ELEMENTS

THE QUEST TO BUILD A TELESCOPE ON THE MOON

If the FarView radio telescope is built, it would double as a demonstration of two unprecedented activities: mining and manufacturing in space.

By Matthew Hutson

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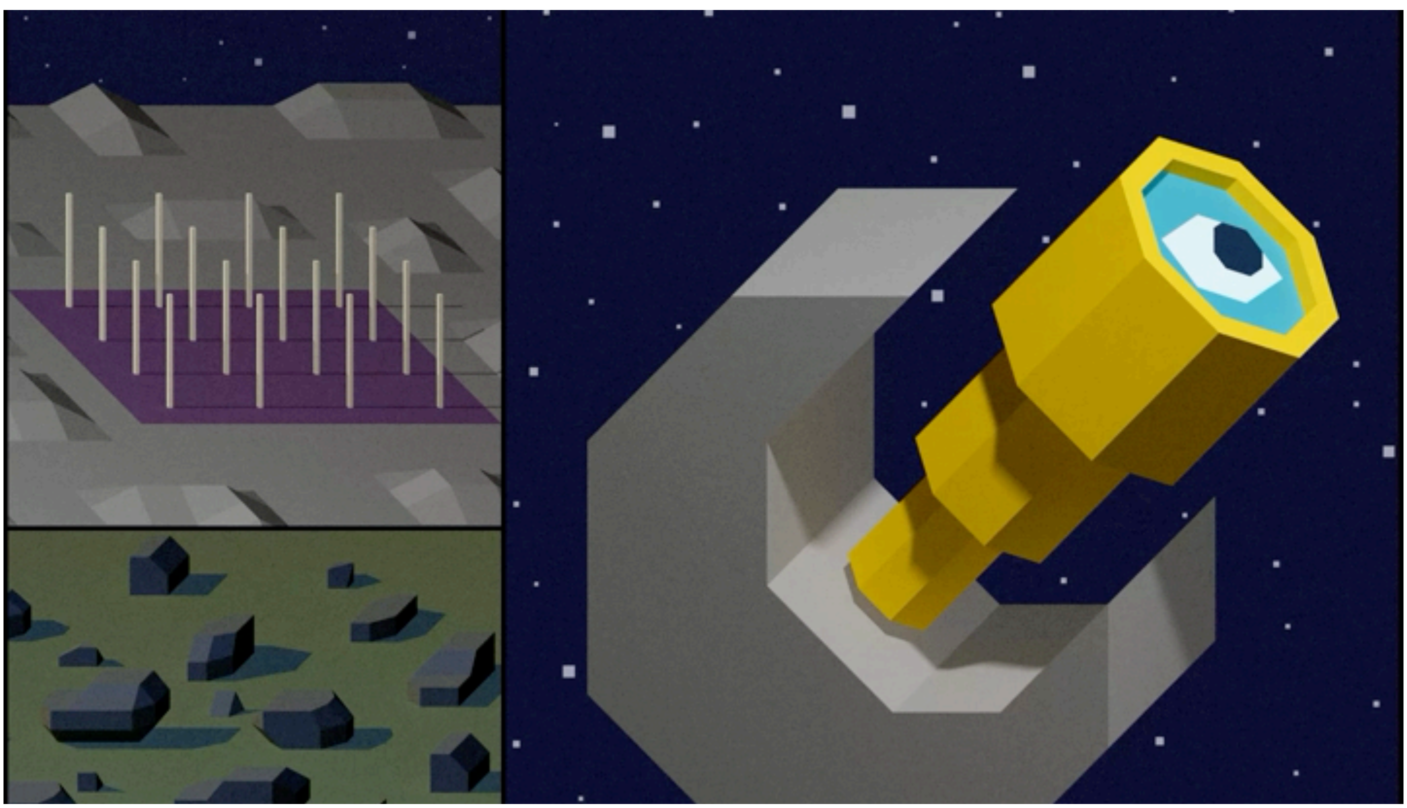

