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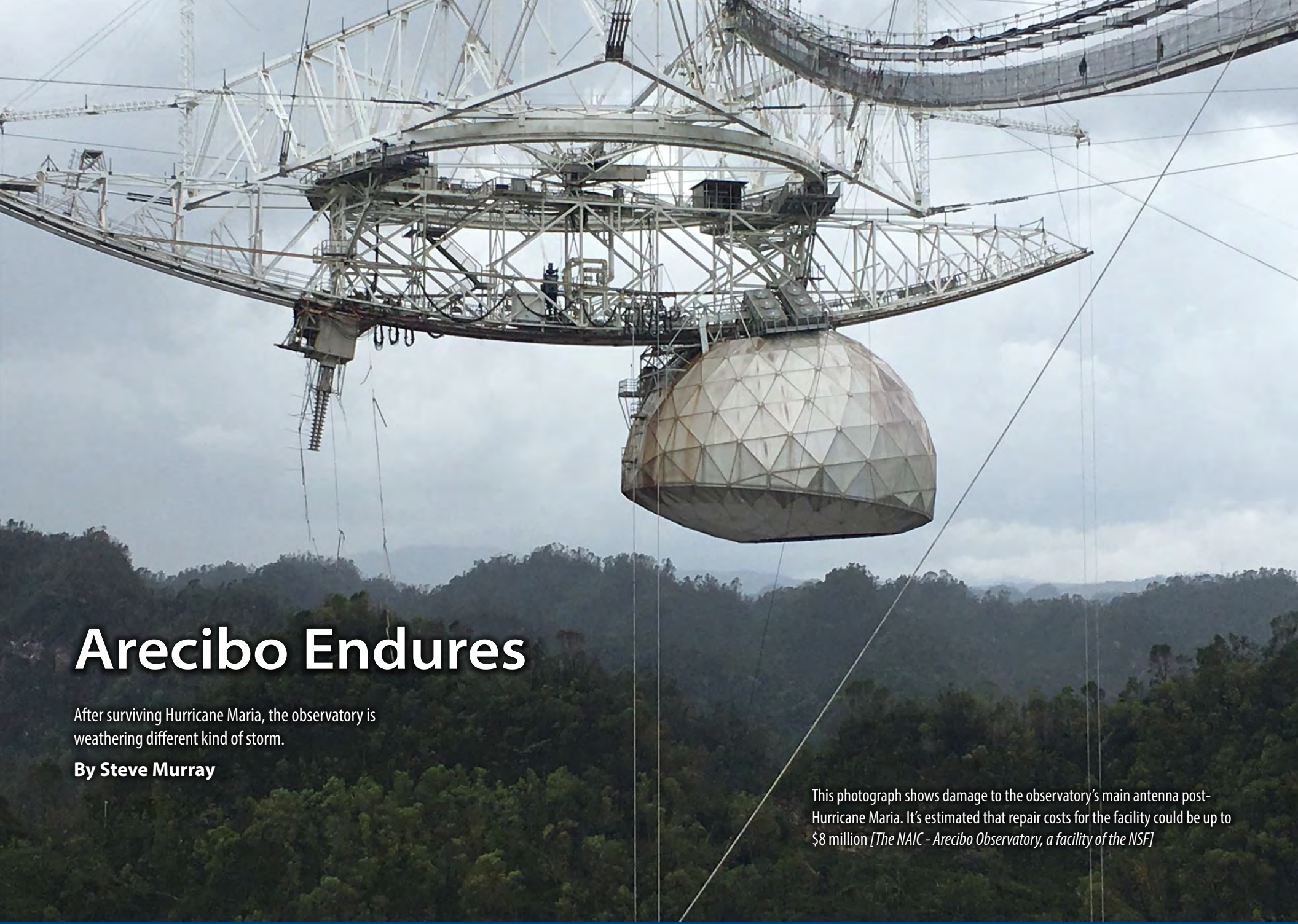
on the cover

Front: This observation of the center of our galaxy, spanning the sky from the constellations of Sagittarius to Scorpius, includes the dust-choked lanes of the Milky Way. Hidden inside this dust is the location of Sagittarius A*, the home of our galaxy's supermassive black hole. This image is part of the ESO's GigaGalaxy Zoom project which captured a 340-million-pixel view of these Southern Hemisphere skies. *Credit: ESO/S. Guisard (www.eso.org/~sguisard)*

Back: This Hubble Space Telescope observation of the globular cluster Messier 79, or M79, shows about 150,000 stars glistening like a snow globe. Released in December 2017, this beautiful view of one of the Milky Way's satellite galaxies came just in time for Christmas. *Credit: NASA/ESA/S. Djorgovski (Caltech) and F. Ferraro (University of Bologna)*



Arecibo Endures

After surviving Hurricane Maria, the observatory is weathering different kind of storm.

