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THE CHOICE

The designs and backstory underlying the U.S. Navy's unmanned tanker competition

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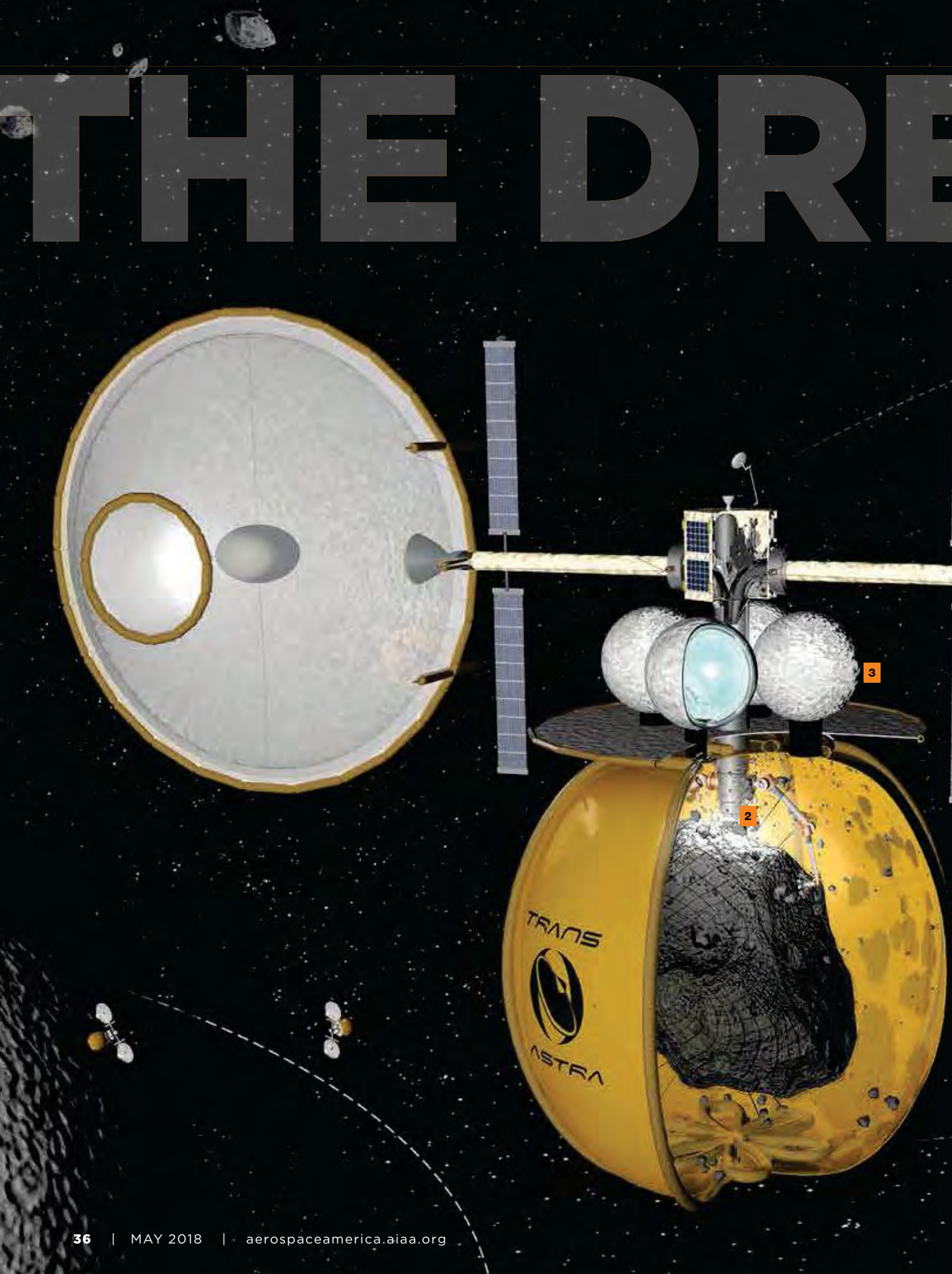