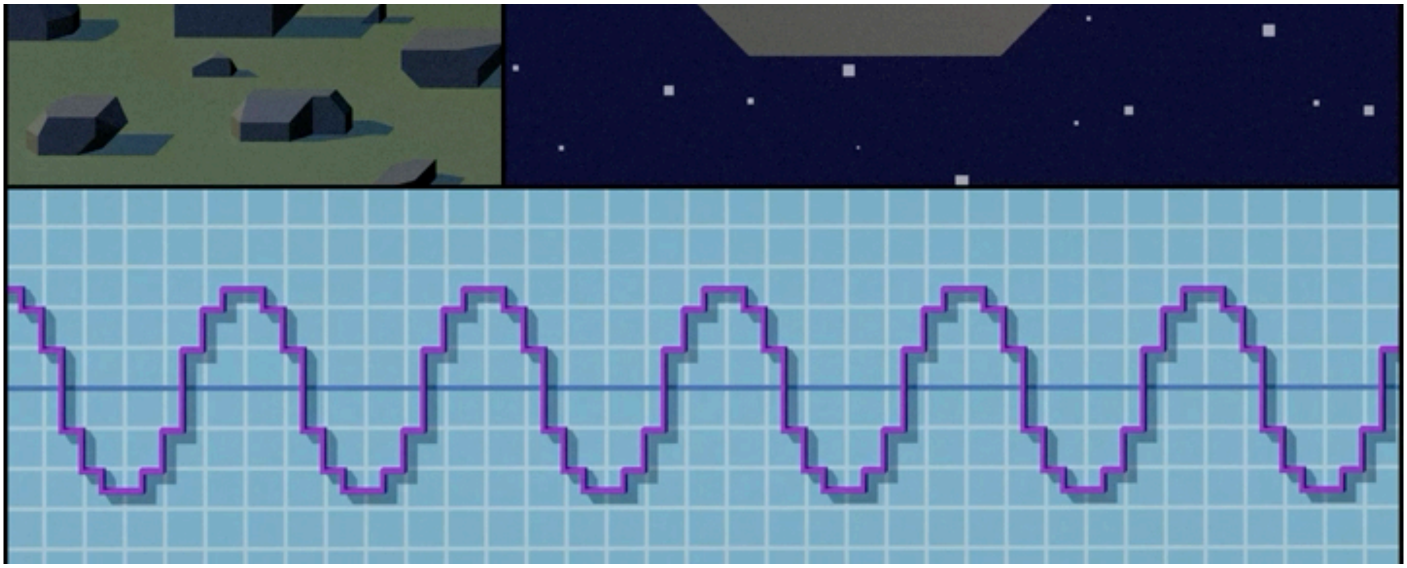

Illustration by Todd St. John

A few months ago, I flew to Houston to visit a small startup called Lunar Resources, which aspires to build the largest telescope in the solar system—not on Earth but on the far side of the moon. Houston is nicknamed Space City; on the ride from the airport, I passed the ballpark where the Astros play, and, outside a McDonald's on East NASA Parkway, I saw a giant sculpture of an astronaut holding French fries. I found Lunar Resources in a boxy building where the company leases square footage from the aerospace contractor Lockheed Martin.

Elliot Carol, the C.E.O. and co-founder of Lunar Resources, is thirty-three, with a cherubic face and curly hair speckled with gray. Although he grew up in Connecticut and previously worked as a hedge-fund manager, he was wearing black cowboy boots. He led me to a provisional-looking conference room—the company hadn't had a chance to renovate yet—and uncapped a dry-erase marker. Then, on a whiteboard, he drew a large circle, to represent the moon. Inside the circle, he drew a small square, which represented about two hundred square kilometres of the lunar surface. This was the potential site of the FarView radio-telescope array.

Unlike telescopes such as the Hubble and the James Webb, which are made from mirrors and lenses, FarView would comprise a hundred thousand metal antennas made on-site by autonomous robots. It would cover a Baltimore-size swath of the moon. To show the FarView site up close, Carol drew a big square filled with dots. Each dot represented a cluster of four hundred antennas; all the clusters together would be sensitive enough to detect a cell phone on Pluto. They would perceive light that is nearly undetectable from Earth: radio waves from a mysterious period known as the Cosmic Dark Ages.

To develop a plan for FarView, Lunar Resources, which is privately owned, has formed a consortium with several scientists and universities. "Usually, these missions are pursued by large academic and research institutions," Carol told me. "But we said, 'No, we want to support and fund the development of this observatory.' " The company's goals go well beyond the construction of a telescope. FarView would double as a demonstration of two unprecedented activities: off-planet mining and manufacturing, which are known in the business as "in-situ resources utilization" (I.S.R.U.).