By Steve Murray

This photograph shows damage to the observatory's main antenna post-Hurricane Maria. It's estimated that repair costs for the facility could be up to $8 million *[The NAIC - Arecibo Observatory, a facility of the NSF]*

The last few months have been filled with drama for Arecibo Observatory. Even as its staff cleaned up after Hurricane Maria, they knew that another threat was on the horizon. For years, the National Science Foundation (NSF) had been anxious to reduce its funding support for the facility and a November 2017 board meeting was set to discuss the observatory's future with a decision soon to follow.

Arecibo may have weathered a major storm, but would it weather governmental money debates?

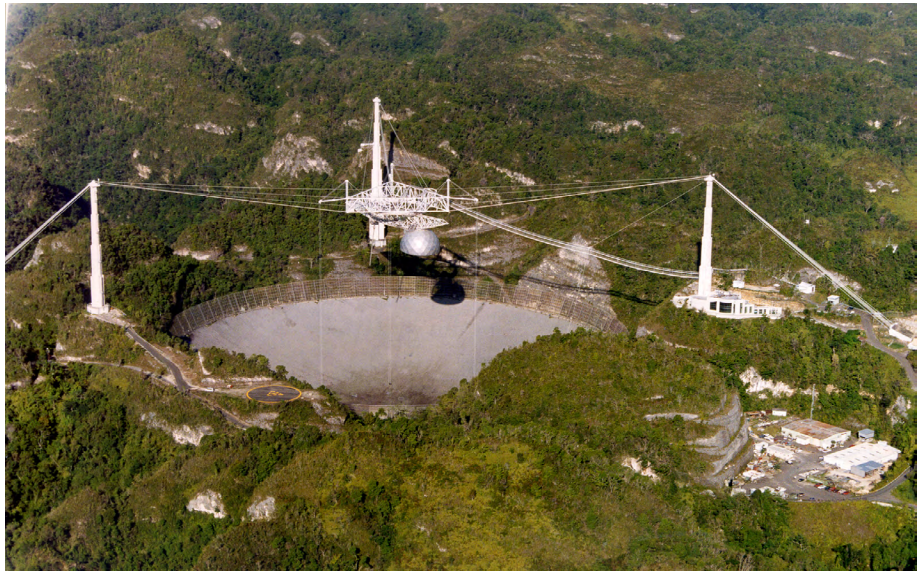
Still Special After All These Years

The construction of Arecibo Observatory was completed in 1963. With a 1,000 foot (305 meter) dish resting in the karst hills of northwestern Puerto Rico, it operated as the world's largest radio telescope until 2016 when the 1,600 foot (500 meter) dish of the Chinese Five hundred meter Aperture Spherical Telescope (FAST) Observatory was finished. Arecibo will still claim bragging rights as the largest operational dish, however, until all FAST checkout tests are concluded.

A 900-ton receiver platform containing secondary reflectors and four-line feed radar antennas is suspended over the dish by cables. Moving the platform around a bow-shaped track gives astronomers an observing cone of almost 40 degrees over its zenith by focusing on different parts of the spherical dish.

Arecibo was originally built as a tool for U.S. defense studies into properties of the upper atmosphere. Scientists were quick to realize its broader potential, however, and pushed for additional uses. Today, the observatory supports research projects in atmospheric science, radio astronomy, and planetary (radar) science.

Atmospheric scientists measure emissions like airglow with passive optical instruments and light scattering with active LiDAR (laser) systems. Studies of plasma in the ionosphere, however, brings the world's most powerful incoherent scatter radar into play.