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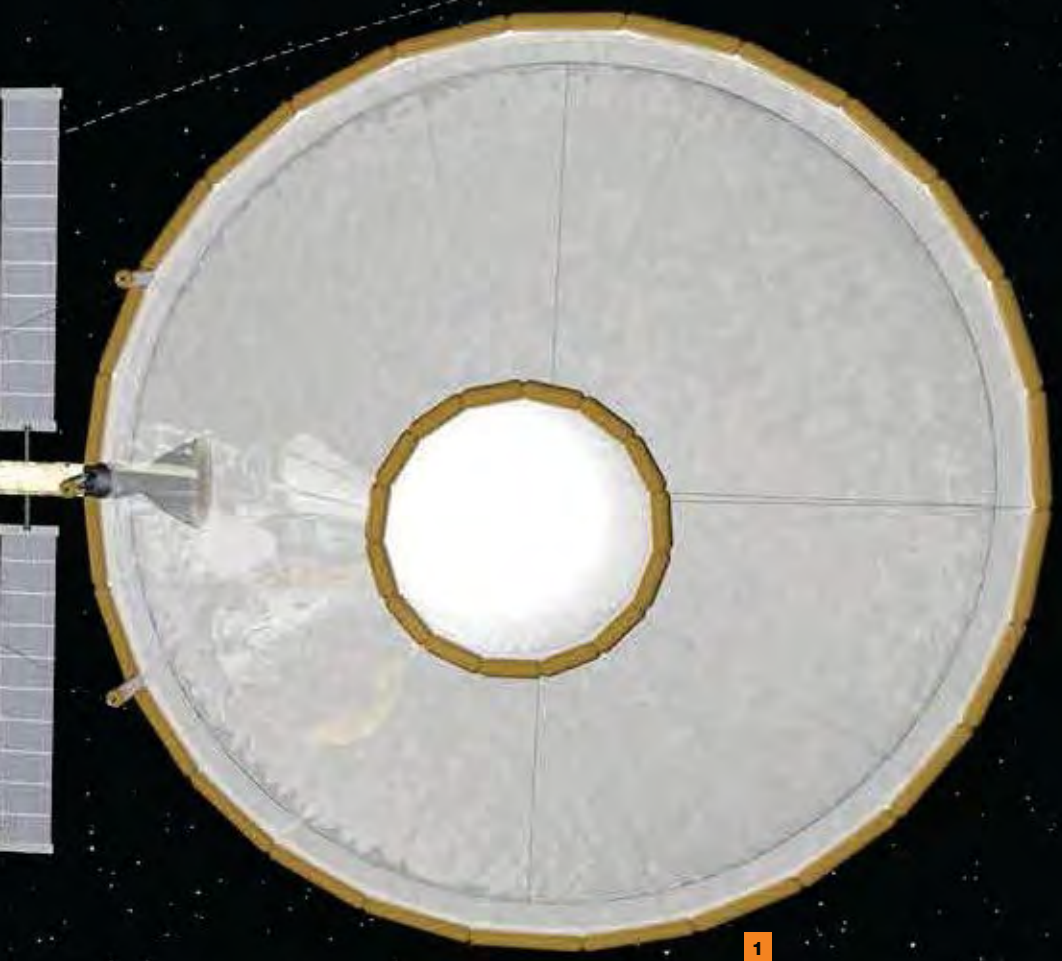

OPTICAL MINING

TransAstra Corp. plans to launch unmanned spacecraft called Honey Bees to asteroids to excavate and process materials by concentrating solar energy to break an asteroid's surface, releasing gases to be collected and turned into transportable ice.