No one has ever built a city-size structure in space, in large part because of the astronomical costs of transporting building materials from Earth. According to some estimates, delivering just one kilogram of payload to the surface of the moon can cost more than a million dollars. At prices like that, it would be prohibitively expensive to colonize the moon, let alone another planet. The success of such efforts almost certainly requires humans to harvest resources such as building materials, fuel, and water from other celestial bodies. In other words, the future of space exploration may depend on I.S.R.U. "NASA and its partners must plan a transition of Earth-derived to ISRU-derived products," a recent NASA report, "Moon to Mars Architecture Definition Document," declared.

Much of FarView's infrastructure—robots, amplifiers, computers—would need to be delivered, perhaps by a space contractor such as Elon Musk's company SpaceX. But Lunar Resources believes that robots carrying its tools could one day roam the surface of the moon, first to mine aluminum and silicon from moon rocks, and then to manufacture antennas, electrical lines, solar cells, and possibly batteries that can last through the two-week lunar night. These innovations could provide a test case for how humanity could live and work in space. Gerald Sanders, who leads NASA's I.S.R.U. efforts, told me that a lunar colony "has always been, to some extent, the dream."

FarView might not be completed for a decade or more, if at all, and could cost upward of two billion dollars. But it is part of a larger dream that, one day, moon-based mines might produce helium for fusion reactors, and lunar and orbital factories might build satellites that are too large to launch from Earth. Lunar ice could provide hydrogen and oxygen for rocket fuel, which could power trips to deep space. According to a market assessment from the professional-services company PwC, the lunar economy could be worth a hundred and seventy billion dollars by 2040. DARPA, a Defense Department research agency, is currently funding fourteen companies to explore potentially valuable lunar-infrastructure projects. (Northrop Grumman, for example, wants to build a "lunar railroad network" using robots.)

In the coming centuries, whole lunar cities could spring up, filled with factories, farms, and even hotels. "Go back to 1600, when the world had been circumnavigated," Ronald Polidan, the principal investigator of FarView and the former chief technologist at NASA's Goddard Space Flight Center, told me. "If you talked to people then about what the economy of the world would look like in four hundred years, no one would have even guessed this level of capability. This is a door that's just starting to open."

The dream of a lunar telescope dates to the nineteen-sixties. The moon has the advantage of being hundreds of thousands of miles away from earthly electronics; on the far side of the moon, in particular, there's virtually no noise from human technology or the Earth's magnetosphere. After the Apollo landings, however, interest in the moon waned. Jack Burns, an astrophysicist who is now at the University of Colorado Boulder, has been advocating for a moon-based telescope since 1984. "I never, never would have guessed that it would take this long," he told me. "I just won't accept no for an answer." Today, Burns is the chief scientist of FarView, as well as the primary investigator of a sort of mini-FarView: FARSIDE, which would have one or two hundred antennas instead of a hundred thousand.

If FarView is built, it would be able to detect some of the oldest light in existence. The universe began 13.8 billion years ago as a dense, fast-expanding soup of matter and energy; around three hundred and eighty thousand years later, it had cooled enough for hydrogen atoms to hold together. After that came the Cosmic Dark Ages: millions of years without stars or galaxies, a period we know very little about. But hydrogen occasionally releases light with a wavelength of twenty-one centimetres—radio waves. Some of that light is still around.

Because twenty-one-centimetre radiation is stretched by the steady expansion of the universe—it's now tens to hundreds of metres long—scientists can figure out how old it is, and how far away. (The longer the wavelength, the older the light and the more distant its source.) This means that if scientists can build a radio telescope on the moon, they will be able to create a three-dimensional picture of the early universe.

Carol, Lunar Resources's C.E.O., is an unlikely participant in this effort. When he was an undergraduate, at the University of North Carolina Wilmington, he co-founded a company called Lumina Investments, which *New York* magazine lampooned as "the World's Youngest, Most Charmingly Oblivious Hedge Fund." (It eventually morphed into Dalma Capital Management.) Within a few years, he was disillusioned. He started to ask himself, "Is this what my life will be about for the next fifty years?" Although he had little background in science, he considered space exploration, artificial intelligence, and quantum computing to be growth industries; of those three, he picked space. "I thought it was a meaningful and worthy endeavor," he said. But he remembers thinking, "We're probably gonna fail." In 2017, he became the C.F.O. at Ripple Aerospace, a Norwegian company that wanted to launch rockets from the ocean; within a year and a half, it fizzled out.

