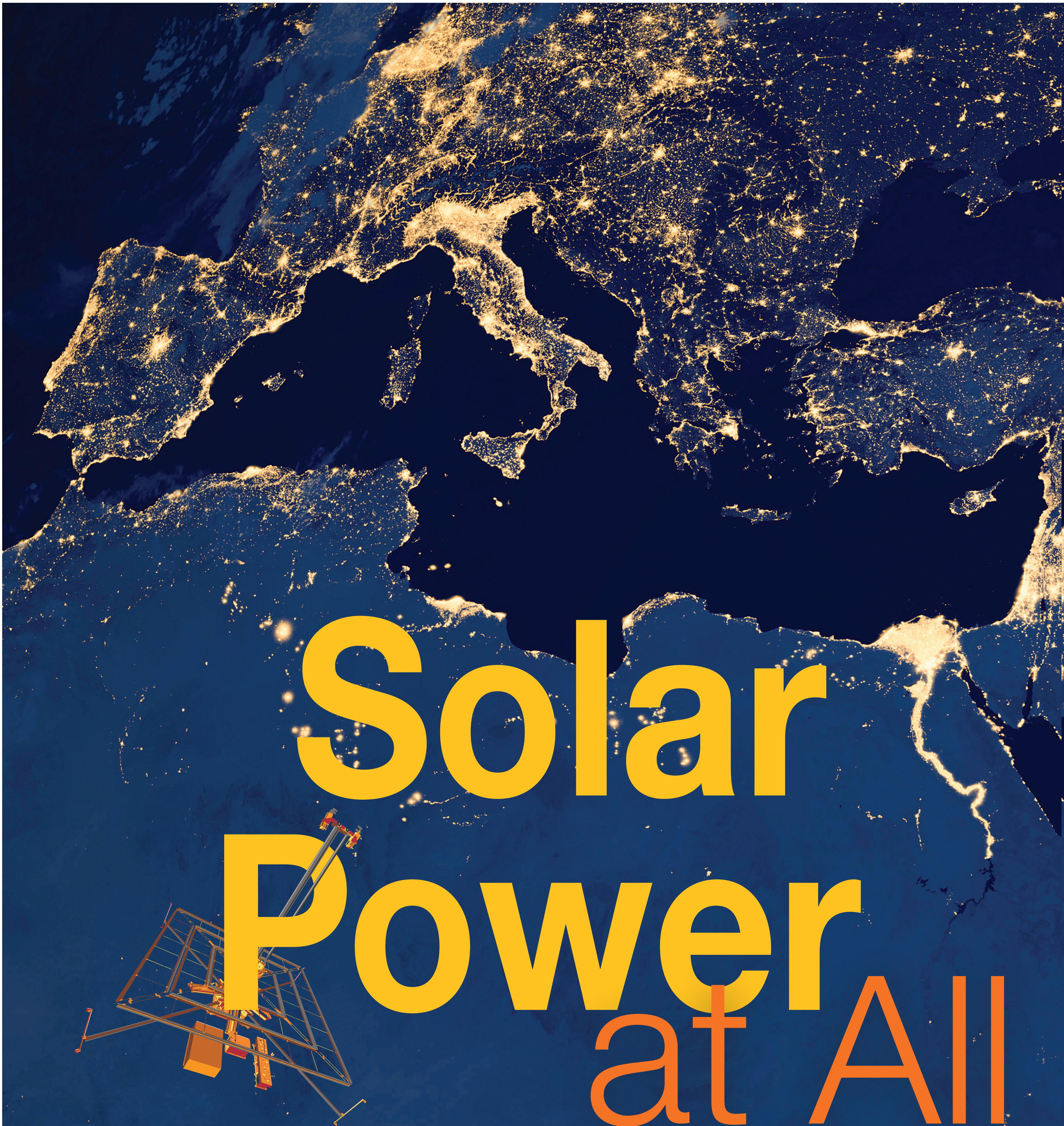
Solar Power at All



Hours

By Ker Than

Caltech researchers hope to **harness the sun's energy** and **power the planet** from **300 miles above.**

On a cool, clear evening in May 2023, Caltech electrical engineer Ali Hajimiri and four members of his lab gathered on the roof of the Gordon and Betty Moore Laboratory of Engineering to await a signal from the heavens.

