THE COMING MOON RUSH

Technology, billionaires, and geopolitics will all help get us back to the moon, but they won't be enough to let us live there indefinitely

By Eliza Strickland & Glenn Zorpette

FIFTY YEARS AGO this month, two people walked on the moon. It was by any measure a high point in human history, an achievement so pure and glorious that for a moment, anyway, it seemed to unite the world's fractious, cacophonous communities into a kind of triumphant awe. Over the next three and a half years, 10 more people had the honor of leaving tracks on another world. And then it all came to a halt. • It's time to go back, and this time for a lot more than a series of multibillion-dollar strolls. • After decades of scattered objectives and human missions that literally went nowhere (aboard the International Space Station), the world's space agencies are coming into surprising, if delicate, alignment about returning to the moon and building a settlement there. NASA is leading the charge, with new and aggressive backing from the White House. The U.S. space agency has officially declared its intention to return humans to the moon by 2024—although many observers question whether it can adhere to such an ambitious timetable. • So far, NASA and its partners have drawn up the most detailed plans and spent the most money. But the enthusiasm goes far beyond the United States. This past April, Zhang Kejian, director of the China National Space Administration, said the country planned to build an inhabited research station near the moon's south pole "in about 10 years." China has the world's second-largest

ROCK AND ROVER: During the Apollo 17 mission, Harrison Schmitt paused near Tracy's Rock, about 3 kilometers from the landing site.

space budget behind the United States, and it has already put two landers and two rovers on the moon.

Even before China's announcement, Russia had declared its intention to land cosmonauts on the moon in 2031 and to begin constructing a moon base in 2034. The head of the European Space Agency, meanwhile, has been promoting a concept called the Moon Village—an international settlement that would support science, business, and tourism on the lunar surface.

Regard all of these plans and dates skeptically (particularly the Russian ones), but don't dismiss them as pipe dreams. Unlike the Apollo-era space race, this time around the rush to the moon isn't being driven solely by space agencies and national pride. The past two decades have seen the emergence of a commercial space industry, with companies building rockets and rovers and pursuing more speculative goals. In the United States, this private-sector enterprise is fueled in part by the spacefaring visions of two famous billionaires, Jeff Bezos and Elon Musk.

NASA's scheme for lunar exploration may have room for these companies, but the agency's plan is very much in flux, and it has already drawn fire from experts who find it needlessly complicated. It depends on a small space station in high lunar orbit—called the Gateway—that would serve as a combination way station, storehouse, assembly facility, and laboratory for people and equipment traveling between Earth and the moon. NASA insists such a station is necessary because the spaceships it's currently developing don't have the propulsive capacity to go directly to low lunar orbit. The agency also says that operating the Gateway will give it deep-space experience for a crewed mission to Mars. But outsiders have attacked the idea as an unnecessary expense and an additional point of vulnerability, with one former NASA administrator going so far

PREVIOUS PAGES: ALEXANDER RIEBER/EYEEM/GETTY IMAGES; THIS PAGE: EUGENE CERNAN/NASA as to call it "stupid." For a detailed consideration of the pros and cons, turn to "Gateway or Bust" (p. 32).

The Gateway plan, which NASA began formulating nearly a decade ago, calls for a very large rocket to ferry people and supplies to the orbiter, as well as a fleet of landers to travel between the Gateway and the moon's surface. The first version of the rocket, known as the Space Launch System (SLS) Block 1, is designed to carry a crewed space capsule called Orion that will weigh 23 metric tons. The SLS has been under construction for eight years by a consortium led by Boeing and including United Launch Alliance, Northrop Grumman, and Aerojet Rocketdyne. So far it has cost about US $17 billion and is three years behind schedule.

Orion, meanwhile, is being built by Lockheed Martin with help from the European Space Agency and Airbus, and is supposed to support six astronauts. The Orion partners are officially planning to launch a test mission in 2020 or 2021 (stay tuned), in which an unoccupied Orion will go into orbit around the moon and then return to Earth.

Until this past March, NASA had been aiming for a moon landing in 2028, but under pressure from the Trump White House the agency moved its target up to 2024. And that's where the billionaires could come in. Musk's and Bezos's rocket companies, SpaceX and Blue Origin, are both developing heavy-lift rockets capable of reaching the moon. At its highest levels, NASA remains committed to the SLS rocket and the Gateway. Nevertheless, the agency has also sporadically flirted with the idea of Orion being lofted by SpaceX or Blue Origin rockets, which some observers insist are being developed at a swifter pace than the SLS.

Both companies seem up for the challenge: SpaceX already has a contract with NASA to build crewed spacecraft to ferry astronauts to the International Space Station. And Blue Origin is building both heavy-lift rockets and a crewed lunar lander, named Blue Moon, which Bezos says will be ready for action in 2024. Even if NASA doesn't employ their services, it's entirely possible that one or both of these companies will go it alone. In "The Heavy Lift" (p. 26), *IEEE Spectrum* contributor Mark Harris appraises the Blue Origin rocket engine that aims to launch a new era in space exploration.

Clearly, the establishment of a reliable and efficient system for moving cargo and crew to the moon's surface is an enormous undertaking. Big as it will be, it won't make much sense unless it's just the opening act of an epic saga in which humans establish a permanent presence there. As we explain in this special report, taking up residence on the moon will involve stupendous challenges.

For example, in "Homesteading the Moon" (p. 40), Matthew Hutson spotlights the architects and engineers who are designing habitats that can withstand extreme temperatures, withering radiation, and moondust so abrasive it can eat through a space suit. One of the most promising building techniques uses that very dust, technically known as regolith, as raw material for 3D printers.

Navigating in the bleak lunar landscape will also be tough. With no GPS to guide them, astronauts in a rover could easily get lost in an endless ashen expanse. In "Turn Left at Tranquility Base" (p. 48), we describe how space startups are solving the problem with extraordinary feats of mapping-on-the-fly. One company, Astrobotic, says its simultaneous localization-and-mapping software will also guide rocket-powered drones that will explore the moon's lava tubes. These huge natural underground tunnels are candidates for next-generation settlements, as they offer more moderate temperatures and shielding from radiation.

To be truly sustainable, a lunar settlement will have to make use of local resources. So engineers are already designing the mining operations that will extract water ice from the regolith in the moon's permanently shadowed craters. The infographic "Squeezing Rocket Fuel From Moon Rocks" (p. 46) explains how those water molecules can then be split into hydrogen and oxygen, basic components of rocket propellant.

If we master these and other challenges, we'll be poised for a great leap. In the second half of the 20th century, as humankind began taking the idea of spaceflight seriously, a base on the moon was invariably regarded as the logical perch from which to study, and eventually spread out into, the solar system. What we learned then was that space exploration timetables are long, and political will capricious. But now, as it did in the 1960s, the United States finds itself in a fast-moving great-power rivalry. As it was then, it is inclined to a showy demonstration of technological prowess. And this time the endeavor has the backing of billionaires on a mission.

All that might just be enough to get humans back to the moon. To make a permanent home there, though, will take something more. Such as? Well, international cooperation on a scale seldom seen outside of warfare comes to mind. Our biggest comparable model of colonization is Antarctica: many separate bases, each built and maintained by a different country. It is difficult to imagine that on the moon.

Perhaps the goal of living on the moon will at last provide an objective so grand and sublime that it will unite nations that compete economically. Eventually, it might even unite ones that compete geopolitically. It would be a fitting start to humankind's final migration. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/projectmoonbase0719

BURN, BABY, BURN: Blue Origin's BE-4 engine shows off its abilities during a static firing at the company's West Texas test facility.

THE HEAVY LIFT

Blue Origin's next rocket engine could power our return to the moon

JEFF BEZOS, THE FOUNDER of Amazon and the richest person on Earth, is of course a man who thinks big. But exactly how big is only now becoming clear. • "The solar system can support a trillion humans, and then we'd have 1,000 Mozarts, and 1,000 Einsteins," he told a private aviation group at the Yale Club in New York City this past February. "Think how incredible and dynamic that civilization will be." The pragmatic entrepreneur went on to say that "the first step [is] to build a low-cost, highly operable, reusable launch vehicle." And that's precisely what he is doing with his private aerospace firm, Blue Origin. • Blue Origin is not just a company; it's a personal quest for Bezos, who currently sells around US $1 billion of his own Amazon stock each year to fund Blue Origin's development of new spacecraft. The first, called New Shepard, is a suborbital space-tourist vehicle, which should make its first crewed flight later this year. But it is the next, a massive rocket called New Glenn, that could enable cheap lunar missions and kick-start Bezos's grand vision of human beings living all over the solar system. • New Glenn's first stage will use seven enormous new BE-4 engines, each powered by methane (the same fuel used in some of Amazon's less-polluting delivery vans in Europe). Like SpaceX's Falcon booster, the New Glenn's first stage will also use its engines to steer itself gracefully back down to a landing ship for reuse.

By Mark Harris

IN THE MAKING: A Blue Origin worker inspects these giant nozzles destined to become part of the company's new BE-4 rocket engines.

After eight years of development, the BE-4 represents the cutting edge of rocket science. It promises to be simpler, safer, cheaper, and far more reusable than the engines of yesteryear.

Blue Origin is also working on two other engines, including one (the BE-7) destined for the company's Blue Moon lunar lander. But the BE-4 is the largest of the three, designed to generate as much as 2,400 kilonewtons of thrust at sea level. That's far less than the 6,770 kN provided by each of the five F-1 engines that sent men to the moon a half century ago. Even so, 2,400 kN is quite respectable for a single engine, which in multiples can produce more than enough oomph for the missions envisioned. For comparison, the Russian RD-171M engine provides a thrust of 7,257 kN, and Rocketdyne's RS-68A, which powers the Delta IV launch vehicle, can generate 3,137 kN.

But the real competition now arguably comes from the other swashbuckling billionaire in the United States' new space race: Elon Musk. His aerospace company, SpaceX, is testing a big engine called Raptor, which is similarly powered by liquid methane and liquid oxygen. Although the Raptor is slightly less powerful, at 1,700 kN, it is destined for an even larger rocket, the Super Heavy, which will employ 31 of the engines, and the Starship spacecraft, which will use 7 of them.

With SpaceX working at a blistering pace on various space missions and the oft-delayed BE-4 still two years from its first flight, Bezos could find his futuristic engine overshadowed before it begins launching payloads into orbit. Even so, Bezos's new rocket engine could prove more reliable and less costly than its rivals, which would make it enormously influential in the long run.

EVERY ASPECT of the BE-4's design can be traced back to Bezos's requirements of low cost, reusability, and high operability.

The overwhelming majority of orbital rocket engines ever made, typically costing millions of dollars apiece, have been used just once, ending up on the bottom of the sea or scattered over a desert. That single-shot approach makes about as much sense, Musk likes to say, as scrapping a 747 airliner after every flight.

The space shuttle was supposed to change all that, combining two reusable boosters with an orbiter housing three main engines that could be flown over and over again. But the shuttle proved far different from the workhorse it was

PREVIOUS PAGES AND THIS PAGE: BLUE ORIGIN intended to be, requiring painstaking evaluation and reconstruction after every flight. As a result, each shuttle mission cost an estimated $450 million. Riffing on Musk's airliner analogy, Bezos said recently, "You can't fly your 767 to its destination and then X-ray the whole thing, disassemble it all, and expect to have acceptable costs."

In the end, Blue Origin took inspiration for the BE-4 not from the U.S. space program but from the program's archrival, that of the Soviets.

As far back as 1949, Soviet engineers started adopting staged combustion engines, where some fuel and oxidizer flows first through a preburner before reaching the main combustion chamber. That preburn is greatly restricted, providing just enough pressure increase to drive the turbines that pump fuel and oxidizer into the combustion chambers. This scheme is more efficient than those used in simpler engines in which some propellant is burned just to drive the engine's pumps. In that case, the hot gases that result are vented, which squanders the energy left in them. In their designs, Russian engineers focused on a type of staged combustion that uses a high ratio of oxidizer to fuel in the preburner and delivers exceptional thrust-to-weight performance.

American engineers considered this approach to be impractical because high levels of hot, oxygen-rich gases from the preburner would attack and perhaps even ignite metallic components downstream. They opted instead to develop "fuel-rich" preburner technology, which doesn't have this problem because the hot gases leaving the preburner contain little oxygen. American engineers used this approach, for example, in the shuttle's main engines.

The Soviets persevered, using oxygen-rich staged combustion in an engine called the NK-33 for the USSR's secret moon-shot program in the late 1960s. The result of that program, a powerful but ungainly rocket called the N1, suffered a series of spectacular launchpad failures and never reached orbit. Dozens of NK-33s were mothballed in a warehouse until the mid-1990s, when the U.S. engine company Aerojet bought them to study and rebuild.

By the time Blue Origin started work on the BE-4 in 2011, American rocket engineers were ready to take on the challenges of oxygen-rich staged combustion to achieve the higher efficiency it offered. So that's what Blue Origin decided to use in this new rocket engine. SpaceX, too, will have an oxygen-rich preburner in its Raptor engines, which will also have a fuel-rich preburner, a configuration known as full-flow staged combustion.

AS THE SOVIETS LEARNED vividly with the N1, complexity is the enemy of reliability—even more so when an engine needs to be reused many times. "Fatigue is the biggest issue with a reusable engine," says Tim Ellis, a propulsion engineer who worked on the BE-4 from 2011 to 2015. "Rocket engines experience about 10 times more stress, thrust, and power than an aircraft engine, so it's a much harder problem."

To help solve that problem, Ellis suggested incorporating 3D-printed metal parts into the BE-4. Using 3D printing accelerated the design process, replacing cast or forged parts that used to take a year or more to source with parts made in-house in just a couple of months. The technology also allowed intricately shaped components to be made from fewer pieces.

"Fewer parts means fewer joints, and joints are one of the areas that can fatigue more than anything else," says Ellis. The 3D metal printing process involves sintering metal powders with lasers, and the resulting material can end up even stronger than traditional machined or cast components. Ellis estimates that up to 5 percent of Blue Origin's engine by mass could now be 3D printed.

"True operational reusability is what we have designed to from day one," says Danette Smith, Blue Origin's senior vice president of Blue Engines, in an interview over email. Each BE-4 should be able to fly at least 25 times before refurbishment, according to Bezos. When the expense of building each engine can be shared over dozens of flights, running costs become more important.

Blue Origin and SpaceX have both settled on methane for fueling their new engines, but for different reasons. For Musk, methane meshes with his interplanetary ambitions. Methane is fairly simple to produce from just carbon dioxide and water, both to be found on Mars. A spaceship powered by methane engines could theoretically manufacture its own fuel on Mars for a journey back to Earth or to other destinations in the solar system.