Carol then took an interest in mining and manufacturing in space. Along with three researchers whose work he'd been following, he invested his own money to found Lunar Resources, in 2018. They and scientists at several universities formed the FarView consortium, and, in 2021, NASA's Institute for Advanced Concepts (NIAC) granted the group a hundred and twenty-five thousand dollars to develop its design. Last year, the agency granted another six hundred thousand. (Lunar Resources also works on other projects; I saw one device, built to test a material-printing method for a military organization I can't name, being prepared for space launch.)

Before you can build antennas on the moon, you have to experiment with building antennas on Earth, using materials similar to those available on the moon. To this end, Lunar Resources buys fake moon dirt, or "lunar regolith simulant," from Off Planet Research, one of various labs that manufacture the stuff. ("Regolith" is a fancy term for rock and dust.) During a tour of Lunar Resources, Carol gave me a sample that resembled dark-gray sand. Off Planet's recipes combine several rocks, including anorthosite and basalt. They also mix in agglutinates or additives such as ilmenite, iron oxide, and silica oxide.

Carol led me to a cramped room full of tools and equipment for testing deposition manufacturing—building things by depositing one or more layers of material, as with a can of spray paint or a 3-D printer. Michael Fitchette, a physicist whose work boots, jeans, and beard made him look like a stylish lumberjack, showed us around. When radio waves strike a metal antenna, they push its electrons back and forth, generating a current. Old-school radios convert currents into sound, but radio *telescopes* record the current to construct a picture of deep space. Although antennas come in a variety of shapes (poles, loops, corkscrews, dishes), Lunar Resources wants to build them as simply as possible. One approach would be to spray ten-metre-long strips of aluminum directly onto the surface of the moon.

So far, Lunar Resources has successfully sprayed aluminum onto simulant in a small vacuum chamber, which mimics the emptiness of space. The company also plans to manufacture solar cells by melting patches of the moon's surface, forming a glassy substrate, and then coating it with aluminum, silicon, and aluminum again. Fitchette handed me a small piece of test glass onto which a gold film had been deposited. His touch left a scuff on the smooth surface. "My fingers are probably rougher than they used to be," he said with a laugh.

Carol and I entered a cavernous bay and found what looked like a machine shop, with tools and equipment arranged under long neon lights. "When NASA comes in here, they're just, like, 'Where's the clean rooms? These hoses can't be on the ground! It's a safety hazard,' " he said. Meanwhile, he joked, employees from industrial backgrounds sometimes ask, "Why is this place so clean?" I reminded him of the culture clash in the film "Armageddon" between Bruce Willis's character, an oil driller, and NASA, which wants him to drill into an asteroid. "Bingo!" Carol said.

At one end of the room, an engineer was building a mechanism for 3-D-printing wires. The wires between FarView's antennas wouldn't necessarily be unwound from a spool; instead, molten aluminum harvested from the moon might be extruded into lines on the ground, in roughly the way that a glue gun extrudes melted glue. Elsewhere in the bay, we found several reactors for molten-regolith electrolysis, a process that can extract metals from melted moon rock. They looked like pottery kilns. "You cannot believe how long it's taken to develop these," Carol said. "We thought it would be the easiest part. Melting the regolith is the *hardest* part, without question. And making a heater that can last more than one run is the second-hardest part." Molten regolith "destroys everything," he added.

The largest reactor, Big Bertha, was a rusty hunk of metal about three feet across. Carol handed me a piece of slag—black, glassy rock—that had come from one of the reactors after the extraction of key elements. Up to this point, Lunar Resources has retrieved iron, magnesium, aluminum, and silicon, but there could also be a use for what's left: Lunar Resources is now working with Icon Technology to 3-D-print melted regolith into building structures.

In a vacuum like the lunar surface, there's no air to carry away heat, and materials emit gas and solidify at rates different from those on Earth. Lunar Resources has been acquiring an arsenal of vacuum chambers for testing. Carol pointed to a steel cylinder, which was a few feet high and checkered with improvised tubes and windows. "We call this Frankenstein, because it's been butchered so many times," he said. He showed me a photo of a new vacuum chamber, which was waiting at a welder's shop thirty minutes away. "I can't wait for that to get here," he said. (It's now in operation.)

Carol asked Rabi Ebrahim, a University of Houston physicist and materials scientist who directs research development at Lunar Resources, to show me another method for making antennas. On a table in front of us, a trench about two feet long had been traced into a bed of fake moon dust. When a crucible of molten aluminum was tipped over the trench, a stream of silver metal filled it and hardened into a sort of wand. "It takes seconds," Ebrahim said. "If you have a larger crucible with a valve, you can fill many, many trenches." He gave me the rod as a souvenir. (I would later contribute it to the T.S.A.) FarView is far from science fiction, Carol argued. "You're seeing the hardware, right?" he told me. "This isn't some dream."