1. Solar concentrators focus sunlight into light tubes to deliver energy to surface of asteroid
2. Optical mining excavates and extracts gases with concentrated sunlight
3. Storage bags passively cool gases
4. Reusable Worker Bee carries product of optical mining to crewed spacecraft

Source: TransAstra Corp.

A cadre of technologists and entrepreneurs think asteroids could be the linchpin for establishing an entire economy in space. Henry Canaday spoke to some of those leading the way.

BY HENRY CANADAY | htcanaday@aol.com

Scientists and engineers operating mostly out of small offices from Los Angeles to Silicon Valley and Europe have a vision of extracting trillions of dollars worth of precious or useful metals from asteroids and bringing them back to Earth. Some of us, they suggest, might even choose to live on these rocky objects.

The desirability and economic benefits of such ventures remain to be seen, but if asteroids and other deep space targets are to be vigorously explored and exploited, doing so will require new ways of thinking about some familiar problems.

First and foremost, success will mean breaking "the tyranny of the rocket equation." If all propellant for deep space exploration must be lifted against Earth's gravity, that requirement severely limits what else rockets can carry, how far they can go and what they can do once they get to their destinations.

So why not create propellant in space by harvesting chemicals from low-gravity asteroids near Earth? Or maybe gather raw materials and manufacture machines in space instead of launching them a few components at a time from Earth. The efficiencies would be enormous, provided the concepts can be proved feasible.

How enormous? A 2017 NASA-funded report, "Stepping Stones: Economic Analysis of Space Transportation Supplied From NEO Resources," estimates that privately developed spacecraft powered by propellants extracted from asteroids could achieve 20 years of vigorous human space exploration and tourism at about a quarter the cost of traditional methods. Specifically, the total cost of exploring the moon's surface, near Earth objects, and Mars would be $90 billion if "commercial best practices" are combined with "asteroid resources," compared to $392 billion without such innovations, the report says.

The report, funded by a NASA grant, was written by former Air Force Research Laboratory adviser Joel Sercel who in 2015 founded the company TransAstra, a two-person firm in Los Angeles, where Sercel is the principal engineer. The firm's board includes former U.S. astronaut and physicist Stanley Love, and the company has received about

$1 million under NASA's Small Business Innovation Research and NASA Innovative Advanced Concepts programs. The company is now seeking its first venture capital funds.

Other companies, including Silicon Valley's Deep Space Industries and Redmond, Washington's Planetary Resources, are eager to tap asteroids for propellant too. And companies such as Los Angeles' SpaceFab are looking further ahead, to manufacturing spacecraft on asteroids with material extracted from them.

Funding

TransAstra's Sercel envisions establishing a public-private partnership with "significant public investment up front and a government commitment to buy extracted propellant at a reasonable price."

In contrast, Deep Space Industries hopes to raise initial investment from high-net-worth individuals and venture capital funds. The company's strategist Peter Stibrany was formerly a system engineer for Canada's Radarsat imaging constellation and designer of components of the International Space Station. While Deep Space Industries focuses on private funding, Stibrany says his company will appreciate any revenue it eventually obtains from selling propellant to national space agencies. "It's always great to get more customers," he says. Deep Space Industries also plans to earn revenue by developing new propellant systems and spacecraft and selling them to space agencies and private companies.

Prospecting

For each potential target, the goal would be to determine the object's composition, diameter, rotation and other features that could impact suitability for mining. By 2020, Deep Space hopes to launch its Prospector-1 spacecraft, which would fly close enough to interesting asteroids to map their surfaces and subsurfaces with visual and infrared imaging. The idea would be to judge the asteroid's value as a source of ingredients for propellants.

TransAstra and Sercel have a different approach. To avoid the expense of sending prospecting vehicles close to candidate asteroids, they propose launching three small space telescopes at a total cost of $50 million as piggybacked payloads into orbits around the sun. This heliocentric constellation would be called Sutter, a reference to American pioneer John Sutter, whose discovery of gold on his property in 1848 precipitated the California Gold Rush of the 19th century.

