A TECHNOLOGY ROADMAP TOWARDS MINERAL EXPLORATION FOR EXTREME ENVIRONMENTS IN SPACE

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WHAT DO WE MEAN BY A SPACE MINING TECHNOLOGY ROADMAP?

• What is a “technology roadmap” (TR)?
• The 2015 NASA Technology Roadmap is a good archetype.
• According to the 2015 NASA Technology Roadmaps, the TR links a needed mission capability to a Strategic Technology Investment Plan (STIP)
  • A needed mission capability is derived from the mission goal—in this case, mineral exploration.
  • The STIP prioritizes technology candidates and provides guiding principles for technology investment.
• The TR accomplishes this linking by laying out a schedule and deliverables for
  • New technological capabilities
  • Building on already-proven technological capabilities.
• These capabilities are laid out in specified categories in the 2015 TR.
  • Specific areas
  • Cross-cutting technologies
  • In 15 separate areas

Source: 2015 NASA Technology Roadmaps
WHERE DOES THE NASA TECHNOLOGY ROADMAP ADDRESS ASTEROID MINING TECHNOLOGY NEEDS?

- Short answer — It doesn’t. (Not explicitly, at least.)
- Why not?
- The FY 2014 NASA Strategic Plan gives some insight.
- There are 3 strategic objectives.
  - Expand the frontiers of knowledge, capability, and opportunity in space.
  - Advance understanding of Earth and develop technologies to improve the quality of life on our home planet.
  - Serve the American public and accomplish our Mission by effectively managing our people, technical capabilities, and infrastructure.
- Objective #2 is the only one where asteroid mining (and mining writ large) is mentioned.
- It is referred to in the context of commercial ventures—in other words, it is regarded as a strategic objective that will be set and pursued in the private sector.

Source: 2014 NASA Strategic Plan
TO ADDRESS ASTEROID MINING TECHNOLOGY NEEDS, THE CURRENT ROADMAP COMPRISES MUCH OF THE ENABLING TECHNOLOGY

• Much of the technology needs of space mining and those from the NASA Technology Roadmaps coincide.
• The same enabling technologies further both NASA’s strategic objectives and those of potential asteroid mining concerns.
• Particularly in the areas of:

  TA 2: In-Space Propulsion
  TA 3: Space Power and Energy Storage
  TA 4: Robotics and Autonomous Systems
  TA 7.1: In-Situ Resource Utilization
  TA 11: Modeling, Simulation, Information Technology, and Processing
  TA 12: Materials, Structures, Mechanical Systems, and Manufacturing
  TA 14: Thermal Management Systems
WHERE WOULD THE DIRECT TECHNOLOGY NEEDS FOR ASTEROID MINING BE ADDRESSED?

- The area of the Technology Roadmap that comes closest (though not quite there) to directly addressing the needs of asteroid mining is that of *Reconnaissance, Prospecting, and Mapping (TA 7.1.1), Resource Acquisition (TA 7.1.2)* and *Processing and Production (TA 7.1.3)*.

- For brevity, the rest of this presentation will largely focus on the technology needs for **TA 7.1.1**.

- Currently, the following are subareas of 7.1.1 that are cited as technology advancement candidates for prospecting:
  - Penetrometers, Shear Gauges, Compaction, Density Instruments
  - Flow Instruments
  - Drill Embedded Chemical Instrument – Laser Induced Breakdown Spectroscopy
  - Drill Embedded Chemical Instrument – Neutron Spectrometer
  - Drill Embedded Physical Instruments (Resistivity, Thermal, Shear, etc.)
  - Sensor to Measure Blowing Rate of Material During Landing
  - Instruments to Measure Chemical Compositions
WHAT ARE WE MISSING HERE?

• New exploration methods!
• Both
  • Methods applicable to space mining in and of themselves, and
  • Methods being developed for advanced *terrestrial* mining that may be adaptable for space/microgravity/extreme environment adaptations
SOME VALUABLE PRIVATE-SECTOR SOURCES

Three major new terrestrial mining technology areas:

- Exploration Under Cover
- Data-driven mining decisions
- Robotics and automation
FRAMING THE PROBLEM IN MISSION FORM

- The ASTRA Report completed a SWOT (Strengths, Weaknesses, Opportunities, and Threats) trade study which made recommendations for the first attempted asteroid mining mission.