Several missions now aim to take advantage of the quiet lunar environs. In February, another Houston startup, Intuitive Machines, guided the first commercial lander to the lunar surface. It carried a small radio receiver called ROLSES, whose eight-foot antennas are measuring background radio waves from the moon, sun, and Earth—the interference that lunar telescopes would have to peer through to perceive twenty-one-centimetre radiation. "I think we can say that we've got the first radio-astronomy data from the moon," Burns, FarView's chief scientist, told me after the landing. In 2026, he and his colleagues will send ROLSES II to the near side of the moon, and, to the far side, an instrument called LuSEE-Night, which aims to measure the twenty-one-centimetre signal.

NASA's Jet Propulsion Laboratory (J.P.L.) is also exploring the idea of a radio-wave detector, the Lunar Crater Radio Telescope (L.C.R.T.), inside a 1.3-kilometre-wide moon crater. A lander would touch down at the center and shoot harpoons at the rim. Wire mesh would then unfold along the harpoon cables, creating a huge parabolic dish. "Harpoons are exciting," Saptarshi Bandyopadhyay, a robotics technologist and the project's principal investigator, told me. "They're really scary," he went on, because so much can go wrong—they might miss their targets or fail to stick the landing. "But, in the grand scheme of things, we have to accept some risk."

By peering into the Cosmic Dark Ages, radio telescopes could help explain how the universe as we know it came to be. In the beginning, matter was distributed very evenly. "The universe was smoother than a billiard ball," Jonathan Pober, a physicist at Brown University who's working on FarView, told me. "And then look at us today. The universe is filled with galaxies and stars and planets and people." Scientists have modelled how we got here, but it's difficult to test the models without a telescope like FarView. "It's the way to probe the big bang, dark matter, in ways that nobody else can do," Pober said. It could also study solar flares and detect planets with magnetospheres, which may be required for life.

It will take many years to learn how to mine and manufacture on the moon, however. From Lunar Resources, I walked ten minutes to NASA's Johnson Space Center (J.S.C.). The new Lunar Resources vacuum chamber is only the size of a walk-in closet; J.S.C.'s Lunar Development and Test Facility contains two vacuum chambers that were built in the nineteen-sixties by Chicago Bridge & Iron Company. The largest, a sphere that measures fifteen feet across on the inside, fell out of frequent use about twenty years ago, until NASA scientists gave it a second life.

The sphere is now rigged to heat and cool things—space gets very hot and very cold—and to handle simulant, which would muck up a standard vacuum system. Kristopher Lee, a goateed and bespectacled engineer who leads the Energy Systems Test Area, showed me specialized pumps and filters beneath the beast. Then we climbed some stairs and stepped through its large, circular mouth.

Recently, a contractor came here to blast simulant with a laser, to simulate focussed sunlight, and successfully extracted oxygen from it. I asked Lee, who has worked with Lunar Resources on research proposals, about the challenges the team will face while building FarView. Workers won't be able to make repairs, he pointed out: "How do we operate on the moon without being able to just go service equipment?" Corrosive lunar dust levitates and coats everything. There's radiation. There are micrometeorites and occasional larger impacts. There are temperature extremes. "But tough problems are what people solve," he told me. Lunar infrastructure, he said, is "going to teach us how to explore."

Bill Nelson, the current administrator of NASA, went to space in 1986, on a Space Shuttle mission that he joined when he was a U.S. representative from Florida. Recently, we spoke by video call; he was sitting in front of a gold-framed painting of a rocket launch, snacking on Reese's Miniature Cups. He was optimistic that lunar regolith will one day serve as a building material, and that lunar telescopes will tell us more about the origins of the universe. "Do I think that there's life out there in the vastness of the cosmos?" he said. "Yes, I do."

There's important science to be done on the lunar surface, but Nelson sees the moon as a stepping stone. "We're not going back to the moon just to go back to the moon," he said. "We are going back to the moon to learn things in order to go to Mars." When I asked him why people should go to Mars, he replied that discovery is part of the human experience. "Every time we do something like this, we learn something more about who we are, and where we are in this vast cosmos," he told me. "And I suspect that, years into the future, we'll be going beyond Mars." ♦

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