Graphical processing units on each telescope would rely on matched filter algorithms, a kind of signal processing, to measure composition and other factors. He believes the technique can prospect even fast-moving and faint near Earth asteroids.

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TransAstra asked Daniel Britt, a professor of astronomy and planetary sciences at the University of Central Florida who once managed the camera on NASA's Mars Pathfinder lander, to assess its plan for the Sutter constellation. "There are various proposals for space-based detectors," Britt says. "Joel's is a good idea."

Sutter prospecting telescopes would first be tested in Earth orbit. And eventually, the three-satellite constellation would be enhanced as Extreme Sutter with more and larger telescopes, including an infrared device.

Once prospecting is done, TransAstra would launch autonomous spaceships called Honey Bees on vehicles such as SpaceX's Falcon 9 to coast to house-sized asteroids. There, lightweight solar reflectors would concentrate heat to fracture the asteroid surface, releasing carbon dioxide, carbon monoxide or methane gasses to be captured in a bag. The reflectors would then be turned around to act as heat shields, so gases can be cooled to transportable ice. The technique, optical mining, is like that proposed for NASA's now-abandoned Asteroid Redirect Mission.

These frozen contents would then be carried by autonomous space tugs called Worker Bees to a crewed space station orbiting between the Earth and moon. Each Worker Bee would be propelled by about 40,000 kilograms of water stored in stainless steel tanks and heated by the solar reflectors. The resulting water vapor would shoot out a nozzle to generate thrust. The crew of the space station would store water as propellant for solar thermal rockets or convert contents into conventional rocket propellants: liquid oxygen-liquid hydrogen or liquid oxygen-liquid methane. Space vehicles from Earth

could load up at the facility for Mars or other destinations and avoid carrying so much propellant on the way. The minimal energy required to coast to and approach asteroids with near Earth orbits, then depart and coast back to the propellant facility, makes this an efficient option.

Sercel stresses that optical mining is only one method for extracting water. Another, confidential technique might also extract water. And TransAstra must still determine which propellants are most desirable and cost-effective to make and store at the Earth-orbiting depot.

Deep Space is less specific about its mining plans. It has been designing its proposed small fleet of extraction spacecraft, called Harvestors, for five years. Extraction processes are confidential and partly depend on what Prospector reveals about asteroids. Also confidential is how and where asteroid minerals would be processed. "We have developed what we believe is a very effective system architecture," Stibrany says.

Deep Space's Prospector and Harvestors could be launched on rideshare vehicles such as Falcon 9 and India's Polar Satellite Launch Vehicle or on a dedicated small-satellite launcher. The firm is developing a green bipropellant propulsion system for its spacecraft that Stibrany says will be safer, less expensive and easier to carry on rideshare vehicles

Deep Space Industries would send small Prospector craft to find resources on asteroids.

