent water, contains 150 million metric tons of water. If this had to be launched from Earth’s surface it would cost 2,250 trillion dollars, which is obviously impractical.
- Mundane materials in space are as valuable as REE and Platinum Group Metals on the ground.
THE SPACE ECONOMY: A MODERN DAY GOLD RUSH
Asteroid Mining Will Create A Trillion-Dollar Industry

As our population grows we need to find a sustainable supply of natural resources to fuel exploration in space and prosperity on Earth.

Platinum-rich Asteroid
Could contain more Platinum Group Metals than what's been mined on Earth in all of history.

Uses of Platinum Group Metals on Earth

Reduce Cost of Electronics
Electrify Transportation
Drive Innovation, and Create a Greener Earth

More Asteroids Discovered Near Earth Everyday

Near-Infinite Supply of Precious Resources

One 500m Platinum-rich Asteroid

Water-rich Asteroid
One water-rich asteroid could produce enough fuel for every rocket launched in history.

Uses of Water in Space

Rocket Fuel
Breathable Air
Drinkable Water

One 500m Water-rich Asteroid

Uses of Platinum in Space

Asteroid mining will open a trillion-dollar industry and provide a near-infinite supply of Platinum Group Metals and water to support our growth both on this planet and off.

Table of Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Value if sold at today's market price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductors</td>
<td></td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>1.24E-08</td>
</tr>
<tr>
<td>Gallium (Ga)</td>
<td>4.98E-10</td>
</tr>
<tr>
<td>Germanium (Ge)</td>
<td>3.45E-11</td>
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<tr>
<td>Arsenic (As)</td>
<td>1.29E+07</td>
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<tr>
<td>Selenium (Se)</td>
<td>3.15E-09</td>
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<tr>
<td>Indium (In)</td>
<td>3.97E-08</td>
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<tr>
<td>Antimony (Sb)</td>
<td>4.11E-05</td>
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<tr>
<td>Tellurium (Te)</td>
<td>1.13E-08</td>
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<tr>
<td>Platinum and Precious Metals</td>
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<tr>
<td>Ruthenium (Ru)</td>
<td>1.46E-11</td>
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<tr>
<td>Rhodium (Rh)</td>
<td>6.61E-11</td>
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<tr>
<td>Palladium (Pd)</td>
<td>5.52E-10</td>
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<tr>
<td>Silver (Ag)</td>
<td>7.59E-08</td>
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<tr>
<td>Rhenium (Re)</td>
<td>1.98E-10</td>
</tr>
<tr>
<td>Osmium (Os)</td>
<td>2.25E-11</td>
</tr>
<tr>
<td>Iridium (Ir)</td>
<td>1.13E-12</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>3.33E-12</td>
</tr>
<tr>
<td>Gold (Au)</td>
<td>3.89E-10</td>
</tr>
<tr>
<td>Other Important Metals</td>
<td></td>
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<tr>
<td>Copper (Cu)</td>
<td>1.60E-09</td>
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<tr>
<td>Cobalt (Co)</td>
<td>1.71E-11</td>
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<tr>
<td>Titanium (Ti)</td>
<td>1.35E-09</td>
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<tr>
<td>Chromium (Cr)</td>
<td>8.64E-09</td>
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<tr>
<td>Nickel (Ni)</td>
<td>1.55E+10</td>
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<tr>
<td>Molybdenum (Mo)</td>
<td>4.32E-05</td>
</tr>
<tr>
<td>Total</td>
<td>6.20E-12</td>
</tr>
<tr>
<td>Value</td>
<td>$6.2 trillion</td>
</tr>
</tbody>
</table>
Near-Earth Objects:
Generally between the orbits of Venus and Mars, with Apollo (60%) and Aten (6-8%) Asteroids crossing Earth’s orbit and Amor (30%) Asteroids outside Earth’s orbit and may cross Mars’ orbit. Inner-Earth Objects are within Earth’s orbit and may cross Venus’ orbit. Dormant Comets may comprise 1-6% of total number.

C-Type
253 Mathilde

75% of known asteroids
CI and CM chondrites: volatiles: 5-20% water

S-Type
951 Gaspra

15% of known asteroids
dominant in inner belt: olivine, pyroxene, Fe

M-Type
3554 Amun

10% of known asteroids
Fe, Ni, Co, Pt-group
IRR at Year 10 for Resource Return Missions

Mission Return Value $500 B

Mission Return Value $50 B

Mission Cost (ranging from $5 to 50 Billion)
Market Value of a Metallic Asteroid Based on Its Radius

Value In 2012 US Dollars

Radius of Metallic Asteroid (meters)
Left: Asteroid Return Mission with returns starting at year 9, continuing through year 20 with a total value of $100 Billion. Mission Cost $15.01 Billion

Right: Asteroid Return Mission with returns starting at year 9, continuing through year 20 with a total value of $500 Billion.
Significant attention has been directed toward mining the asteroids recently, but we have known of their value for more than 75 years.
Last year, the estimated value of mineral production in the U.S. was $74.3 billion, a slight decrease from $75.8 billion in 2012. According to the U.S. Geological Survey’s annual Mineral Commodity Summaries 2014 report, the 2013 decrease follows three consecutive years of increases. Net U.S. exports of mineral raw materials and old scrap contributed an additional $15.8 billion to the U.S. economy.

"To put this in context, the $90.1 billion value of combined mined, exported, and recycled raw materials is more than five times greater than the 2013 combined net revenues of Internet titans: Amazon, Facebook, Google, and Yahoo.

This illustrates the fundamental importance of mineral resources to the nation’s economy, technology, and national security," said Larry Meinert, USGS Mineral Resources Program Coordinator.
The SPST (Space Propulsion Synergy Team) has taken the position that the ultimate reason for man’s establishing habitation and industrialization in low-Earth orbit and beyond is to provide improved quality of life on Earth and eventually for the continued evolution and survival of mankind.

(Henderson, E.M., Knuth, B., Rhodes, R.E., and Robinson, J. July 14-17, 2013 San Jose, CA, [49"" ASME/SAE/ASEE Joint Propulsion Conference])