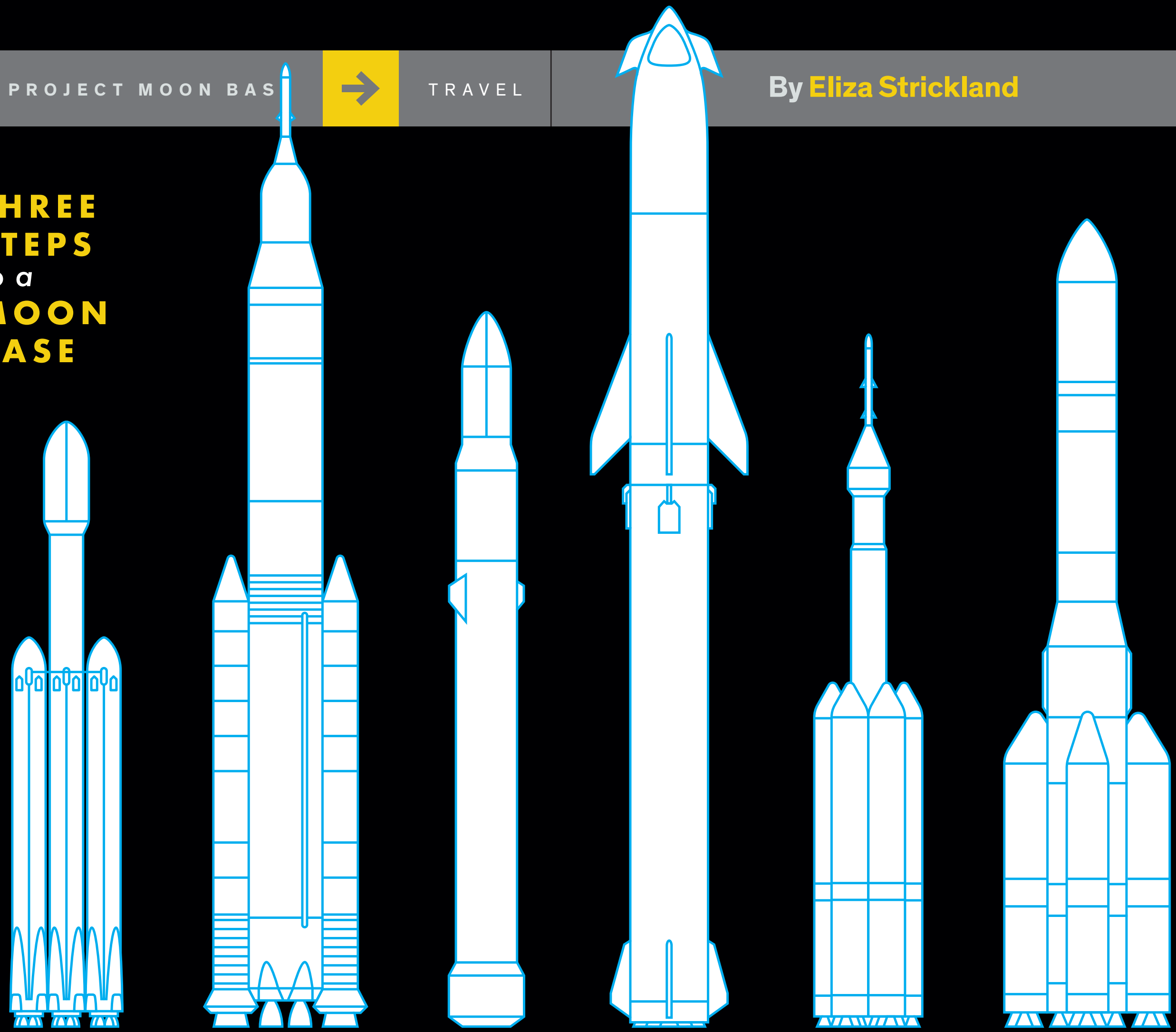
Blue Origin's choice was driven by more pragmatic concerns, says Rob Meyerson, president of Blue Origin from 2003 to 2018: "We found that LNG [liquefied natural gas] you could buy right out of | CONTINUED ON PAGE 56

HAZARDS of LUNAR LIFE

Moondust: Compared with dust on Earth, lunar regolith is chemically reactive and irritates eyes, lungs, and nostrils. Worse, it can damage DNA, potentially leading to cancer and neurodegenerative diseases. No one knows yet how much moondust is too much.

By Eliza Strickland

THREE STEPS *to a* MOON BASE



Falcon Heavy
SPACEX/2018
(ALREADY IN SERVICE)

Space Launch System
NASA, BOEING/2020

New Glenn
BLUE ORIGIN/
2021

Super Heavy and Starship
SPACEX/2023

Yenisei
ROSCOSMOS/
2028

Long March 9
CHINA NAT'L SPACE
ADMIN./2030

1. Getting to the Moon

SUPER-HEAVY-LIFT ROCKETS: NASA is relying on the Space Launch System (SLS) for its 2024 lunar return plan—although the rocket is over budget and behind schedule. China is working to upgrade its current Long March 5 rocket (which failed in its second flight) to the Long March 9. Russia says it has finalized the design for its Yenisei rocket, but experts wonder if it will actually get built. Blue Origin and SpaceX's rockets use reusable stages, which could make them much more economical. SpaceX's Starship is the most futuristic of the lot, comprised of reusable stages and a built-in crew capsule.

3. Building on the Moon

HABITATS: The European Space Agency is funding architectural and engineering work for the Moon Village, its proposed cooperative international settlement.

P. 40

MINING: Researchers at the Colorado School of Mines and Honeybee Robotics have proposed schemes to mine water ice for the components of rocket fuel.

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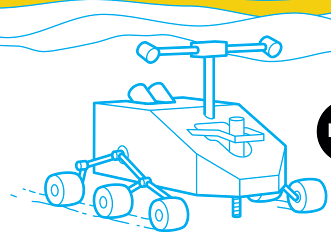
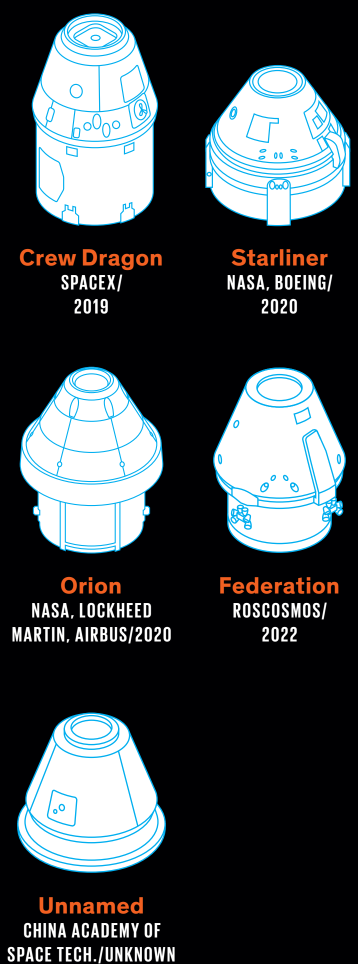


Once we manage to get humans and their gear to the lunar surface, what happens next? Many companies and researchers are actively pursuing technology projects that will enable a permanent settlement on the moon. Here are a few that we find particularly interesting.

ILLUSTRATION BY James Provost

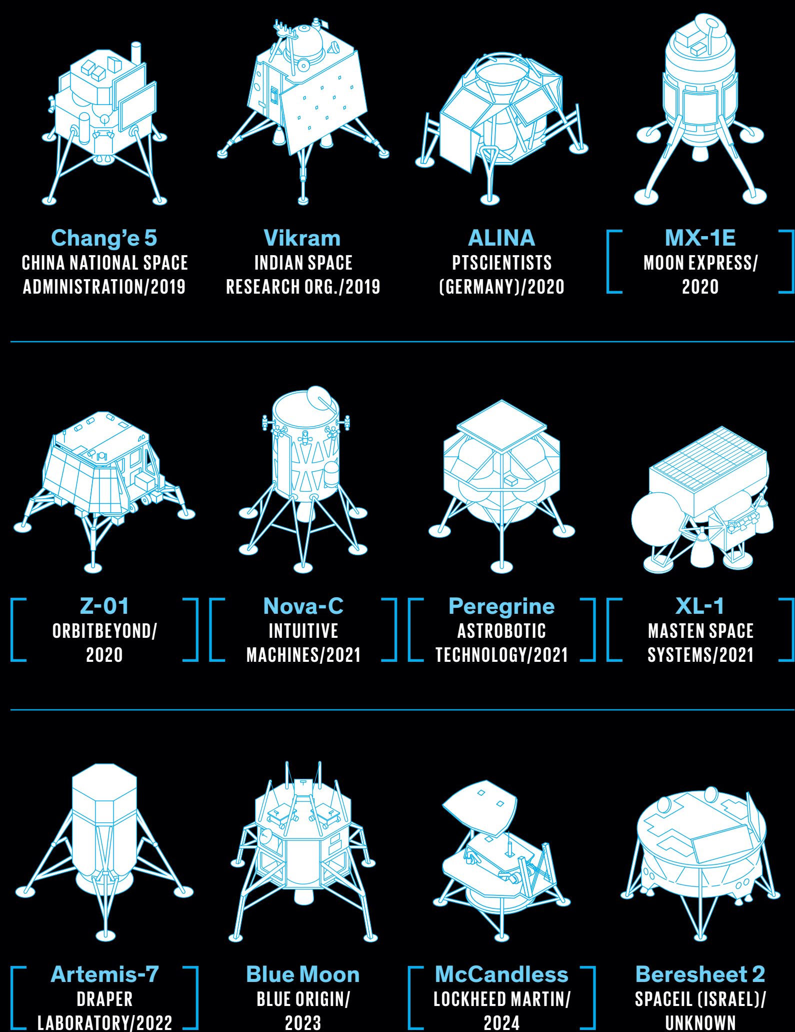
YEAR: PROPOSED LAUNCH DATE



CREW CAPSULES: The Crew Dragon and Starliner are scheduled to begin crewed flights to the International Space Station this year and next.

2. Landing on the Moon

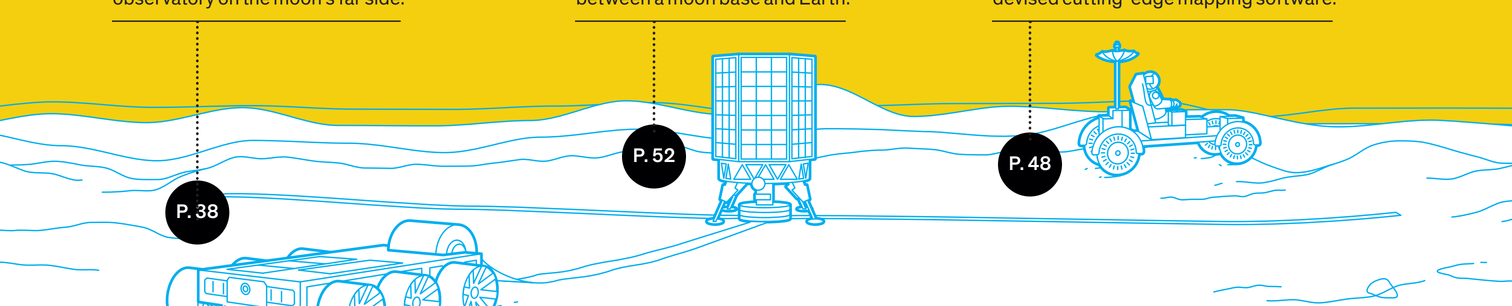
LANDERS: NASA has pushed for lunar cargo landers by working with companies [in blue brackets] in its Commercial Lunar Payload Services program. In May, its first contracts went to Astrobotic Technology, Intuitive Machines, and OrbitBeyond. But NASA's work with companies developing crewed landers has only just begun. The Israeli nonprofit SpaceIL's first lander, Beresheet 1, crashed on the lunar surface in April; it has vowed to build another. China's Chang'e 5 is scheduled to blast off on a sample return mission in December. Blue Origin's lander could be converted to a crewed vehicle.



SCIENCE: Astrophysicists at the NASA-funded Network for Exploration and Space Science have a plan for a radio observatory on the moon's far side.

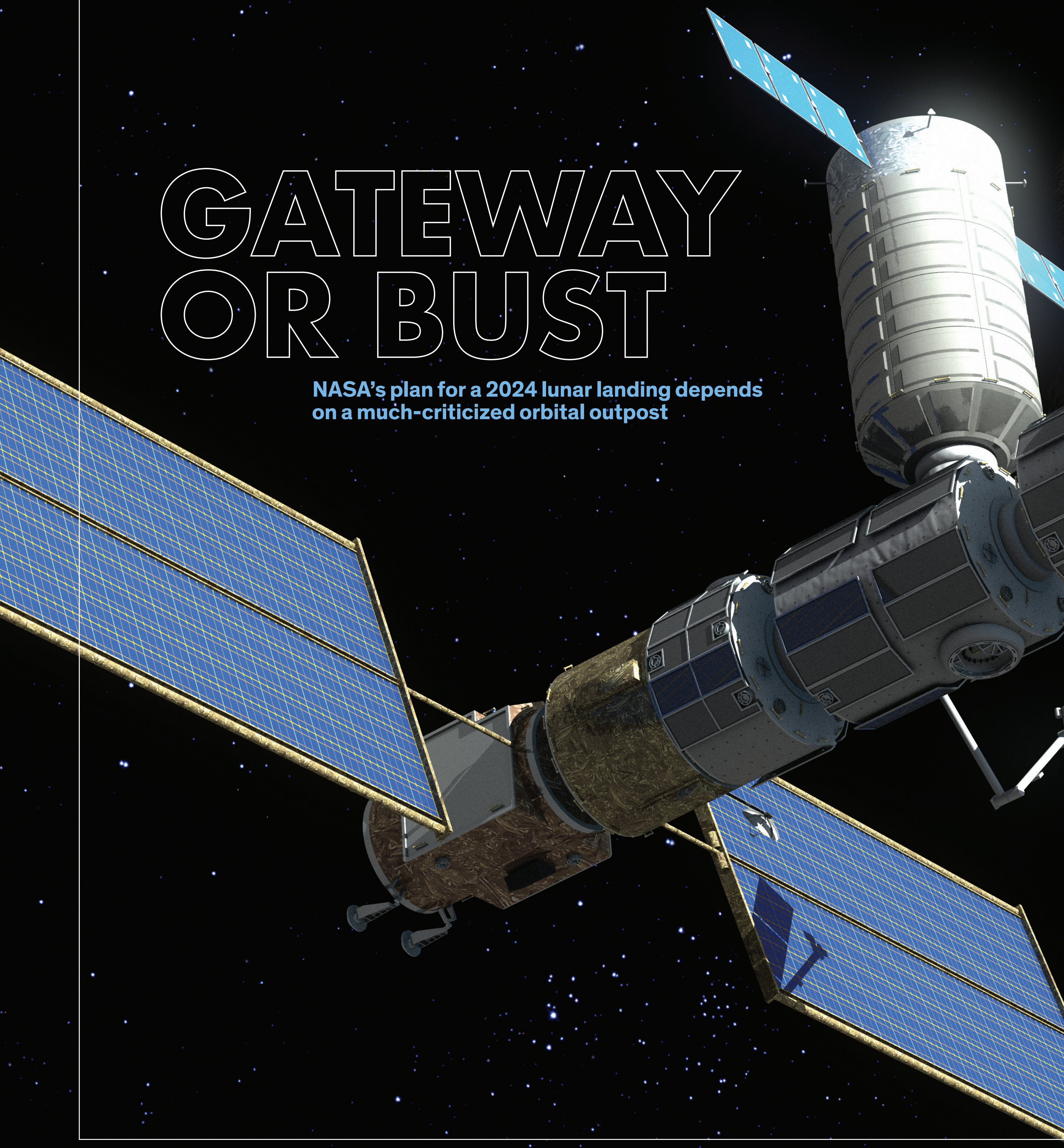
COMMUNICATIONS: NASA and MIT's Lincoln Lab have developed laser systems for high-bandwidth communications between a moon base and Earth.