In preparation, the researchers had strewn portable floodlights across the floor and erected a collapsible canopy in a corner of the roof to shelter instruments and monitors stacked atop a small folding table. Two antennae perched nearby on heavy-duty tripods, their electronic gazes steadily tracking an invisible target drifting more than 300 miles overhead. The signal—if it came—would arrive in the form of a weak microwave beam transmitted from the Space Solar Power Demonstrator (SSPD-1), a 110-pound set of Caltech payloads that had launched into space five months earlier aboard a SpaceX rocket on the Momentus Vigoride-5 spacecraft. SSPD-1 is the first spaceborne prototype from Caltech's Space Solar Power Project (SSPP).

The source of the evening's anticipated signal was the Microwave Array for Power-transfer Low-orbit Experiment (MAPLE), a series of flexible lightweight microwave power transmitters built in Hajimiri's lab that make up one of SSPD-1's three main experiments. Hajimiri, an SSPP co-director and principal investigator, and others have estimated that space-based harvesters founded on the technology demonstrated by MAPLE could one day provide access to eight times as much solar energy on average as their terrestrial counterparts.

"This is a system able to provide stable power over time," adds aerospace engineer Sergio Pellegrino, an SSPP co-director and principal investigator, whose lab worked on SSPD-1's ultralight deployable structure. "There is potential for a breakthrough in the provision of clean renewable energy."

That harvested energy could then be dispatched to any place on Earth, including areas devastated by war or natural disaster, or regions with poor energy infrastructure, explains nanophotonic and solar-energy expert Harry Atwater, who is also one of SSPP's principal investigators. "You could imagine in places like that, where you want to bring power to a large city, you could immediately do that without building a large power grid," Atwater says. "The thing that's really transformative about space solar power is that, unlike solar power on Earth, it has potential to eliminate the need for storage. You get power continuously, 24 hours a day, and you don't have to come up with day-to-night storage, like in the form of batteries, or season-to-season storage."

The May rooftop experiment was long planned but had to be rapidly executed on short notice. The Caltech engineers had just three hours to haul their equipment to the roof, having received the green light from Momentus to conduct their experiment only that evening. "It wasn't like we had everything set up, and we were just sitting around waiting," recalls Raha Riazati, an undergraduate researcher in Hajimiri's lab who designed the receiving antennae for the test. "It was definitely a mad rush, and I remember being very stressed and thinking, 'I really hope we can get everything ready in time, because if we don't, this will be a wasted opportunity.' It was pretty nerve-racking."

Around 10 p.m., the team paused its various activities to huddle around a single monitor. From where they were on the rooftop, there was only a seven-minute window in which the signal could be detected, and the countdown had begun. "In the beginning, we weren't seeing the signal," Hajimiri recalls.

A minute passed. Then a few more. Before the team's apprehension could turn into alarm, a digital peak heralding the signal appeared on-screen. The growing spike carried the precise power level and frequency shift the team had predicted based on the beam's travel from orbit. "It took a few seconds for it to sink in that, yes, this is happening," Hajimiri notes. MAPLE's demonstration marked the first time that power was transmitted and received in space, directed toward Earth, and then detected, according to Hajimiri. "The level of energy, of course, is very small at this point," he says. "This was mostly about detection, but it is a first step."

Despite lasting only 90 seconds, the microwave signal detection at Caltech on May 22 marked a major milestone toward realizing a century-long dream to harvest solar energy in space and beam it wirelessly down to Earth. The experiments on SSPD-1 are designed to test key technologies that could enable Caltech's unique take on this vision, which involves deploying a fleet of nimble, modular spacecraft, each equipped with a flexible ultralight membrane that can function as both solar panel and energy transmitter. Like a starling murmuration, the spacecraft will come together as a "flock" to create enormous floating power stations above Earth, but each spacecraft will also be able to operate independently.

In addition to MAPLE, SSPD-1 has two other main experiments: Deployable on-Orbit ultraLight Composite Experiment (DOLCE), a structure designed and built in Pellegrino's lab that measures 6 feet by 6 feet and that will test the architecture, packaging scheme, and deployment mechanisms of the spacecraft; and ALBA (Italian for "dawn"), a collection of 32 different types of photovoltaic (PV) cells, some built in Atwater's lab and at other Caltech labs, and some sourced from other researchers around the world. Atwater's team is conducting tests to determine which of these cells operate best in the punishing environment of space.

In total, about 35 faculty members, postdocs, graduate students, and undergrads at Caltech worked on the SSPD-1 project.

