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SATELLITE RESCUE

NEW SPACECRAFT WILL REFUEL, REFURBISH, AND RELOCATE SATELLITES IN ORBIT—MAYBE EVEN WASH THE WINDSHIELDS.

On Monday, February 24, 2020, at about 9 p.m. U.S. Eastern time, a robotic spacecraft named MEV-1 is traveling some 22,000 miles above the Pacific Ocean in a geosynchronous orbit. A satellite at that location holds a fixed position over the equator because its speed matches that of Earth's rotation. At the moment, MEV-1, which stands for Mission Extension Vehicle-1, is in pursuit of its client, a $200 million satellite called IS-901.

Intelsat owns and operates the satellite, which was launched 19 years ago. In December, IS-901 reached the end of its expected lifespan, and because it was low on fuel and unable to remain stationary over the equator, Intelsat commanded onboard thrusters to push the satellite 185 miles farther from Earth, into the so-called "graveyard orbit," where geo spacecraft go to die.

BY MICHAEL BEHAR

Such is the fate of satellites, Joe Anderson tells me. Anderson is vice president of SpaceLogistics, LLC, a Northrop Grumman subsidiary. "The vast majority of satellites are decommissioned primarily because they have run out of fuel," he says. Others in the graveyard orbit may have experienced technical hiccups. Like a magic lamp releasing a genie, satellites must unfold various components after separating from their launch vehicles. But things can get stuck. "It might be a solar array or antenna that doesn't deploy correctly, and it simply needs a nudge," he says.

Satellites also suffer component failures, such as decayed batteries and computers, or malfunctions in propulsion and attitude-control systems.

The decision to retire a satellite versus fixing or refueling it is a straightforward calculation that measures future revenue against the servicing cost. Many commercial satellites generate millions of dollars per year in revenue, explains Joseph Parrish, program manager for the Defense Advanced Research Projects Agency (DARPA) Robotic Servicing of Geosynchronous Satellites program. "So, if you could extend the life of those spacecraft for just a few years at a cost that's significantly less than their revenue over that period, it's a win-win for both the servicer and the client."

Northrop Grumman's MEV-1 was sent to extend a life. The first robotic spacecraft designed to res-

⬆ Technicians at Northrop Grumman Innovation Systems in Dulles, Virginia rehearse the delicate procedure by which MEV-1, their satellite tug, will dock with IS-901, a 19-year-old satellite in need of renewal.

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cue ailing satellites, it was assigned to dock with IS-901—a feat never before attempted between two uncrewed commercial spacecraft—and then function "as a jet pack," as Anderson puts it. Fueled with xenon gas, MEV-1 will use its electric-propulsion thrusters to tow IS-901 back to geo orbit, then haul it halfway around the world to a new position over the Atlantic Ocean, where it will take over for another aging Intelsat spacecraft.

Industry analysts at Northern Sky Research in Cambridge, Massachusetts last year projected revenues for the in-orbit satellite servicing market would reach $4.5 billion by 2028. They predicted growth in salvage operations, defunct satellite disposals, robotic repairs and inspections, orbital relocations, and refueling services. Their projections are bullish considering that today most satellites still are helpless when something goes awry. Northrop Grumman is hoping to change that.

MEV-1 was launched in October 2019 and took 139 days to reach IS-901. (Electric thrusters are dreadfully slow but extremely efficient.) Now, in late February 2020 at Northrop Grumman Innovation Systems in Dulles, Virginia, the Mission Operations Center is bustling with ground controllers and engineers overseeing the MEV-1 docking. Anderson is here for the big moment. His eyes are glued to wall-mounted monitors receiving live video feed from eight cameras aboard MEV-1.

When IS-901 first comes into view, it's a shimmering speck amid a black void, like a diamond in a tar pit. MEV-1 stops at its "far hold" position, about 260 feet from IS-901.

The MEV has been in development since the mid-2000s, when aerospace firm Alliant Techsystems, or ATK, began exploring the feasibility of servicing spacecraft in geo, where some 500 satellites are in orbit. Anderson, who had spent 20 years at Intelsat, moved to ATK in 2012, believing it had the money and expertise to make the MEV happen. After a series of mergers and buyouts endemic to the aerospace industry, the project—and Anderson—wound up at Northrop Grumman.