Bryan Versteeg/
Deep Space Industries

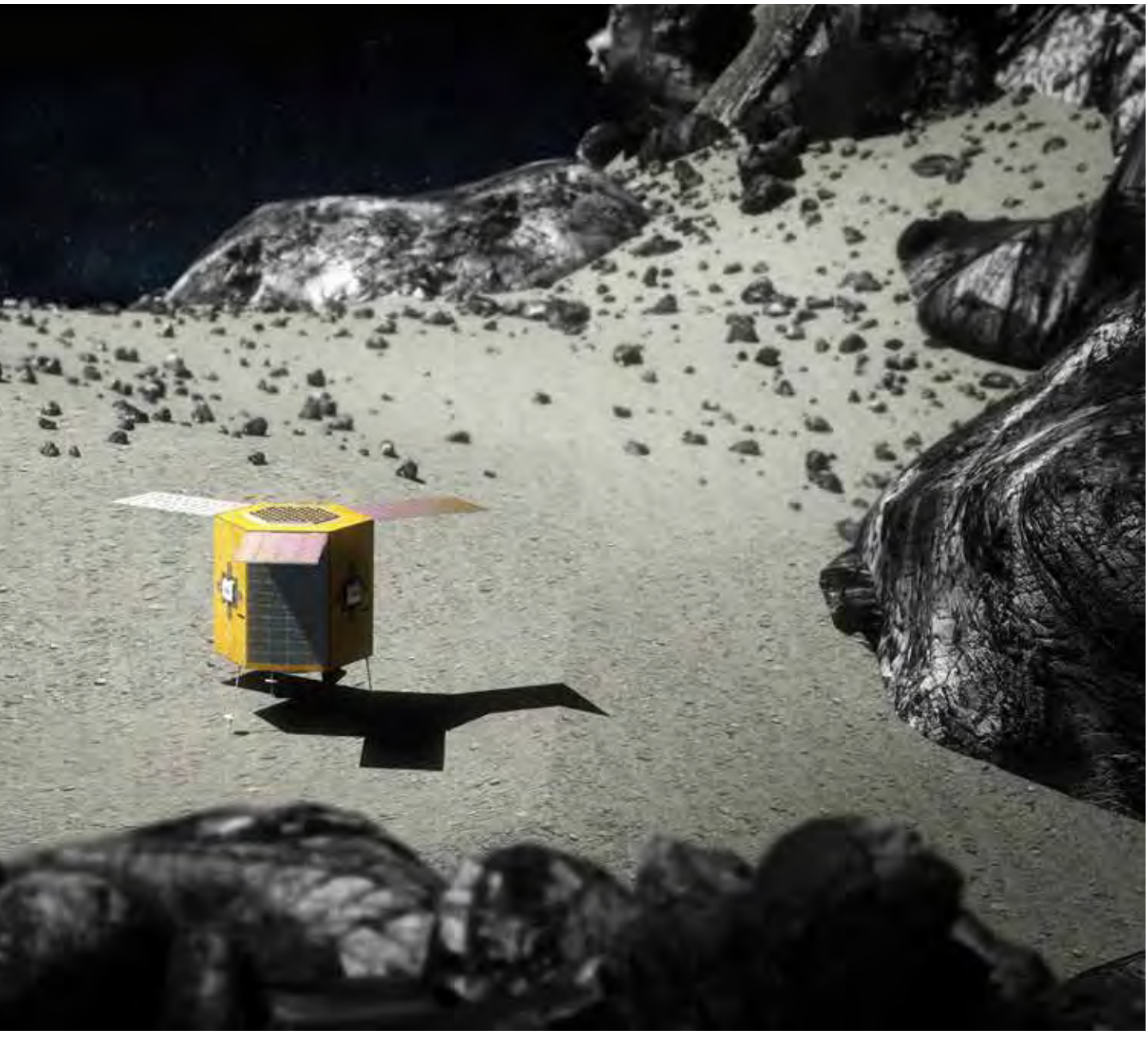
than today's hydrazine monopropellant systems.

Each Harvestor would initially be autonomous, or have what Stibrany calls "supervised autonomy," that is, with humans intervening at critical points and capable of asserting more control over robotic equipment when necessary. He acknowledges that deep space differs from near Earth environments by presenting tougher challenges in propulsion, communications, navigation and surviving radiation.

As for the market, Stibrany says it will materialize gradually and steadily, provided the right strategies are pursued. He says too many business plans envision either demand for materials without a supply infrastructure or the reverse, an expensive supply system without adequate demand. He says Deep Space has an incremental road map that develops supply along with demand. The company already earns revenue from delivering commercial products such as water-based propulsion for small satellites that will support its long-range goals, he says.

"As mining and manufacturing infrastructure in space expands, more materials found on asteroids will become commercially attractive," he predicts.

He speculates that asteroid mining of minerals could ultimately generate sums comparable to the $3 trillion a year now generated by oil, gas and water industries.