With the May test successfully concluded, Hajimiri's team erupted in cheers and high-fived one another before beginning the laborious task of dismantling the equipment and clearing off the roof. It was only later when she was back in her room that Riazati could reflect on the night's achievement. "That was when it clicked in my head that this project I'd been working on for over a year and a half had finally worked, and that we'd gotten this groundbreaking result," she says. "I was like, 'Wow, that was pretty awesome.'"

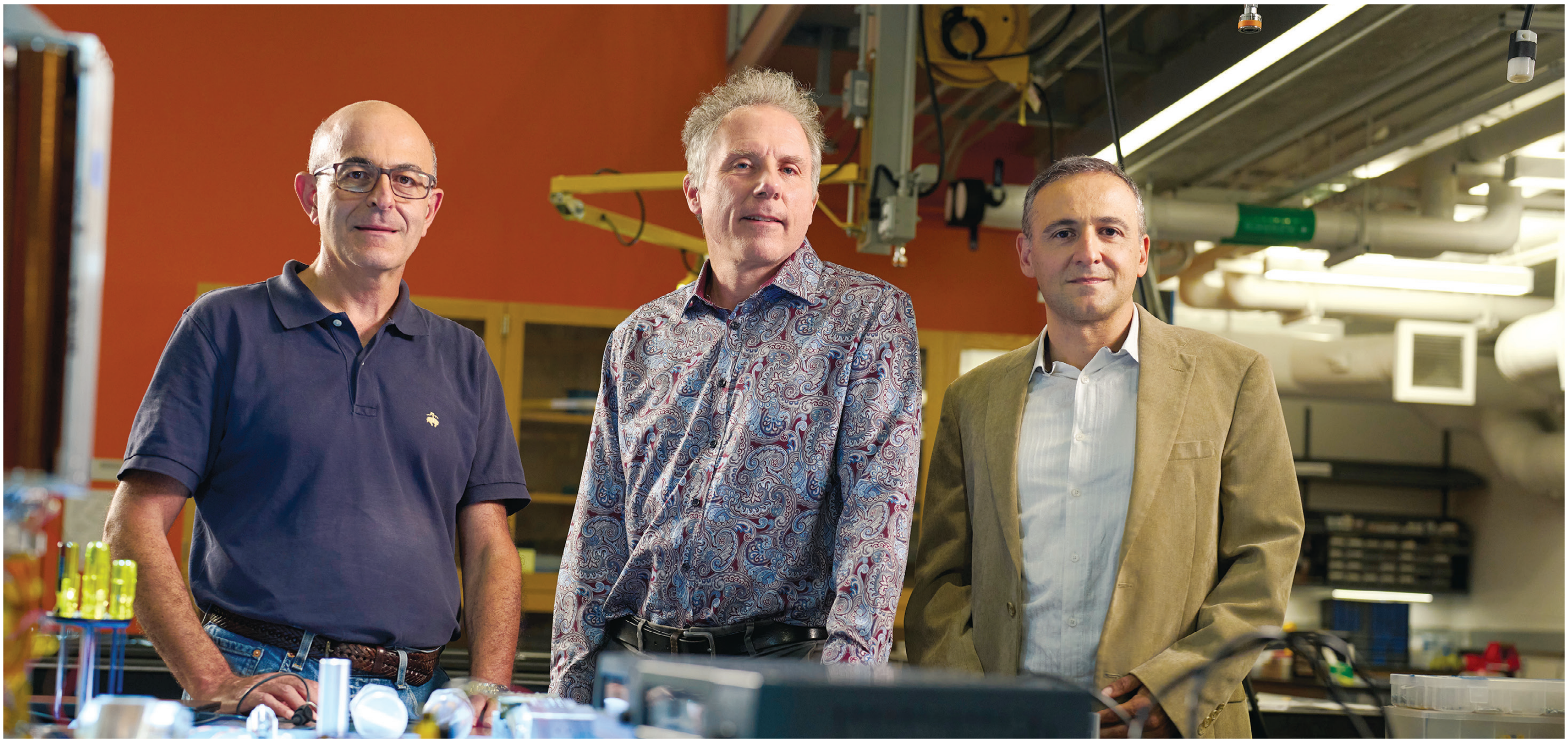
Space-based solar power may also one day power rovers on the Moon or Mars.

A Long Journey

The idea of space-based solar power dates back to as early as 1923 when Russian theorist Konstantin Tsiolkovsky proposed using mirrors in space to concentrate a strong beam of sunlight down to Earth. Years later, the science-fiction writer Isaac Asimov, in his 1941 short story "Reason," imagined solar-powered satellites beaming energy in the form of invisible microwaves to Earth and human settlements across the solar system. Learning of this for the first time, Asimov's robot character asks, "Do you expect me to believe any such complicated, implausible hypothesis as you have just outlined? What do you take me for?"