NAVIGATION: For precision landings and safe exploration, Astrobotic Technology and Draper Labs have both devised cutting-edge mapping software.



GATEWAY OR BUST

NASA's plan for a 2024 lunar landing depends on a much-criticized orbital outpost



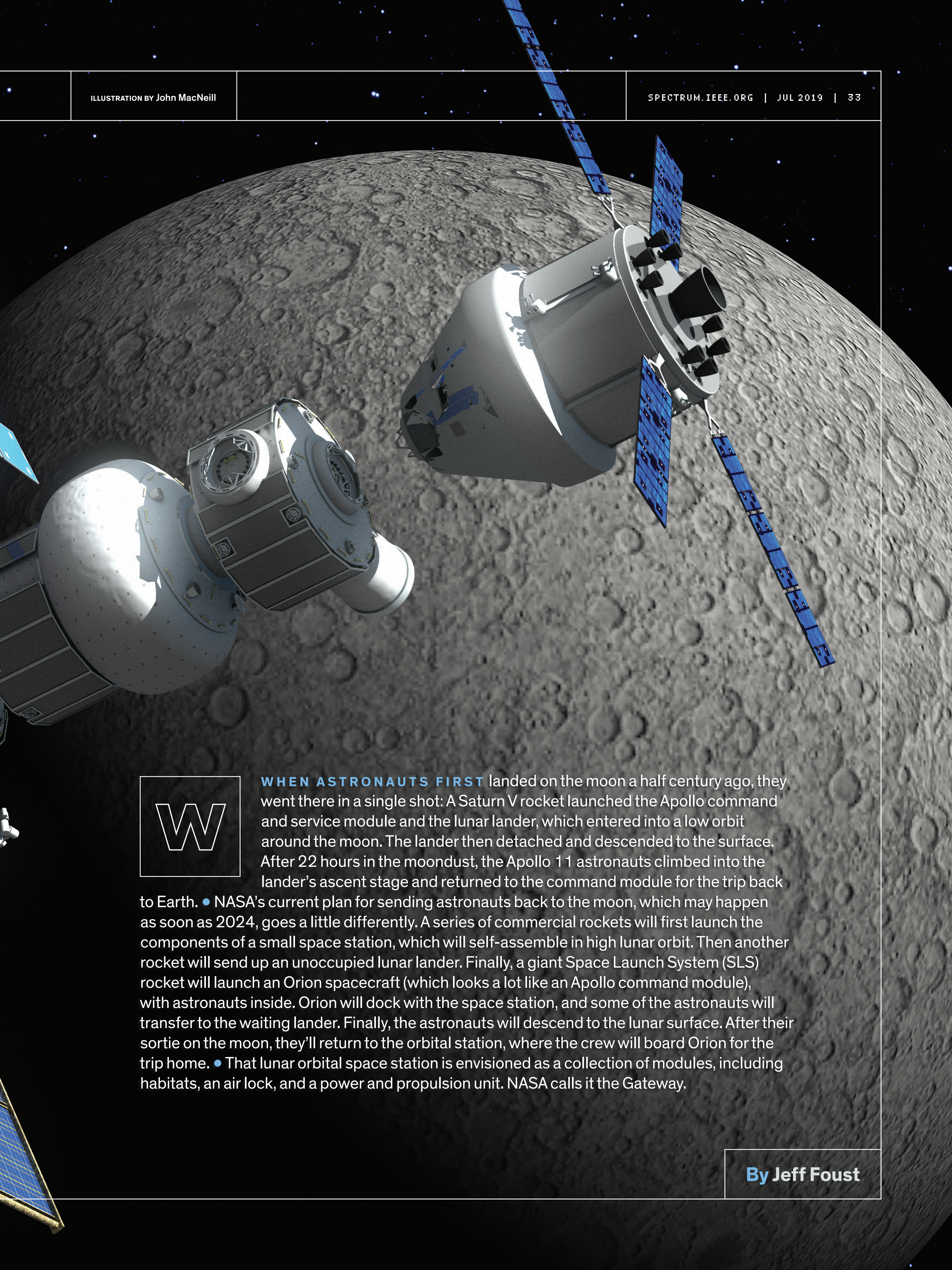
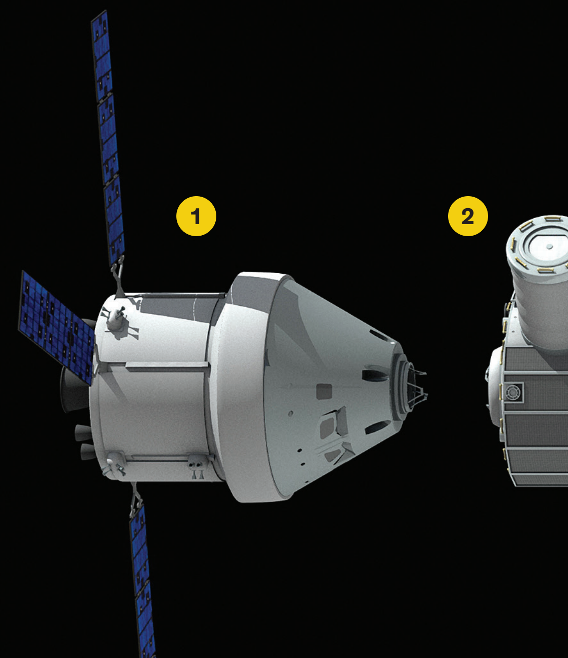


ILLUSTRATION BY John MacNeill

WHEN ASTRONAUTS FIRST landed on the moon a half century ago, they went there in a single shot: A Saturn V rocket launched the Apollo command and service module and the lunar lander, which entered into a low orbit around the moon. The lander then detached and descended to the surface. After 22 hours in the moondust, the Apollo 11 astronauts climbed into the lander's ascent stage and returned to the command module for the trip back to Earth. • NASA's current plan for sending astronauts back to the moon, which may happen as soon as 2024, goes a little differently. A series of commercial rockets will first launch the components of a small space station, which will self-assemble in high lunar orbit. Then another rocket will send up an unoccupied lunar lander. Finally, a giant Space Launch System (SLS) rocket will launch an Orion spacecraft (which looks a lot like an Apollo command module), with astronauts inside. Orion will dock with the space station, and some of the astronauts will transfer to the waiting lander. Finally, the astronauts will descend to the lunar surface. After their sortie on the moon, they'll return to the orbital station, where the crew will board Orion for the trip home. • That lunar orbital space station is envisioned as a collection of modules, including habitats, an air lock, and a power and propulsion unit. NASA calls it the Gateway.

By Jeff Foust

ILLUSTRATION BY John MacNeill



THE GRAND GATEWAY VISION

Its origins predate NASA's current plan to return to the moon, which the agency recently rebranded as the Artemis program, and the proposed facility has grown and shrunk in response to changing policies and budgets. NASA argues that the Gateway is an essential part of its human space exploration plans. But others wonder if it's necessary at all.

THE GATEWAY'S ORIGINS can be traced back to President Barack Obama's cancellation of NASA's *last* plan to return humans to the moon (the Constellation program). In an April 2010 speech announcing a new direction for NASA's human spaceflight efforts, Obama called on the agency to develop vehicles for deep space missions, starting with a trip to a near-Earth asteroid in 2025. However, NASA quickly determined that this goal was too ambitious, as it would require a crewed mission lasting many months. So the agency suggested an alternative: Instead of sending astronauts to an asteroid, they would bring an asteroid to the astronauts.

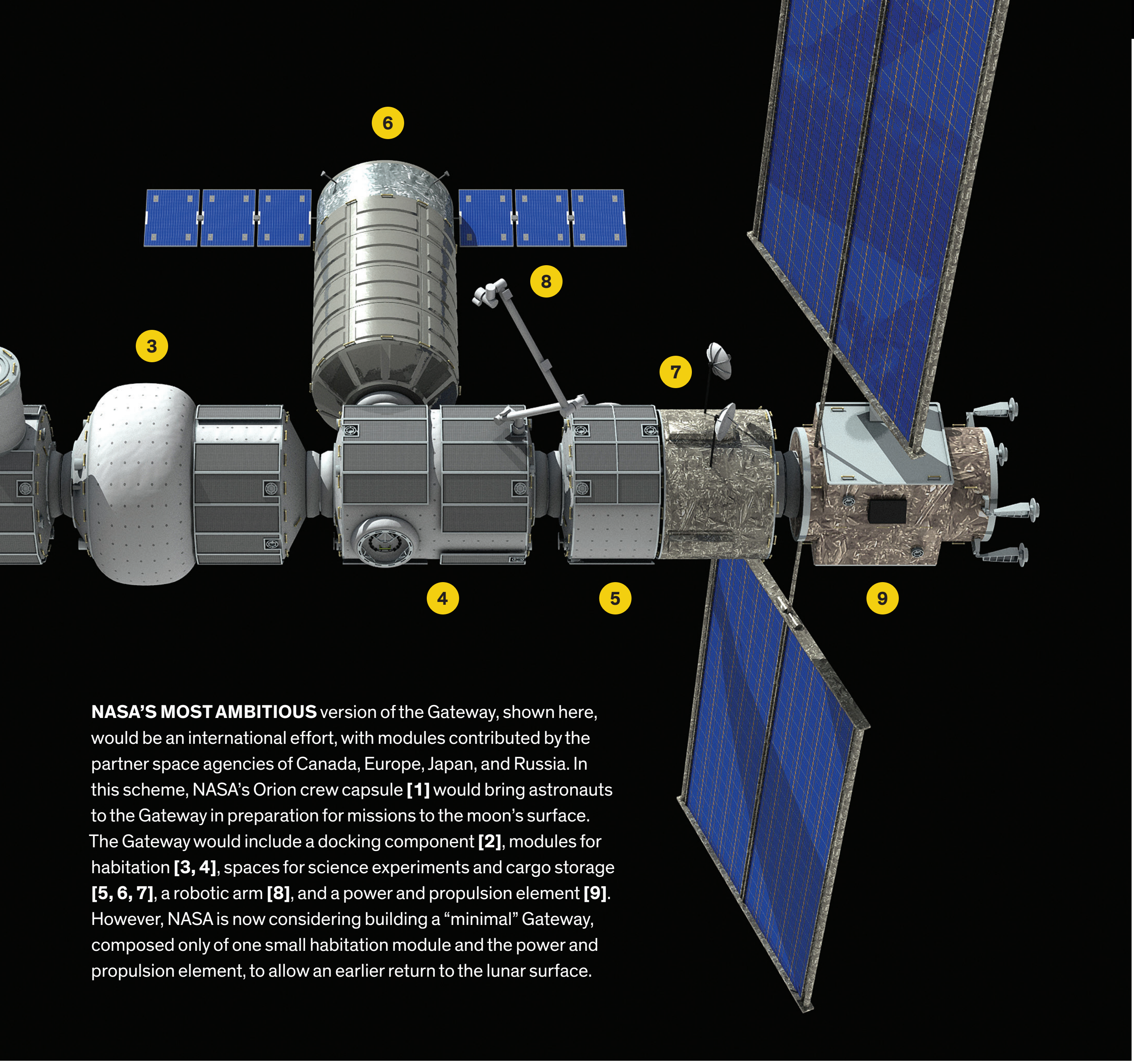
That idea led to the Asteroid Redirect Mission (ARM), announced in 2013. A robotic spacecraft would grab a small near-Earth asteroid—no more than 10 meters wide—and gradually shift it into a high, stable orbit around the moon, called a distant retrograde orbit, where it could be visited by astronauts on short-duration missions. But doubts about ARM's feasibility and utility doomed the program when it came up for budget approval in the U.S. Congress.

In 2017, under the new administration of President Donald Trump, NASA pivoted again. The agency had long maintained that the space program would benefit from having a presence in cislunar space—the area between the Earth and the moon—to test technologies for future missions to Mars and beyond. NASA's next proposal, revealed in March 2017, was a concept called the Deep Space Gateway: a collection of modules in a distant retrograde orbit around the moon. By the late 2020s, astronauts at this built-out Gateway could begin assembling a separate spacecraft, the Deep Space Transport, for long-duration missions to Mars.

That plan also fell by the wayside, though, after President Trump declared a new priority for NASA: sending astronauts back to the moon's surface, and beginning to build a permanent presence in space.

"THIS TIME, we will not only plant our flag and leave our footprints," President Trump said in December 2017. He had just signed a space policy directive that refocused the U.S. space program on human exploration, and most immediately on returning American astronauts to the moon. The "long-term exploration and use" of the moon, he said, was a step toward even grander projects. "We will establish a foundation for an eventual mission to Mars, and perhaps someday, to many worlds beyond."

The directive called on NASA to return humans to the surface of the moon using commercial and international partnerships—but left it up to the agency to figure out the best way to do so. NASA's approach was to repurpose the Gateway, formally renaming it the Lunar Orbital Platform-Gateway and presenting it as a staging area for lunar missions. The Gateway would be assembled in a different orbit, a highly elliptical one over the poles of the moon called a near-rectilinear halo orbit. Spacecraft from Earth can reach this orbit using minimal fuel, so supplies could be shipped up relatively easily and cheaply. With this setup, NASA said, astronauts would return to the lunar surface in 2028.



NASA'S MOST AMBITIOUS version of the Gateway, shown here, would be an international effort, with modules contributed by the partner space agencies of Canada, Europe, Japan, and Russia. In this scheme, NASA's Orion crew capsule **[1]** would bring astronauts to the Gateway in preparation for missions to the moon's surface. The Gateway would include a docking component **[2]**, modules for habitation **[3, 4]**, spaces for science experiments and cargo storage **[5, 6, 7]**, a robotic arm **[8]**, and a power and propulsion element **[9]**. However, NASA is now considering building a "minimal" Gateway, composed only of one small habitation module and the power and propulsion element, to allow an earlier return to the lunar surface.

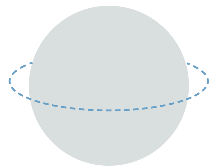
NASA also worked to bring in international partners, many of which were already involved with the International Space Station. By early 2019, the Gateway was taking form in a much grander configuration than ever before. The proposed configuration featured a power and propulsion element, which would use a solar-electric system to power the Gateway and move it around cislunar space, as well as two habitation modules, utilization and multipurpose modules, and a robotic arm. Canada promised to build the robotic arm; in February 2019 Canadian prime minister Justin Trudeau announced that the country would spend CAN $2 billion on the project. In the Gateway concept drawings, other modules were optimistically emblazoned with the logos from the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA), and Roscosmos, the Russian space agency.

"This is an aspirational vision of the Gateway," said NASA administrator Jim Bridenstine in a speech in mid-March. He was discussing NASA's fiscal year 2020 budget proposal, which included US $821 million for Gateway development. But, he added, he had talked with the leaders of other space agencies, and "they are very excited about partnering with us on going to the moon."

TWO WEEKS LATER, the aspirational vision changed dramatically once again. In a speech at a meeting of the National Space Council on 26 March, Vice President Mike Pence ordered NASA to accelerate its plans for lunar return. "At the direction of the president of the United States, it is the stated policy of this administration and the United States of America to return American astro-

ORBIT OPTIONS

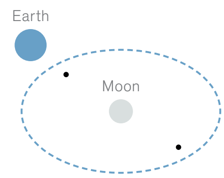
NASA has considered a variety of orbits from which to stage a lunar landing. They all have trade-offs: High orbits are cheaper to access from Earth, but low orbits provide quick access to the moon's surface.