Developing the necessary rendezvous and docking technologies took time and money. "We suffered a classic innovator's dilemma," Anderson says. "We had no financing because we had no customer commitments, and we had no customer commitments because we were not financed." It wasn't until 2016 that ATK decided to fund the development and launch for the first MEV. "Just a couple of months later we had our first contract for five years of life-extension service with Intelsat."

Now, eight years after the first serious considerations of satellite servicing, MEV-1 is about to

ASSUMING THE MISSION SUCCEEDS, IT WILL NOT ONLY MAKE HISTORY BUT ALSO HERALD THE BIRTH OF AN ENTIRELY NEW INDUSTRY.

[redacted]

dock with IS-901. Assuming the mission succeeds, it will not only make history but also herald the birth of an entirely new industry.

STATION TO STATION

Satellites need fuel to perform "station-keeping" maneuvers using small chemical or electric thrusters. "Their orbit is always changing because of gravitational forces from the Earth, sun, and moon," explains Anderson. "Most satellites are

➡ When Intelsat 603 stalled in low Earth orbit, it required an expensive 1992 space shuttle mission to capture and relaunch it. MEV-1 aims to make such orbital corrections far simpler and cheaper to perform.

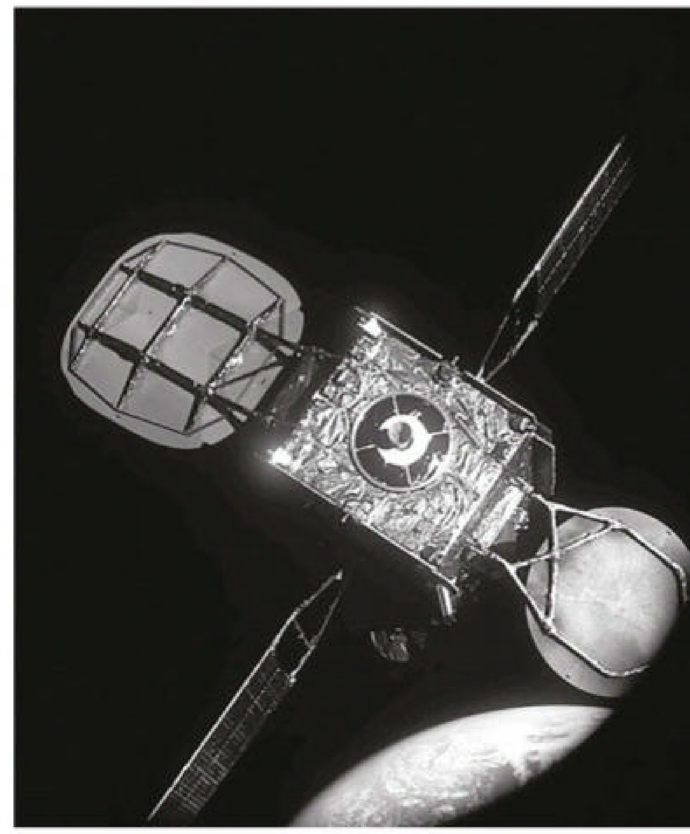
➡ From its "near-hold" position of 60 feet away before docking with IS-901, MEV-1 snapped a historic portrait of its client on February 25, 2020. The tug returned IS-901 to service in a new orbit 36 days later. The successful relocation could portend a dramatic reshaping of the space industry.

TOP AND BOTTOM: NASA (2)

doing maneuvers weekly, and that's why they run out of fuel." Before launch, fuel is added through a port called a fill/drain valve: The tank is topped off and a cap is sealed to the inlet (the drain is for emergencies while still on the ground).

A thick multi-layer insulation blanket, or MLI, is wrapped around the satellite to further protect it from dust and debris, sealing it up like a submarine swaddled in tinfoil. With the blanket in place, it would be hard for a repair robot to access any components that aren't attached to the bus exterior, such as solar arrays, radio antennas, sensors, and cameras.