The first patent for a microwave-based method of transmitting power from orbit was granted in 1973 to NASA engineer Peter Glaser, who also outlined the engineering concepts for his proposal in an influential 1968 *Science* article titled "Power from the Sun: Its Future." Glaser's ambitious plan called for massive satellites equipped with solar-panel arrays capable of harvesting sunlight in space, converting the sunlight into energy, and then beaming that energy wirelessly toward 5-mile-wide receiving antennae on Earth. "It is an incredibly complex piece of infrastructure. It needed to be giant to make sense," Pellegrino says.

Glaser also articulated the rationale for harvesting solar energy in space: high above the atmosphere where the sun never sets, sunlight can be collected around the clock, irrespective of clouds, weather, or nightfall. This prospect so intrigued the U.S. government that it spent $20 million to investigate the technology (inspired by the shift toward reducing dependence on fossil fuel due to the oil crisis of



Left to right: Sergio Pellegrino, Harry Atwater, and Ali Hajimiri, the principal investigators of the Space Solar Power Project.

the 1970s), only to deem it too complex and expensive a few years later. But thanks to recent advances in photovoltaics, materials engineering, and electronics, combined with decreasing launch costs and urgent calls for more clean energy sources, space-based solar power is enjoying a new moment in the sun.

The European Space Agency recently approved two concept studies of a European space-solar network as part of its SOLARIS initiative, which aims to establish the technical, political, and programmatic viability of space-based solar power. The China Academy of Space Technology plans to launch its own power-beaming satellite prototype by 2028, and the U.S. Naval Research Laboratory recently tested technology to convert sunlight into microwaves in space, although it did not actually transmit that energy anywhere. India, Japan, and the United Kingdom have also expressed interest in developing their own technologies.

Of these global efforts, Caltech's is arguably the furthest along: SSPD-1 is the first space-based solar power demonstrator to reach orbit and demonstrate wireless energy transfer in space. "Demonstration of wireless power transfer in space using lightweight structures is an important step toward space solar power and broad access to it globally," Atwater says.

The Caltech Concept

The Caltech effort began after philanthropist Donald Bren, chairman of Irvine Company and a life member of the Caltech community, first learned about the potential for space-based solar energy manufacturing as a young man after reading an article in *Popular Science* magazine. Intrigued by the potential for space solar power, Bren approached Caltech's then-president Jean-Lou Chameau in 2011 to discuss the creation of a space-based solar power research project. In the years to follow, Bren and his wife, Brigitte Bren, a Caltech trustee, agreed to make a series of donations (which ultimately amounted to a total commitment of $100 million) through the Donald Bren Foundation to fund the project and endowed professorships.

"The hard work and dedication of the brilliant scientists at Caltech have advanced our dream of providing the world with abundant, reliable, and affordable power for the benefit of all humankind," Donald Bren says.

In addition to the support received from the Brens, Northrop Grumman Corporation also provided Caltech $12.5 million between 2014 and 2017 through a sponsored research agreement that aided the development of technology and advancement of science for the project.

Bren charged Caltech with making solar power feasible and—equally as important—economically viable. The Institute responded by asking Hajimiri, Pellegrino, and Atwater's teams to invent the necessary new technologies, materials, and manufacturing processes. "You could characterize our work at Caltech as a component-led

Fact:
Modern terrestrial solar panels are about 20 percent efficient at converting sunlight into energy. Space solar panels are about 30 percent efficient.

revolution," Atwater says. "In the solar-energy-technology part of SSPP, we need to achieve a kind of photovoltaic technology that does not exist today that is ultralight, efficient, low cost, and resistant to radiation."

The Brens approached Hajimiri due to his work in electronics and photonics that laid the groundwork for 5G communications and radar sensors in cars. But at first Hajimiri had reservations. "The way that space solar power had been envisioned previously, it was not practical at all," Hajimiri remembers.