Construction of the Arecibo Observatory was completed in 1963 and, until 2016, the radio telescope was the largest single aperture dish on the planet *[NAIC - Arecibo Observatory, a facility of the NSF]*

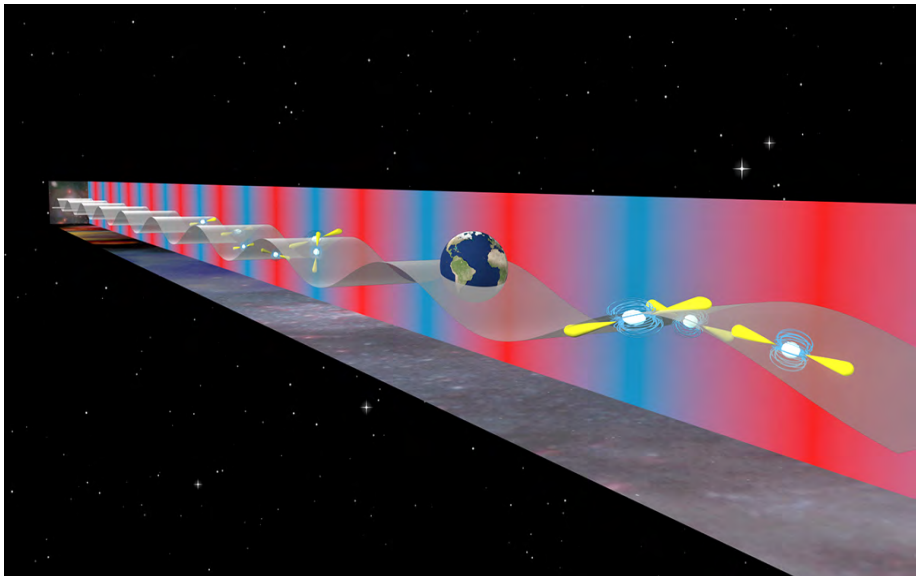
"The radar and the big collecting dish can make incredibly precise measurements of waves in plasmas," says Herbert Carlson, research professor at Utah State University. "Arecibo allows us to study the fundamental physics of plasmas better in space than in the lab. You send up radar energy to 'kick' the plasma, then measure how it responds. Arecibo's radar gives you a time lapse movie of basic processes."

James Cordes, George Feldstein Professor of Astronomy at Cornell University, uses the facility in support of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) program, which searches for gravitational waves by measuring their

effects on pulsars.

"Arecibo is one of the major elements of the North American Pulsar Tracking Array," says Cordes. Unlike the Laser Interferometer Gravitational-wave Observatory (LIGO) program, which detects the high-frequency space-time ripples generated as black holes collide and merge, "we're looking at [gravitational] waves from an earlier phase of their inward spiral, so the waves are weaker and at a higher frequency. They're as different [from the phenomena sensed by LIGO] as radio waves are from X-rays."

Victoria Kaspi, professor of physics at McGill University, relies on the sensitivity of Arecibo to look for new pulsars that can be added to the NANOGrav network and to study Fast Radio Bursts (FRBs). Although these extremely brief high-energy pulses have been discovered before, Arecibo was the first instrument to detect a repeating FRB in 2016.



With the help of Arecibo and other radio observatories, astrophysicists are using pulsars to measure the Earth's motion caused by the passage of low-frequency gravitational waves *[NRAO/AUI/NSF]*