It's for this reason that Northrop Grumman opted to make MEV perform more like a tow truck than a mechanic, albeit a tow truck that stays affixed to the car long-term. "We believe in keeping it simple," Anderson says. MEV-1 will remain attached to IS-901 for five years, at which point it will return the satellite to the graveyard orbit, where it'll be decommissioned. Then MEV-1 will fly to its next client and repeat the docking and renewal procedure. By this time, a second mission-extension spacecraft, MEV-2 will be in geo orbit, hitched to another Intelsat client. Each MEV can service up to 10 satellites, or remain with the same one for the entirety of its 15-year design life. "We've built it to be compatible with about 70 to 80 percent of all geo satellites," Anderson says. If



the satellite uses one of the common cone-shape liquid apogee engines, then MEV-1 can very likely latch on to it. Satellites that use a different engine design would stymie the repair craft.

Anderson won't tell me how much Northrop Grumman charges for this service, but assures me the business model is compelling to satellite operators. "We could service low Earth orbit too," he says. "If there's a market there, we'll go."

HISTORY HAS ITS EYES ON YOU

Northrop Grumman isn't the only group preparing to service satellites. NASA and DARPA are also planning missions, and DARPA's Parrish tells me, "The entire on-orbit servicing community is watching [MEV-1's] progress with great interest, hoping for the very best on that mission."

That's part of what makes Anderson nervous while he waits for MEV-1 to move from its "near-hold" position 60 feet from IS-901 to the "capture box" position roughly three feet from the client. The journey between the two points takes about 45 minutes. At the end of that period, IS-901's controllers place it into a free-drift state, meaning simply that they are no longer controlling its attitude.

Now the moment of truth has arrived: Northrop Grumman controllers send the MEV-1 the command to begin its autonomous docking procedure. Now the seconds feel like minutes to Anderson. "This is where my heart really starts beating, because it's the point of no return," he says.

Having received the command to commence docking, MEV-1 is untethered from its puppeteers in Virginia. Both satellites are now in tight formation, drifting in tandem at thousands of miles per hour. The most minute maneuvering error could be catastrophic. That's because the distance between Earth and geo orbit creates a communications delay, or latency, of about 540 milliseconds round-trip. A half-second doesn't sound like much, but it's way too long for an operator in Virginia to safely mate two spacecraft 22,000 miles away. Hence the need for both spacecraft to be placed in an autonomous state. "The reason we go 'open loop' is so there are no other forces in the system," Anderson explains. "Having a human in the loop would just get in the way."

He's been awake for nearly 20 hours when ground controllers declare that IS-901 has been captured at exactly 2:15 a.m. EST on Tuesday, February 25, 2020. IS-901 returned to service in its new orbit on April 2.

Northrop Grumman's success gives satellite operators like Intelsat their first proof that servicing in orbit is possible. It's also deeply encouraging to engineers at DARPA and NASA, who are pursuing considerably more ambitious and complex satellite-servicing missions.

ROADSIDE ASSISTANCE IN ORBIT

At NASA Goddard Space Flight Center in Maryland, the OSAM-1 mission is in planning. Formerly known as Restore-L, with the "L" denoting low Earth orbit, OSAM-1 (the acronym is for On-orbit Servicing, Assembly, and Maintenance) is focused not on geo, as the MEVs are, but on low Earth orbit, home to approximately 2,200 active satellites. The OSAM-1 spacecraft is scheduled to launch in 2023. Once in orbit—at an altitude of about 435 miles—it will attempt to refuel the $500 million Landsat 7, an Earth-imaging satellite launched in 1999 and operated by the U.S. Geological Survey and NASA. OSAM-1 will be equipped with three robotic arms: two built at NASA Goddard (one is essentially a backup for the other) and a third built by Maxar, a space technology company in Westminster, Colorado. Maxar's apparatus, called SPIDER (for Space Infrastructure Dexterous Robot), is based on similar arms the company has built for NASA's Mars landers.