LOW LUNAR ORBIT

Altitude
100 kilometers

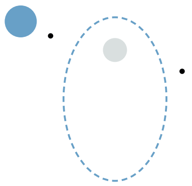
Orbit period
2 hours



DISTANT RETROGRADE ORBIT

Altitude
70,000 km

Orbit period
2 weeks



NEAR-RECTILINEAR HALO ORBIT

Altitude
2,000–75,000 km

Orbit period
~1 week

nauts to the moon within the next five years," Pence announced in the speech. The ambitious goal–a moon landing in 2024–took the world by surprise.

It also sent NASA scrambling to figure out how to reach that goal. In an April speech at the Space Symposium in Colorado Springs, Bridenstine said NASA would adjust its plans for lunar exploration, and would focus on only the basic elements required to get humans to the surface in five years. "The first phase is speed. We want to get those boots on the moon as soon as possible," he said. "Anything that is a distraction from making that happen we're getting rid of." And much of the Gateway seemed to qualify as a distraction. Bridenstine suggested that the only parts of the Gateway needed for a lunar landing would be the propulsion module and a habitation node where the Orion spacecraft and lunar landers could dock.

NASA's international partners were also shocked. The space agencies that had been considering building Gateway components suddenly didn't know when, or even if, their potential contributions would be needed. Bridenstine acknowledged this confusion in his April speech. "It has been a concern to our international partners, and they have expressed that to me throughout this conference," he said. But, he argued, these partners could still play roles in the second phase of NASA's lunar exploration plans–after that initial 2024 landing. Then, he said, NASA will prioritize long-term sustainability in cislunar space, which will include building out the Gateway to something like the configuration discussed earlier.

In the weeks that followed, NASA increasingly talked about building a "minimal" Gateway to support a 2024 lunar landing. In May, NASA announced that the White House would seek an additional $1.6 billion in funding in 2020 as a "down payment" toward meeting that deadline. The additional money is primarily intended to support commercial companies in their speedy development of lunar landers and to boost the lagging SLS and Orion programs, both of which are years behind schedule and billions of dollars over budget. The proposal also cut $321 million from the budget for the Gateway.

This revised budget "refocuses Gateway a little bit," said NASA's associate administrator for human exploration and operations, William Gerstenmaier, in a hastily arranged call with reporters. "Gateway was focused towards a little bit of a larger capability, more than we need just for the landing. This focused Gateway back to just the initial components that are needed to land on the moon." At the end of May, Bridenstine announced that NASA had selected the Colorado-based company Maxar Technologies to build the Gateway's power and propulsion element.

CRITICS OF THE GATEWAY argue that NASA shouldn't just scale back the space station–it should cancel the project altogether. If you want to go to the surface of the moon, the refrain goes, go there directly, as the Apollo missions did a half century ago. Building an outpost in lunar orbit adds expense, delay, and complications to a task that is already hard enough.

Among those critics is former NASA administrator Michael Griffin. Last November, during a meeting with an advisory group of the National Space Council, he offered a devastating critique of the space station. "The architecture that has been put in play, putting a Gateway before boots on the moon, is, from a space systems engineer's standpoint, a stupid architecture," he said. NASA should instead go directly to the lunar surface, he argued, and only then set up something like the Gateway to support such missions, particularly once astronauts are able to tap into resources like water ice at the lunar poles. "Gateway is useful when, but not before, they're manufacturing [rocket] propellant on the moon and shipping it up to a depot in lunar orbit."

Another prominent critic is Robert Zubrin, founder and president of the Mars Society. He likens the Gateway to a tollbooth, arguing that it adds expense to any future missions to the moon or Mars. He has proposed an alternative plan called Moon Direct that would make use of existing commercial launch vehicles to gradually build up a base on the lunar surface.

Aware of such criticisms, NASA is defending the Gateway. In May, the agency quietly distributed a white paper titled "Why Gateway?" that makes the case for the space station. "NASA's position, based on technical and programmatic analysis, is that the Gateway enables the most rapid landing of the next Americans on the moon," it stated. Among the reasons it cited: Orion's main engine is too weak to propel the spacecraft into a low orbit around the moon, requiring a staging area like the Gateway in its higher orbit.

"On balance, the near- and long-term benefits of pressing forward with the Gateway architecture far outweigh the risks of incurring substantial delays and inefficiencies that would inevitably result from a change to the architecture at this late date," the white paper concluded. Such changes, like increasing the performance of the Orion's propulsion system to enable it to reach low lunar orbit, might add billions to the roughly $30 billion spent to date on SLS and Orion and do nothing to achieve the 2024 deadline.

That reliance on SLS and Orion worries some moon enthusiasts, as both technologies are still under development–and both projects have encountered significant cost overruns and delays. Last October, NASA's inspector general issued a scathing report of the SLS program, which at that time was three years behind schedule and billions of dollars over budget. Yet NASA and its allies say there's no other way to the moon.

"The elements that we have right now can't do that [lunar landing] mission without Gateway," said Mike Fuller, who handles business development for NASA programs at Northrop Grumman. He believes Orion's limited propulsion is actually a design strength. The Apollo missions sent the control modules into an orbit about 100 kilometers above the moon, but "it was disadvantageous to go that deep" into the moon's gravity well, he says. Having Orion come to rest at a higher orbit makes it easier to abort back to Earth, as less propulsion is required.

Would it be possible for NASA to abandon the Gateway and its mission architecture entirely? Critics say that technological alternatives are emerging in the commercial space sector. They look to Blue Origin, the space company founded by Amazon billionaire Jeff Bezos and based near Seattle. Blue Origin is building both a reusable heavy-lift rocket, called New Glenn, and a lunar lander known as Blue Moon. Another contender is Elon Musk's SpaceX, based in Hawthorne, Calif., which is also working on a fully reusable rocket. It will carry an upper stage called Starship, which the company says could land directly on the moon and carry heavy cargo. "Having that vehicle on the moon can basically serve as the core of a pretty significant lunar outpost, growing with time," said Paul Wooster, principal Mars development engineer at SpaceX.

However, the exciting spacecraft from these companies are still under development, and it may be years before they're ready for lunar-landing missions. Moreover, any attempt to cancel SLS or Orion would likely face stiff opposition in Congress, particularly by influential members in states where work on those vehicles takes place. Perhaps it's no surprise, then, that NASA is doubling down on its Gateway plan. In May, while discussing NASA's revised budget proposal, Bridenstine said the Gateway is vital to achieving a 2024 lunar landing. "The Gateway is as important now as it was before," he said. "We cannot overemphasize how important the Gateway is."

If NASA, heedful of sunk costs and political realities, continues to march toward the Gateway, we may indeed witness a triumphant return of NASA astronauts to the moon's surface in 2024. NASA has defied the odds and met grand challenges before. But it's also possible that the plan won't survive budgetary debates in Congress, or that the 2020 elections will bring a new administration that will change the course of the lunar exploration program yet again. In which case, the determined billionaires behind SpaceX and Blue Origin might not wait around for NASA, and the next moon boots in the regolith might stamp a corporate logo in the dust. ■

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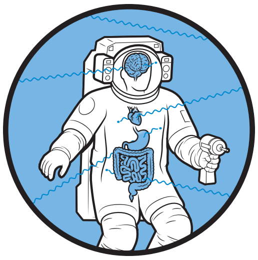
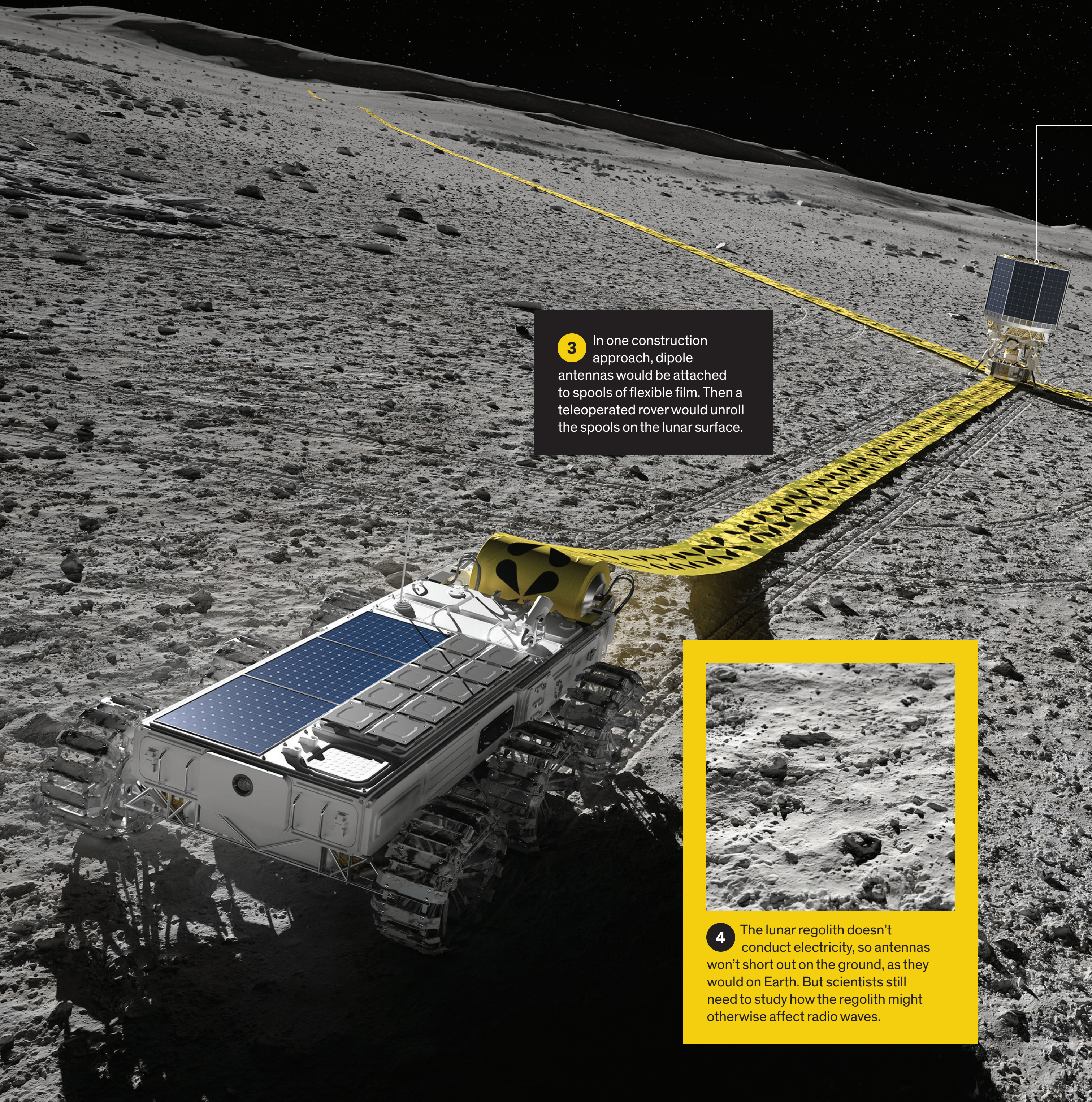


HAZARDS *of* LUNAR LIFE

Cosmic rays: In low Earth orbit, the planet's magnetic field deflects some of this high-energy radiation, almost entirely composed of atomic nuclei speeding in from outside the solar system. The moon lacks such a radiation shield. Particle-accelerator experiments on Earth suggest that cosmic rays can damage the gastrointestinal tract and cause cognitive decline.

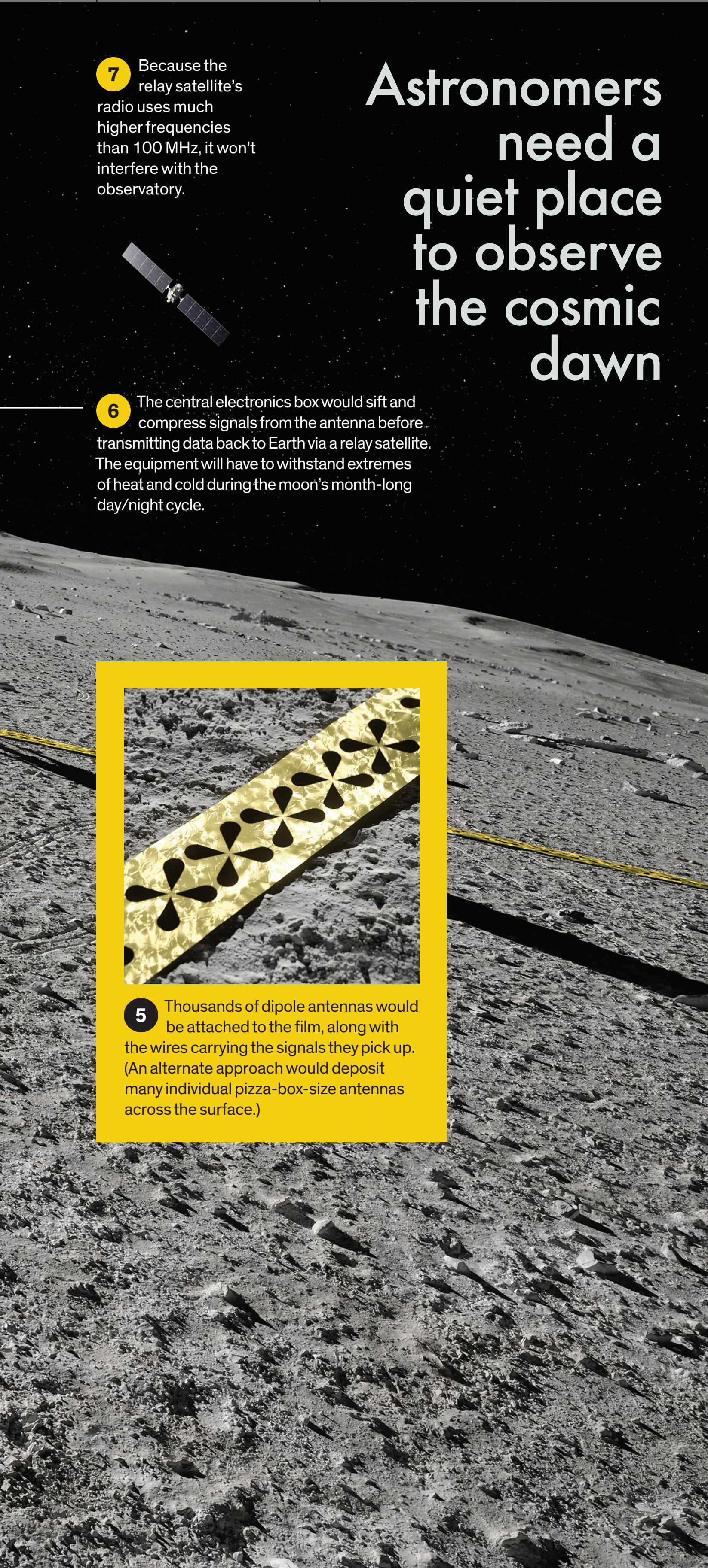
1 Early designs for far-side radio observatories envisioned large parabolic antennas nestled in craters, much as Earth's Arecibo telescope is nestled into a sinkhole in Puerto Rico.

2 But modern plans for moon-based astronomy focus on the low-frequency signals from the cosmic dawn, when the first stars and galaxies formed. These frequencies, which are below 100 megahertz, can best be detected by a large array of antennas.