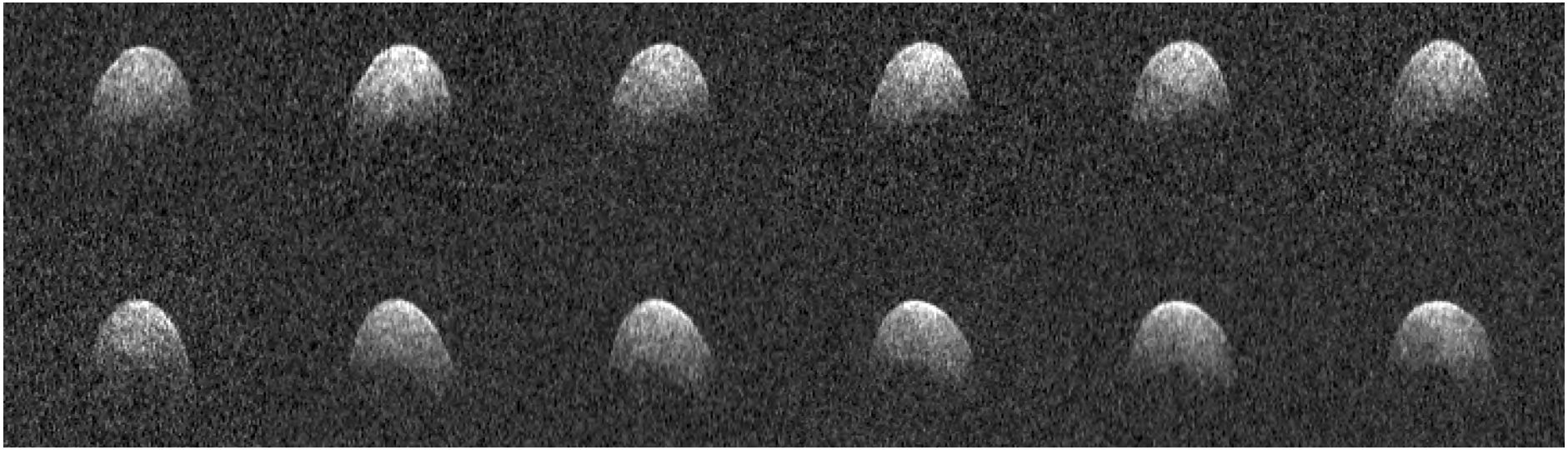
"Nobody knew they could repeat," says Kaspi, "but when you have a big dish you have great sensitivity. We wouldn't know about if we didn't have Arecibo."

Some of the observatory's most critical work, however, may be the detection and tracking of near-Earth objects (NEOs) that could cross Earth's orbit. "It's the bulk of what Arecibo does with its planetary radar," says Lance Benner, planetary scientist at NASA's Jet Propulsion Laboratory. "In recent years, they've been observing between 70 and 100 near-Earth asteroids per year. The observatory can get images of near-Earth asteroids that are comparable to what you can get with a spacecraft flyby—at a very small fraction of the cost of a space mission, of course."

Time to Move On?

Despite its powerful and varied capabilities, Arecibo must still compete with other projects within tight government budgets. Its primary sponsor, the National Science Foundation (NSF), has been trying to cut back its support for several years so it can fund newer telescopes like the Large Synoptic Survey Telescope (LSST) that's being constructed in Chile. The foundation currently provides about $8.3 million a year to Arecibo, and NASA throws in an additional $3.6 million to support the search for hazardous asteroids and other NEOs. While NSF would like to keep Arecibo open as a science facility, it wants to gradually—but significantly—reduce its support.

The observatory is now operated under a cooperative agreement by a consortium of SRI International, the Universities Space Research Association (USRA) and Universidad Metropolitana (UMET) in Puerto Rico. Funding under that agreement, however, will end in March 2018. Other partners will need to step forward and cover the difference, if the observatory is going to stay viable.



The Arecibo Observatory Planetary Radar returned to normal operations in December, capturing a series of observations of the spheroidal asteroid 3200 Phaethon as it made a close approach with Earth *[NASA/JPL-Caltech/Arecibo Observatory/USRA/NSF]*

NSF is in a difficult position. Only so many instruments can be funded and, as radio telescopes go, there are only a handful of operational observatories in the entire world older than Arecibo. Nevertheless, the observatory still has very unique capabilities and a strong group of astronomers who rely on them. About 200 scientists use the facility each year for their research. Arecibo's two selling points are its powerful radars and its enormous dish. "To astronomers, the only difference between radar and radio is that you can at will enhance the brightness of what you want to look at for nearby sources," says Carlson. "We are, in effect, shining a searchlight on an object in the sky.

"For atmospheric science, it's totally unique," he adds. "There aren't any discussions anywhere in the world even starting to think about a capability that would approach Arecibo's. All other radars in the world are miniscule compared to this observatory."

Cordes sees Arecibo as essential to NANOGrav's purpose. "Arecibo and Green Bank are really the best telescopes for doing pulsar timing, at least for now. We're skeptical that any of the new telescopes will fill the need and NANOGrav would be in very bad shape if they went away."

Loss of Arecibo would be devastating "to the whole small body community," says Lance Benner, "Using radar we can identify very close approaches much further into the future than if radar were not available. Arecibo is the best facility in the world for doing that." Some trajectories can be mapped up to a century ahead.