Propellants gathered from asteroids could provide a less expensive way of shifting geosynchronous satellites into circular orbits.

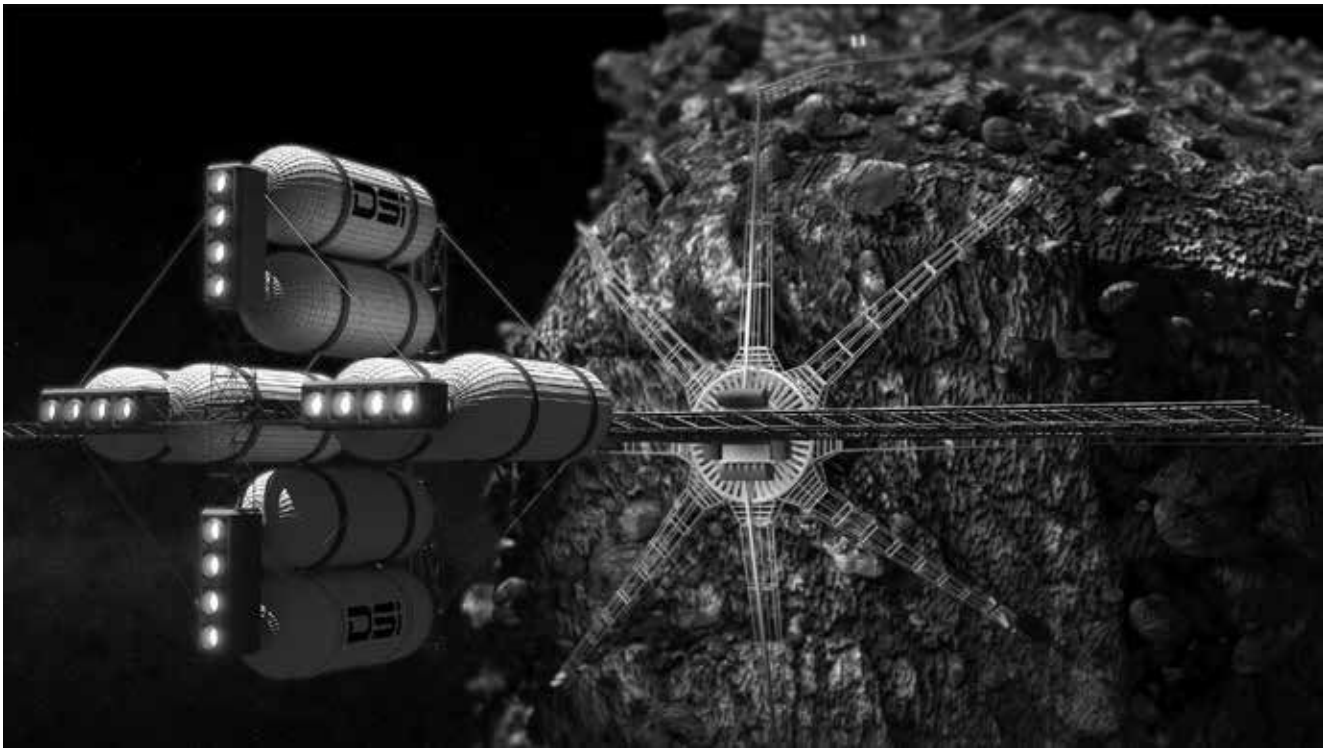
Stibrany believes that the 2017 cancellation of NASA's Asteroid Redirect Mission, which included a robotic spacecraft that would have plucked a boulder from an asteroid, makes information generated by Prospector more attractive to scientists.

What he needs most from governments is speedy regulatory approvals. The Hague Space Resources Governance Working Group, set up in 2014 to consider regulation of space resources, is discussing an international framework for asteroid mining. Stibrany says, "the basic ideas are beginning to gel."