"We are flying a robot arm for the first time that will manipulate a fill/drain valve on a satellite," says Brent Robertson, the OSAM-1 project manager. The NASA arm will grab a ring encircling the base of Landsat 7, a Marman clamp that fastened the spacecraft to its launch vehicle. Next, the arm will guide Landsat 7 into so-called "berthing posts," where it will be secured to its rescue satellite. Now free from holding Landsat 7, the arm will use its tool set to cut away the insulation blanket, snip locking wires around the fill/drain valve, and unscrew its cap. Then OSAM-1 will add 254 pounds of fuel. That will allow Landsat 7 to maintain its orbit for years, and eventually to perform de-orbiting maneuvers. OSAM-1 will carry more than 6,000 pounds of biopropellant fuel to allow it to intercept and dock with other "clients" should its one-year mission be extended.

Besides refueling, the OSAM-1 spacecraft will demonstrate assembly and manufacturing. Because there is no dirt in space, it's possible for OSAM-1 to disassemble and reassemble a satellite for ser-

A Northrop Grumman technician tests the corkscrew-probe tool the satellite tug MEV-1 will use months later to latch onto a com-sat and carry it to a new geosynchronous orbit.

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vicing with little contamination risk.

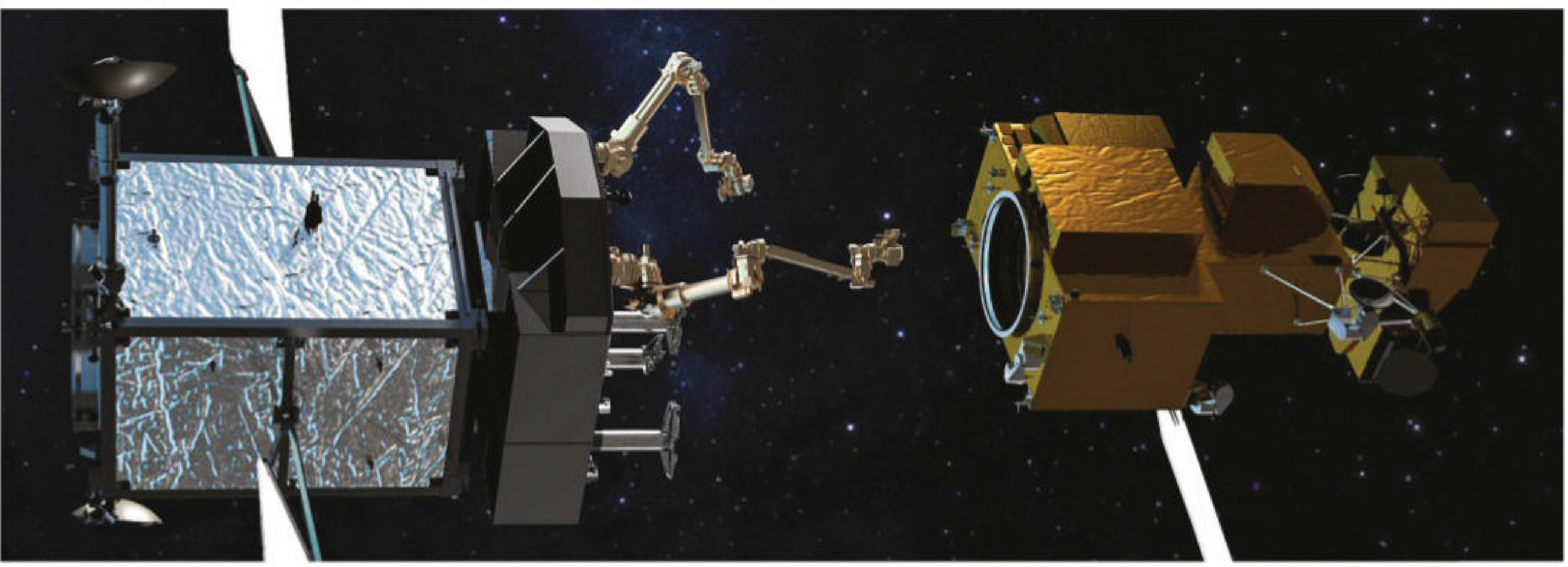
This is where SPIDER comes in. OSAM-1 will carry a segmented radio dish antenna into orbit, which SPIDER will put together. "We're going to send a [radio] signal through that antenna to ground stations," Robertson explains. "And then we're going to disassemble the antenna and assemble it again to show it's a repeatable task." Next, OSAM-1 will manufacture a rigid 10-meter beam, extruding fused carbon from a device that works something like a Play-Doh squeeze press. "The beam will have the associated stiffness appropriate for assembling a spacecraft," Robertson says.