Any change to Arecibo's status would also have an economic and cultural impact on the island. "Over 80 percent of our staff is from Puerto Rico," says Francisco Córdova, director of Arecibo Observatory. "We host over 90,000 visitors each year," he adds, "many of whom are local students who benefit from access to a world class research facility like Arecibo, and our Angel Ramos Science and Visitors Center is one of the few informal STEM education facilities in

Puerto Rico."

The facility has even been listed with the U.S. National Register of Historic Places and Puerto Rico's State Historic Preservation Office.

Hurricane Alert

On Sept. 20, 2017, as NSF wrestled with long-term budget issues, Hurricane Maria struck Puerto Rico. Parts of the island got hit with 30 inches of rain in a single day (the same amount that Houston received in three days of Hurricane Harvey). Maximum winds of 155 miles per hour (135 knots) destroyed some National Weather Service sensors, forcing meteorologists to measure the storm entirely by satellite.

Arecibo is no stranger to storms, however, and the staff had time to prepare the facility. Observatory staff locked down the telescope, dismantled a portion of the antenna, put up storm shutters and checked generators and fuel supplies. Operations were then suspended to allow staff members to prepare their homes. A small group of workers rode out the hurricane at the observatory with water, food and diesel supplies. "The observatory is designed to withstand a direct hit from a major hurricane," notes Benner. "It's one of the safest places on the whole island."

Anticipating that the tree-lined road to the observatory would likely be impassable for several days after the storm, short-wave radios were set up so staff members who lived near Arecibo could communicate with each other if Internet and telephone access were lost.

One staff member used the short-wave system to send out the first damage reports late on Sept. 21. Fortunately, things weren't as bad as expected from such a powerful storm. The sinkhole underneath the dish was flooded and a 430 MHz line feed radar antenna fell into the dish and damaged some panels. Otherwise, the telescope was operational.

A first glimpse of Arecibo after Hurricane Maria struck Puerto Rico *[Helen Minchin]*

Observatory staff soon turned to assisting others, a role they've taken on before. With its deep water well and generator power, Arecibo has been a place where people from nearby towns could gather, reorganize, and recover.

About 14,000 gallons (53,000 liters) of drinking water were distributed each day to surrounding neighborhoods from a standpipe at the observatory gate. "Our staff used their own time to distribute food and bottled water, provided by FEMA and the Coast Guard, to more than ten surrounding communities," says Córdova. "We continue to provide water to the community as needed."

The entire facility was offered to FEMA and, for a time, became the agency's headquarters for recovery efforts.

Police and power authorities made early use of the observatory's radio repeaters for emergency response and the Arecibo helipad served as a logistics point for supply distribution to the island's hard-to-reach central areas.

After the receiver platform was inspected and its reflectors were aligned, the observatory then got back to science work using diesel-powered generators. Drift scan astronomy was restarted on Sept. 29, although a Twitter post from the observatory announced Nov. 7 as the first day of tracking work. Only its radar projects were still curtailed, as the diesel generators needed to power its high frequency transmitting equipment took a back seat to more essential fuel requirements elsewhere around the island.

"Many staff still don't have power at home, although most now have water," says Robert Minchin, Group Lead for Radio Astronomy at the observatory. "The water supply is still under a 'boil advisory' across the entire island, so our tap water is not actually potable. There are three families still living on-site at the observatory in our visiting scientists' quarters."