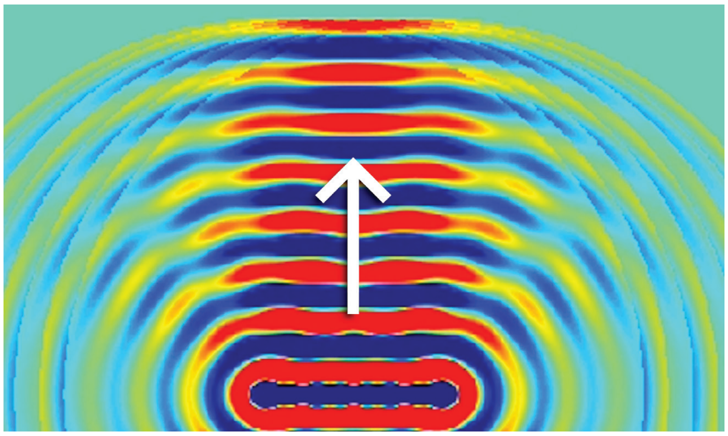
Atwater had a similar initial reaction. "It took me a long time to overcome my own skepticism," he recalls. "But it's one of those things: you start thinking about how you might do it, and it really gnaws at you, and you can't let go of it."

The more Atwater, Hajimiri, and Pellegrino began chewing on the problem together, the more realistic it began to seem. "It became clear that we needed to replace the basic components that other people had imagined being part of the system," Atwater says. "If you change the components, suddenly you can have a much higher power-to-weight ratio, and that reduces the mass to orbit and, therefore, the launch cost."

The trio eventually came up with a design plan now known as the Caltech Concept, which is radically different from the one Glaser outlined decades earlier. "The Caltech Concept is not a giant monolithic object. It is a collection of spacecraft—many, many, many spacecraft—that are all identical," Pellegrino explains. "They're synchronized, and they provide energy to Earth."

As initially envisioned, each spacecraft will carry a square-shaped membrane measuring roughly 200 feet on each side. The membrane is made up of hundreds or thousands of smaller units, called tiles, which have PV cells embedded on one side and a microwave transmitter on the other. The tiles are arranged into long strips suspended between four telescoping booms that provide structure and tension for the membrane. The strips are folded and coiled for launch and unfurl once the spacecraft reaches orbit. Each spacecraft would operate and maneuver in space on its own but also possess the ability to hover in formation and configure an orbiting power station spanning several kilometers with the potential to produce about 1.5 gigawatts of continuous power.

Since each power station would consist of individual spacecraft operating collectively, there would be no need for complex wiring and a heavy central antenna. "This is a paradigm shift," Hajimiri says. "The analogy I use is going from one big elephant to an army of ants."



Space Solar Power Project transmitters are designed to direct power toward Earth using the physical phenomenon of interference.

Ali Hajimiri's team is developing algorithms that will allow a spacecraft to determine the current configuration of its transmitting-antenna flexible-array elements and make real-time corrections to them.

Ants Versus Elephant

The ability of each tile to transmit energy wirelessly through space is based on a physical phenomenon called interference, which arises due to the wave-like nature of light. To understand interference, Hajimiri says, imagine sitting at the edge of a pond and putting both of your hands in the water and moving them up and down. Each hand makes a wave, but because of how the waves and their energy interact, some waves will be bigger and others will be smaller. Like big waves in water, synchronized light waves overlap, their peaks meet and create a greater peak; this is called constructive interference.

"If you have multiple sources that are operating in concert, in the same phase, you can actually direct energy in one direction so all of them will only add in one direction and will cancel each other out in all other directions," Hajimiri explained in a recent video that accompanied an announcement of SSPD-1's launch. "The same way that a magnifying glass can focus light into a small point, you can actually control the timing of this in such a way that you can focus all of that energy in a smaller area than the area that you started with."

The upshot of being able to control direction by manipulating timing is that no moving mechanical parts are required, and energy can be redirected in mere nanoseconds to a receiver in space or on the ground. "It's as if you have an army of ants that are working in perfect synchronization, and each one of them contributes a little bit of energy, but as a whole they send it to the right place," Hajimiri said in the video.

Engineering "Backward"

If the Caltech Concept is ever to be realized, everything about current PV-cell technology will need to be rethought and vastly improved, Atwater says. The PV cells used in space to power satellites and the International Space Station are about 32 percent efficient at converting sunlight to energy. They weigh about 2.1 kilograms per square meter and have a power-to-weight ratio, or specific power, of 200 watts per kilogram. They cost about $10,000 per square meter to manufacture.

SSPP aims to develop a PV cell with an efficiency level of 25 percent that is 100 times less expensive ($100 per square meter), 40 times lighter (0.05 kilograms per square meter), and with a specific power 33 times greater (6.6 kilowatts per kilogram) than current space PV cells.