The tough part of OSAM's mission—refueling—is not on the to-do list of DARPA's Robotic Servicing of Geosynchronous Satellites program. "It's an incredible technical feat to be able to do that," reckons Parrish. "The [OSAM-1] team has spent years developing the technology. They've done numerous experiments and demonstrations in space to back up their analyses and simulations on the ground." Instead, the RSGS is inventing an orbiting handyman. The spacecraft will carry dual six-foot-long robotic arms that can extend, flex, and rotate with seven degrees of freedom—nearly identical to human dexterity. "There is also a wrist mechanism that allows for tools to be interchanged," Parrish notes.

After it launches in late 2022, the geo-orbiting RSGS spacecraft will employ powerful radar and sensors to inspect satellites. "We can fly around the client and take images without ever touching it," explains Parrish. If it spots any damage, the RSGS will grasp the Marman clamp on a client satellite with one arm, leaving the other free to make repairs. The RSGS craft also could move its client to a new position in geo or relocate a dead satellite to the graveyard orbit, like a trash collector hauling away space junk.

I ask Anderson whether our military could convert a servicing satellite into a weapon, perhaps using it to dismantle an enemy spacecraft. After all, it's DARPA, I point out, that's developing satellites with the most complex and versatile robotic capabilities. He quickly dispels my proposition. "It's really in the realm of science fiction," he says. "To do it without the cooperation of a client would essentially mean the termination of my servicing vehicle." It would be impossible to maintain a safe separation between both spacecraft, since the "enemy" satellite would have to be in an open loop for a docking to succeed. "It's very easy for someone to see an MEV approaching another spacecraft because it's moving so slowly [relative to the other spacecraft]," says Anderson. "You can't really do this in secret."

Parrish believes the RSGS could handle almost any type of servicing job because its robotic capabilities can be augmented later. "We don't have to imagine every tool we might ever need because we can fly up new ones on future spacecraft," he says. But among the most prized achievements would be saving a brand-new multi-million-dollar satellite that encounters a glitch not long after it enters orbit—one that would be fatal without servicing. Says Parrish: "We can gallop in with our robotic system to the rescue. Now that would be a great day!"



⬆ An artist's conception of DARPA's OSAM-1 craft depicts an all-purpose "roadside assistance" vehicle for errant satellites. Its three dexterous limbs will allow it to not only capture and refuel depleted satellites, but to disassemble and repair them too. The spacecraft's first mission is set for 2023.

NASA

MADE IN SPACE

Refueling and repairing satellites could extend their lifespans significantly, sparing operators the exorbitant expense of replacing them. The task would be easier if satellite builders adopted technical standards. DARPA has funded an industry organization called CONFERS (Consortium for Execution of Rendezvous and Servicing Operations) to develop such standards. But not all members agree on how to proceed. “There are two sides to the coin,” Anderson tells me. “One side says that setting standards too early will stifle innovation. The other side believes standards can help grow the market.” Parrish adds: “It’s always been a chicken and egg situation. Spacecraft developers didn’t [design their satellites to be serviceable in orbit] because there was no servicer. And there was no servicer because there was nothing up there that was accommodating. In the future, we hope that satellites will be designed to accommodate on-orbit refueling. That will make this operation much simpler, take less time, and be more economical than the operations needed to refuel an unprepared spacecraft.”