A FEMA helicopter carries out relief work at Arecibo. *[Robert Minchin]*

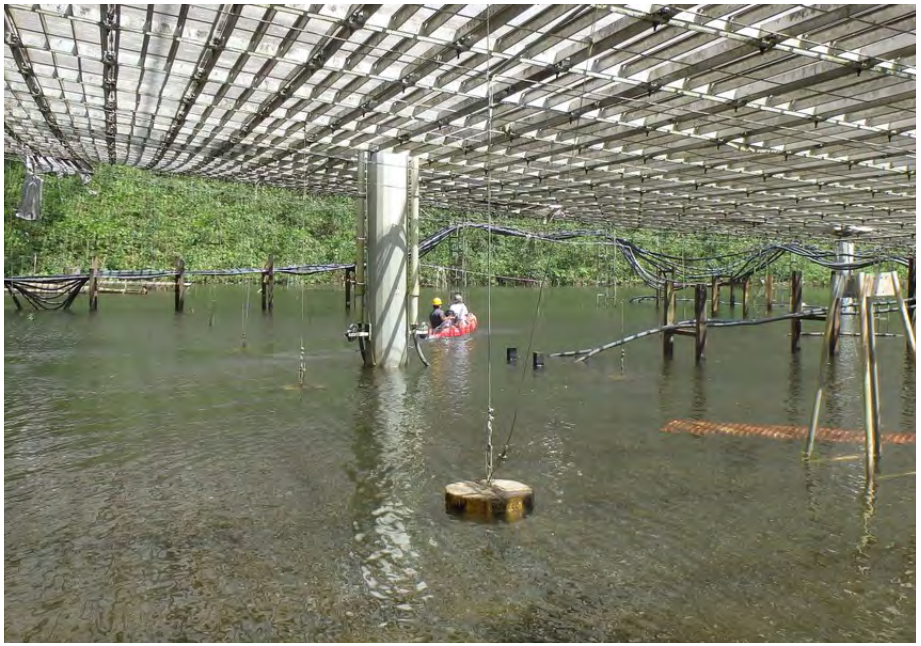
Herbert Carlson had been a former director of the Ionospheric Research Department at Arecibo Observatory and wasn't at all surprised by the stories coming out of the facility. "A unique aspect is the staff, which is something that gets very little attention," he notes. "They're bright, they're educated, and they really care about the place. I've been to a lot of observatories, but there's something special about the staff at Arecibo; they really go all out to support the mission. It's hard to quantify but it's something that I'm always impressed with."

Rescued

With the NSF already working on plans to reduce funding and potentially close the observatory, big repair bills might have been the last straw in its decision-making. NSF estimated the repair costs between $4 million and $8 million, however, which it appears willing to pay.

On Nov. 16, the NSF released a public statement regarding its Arecibo decision. Its board could have selected from alternatives that ranged from maintaining current funding to completely mothballing the site. The foundation issued the welcome news that they would continue science operations "with reduced agency funding," and would search for new collaborators. NSF specified in their decision that any new operators would have to continue support for the radio astronomy and aeronomy science activities at the observatory.

James Ulvestad, director (acting) of Mathematical and Physical Sciences at NSF, stated that this was only possible because one or more viable partners had made proposals in response to the agency's solicitation earlier in the year. A new cooperative agreement will



The sinkhole beneath Arecibo's dish was flooded after Maria *[Arecibo Observatory Staff]*

be awarded on or after April 1, 2018 with an anticipated duration of five years. In that time, NSF support for Arecibo will begin to ramp down to $2 million as new management partners pick up the difference. The agreement could be renewed for an additional five years, following a successful future review.

"I think the decision was very positive," says Córdova. "It clearly defines the future of the site, and that is what we really want at the end of the day. It also takes off the table any concerns over potential destruction or mothballing of the facility.

"I see it as an opportunity to increase the scope of research programs at Arecibo and obtain funding from some less traditional sources."

The Next Chapter

Demand for the telescope remains strong. "There's massive competition for Arecibo time," notes Kaspi. "That's the sign of a healthy observatory that's doing great science—when everybody wants to use it." After an emotional fall, Arecibo's staff can begin long-term planning again. It looks like its 54 years of operation will now be extended for another five years. Some scientists wish for an even longer life for the observatory.

"The worst case would be if Arecibo and Green Bank went away in five to ten years," he says. "NANOGrav would be in very bad shape. We're getting a lot of time on these instruments, and it would be very hard to get an equivalent amount of time on other telescopes. Our plan A is that we'd like to keep both scopes for the whole next decade. In fact, what we'd really like to have is an Arecibo for sampling the southern sky, too."

Even a few weeks without Arecibo's radar has pinched some current work. "During the time they've been offline they've missed at least 10 near earth asteroids they were planning to observe," says Benner. "We have a whole bunch of really scientifically compelling targets coming in the next one to two months, and I really hope Arecibo will be back up in time for those."

Someday, of course, technology and scientific interests will change and the research community will move on to other instruments. But for Arecibo Observatory, that day is still in the future. Like Mark Watney, the stranded astronaut in "The Martian," organizations decided that they needed to save a valued resource. ✪

STEVE MURRAY is a freelance science writer and NASA Solar System Ambassador. A former research engineer, he follows developments in astronomy, space science, and aviation.