3 In one construction approach, dipole antennas would be attached to spools of flexible film. Then a teleoperated rover would unroll the spools on the lunar surface.

4 The lunar regolith doesn't conduct electricity, so antennas won't short out on the ground, as they would on Earth. But scientists still need to study how the regolith might otherwise affect radio waves.



Astronomers need a quiet place to observe the cosmic dawn

7 Because the relay satellite's radio uses much higher frequencies than 100 MHz, it won't interfere with the observatory.

6 The central electronics box would sift and compress signals from the antenna before transmitting data back to Earth via a relay satellite. The equipment will have to withstand extremes of heat and cold during the moon's month-long day/night cycle.

5 Thousands of dipole antennas would be attached to the film, along with the wires carrying the signals they pick up. (An alternate approach would deposit many individual pizza-box-size antennas across the surface.)

THE VIEW FROM THE FAR SIDE

FOR DECADES, astronomers have gazed up at the moon and dreamed about what they would do with its most unusual real estate. Because the moon is gravitationally locked to our planet, the same side of the moon always faces us. That means the lunar far side is the one place in the solar system where you can never see Earth—or, from a radio astronomer's point of view, the one place where you can't *hear* Earth. It may therefore be the ideal location for a radio telescope, as the receiver would be shielded by the bulk of the moon from both human-made electromagnetic noise and emissions from natural occurrences like Earth's auroras.

Early plans for far-side radio observatories included telescopes that would use a wide range of frequencies and study many different phenomena. But as the years rolled by, ground- and satellite-based telescopes improved, and the scientific rationale for such lunar observatories weakened. With one exception: A far-side telescope would still be best for observing phenomena that can be detected only at low frequencies, which in the radio astronomy game means below 100 megahertz. Existing telescopes run into trouble below that threshold, when Earth's ionosphere, radio interference, and ground effects begin to play havoc with observations; by 30 MHz, ground-based observations are precluded.

In recent years, scientific interest in those low frequencies has exploded. Understanding the very early universe could be the "killer app" for a far-side radio observatory, says Jack Burns, an astrophysics professor at the University of Colorado and the director of the NASA-funded Network for Exploration and Space Science. After the initial glow of the big bang faded, no new light came into the universe until the first stars formed. Studying this "cosmic dawn," when the first stars, galaxies, and black holes formed, means looking at frequencies between 10 and 50 MHz, Burns says; this is where signature emissions from hydrogen are to be found, redshifted to low frequencies by the expansion of the universe.

With preliminary funding from NASA, Burns is developing a satellite mission that will orbit the moon and observe the early universe while it travels across the far side. But to take the next step scientifically requires a far larger array with thousands of antennas. That's not practical in orbit, says Burns, but it is feasible on the far side. "The lunar surface is stable," he says. "You just put these things down. They stay where they need to be." **—STEPHEN CASS**

HOMESTEADING THE MOON

Lunar pioneers and their robot companions will need a cozy place to call home

SKIDMORE, OWINGS & MERRILL is the architectural firm known for designing and engineering Dubai's Burj Khalifa, the world's tallest building, such iconic structures being one of the firm's specialties. But at its New York City office, architects are working on something even more striking—drawings for SOM's first extraterrestrial assignment. The firm is designing a moon base in collaboration with the European Space Agency (ESA) and MIT. • Daniel Inocente, the lead designer, presents schematics and renderings of white puffy pods scattered across the lunar landscape, connected by tubular walkways and surrounded by robots and solar panels and astronauts, all overseen by a recognizable blue orb in the sky. • These visions may never come to be, but they're helping ESA think through possible futures. The moon offers many opportunities. Planetary scientists want to study its composition to learn about the early solar system and Earth's origins. Astronomers want to build radio telescopes on the far side. Medical researchers want to understand how the human body reacts to extended stays in low gravity. Explorers want to test equipment or produce propellant for voyages to asteroids, Mars, and beyond.

By Matthew Hutson

EARTH RISE: An artist's rendering shows Skidmore, Owings & Merrill's vision for an expanding lunar colony.

Talk of sending people back to the moon—for the first time since the Apollo missions ended in the 1970s—has heated up recently. In 2016, the head of ESA announced Moon Village, a deliberately nebulous vision encouraging private and public players to collaborate on robotic and human exploration of the moon. Last year, eight Chinese volunteers completed a yearlong stay in a simulated habitat called Lunar Palace 1 to test life-support systems.

And while private industry doesn't plan to send people to the moon's surface anytime soon, rockets from SpaceX and Blue Origin could drastically reduce the cost for governments to do so. Just a few months ago, U.S. vice president Mike Pence pledged to return astronauts to the moon within five years.

But settling people on the moon will require experts to work out some kinks, to put it lightly. These include coping with the harsh environment, building structures out of locally sourced materials, mastering life support, and dealing with one potentially deadly complication for which we currently have no clear solution: dust.

THE THREE MOST important factors in identifying a site for a lunar settlement are, as any realtor will tell you, location, location, location. Skidmore, Owings & Merrill (SOM) has deemed the most enticing option to be a nice bit of property on the rim of the Shackleton Crater near the moon's south pole.

There's strong evidence that permanently shadowed regions of the crater contain water ice from ancient comets—good for drinking, cooking food, bathing, making concrete, and splitting into oxygen and hydrogen for rocket propellant.

Wherever they build, space architects and engineers face constraints that traditional practitioners never worry about. The moon has almost no air, of course, so any habitat must be sealed and pressure-tight. And while most space rocks burn up in Earth's atmosphere, the moon's surface is constantly pelted with micrometeoroids. So structures would have to be built to take that punishment.

Gravity is about one-sixth as strong there as on Earth. That can allow for long-span structures, but it also requires more anchor points. And weak gravity makes it hard to dig: Pushing down pushes you up. Where temperatures are extreme, habitats will need to incorporate powerful heating and cooling systems, and the materials they are made of will have to withstand dramatic amounts of expansion and contraction.

Then there's the radiation. The sun emits a constant stream of high-speed protons and electrons—the solar wind. While Earth's magnetic field shields us from most of this wind, the moon has no magnetic field, so it all hits the surface. Even more dangerous are the sun's coronal mass ejections. These events hurl bursts of higher-energy protons and electrons into space. A strong one could generate several sieverts—a sievert being a measure of radiation exposure—on the moon's surface, enough to kill a person if she or he doesn't return to Earth for a bone marrow transplant. And if such dangers weren't enough to endure, astronauts on the moon will also be subject to a constant shower of galactic cosmic rays, which will probably increase their lifetime risk of cancer.

MOBILE HOME: Prefabricated habitat modules designed by Skidmore, Owings & Merrill would be encased inside rocket fairings for launch.

AT SOM'S NEW York City office, Inocente describes his firm's proposal to 3D-print walls around the pods of a lunar habitat to guard against deadly radiation. Long-term occupants will need up to 3 meters of shielding to protect themselves from galactic cosmic rays. It wouldn't make sense to ship tons of concrete from Earth, so astronauts will apply what's known as in situ resource utilization—in other words, they'll use what's there.

In SOM's conception, the walls will be made from lunar soil—which, lacking organic material, is more properly called regolith. One way to do this is to 3D-print the walls, either all in one piece where they'll stand, or as bricks that lock together when stacked. Some space architects propose depositing regolith-based cement, layer by layer, through a robotically controlled nozzle.

But what if the liquid used in the cement mixture evaporates or freezes before the concrete in the wall or brick sets? European researchers working with the architecture firm Foster + Partners have explored binding liquids and injection methods that would prevent this, and they have printed a section of a wall using a regolith simulant. However, con-

PREVIOUS PAGES AND THIS PAGE: SOM/SLASHCUBE

tractors would still need to ship the liquid binder or special cement powder to the moon.

SOM prefers extruding melted regolith through a nozzle like hot glue. Yet another approach is sintering—heating regolith to near its melting point until it fuses. In one ESA project, called RegoLight, researchers focused sunlight into an intense beam and traced it over the surface of regolith simulant, baking bricks layer by layer. The process was slow, though, and the test bricks were weak, so many researchers believe the winning strategy will be microwave sintering, which uses microwave ovens or beams to bind dust. SOM is closely following the sintering research.

For relatively low habitats, regolith may simply be piled on top of metal structures (with space left open for maintenance). Another, more speculative option, is to place habitat modules inside the moon's lava tubes—large empty tunnels through which molten rock once flowed.

Regolith will be used not only to protect buildings but also to pave launchpads and roads. Brent Sherwood, chair of the Space Architecture Technical Committee of the American Institute of Aeronautics and Astronautics (AIAA), suggests baking regolith paving tiles in microwave ovens. Spacecraft landing on platforms or vehicles driving on roads made of these tiles would kick up less dust. The roads would also make it easier for robots to navigate the terrain. "You basically want to make the surface of the moon into a predictable factory floor, like an Amazon warehouse," he says.

Hanna Läkk, a space architect at ESA with a background in architecture and textile technology, has offered a more far-out use of regolith. With collaborators, she's managed to melt simulant and extrude it into fibers that can be robotically wound across metal frameworks into fibrous shell structures. With this fabrication method, a habitat module could be placed in a crater with woven webs spanning

TRIPLE DECKER: Each Skidmore, Owings & Merrill habitat would have three levels, with a ladder running through the module's core.

it, supporting more regolith piled on top. They have also used a robot to fabricate a miniature version of such a cover. In the end, many techniques for using regolith will likely be adopted in any future moon colony.

BEHIND BARRIERS made of moon regolith, what will lunar habitat modules actually look like? SOM's in-progress designs are an outgrowth of proposals made by engineers over the decades, usually for domes or cylinders, sometimes buried or half-buried.

Space architects and engineers widely believe that the first moon habitats will resemble units of the International Space Station (ISS). "The first-generation technology is a little bit less sexy" than sci-fi renderings, says Haym Benaroya, a mechanical and aerospace engineer at Rutgers University and the author of *Building Habitats on the Moon: Engineering Approaches to Lunar Settlements* (Springer, 2018). The original habitat will be some sort of pressure vessel covered in regolith for radiation protection–in a sense, a buried tin can.

According to Sherwood, who worked on ISS modules for Boeing, engineers already know how to fabricate, test, launch, and repair such a unit. "The amount of learning that we've gotten out of the space station is enormous," he says.

Eventually, we might switch to inflatable modules–which could expand to greater volumes, once we better understand how to integrate them with rigid structures and how to pack them so they unfold properly. Bigelow Aerospace, a company based in Las Vegas, licensed NASA patents to build an inflatable unit that was attached to the ISS in 2016 for testing. While it's currently being used only for storage, Bigelow continues to collect data on its response to temperature changes, radiation, and impacts from space debris.

In its work with ESA, SOM has opted for something between a can and a balloon. The module its architects have designed is vaguely cylindrical and stands 9.5 meters tall. It has three floors, with a vertical core that allows inhabitants to climb between them. Three inflatable portions run the height of the module and add living space to all floors. The bottom level has three doors to connect to neighboring units.

SOM hasn't yet decided on the technology for environmental control systems, life support, power, and crew accommodations. But the common architectural practice of getting users involved early should make it a comfortable place to live. Larry Toups, a space architect at NASA overseeing contracts for space habitation concepts, says engineers sometimes need reminders about the user experience: Waste treatment shouldn't go next to the galley, for example.

SOM/SLASHCUBE

ONE THING SOM never had to think about when designing Burj Khalifa was recycling urine. The first life-support system on the moon might be "open loop," like those on the Apollo missions: Oxygen, food, and water are provided, and waste is disposed of on-site. By one calculation, each person would need 5 to 15 metric tons of expendables—mostly air, food, and water—per year.

A more likely first step, though, would be a physicochemical recycling system like that on the ISS. The space station collects urine, wastewater, and condensation from astronauts' sweat and breath, then filters it and makes it drinkable. A set of molecular sieves (using crystals of silicon dioxide and aluminum dioxide) scrubs CO_2 from the air, while electrolysis splits water to create oxygen.

NASA's Next Generation Life Support project is working on some new approaches, but "we are often not trying to invent new chemistry," says Molly Anderson, principal technologist. Mostly NASA wants to increase the efficiency of current systems. The agency also wants to make the hardware lighter, more reliable, and easier to fix. As for new toys, the team is testing prototypes for a compressor to recharge space-suit oxygen tanks, pyrolysis systems that use heat to break down solid waste into useful elements, and portable DNA sequencers for monitoring microbes on surfaces and in the water.

Anderson says the moon makes life support easier than on the ISS in at least one way: Gravity lets you shower and flush toilets.

The next stage for life support on the moon would be a bioregenerative system, in which organisms within the habitat provide food, scrub the air and water, and break down waste. ESA's Micro-Ecological Life Support System Alternative (MELiSSA) program ran an experiment in which three rats and some algae lived together for six months at a time. The rats turned oxygen into CO_2 and the algae did the reverse.

We might even build with biology. ESA's Läkk has grown bricks with mycelium and plant matter and shown that the fungus withstands both simulated weightlessness and the radiation it would encounter on the moon. This locally grown material could potentially replace regolith as a construction material.

Likely, we'll need a hybrid system with some food shipped from Earth. Even if scientists genetically modify crops to produce all the required nutrients, astronauts may still need variety for gut health. People also won't want to eat the same thing every day, and turning plants or algae into food takes a lot of processing. "We don't want to send astronauts there for the purpose of being farmers," Anderson says.

Sherwood of AIAA agrees on the need for variety—especially if the moon is ever to attract space tourists. "You can't have a hotel until you can mix a martini and cook an omelet," he says. But we know little about how to cook in low gravity.

TO ALLOW PEOPLE to live on the moon, SOM must also plan for a robotic workforce. "The surveying, the regolith moving, the construction, the resource extraction, the simple maintenance—none of those things are best done by people," Sherwood says. SOM expects that robots will set up a habitation module, and maybe a food production module, and construct walls of regolith before anyone moves in.

But there's one complication that can be deadly for both humans and machines: dust. For billions of years, micrometeoroid strikes have pulverized the lunar surface to produce sharp, glassy shards of dust in a place with no air or water to smooth out the edges. Between 10 and 20 percent of the mass of the moon's shallow regolith consists of particles smaller than 20 micrometers across, like fine talcum powder.

These particles are electrostatically charged from the solar wind, so they hover, too tiny to see, and stick to everything. On the Apollo missions, after just a few hours of moonwalking, the dust caked boot treads, wore away space suits, scratched lenses, destroyed machinery, clogged air filters, and irritated the astronauts' eyes and noses. If inhaled, it may even cause cancer.

SOM has proposed dust-off areas at habitat entrances, but even if they render interiors spick-and-span, they won't prevent degradation of outside equipment. "We know what's in regolith and we know why it's the way it is," Sherwood says, "but no one has a clue how to design a sustainable system around those environmental conditions."

Getting to the moon was hard, and staying there will be tougher still. But if engineers and architects can overcome the odds, a world of possibilities awaits. ■

HAZARDS of LUNAR LIFE

Low gravity: The moon's gravity is about one-sixth of Earth's, but that's not enough to keep you healthy. Bone mass, muscle strength, and heart-pumping capacity all suffer without gravity. Hours of exercise every day can counteract this problem. Pumping iron on the moon may be a lot easier, but it's also a lot more necessary.