Because OSAM-1 is focused on refueling, Goddard engineers have developed a robot-friendly fuel cap. “We call it the cooperative servicing valve,” Robertson says. “We wouldn’t have to cut wire or MLI blankets. It would require one tool to refuel, as opposed to flying six right now.” NASA has licensed its design to satellite manufacturers, which plan to integrate it into future spacecraft. “We’re actually going to fly it on OSAM-1 to allow us to be refueled,” says Robertson.

What gets program managers most excited, however, is the promise of in-orbit assembly—and not just for satellites. NASA is paying Maxar $142 million to design and build the SPIDER arm for OSAM-1. But Al Tadros, vice president of space infrastructure at Maxar, tells me his engineers envision much broader applications. “The mission is very much to advance technology for NASA and for the U.S. industry,” he says. “For humans going to Mars, or maintaining the [International Space Station], or building new, much larger telescopes—to enable these missions you need this core capability.” According to Tadros, once the RSGS demonstration mission is completed, Maxar will offer in-orbit assembly to its commercial customers.

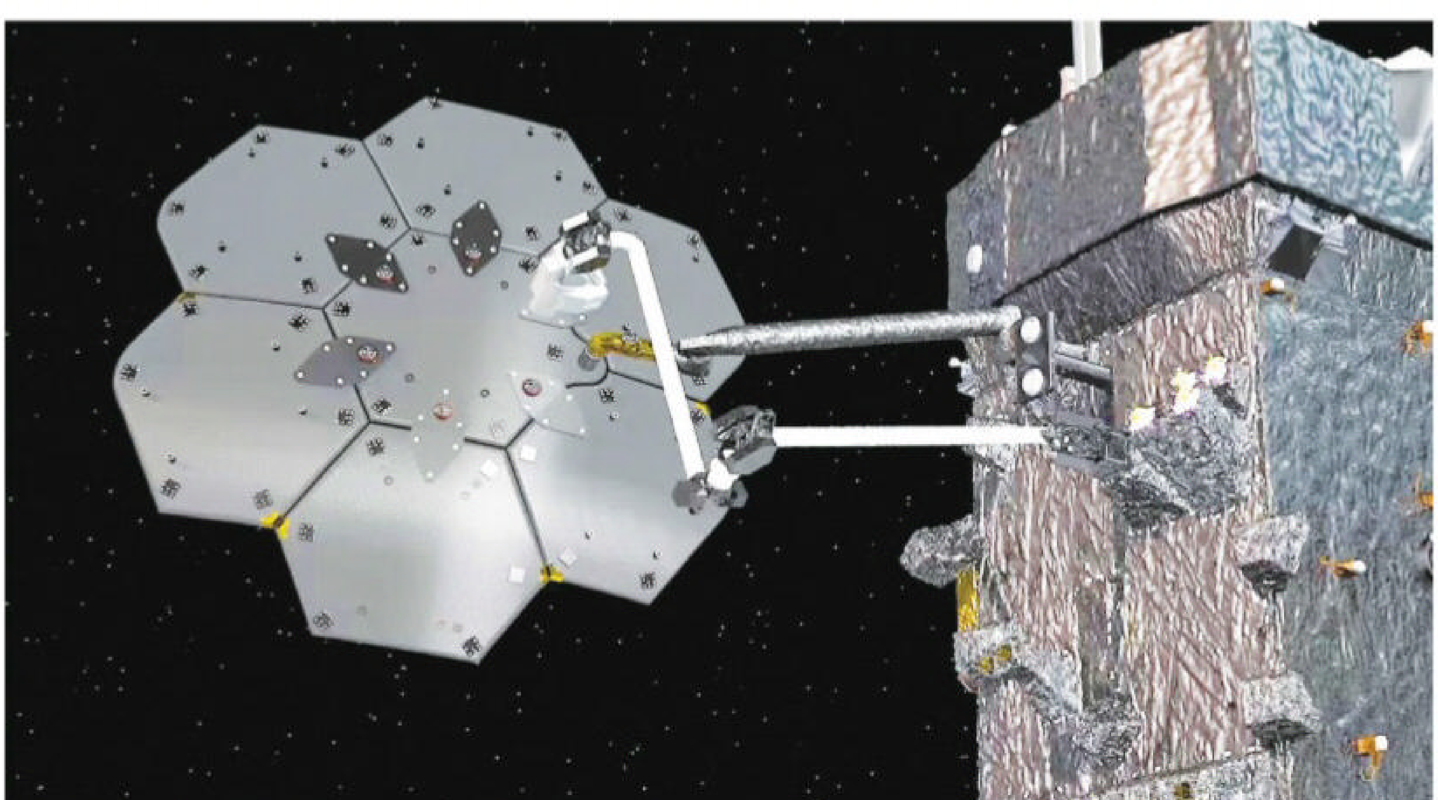
SEND UP THE SPECIALISTS

The various approaches to satellite-servicing—tow truck, refueling, and robotic repairs—serve specific niches, contend the experts. “I think there are good and valid applications for each,” Anderson says. “Our customers are risk-adverse. Our MEV

> “WE CAN FLY AROUND THE CLIENT AND TAKE IMAGES WITHOUT EVER TOUCHING IT, USING CAMERAS AS MICROSCOPES, GETTING WITHIN A CENTIMETER.”
>
> —JOSEPH PARRISH, DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

is a small increment of technology development and, therefore, much lower risk than the ‘satellite surgery’ required to perform refueling on a satellite that was not originally prepared for refueling.”

But he also believes that OSAM-1 “will definitely have business benefits. Once proven feasible…it will be able to refuel a vehicle and extend the lives



⬅ A Maxar Technologies rendering depicts the firm’s Space Infrastructure Dexterous Robot (SPIDER) bolting together a seven-panel communications antenna in orbit. SPIDER is also expected to build a spacecraft beam during its first deployment in 2023.

MAXAR TECHNOLOGIES

NASA/GSFC

In the fall of 2016, Robotic Systems Engineer Zakiya Tomlinson trains at NASA Goddard Space Flight Center with software that will support OSAM-1's satellite-servicing capability. OSAM-1 and similar spacecraft have the potential to create a new industry—and a new future for space exploration.