Another way to think about it: An SSPP spacecraft with a 60-meter-by-60-meter surface area made using today's space PV-cell technology would cost $36 million and weigh nearly 9,000 pounds, or almost as much as a Ford F-450 truck. With the ultra-lightweight PV-cell technology Atwater envisions, it would cost just $450,000 and weigh about 300 pounds, or about as much as an IKEA three-seat sofa.

To achieve these lofty goals, Atwater's team is investigating novel manufacturing techniques and exotic materials for the creation of its PV cells. "We're inverting the normal methodology that you use to make solar panels," Atwater says. "What we said was, 'We have to make this very cheap, so we're going to start with the economic analysis that says it has to cost $100 a square meter. Then we're going to design the cell-manufacturing process, and out of that we're going to make the cell.' It's completely backward."

Atwater's team is using a simple method called spalling to create highly efficient PV cells made from gallium arsenide and indium phosphide. Spalling involves peeling a layer of ceramic material from a bulk crystal to create a film layer that is thinner than the thinnest piece of plastic found in your home. Crucially, spalling doesn't require a vacuum environment, and the PV cells can be baked in a furnace comparable to a consumer oven. "We're using the same kind of processing that we teach Caltech first-year students," Atwater says. "It's very inexpensive."

The ALBA tests, which began in June, have so far shown that gallium arsenide cells perform well in space even though they do not have a protective coating. "It's a point of validation that these low-cost cells we made with processing that you can do in your kitchen will work in space, and they work nicely," Atwater says.

The two other solar-cell technologies being tested by ALBA include PV cells made from thin-film perovskite, and semiconductors known as quantum dots that utilize nanotechnology and quantum mechanics to convert sunlight to energy. In total, 32 PV-cell samples, each made using a variation of one of these three technologies, make up ALBA's science payload. "We're testing their current voltage characteristics and how they perform as a function of temperature," Atwater explains. "This is the first time these kinds of PV cells have ever been tested in space."

Delivery and Deployment

The third SSPD-1 experiment, DOLCE, demonstrates the packaging and deployment mechanism for the flexible membranes populated with PV and radio-frequency components that, although not included in DOLCE, will be required in a complete space-based solar-power spacecraft. The first stage in the deployment occurred in May 2023, and the process was completed in September.

Photovoltaic cells were invented by Bell Laboratories in 1954 to power the first U.S. satellites.

Pellegrino's team has developed a novel method called slip wrapping that packages large membranes tightly and efficiently by first dividing them into precise strips that are compactly folded into a star shape and then carefully wrapped around a central axis to form a tight cylindrical package. DOLCE is the first engineering-scale demonstration of the slip-wrapping technique in space.

The edges of the membranes aboard SSPD-1 are reinforced with deployable "longerons" that are the result of extensive research in Pellegrino's lab. They consist of two tape-measure-like sections of ultrathin composite material made of glass and carbon fiber that are bonded together on one side. The longerons' curved cross section is thin walled and provides high bending stiffness, which allows the longerons to store energy during packaging; this "strain energy" is then used to self-deploy the structure in space.

When combined, the longerons and the slip-wrapping technique allow each membrane strip to be tightly stowed in a cylindrical mechanism. Deployment occurs in two steps: first, the folded strips with the membrane uncoil from a central spool into a star shape, and then the star unfolds into a flat structure. The uncoiling step is controlled by a motor, whereas the unfolding process is driven by the stored strain energy of the longerons.

"We discovered that this is a highly repeatable process, very robust," Pellegrino says. "In fact, we've never broken any of the structures we built by folding and unfolding them, but it took much study to develop the technique for packaging, and even more study to acquire the courage to let the structure deploy by itself."

Looking back, Hajimiri acknowledges it has been a long journey to get to this point, and there is still much ground—and space—left to cover. "Movies often portray a direct path to success. The real path to success has a lot of meandering and a lot of dead ends. But people don't talk about that. There are a lot of things that can go wrong. The key is to learn from each of them and take the next step." [C]

Harry Atwater is the Otis Booth Leadership Chair of the Division of Engineering and Applied Science; Howard Hughes Professor of Applied Physics and Materials Science; director of the Liquid Sunlight Alliance; and a principal investigator of the SSPP.

Ali Hajimiri is the Bren Professor of Electrical Engineering and Medical Engineering, and a co-director and a principal investigator of the SSPP.

Sergio Pellegrino is the Joyce and Kent Kresa Professor of Aerospace and Civil Engineering and a senior research scientist at JPL, which Caltech manages for NASA. He is also a co-director and a principal investigator of the SSPP.