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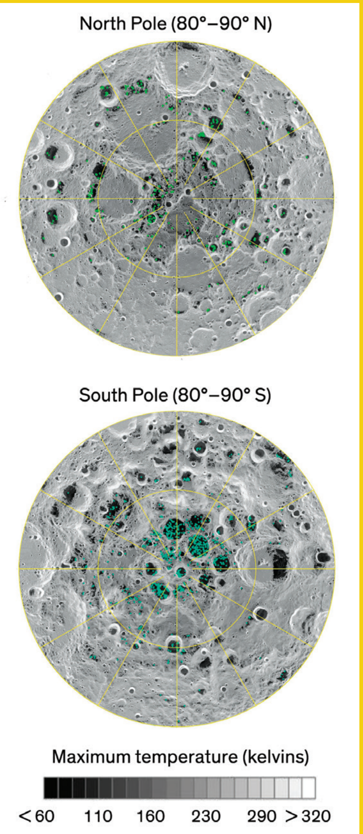
Squeezing ROCKET FUEL *From* MOON ROCKS

THE MOST VALUABLE natural resource on the moon may be water. In addition to sustaining lunar colonists, it could also be broken down into its constituent elements—hydrogen and oxygen—and used to make rocket propellant.

Although the ancients called the dark areas on the moon *maria* (Latin for "seas"), it has long been clear that liquid water can't exist on the lunar surface, where it would swiftly evaporate. Since the 1960s, though, scientists have hypothesized that the moon indeed harbors water, in the form of ice. Because the moon has a very small axial tilt—just 1.5 degrees—the floors of many polar craters remain in perpetual darkness. Water could thus condense and survive in such polar "cold traps," where it might one day be mined.

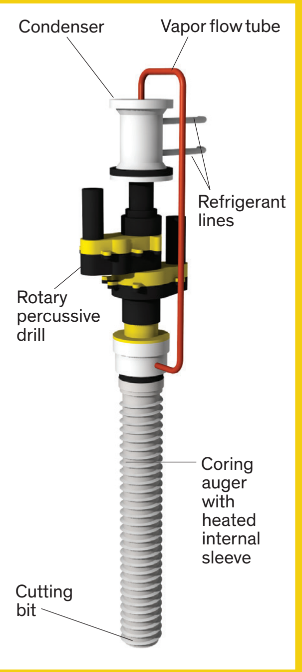
–DAVID SCHNEIDER

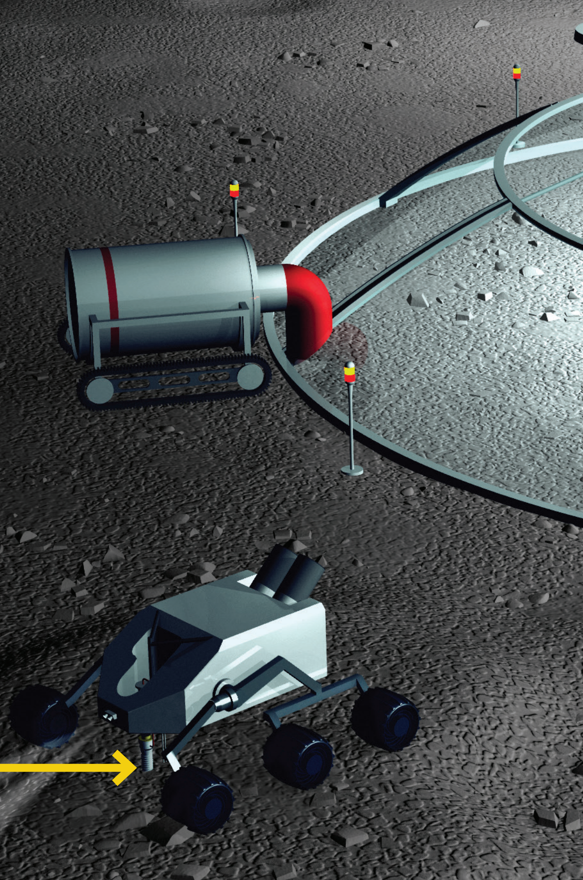
Here's how lunar explorers will mine the regolith to make propellant



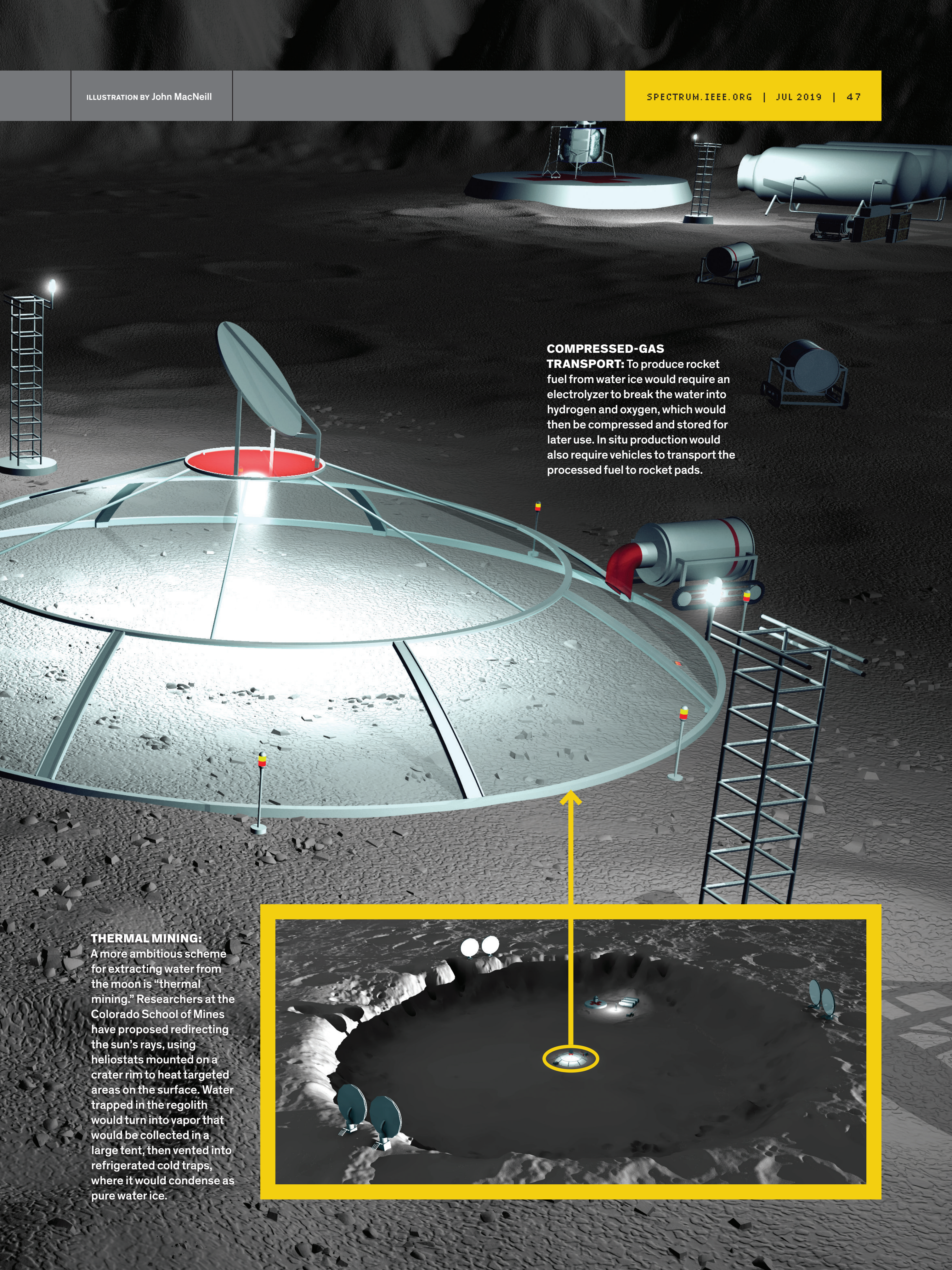
Data source: Li et al., *Proceedings of the National Academy of Sciences*, 4 September 2018

MAPPING THE MOON: Several lunar missions have produced strong evidence of water ice. A NASA instrument called the Moon Mineralogy Mapper (M^3) found indications of water ice on the permanently shadowed floors of some polar craters. However, the measurements suggest that only a small fraction of cold traps contain ice [colored areas], and that the ice is probably mixed with lunar regolith. Finding rich deposits of ice and extracting it may be technically challenging for lunar settlers.





ROVER-MOUNTED DRILL: The most straightforward strategy for extracting water from polar ice deposits uses a rover-mounted drill. Honeybee Robotics has designed a Planetary Volatiles Extractor with an auger that contains heating elements, which would cause any water ice in the drilled regolith to turn into water vapor. That vapor would then travel up the drill and move through a tube to a condenser unit, where it would turn back into ice and eventually be transferred into a storage tank.



COMPRESSED-GAS TRANSPORT: To produce rocket fuel from water ice would require an electrolyzer to break the water into hydrogen and oxygen, which would then be compressed and stored for later use. In situ production would also require vehicles to transport the processed fuel to rocket pads.

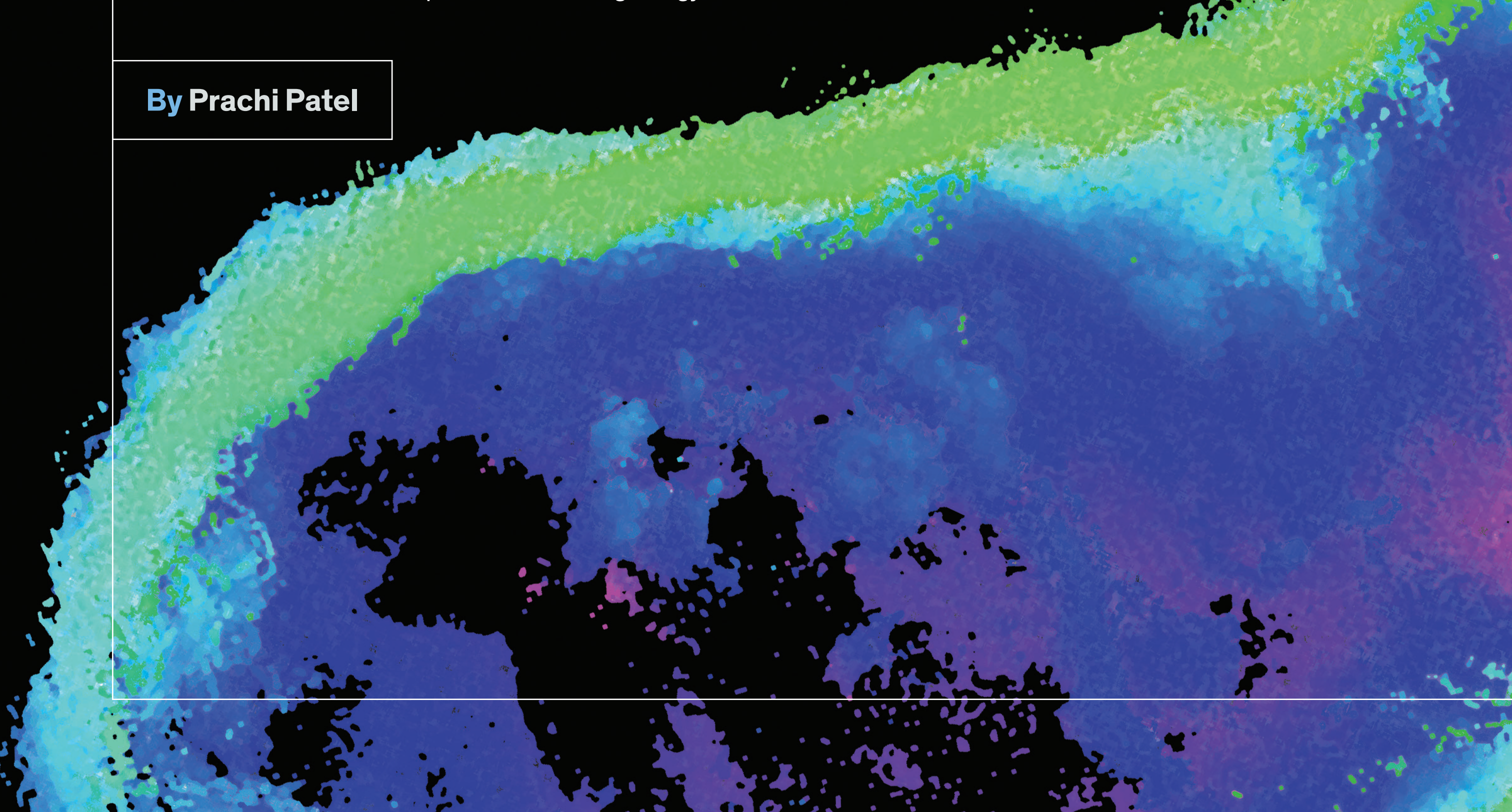
THERMAL MINING: A more ambitious scheme for extracting water from the moon is “thermal mining.” Researchers at the Colorado School of Mines have proposed redirecting the sun’s rays, using heliostats mounted on a crater rim to heat targeted areas on the surface. Water trapped in the regolith would turn into vapor that would be collected in a large tent, then vented into refrigerated cold traps, where it would condense as pure water ice.