of several satellites per year, while our MEV can only extend one satellite a time. Refueling may be a better solution for many healthy satellites due to the potential for lower costs than a dedicated MEV, or for satellites that have special operational needs, like many military satellites. But there is definitely need in the market for both types of services."

Northrop Grumman is also working with DARPA and its RSGS program to develop so-called Mission Extension Pods, or MEPs. These are self-contained servicing pods designed to do propulsion and attitude control.

"The servicer installs the MEP to the client and then flies away," Parrish explains. "This operation doesn't tie up the servicer for an extended period." At the same time, he isn't betting on any specific approach just yet. "I don't think that anyone knows how this is going to play out," Parrish says. "When I first entered this domain, refueling was the application everyone was focused on. But, so far, we've seen only one commercial servicing operation and that is MEV-1 doing attached life extension. I think the role of the technologists and the servicing system designers is to develop a wide variety of servicing modalities and then let the market decide which is best."

At Northrop Grumman, Anderson shows me where technicians conduct vibration and acoustic tests on new spacecraft. Every satellite must withstand the violent forces experienced during liftoff from Earth.

Maryland Sound provides audio for rock concerts and the Fourth of July celebration on the National Mall. You wouldn't think they'd also be in the spaceflight business.

That's where you'd be wrong. Northrop Grumman has hired the company to simulate the ear-pummeling, bone-rattling sonic barrage of a rocket launch. The formal name for this procedure is Direct Field Acoustic Testing.

"They build these towers of speakers requiring one million watts of power," Anderson says. "When they do it, stuff in my office shakes."

This is why satellites cost so much and are so bulky and heavy: They must be robust enough to withstand the clamor and stress of the hellacious ride into space.

"If we could just take up the panels and materials, it would weigh one-tenth of the mass of what we launch today," Anderson says.

Spacecraft assembled in orbit could not only be lighter but also much larger. We are centuries from the sprawling ocean liner-size starships of science-fiction sagas. Nevertheless, the dawn of satellite servicing and in-orbit assembly puts us squarely on that trajectory. ◻