Sercel's TransAstra plan is premised on robust demand for propellant from NASA. Phil Metzger, who worked with NASA's Lunar and Mars Architecture teams and Lunar Exploration Analysis Group, helped develop NASA's technology road map for planetary surfaces and now teaches planetary science at Central Florida, thinks there are other markets. He says propellants gathered from asteroids could provide a less expensive way of shifting geosynchronous satellites into circular orbits after launch than the current technique of firing upper stage rockets.

Making spacecraft in space

Manufacturing spacecraft from materials culled from asteroids is the eventual goal of electrical engineer and computer scientist Randy Chung, CEO of the five-person startup SpaceFab in Los Angeles. Chung started his career at the now-defunct Hughes Aircraft, worked on integrated circuits at storage giant Western Digital in Irvine, California, then managed design of imagers and cameras at Irvine's Conexant. SpaceFab plans to start by launching a space telescope and selling pictures of the Earth and space, unlike current equipment that specializes in either Earth or space imaging. Then Chung plans a mission to bring sample asteroid metals back to Earth. Finally, he wants to mine construction metals from asteroids and manufacture large structures in space.



Bryan Versteeg/Deep Space Industries

▲ **A fleet of Harvestor spacecraft** would extract minerals from asteroids under Deep Space Industries' plan.

SpaceFab is raising seed money through Wefunder.com for a planned launch of its Waypoint telescope in 2019. "Our first step is to build a viable and competitive space telescope business using our unique technology," Chung says. SpaceFab is loading Waypoint with as many features as possible in a low-cost, 12-unit cubesat. It will have three cameras to cover both Earth and space observation and an onboard computer to process images for tracking of asteroids and space debris.

Chung would like to launch his first asteroid mission soon after NASA's Psyche spacecraft, targeted for launch in 2022, begins orbiting the asteroid Psyche 16 in 2026. Psyche 16 is notable as a world made of metal rather than rock or ice, according to Arizona State University, which will lead the mission. Chung believes SpaceFab's mission can get out and back in eight years. Chung expects SpaceX's Big Falcon Rocket will be operational by 2026 and that SpaceFab can get a low-cost rideshare to Mars, then use Mars as a slingshot to the metallic asteroid. He hopes to at least break even by keeping costs low and selling samples of asteroid metals to educational and research institutions. Then his first mining and manufacturing mission would go out in the early or middle 2030s.

Chung believes iron-nickel-cobalt alloys present in metal asteroids will be highly valuable. "FeNiCo alloy is essentially a form of steel and can make the same kind of things we make from steel here on Earth, such as reinforcing bar, sheet metal, pipes and especially machinery. Once we can make machinery, we can make just about anything," he says. Finding and prospecting will not be necessary as several large metal asteroids are already known, for example, 16 Psyche with possibly 40,000 times the amount of steel produced so far on Earth.

Extraction of alloys would be done on the surface by a simple, electromagnetic process. Chung is relying on pieces of metal, the size of sand grains or pebbles, which can be picked up by electromagnets or sorted with an eddy-current separator. Refining might be as simple as melting small metal pieces with an induction heater and straining out stony pieces.

Refined metal would be fed into an autonomous 900- to 1,800-kg factory to fabricate tools, machinery and structures on the asteroid. This factory would also build more fabrication capacity. Initially, tools including 3-D printers, milling machines, motors and bearings would be sent from Earth. Longer term, even these might be fabricated in space.

Chung estimates a solar-powered, autonomous factory can mine and process 0.5 percent of its mass per day, fabricate 30 percent of its mass annually for customers and increase its capacity 30 percent annually. Production capacity would grow to 23 million kg in 30 years, enough to construct 50 International Space Stations annually.

Unlike TransAstra and Deep Space, SpaceFab would neither mine nor be powered by propellants from asteroids. For propulsion, the company is testing an ion thruster, which creates thrust by accelerating ions with electricity. ★