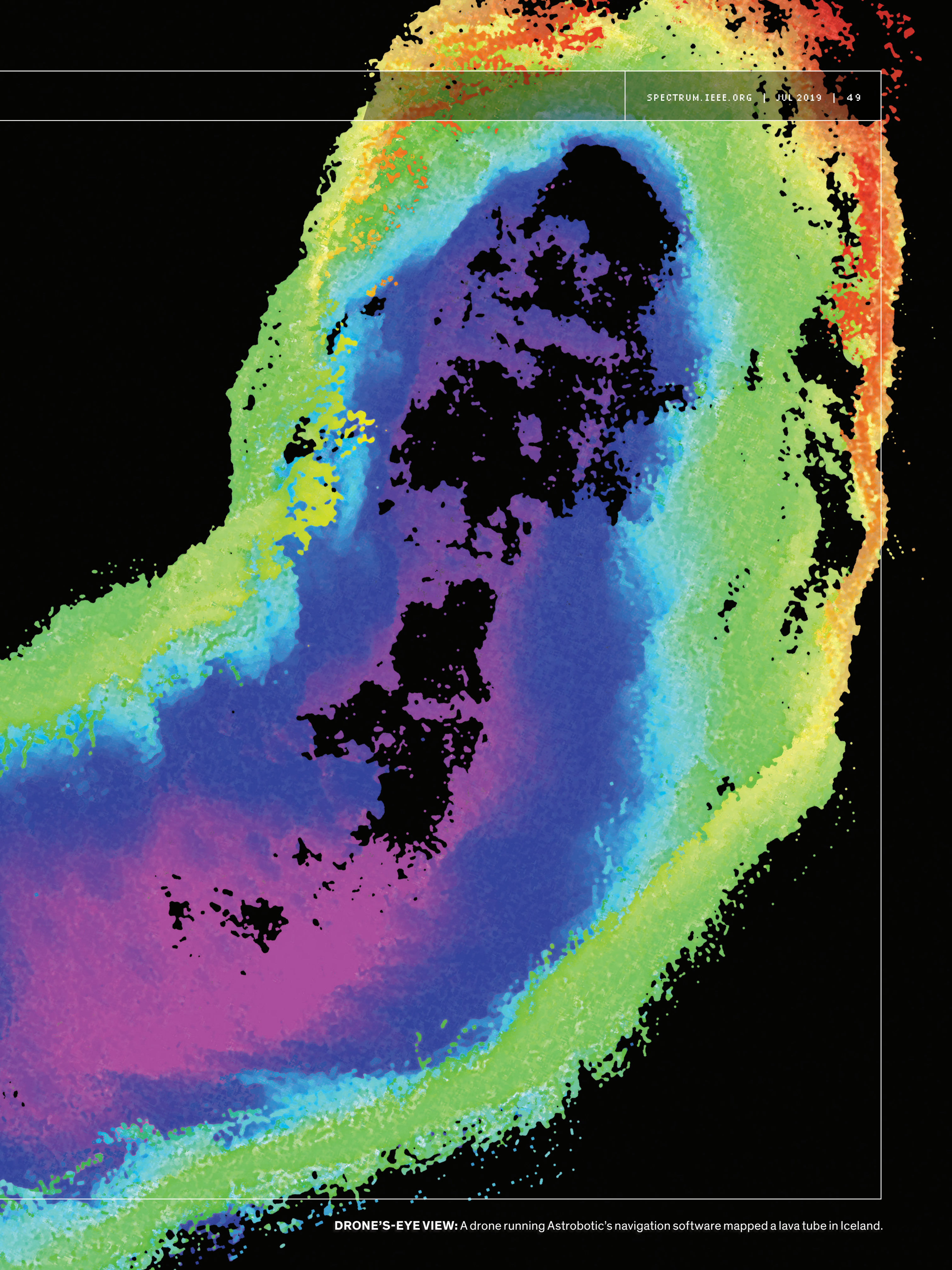
TURN LEFT AT TRANQUILITY BASE

Astrobotic's autonomous navigation will help lunar landers, rovers, and drones find their way

NEIL ARMSTRONG made it sound easy. "Houston, Tranquility Base here. The *Eagle* has landed," he said calmly, as if he had just pulled into a parking lot. In fact, the descent of the Apollo 11 lander was nerve-racking. As the *Eagle* headed to the moon's surface, Armstrong and his colleague Buzz Aldrin realized it would touch down well past the planned landing site and was heading straight for a field of boulders. Armstrong started looking for a better place to park. Finally, at 150 meters, he leveled off and steered to a smooth spot with about 45 seconds of fuel to spare. • "If he hadn't been there, who knows what would have happened," says Andrew Horchler, throwing his hands up. He's sitting in a glass-walled conference room in a repurposed brick warehouse, part of Pittsburgh's Strip District, a hub for tech startups. This is the headquarters of space robotics company Astrobotic Technology. In the coming decades, human forays to the moon will rely heavily on robotic landers, rovers, and drones. Horchler leads a team whose aim is ensuring those robotic vessels can perform at least as well as Armstrong did. • Astrobotic's precision-navigation technology will let both uncrewed and crewed landers touch down exactly where they should, so a future Armstrong won't have to strong-arm her landing vessel's controls. Once they're safely on the surface, robots like Astrobotic's will explore the moon's geology, scout out sites for future

By Prachi Patel





DRONE'S-EYE VIEW: A drone running Astrobotic's navigation software mapped a lava tube in Iceland.

lunar bases, and carry equipment and material destined for those bases, Horchler says. Eventually, rovers will help mine for minerals and water frozen deep in craters and at the poles.

Astrobotic was founded in 2007 by roboticists at Carnegie Mellon University to compete for the Google Lunar X Prize, which challenged teams to put a robotic spacecraft on the moon. The company pulled out of the competition in 2016, but its mission has continued to evolve. It now has a 20-person staff and contracts with a dozen organizations to deliver payloads to the moon, at US $1.2 million per kilogram, which the company says is the lowest in the industry. Late last year, Astrobotic was one of nine companies that NASA chose to carry payloads to the moon for its 10-year, $2.6 billion Commercial Lunar Payload Services (CLPS) program. The space agency announced the first round of CLPS contracts in late May, with Astrobotic receiving $79.5 million to deliver its payloads by July 2021.

Meanwhile, China, India, and Israel have all launched uncrewed lunar landers or plan to do so soon. The moon will probably be a much busier place by the 60th anniversary of Apollo 11, in 2029.

The moon's allure is universal, says John Horack, an aerospace engineer at Ohio State University. "The moon is just hanging in the sky, beckoning to us. That beckoning doesn't know language or culture barriers. It's not surprising to see so many thinking about how to get to the moon."

ON THE MOON, there is no GPS, compass-enabling magnetic field, or high-resolution maps for a lunar craft to use to figure out where it is and where it's going. Any craft will also be limited in the computing, power, and sensors it can carry. Navigating on the moon is more like the wayfinding of the ancient Polynesians, who studied the stars and ocean currents to track their boats' trajectory, location, and direction.

A spacecraft's wayfinders are inertial measurement units that use gyroscopes and accelerometers to calculate attitude, velocity, and direction from a fixed starting point. These systems extrapolate from previous estimates, so errors accumulate over time. "Your knowledge of where you are gets fuzzier and fuzzier as you fly forward," Horchler says. "Our system collapses that fuzziness down to a known point."

A conventional guidance system can put a vessel down within an ellipse that's several kilometers long, but Astrobotic's system will land a craft within 100 meters of its target. This could allow touchdowns near minable craters, at the heavily shadowed icy poles, or on a landing pad next to a moon base. "It's one thing to land once at a site, a whole other thing to land repeatedly with precision," says Horchler.

Astrobotic's terrain-relative navigation (TRN) sensor contains all the hardware and software needed for smart navigation. It uses 32-bit processors that have worked well on other missions and FPGA hardware acceleration for low-level computer-vision processing. The processors and FPGAs are all radiation hardened. The brick-size unit can be bolted to any spacecraft. The sensor will take a several-megapixel image of the lunar surface every second or so as the lander approaches. Algorithms akin to those for facial recognition will spot unique features in the images, comparing them with stored maps to calculate lunar coordinates and orientation.

Those stored maps are a computing marvel. Images taken by NASA's Lunar Reconnaissance Orbiter (LRO), which has been mapping the moon since 2009, have very different perspectives and shadows from what the lander will see as it descends. This is especially true at the poles, where the angle of the sun changes the lighting dramatically.

So software wizards at Astrobotic are creating synthetic maps. Their software starts with elevation models based on LRO data. It fuses those terrain models with data on the relative positions of the sun, moon, and Earth; the approximate location of the lander; and the texture and reflectiveness of the lunar soil. Finally, a physics-based ray-tracing system, similar to what's used in animated films to create synthetic imagery, puts everything together.

Horchler pulls up two images of a 50-by-200-kilometer patch near the moon's south pole. One is a photo taken by the LRO. The other is a digitally rendered version created by the Astrobotic software. I can't tell them apart. Future TRN systems may be able to build high-fidelity maps on the fly as the lander descends, but that's impossible with current onboard computing power, Horchler says.

To confirm the TRN's algorithms, Astrobotic has run tests in the Mojave Desert. A 2014 video shows the TRN sensor mounted on a vertical-takeoff-and-landing vehicle made by Masten Space Systems, another company chosen for NASA's CLPS program. Astrobotic engineers had mapped the scrubby area beforehand, including a potential landing site littered with sandbags to mimic large rocks. In the video, the vehicle takes off without a programmed destination. The navigation sensor scans the ground, matching what it sees to the stored maps. The hazard-detection sensor uses lidar and stereo cameras to map shapes and elevation on the rocky terrain and track the lander's distance to the ground. The craft lands safely, avoiding the sandbags.

Astrobotic expects its first CLPS mission to launch in July 2021, aboard a United Launch Alliance Atlas V rocket. The 28 payloads aboard the stout Peregrine lander will include NASA scientific instruments, another scientific instrument from the Mexican Space Agency, rovers from startups in Chile and Japan, and personal mementos from paying customers.

PREVIOUS PAGES: ASTROBOTIC

IN A SPACE that Astrobotic employees call the Tiger's Den, a large plush tiger keeps an eye on aerospace engineer Jeremy Hardy, who looks like he's having too much fun. He's flying a virtual drone onscreen through a landscape of trees and rocks. When he switches to a drone's-eye view, the landscape fills with green dots, each a unique feature that the drone is tracking, like a corner or an edge.

The program Hardy is using is called AstroNav, which will guide propulsion-powered drones as they fly through the moon's immense lava tubes. These temperature-stable tunnels are believed to be tens of kilometers long and "could fit whole cities within them," Horchler says. The drones will map the tunnels as they fly, coming back out to recharge and send images to a lunar station or to Earth.

Hardy's drone is flying in unchartered territory. AstroNav uses a simultaneous localization and mapping (SLAM) algorithm, a heavyweight technology also used by self-driving cars and office delivery robots to build a map of their surroundings and compute their own location within that map. AstroNav blends data from the drone's inertial measurement units, stereo-vision cameras, and lidar. The software tracks the green-dotted features across many frames to calculate where the drone is.

The company has tested AstroNav-guided hexacopters in West Virginian caves, craters in New Mexico, and the Lofthellir lava tube of Iceland. Similar SLAM techniques could guide autonomous lunar rovers as they explore permanently shadowed regions at the poles.

ASTROBOTIC HAS plenty of competition. Another CLPS contractor is Draper Laboratory, which helped guide Apollo missions. The lab's navigation system, also built around image processing and recognition, will take Japanese startup Ispace's lander to the moon.

Draper's "special sauce" is software developed for the U.S. Army's Joint Precision Airdrop System, which delivers supplies via parachute in war zones, says space systems program manager Alan Campbell. Within a box called an aerial guidance unit is a downward-facing camera, motors, and a small computer running Draper's software. The software determines the parachute's location by comparing terrain features in the camera's images with commercial satellite images to land the parachute within 50 meters of its target.

The unit also uses Doppler lidar, which detects hazards and measures relative velocity. "When you're higher up, you can compare images to maps," says Campbell. At lower altitudes, a different method tracks features and how they're moving. "Lidar will give you a finer-grain map of hazards."

Draper's long experience dating back to Apollo gives the lab an edge, Campbell adds. "We've landed on the moon before, and I don't think our competitors can say that."

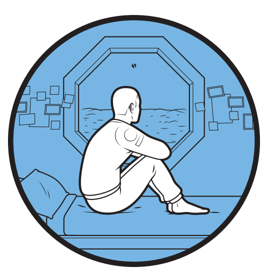
OTHER NATIONS with lunar aspirations are also relying on autonomous navigation. China's Chang'e 4, for example, became the first craft to land on the far side of the moon, in early January. In its landing video, the craft hovers for a few seconds above the surface. "That indicates it has lidar or [a] camera and is taking an image of the field to make sure it's landing on a safe spot," says Campbell. "It's definitely an autonomous system."

Israel's lunar spacecraft Beresheet was also expected to make a fully automated touchdown in April. It relied on image-processing software run on a computer about as powerful as a smartphone, according to reports. However, just moments before it was to land, it crashed on the lunar surface due to an apparent engine failure.

In the race to the moon, there will be no one winner, Ohio State's Horack says. "We need a fair number of successful organizations from around the world working on this."

Astrobotic is also looking further out. Its AstroNav could be used on other cosmic bodies for which there are no high-resolution maps, like the moons of Jupiter and Saturn. The challenge will be scaling back the software's appetite for computing power. Computing in space lags far behind computing on Earth, Horchler notes. Everything needs to be radiation tolerant and designed for a thermally challenging environment. "It tends to be very custom," he says. "You don't have a new family of processors every two years. An Apple Watch has more computing power than a lot of spacecraft out there."

The moon will be a crucial test-bed for precision landing and navigation. "A lot of the technology that it takes to land on the moon is similar to what it takes to land on Mars or icy moons like Europa," Horchler says. "It's much easier to prove things out at our nearest neighbor than at bodies halfway across the solar system." ■



HAZARDS *of* LUNAR LIFE

Isolation: They say that in space, nobody can hear you scream. It's the same on the moon. And the psychological effects of long-term lunar living haven't been well studied. After all, nobody's ever spent more than the equivalent of a long weekend there.

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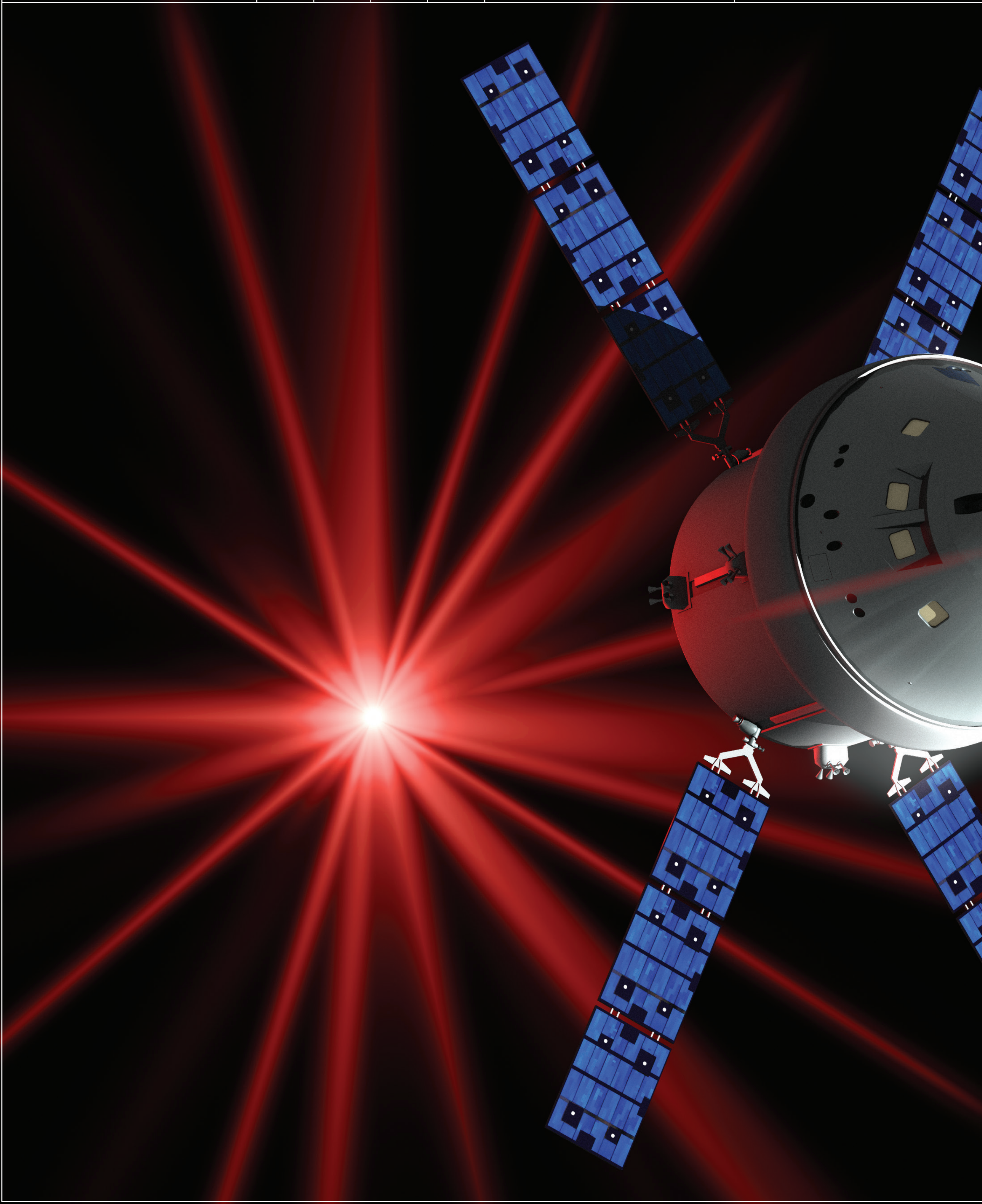
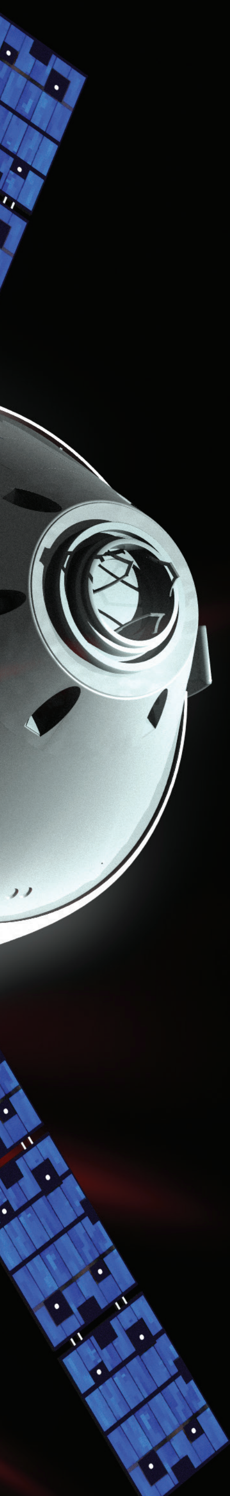


LASER FOCUS: Infrared lasers will allow Orion to beam ultrahigh-definition video back to Earth, as shown in this artist's rendering.