- Their specific recommendation was for a **short-term, fully autonomous, large-asteroid mining mission** described as follows:

  “**Architecture L3**: This unmanned architecture requires robotic assembly of multiple vehicles launched to LEO. The assembled spacecraft travels to the asteroid. The setup of mining equipment, the mining itself, and the processing of the mined materials is all performed robotically. The delivery of extracted materials to Earth follows.”

EXPLORATION UNDER COVER

• **Terrestrial roadmap needs** (METS Report, pg. 53):
  • Directional drilling
  • First principles mineral system/orebody formation
  • 3D seismic exploration
  • Deposit modeling that build on existing characterization datasets
  • 4D geodynamic maps

• **Adaptation for space mining:**
  • Adapt for low gravity (anchoring, etc.)
  • Adapt for icy rock/regolith/low temperatures
  • Surface gravimetric surveying
  • Shock heating and freezing
  • Data analytics (see next slide)

• **Additions/modifications to NASA 2015 Technology Roadmap:**
  • Mostly additions to TR 7.1.1
  • Exploration methods largely constitute a set of “more novel” technology candidates when asteroid mining is the goal.
DATA-DRIVEN MINING DECISIONS

• **Terrestrial roadmap needs** (METS Report, pg. 29):
  - Integrated sensors
  - Sensor durability to high/low temperatures
  - Self-powering sensors
  - Wireless connectivity of in-situ remote sensors
    - Embedded sensors
    - Advanced user interfaces
    - Advanced visualization
    - Improved mathematical models
    - Cyber security

• **Adaptation for space mining:**
  - Radiation and low-temperature hardening of sensors for space applications
  - Exploration studies needed to feed datasets, similar to parallel work done for Mars data-driven prospecting⁵

• **Additions/modifications to NASA 2015 Technology Roadmap:**
  - More elaboration of TR 8.3.3 with regard to hardening of in-situ sensors
  - More elaboration of TR 11.2.4 (Geological Modeling), 11.4.2 (Intelligent Data Understanding), and 11.4.8 (Cyber Security)
**ROBOTICS AND AUTOMATION**

- **Terrestrial roadmap needs** (METS Report, pg. 60):
  - Machine vision
  - Advancer materials and additive manufacturing
  - Miniaturation of batteries
  - Dexterous end effectors

- **Improved computational ability** (integration of sensors, big data, self-calibration)
  - Swarm robotics
  - Distributed control
  - Virtual and augmented reality
  - Haptic commands

- **Adaptation for space mining:**
  - This is largely identical to the needs expressed in NASA TR 4, with the exception of radiation and low-temperature hardening.
  - One possible addition: Self-replicating robotic system for bootstrapping.⁶

- **Additions/modifications to NASA 2015 Technology Roadmap:**
  - For the latter adaptation, I recommend an entirely new sub-roadmap (TR 4.8—Self-replication architecture)
CUSTOMERS FOR AN ASTEROID MINING SPACE TECHNOLOGY ROADMAP

• Government space agencies
• Companies
• Professional organizations
• Privately-funded ventures
• Anyone with an acute interest in accelerating reduction of the long-term cost of investment in off-Earth mining, particularly asteroids

• Although the NASA TR remains the gold standard of space technology roadmaps, *additional guidance for exploration and prospecting technology for asteroids may be found in terrestrial mining roadmaps.*

• Coming cutting-edge terrestrial mining exploration and prospecting techniques, *modified for space,* may be the key input needed for industry partners to plan technology investments for the coming space “gold rush.”
EPILOGUE: ISRU AND INVESTMENT RETURN

• One last point, again from the ASTRA report:

• “As this venture would likely require significant levels of investment for startup and research and development costs, the project is not currently financially viable.” (ASTRA report, pg. 52)

• “The most influential value driver is the mass return ratio. Doubling the ratio from one to two increases the value of the enterprise more than tenfold. Table 10-2 below illustrates this changing of variable.” (Ibid)

<table>
<thead>
<tr>
<th>Mass Return Ratio</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td>Enterprise Value</td>
<td>$90,000,000</td>
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<td>$5,900,000,000</td>
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<tr>
<td>Option Value</td>
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<tr>
<td>Max Investment</td>
<td>$</td>
<td>$2,500,000,000</td>
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</tbody>
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• “In order to come closer to making asteroid mining a financially viable venture, we strongly recommend that engineering efforts be focused on maximizing the mass return ratio.” (italics and boldface mine)
REFERENCES