ILLUSTRATION BY John MacNeill



PHONING HOME, WITH LASERS

Optical communications will provide a high-speed connection to Earth

By Michael Koziol

WITH NASA MAKING serious moves toward a permanent return to the moon, it's natural to wonder whether human settlers—accustomed to high-speed, ubiquitous Internet access—will have to deal with mind-numbingly slow connections once they arrive on the lunar surface. The vast majority of today's satellites and spacecraft have data rates measured in kilobits per second. But long-term lunar residents might not be as satisfied with the skinny bandwidth that, say, the Apollo astronauts contended with. • To meet the demands of high-definition video and data-intensive scientific research, NASA and other space agencies are pushing the radio bands traditionally allocated for space research to their limits. For example, the Orion spacecraft, which will carry astronauts around the moon during NASA's Artemis 2 mission in 2022, will transmit mission-critical information to Earth via an S-band radio at 50 megabits per second. "It's the most complex flight-management system ever flown on a spacecraft," says Jim Schier, the chief architect for NASA's Space Communications and Navigation program. Still, barely 1 Mb/s will be allocated for streaming video from the mission. That's about one-fifth the speed needed to stream a high-definition movie from Netflix. • To boost data rates even higher means moving beyond radio and developing optical communications systems that use lasers to beam data across space. In addition to its S-band radio, Orion will carry a laser communications system for sending ultrahigh-definition 4K video back to Earth. And further out, NASA's Gateway will create a long-term laser communications hub linking our planet and its satellite.

Laser communications are a tricky proposition. The slightest jolt to a spacecraft could send a laser beam wildly off course, while a passing cloud could interrupt it. But if they work, robust optical communications will allow future missions to receive software updates in minutes, not days. Astronauts will be sheltered from the loneliness of working in space. And the scientific community will have access to an unprecedented flow of data between Earth and the moon.

T **TODAY, SPACE AGENCIES** prefer to use radios in the S band (2 to 4 gigahertz) and Ka band (26.5 to 40 GHz) for communications between spacecraft and mission control, with onboard radios transmitting course information, environmental conditions, and data from dozens of spaceflight systems back to mission control. The Ka band is particularly prized—Don Cornwell, who oversees radio and optical technology development at NASA, calls it "the Cadillac of radio frequencies"—because it can transmit up to gigabits per second and propagates well in space.

Any spacecraft's ability to transmit data is constrained by some unavoidable physical truths of the electromagnetic spectrum. For one, radio spectrum is finite, and the prized bands for space communications are equally prized by commercial applications. Bluetooth and Wi-Fi use the S band, and 5G cellular networks use the Ka band.

The second big problem is that radio signals disperse in the vacuum of space. By the time a Ka-band signal from the moon reaches Earth, it will have spread out to cover an area about 2,000 kilometers in diameter—roughly the size of India. By then, the signal is a lot weaker, so you'll need either a sensitive receiver on Earth or a powerful transmitter on the moon.

Laser communications systems also have dispersion issues, and beams that intersect can muddle up the data. But a laser beam sent from the moon would cover an area only 6 km across by the time it arrives on Earth. That means it's much less likely for any two beams to intersect. Plus, they won't have to contend with an already crowded chunk of spectrum. You can transmit a virtually limitless quantity of data using lasers, says Cornwell. "The spectrum for optical is unconstrained. Laser beams are so narrow, it's almost impossible [for them] to interfere with one another."

Higher frequencies also mean shorter wavelengths, which bring more benefits. Ka-band signals have wavelengths from 7.5 millimeters to 1 centimeter, but NASA plans to use lasers that have a 1,550-nanometer wavelength, the same wavelength used for terrestrial optical-fiber networks. Indeed, much of the development of laser communications for space builds on existing optical-fiber engineering. Shorter wavelengths (and higher frequencies) mean that more data can be packed into every second.

The advantages of laser communications have been known for many years, but it's only recently that engineers have been able to build systems that outperform radio. In 2013, for example, NASA's Lunar Laser Communications Demonstration proved that optical signals can reliably send information from lunar orbit back to Earth. The month-long experiment used a transmitter on the Lunar Atmosphere and Dust Environment Explorer to beam data back to Earth at speeds of 622 Mb/s, more than 10 times as fast as Orion's S-band radio will.

DATA RATES FROM THE MOON TO EARTH
(Megabits per second)

20
Orion's optical system

96.25
Average fixed broadband speed in the U.S.

622
Lunar Laser Communications Demonstration

"I was shocked to learn [Orion was] going back to the moon with an S-band radio," says Bryan Robinson, an optical communications expert at MIT Lincoln Laboratory in Lexington, Mass. Lincoln Lab has played an important role in developing many of the laser communications systems on NASA missions, starting with the early optical demonstrations of the classified GeoLITE satellite in 2001. "Humans have gotten used to so much more, here on Earth and in low Earth orbit. I was glad they came around and put laser comm back on the mission."

As a complement to its S-band radio, during the Artemis 2 mission Orion will carry a laser system called Optical to Orion, or O2O. NASA doesn't plan to use O2O for any mission-critical communications. Its main task will be to stream 4K ultrahigh-definition video from the moon to a curious public back home. O2O will receive data at 80 Mb/s and transmit at 20 Mb/s while in lunar orbit. If you're wondering why O2O will transmit at 20 Mb/s when a demonstration project six years ago was able to transmit at 622 Mb/s, it's simply because the Orion developers "never asked us to do 622," says Farzana Khatri, a senior staff member in Lincoln Lab's optical communications group. Cornwell confirms that O2O's downlink will deliver a minimum of 80 Mb/s from Earth, though the system is capable of higher data rates.

If successful, O2O will open the door for data-heavy communications on future crewed missions, allowing for video chats with family, private consultations with doctors, or even just watching a live sports event during downtime. The more time people spend on the moon, the more important all of these connections will be to their mental well-being. And eventually, video will become mission critical for crews on board deep-space missions.

BEFORE O2O CAN even be tested in space, it first has to survive the journey. Laser systems mounted on spacecraft use telescopes to send and receive signals. Those telescopes rely on a fiddly arrangement of mirrors and other moving parts. O2O's telescope will use an off-axis Cassegrain design, a type of telescope with two mirrors to focus the captured light, mounted on a rotating gimbal. Lincoln Lab researchers selected the design because it will allow them to separate the telescope from the optical transceiver, making the entire system more modular. The engineers must ensure that the Space Launch System rocket carrying Orion won't shake the whole delicate arrangement apart. The researchers at Lincoln Lab have developed clasps and mounts that they hope will reduce vibrations and keep everything intact during the tumultuous launch.

Once O2O is in space, it will have to be precisely aimed. It's hard to miss a receiver when your radio signal has the cross section the size of a large country. A 6-km-diameter signal, on the other hand, could miss Earth entirely with just a slight bump from the spacecraft. "If you [use] a laser pointer when you're nervous and your hand is shaking, it's going to go all over the place," says Cornwell.

Orion's onboard equipment will also generate constant minuscule vibrations, any one of which would be enough to throw off an optical signal. So engineers at NASA and Lincoln Lab will place the optical system on an antijitter platform. The platform measures the jitters from the spacecraft and produces an opposite pattern of vibrations to cancel them out—"like noise-canceling headphones," Cornwell says.

One final hurdle for O2O will be dealing with any cloud cover back on Earth. Infrared wavelengths, like the O2O's 1,550 nm, are easily absorbed by clouds. A laser beam might travel the nearly 400,000 km from the moon without incident, only to be blocked just above Earth's surface. Today, the best defense against losing a signal to a passing stratocumulus is to beam transmissions to multiple receivers. O2O, for example, will use ground stations at Table Mountain, Calif., and White Sands, N.M.

THE GATEWAY, scheduled to be built in the 2020s, will present a far bigger opportunity for high-speed laser communications in space. NASA, with help from its Canadian, European, Japanese, and Russian counterparts, will place this space station in orbit around the moon; the station will serve as a staging area and communications relay for lunar research.

NASA's Schier suspects that research and technology demonstrations on the Gateway could generate 5 to 8 Gb/s of data that will need to be sent back to Earth. That data rate would dwarf the transmission speed of anything in space right now—the International Space Station (ISS) sends data to Earth at 25 Mb/s. "[Five to 8 GB/s is] the kind of thing that if you turned everything on in the [ISS], you'd be able to run it for 2 seconds before you overran the buffers," Schier says.

The Gateway offers an opportunity to build a permanent optical trunk line between Earth and the moon. One thing NASA would like to use the Gateway for is transmitting positioning, navigation, and timing information to vehicles on the lunar surface. "A cellphone in your pocket needs to see four GPS satellites," says Schier. "We're not going to have that around the moon." Instead, a single beam from the Gateway could provide a lunar rover with accurate distance, azimuth, and timing to find its exact position on the surface.

What's more, using optical communications could free up radio spectrum for scientific research. Robinson points out that the far side of the moon is an optimal spot to build a radio telescope, because it would be shielded from the chatter coming from Earth. If all the communication systems around the moon were optical, he says, there'd be nothing to corrupt the observations.

Beyond that, scientists and engineers still aren't sure what else they'll do with the Gateway's potential data speeds. "A lot of this, we're still studying," says Cornwell.

In the coming years, other missions will test whether laser communications work well in deep space. NASA's mission to the asteroid Psyche, for instance, will help determine how precisely an optical communications system can be pointed and how powerful the lasers can be before they start damaging the telescopes used to transmit the signals. But closer to home, the communications needed to work and live on the moon can be provided only by lasers. Fortunately, the future of those lasers looks bright. ■

HAZARDS of LUNAR LIFE

Extreme temperature swings: Don't go outside on the moon at night...or in the daytime either. Temperatures at the surface can swing between 127 °C and –173 °C. So check your space suit carefully, or you'll be flash-frozen, toasted, or both.

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CONTINUED FROM PAGE 29

	BE-3	BE-4	BE-7
PROPELLANT	Liquid oxygen Liquid hydrogen	Liquid oxygen Liquid methane	Liquid oxygen Liquid hydrogen
THRUST	490 kilonewtons (sea level), 710 kN (vacuum)	2,400 kN (sea level)	40 kN (vacuum)
APPLICATION	New Shepard, New Glenn (upper stages)	New Glenn booster	Blue Moon lander
STATUS	Launched New Shepard into space multiple times	Multiple ground-based test firings	In development

the pipeline is four times cheaper than rocket-grade kerosene," a more traditional fuel choice. Unlike gaseous methane, which often contains high levels of impurities, LNG is 95 percent pure methane, says Meyerson. Methane is also less toxic than kerosene and is stored at temperatures similar to those used for liquid oxygen, making refueling simpler and safer.

FOR ALL of Blue Origin's technical prowess, media headlines might suggest that it's losing this new space race. Virgin Galactic astronauts have flown the company's suborbital vehicle to space twice, and SpaceX has delivered cargo more than 70 times to Earth orbit and beyond. Blue Origin, meanwhile, is still tinkering with the uncrewed New Shepard and carrying out seemingly interminable ground tests of the BE-4.

But saying Blue Origin is lagging is to misunderstand its mission, says John Horack, professor of aerospace policy at Ohio State University: "Their motto is *Gradatim Ferociter*–to be ferociously incremental, as opposed to making spectacular leaps forward. Test, test, test. Data, data, data. Improve and then do it all again."

Most of Blue Origin's engine and flight tests are carried out on a remote ranch in West Texas, far from prying eyes. The only mishaps that are publicly known are a prototype launch vehicle crashing there in 2011, a booster failure on return in 2015, and a BE-4 exploding on a test stand in 2017.

"If they were funded differently, there would be a need to demonstrate milestone after milestone," says Horack. "But because they're funded through Mr. Bezos's personal wealth, they can afford that strategy. And I think that in the end it will pay off handsomely."

Arguably, it already has. In 2014, rival launch provider United Launch Alliance (ULA) was looking for an engine for its own next-generation launch vehicle, the Vulcan. It offered to invest in the BE-4 program, but only if Blue Origin could increase the engine's planned thrust by nearly 40 percent. For Blue Origin, that would mean not only taking the BE-4 back to the drawing board but redesigning the entire New Glenn rocket to match, likely delaying its maiden launch by years. Worse still, there was no guarantee that ULA would end up buying any BE-4s at all.

For Meyerson, then Blue Origin president, the opportunity to power two new launch vehicles, potentially for a decade or more to come, was worth the risk. "There's not a lot of new rockets," he says. "It's not like the automobile industry, where companies are designing and building new cars every year."

Last September, that gamble finally paid off as ULA confirmed that the Vulcan would use a pair of BE-4 engines. Just weeks later, the U.S. Air Force announced hundreds of millions of dollars in funding for both the Vulcan and the New Glenn to support future military launches. "It's brilliant, because Blue Origin found a way to monetize something they had to do anyway," says Horack. "The more engines you make, the lower your unit cost, the more flight data you get, and the more reliability you can build in. It's a virtuous cycle."

ULA's decision also cleared the way for Blue Origin to start work on a planned BE-4 factory in Huntsville, Ala. Groundbreaking for the $200 million facility began in January. The company already has a factory to build and refurbish New Glenn rockets near the Kennedy Space Center, in Florida. The first New Glenn and BE-4s could lift off at Cape Canaveral as soon as 2021.

Blue Origin would be well advised to keep to that schedule. *Gradatim Ferociter* is a great motto for a billionaire's passion project. But for a rapidly growing business that needs to compete in the race to return to the moon, Blue Origin might need to be a little less *gradatim*, and a little more *ferociter*. ■

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BLUE ORIGIN (3)