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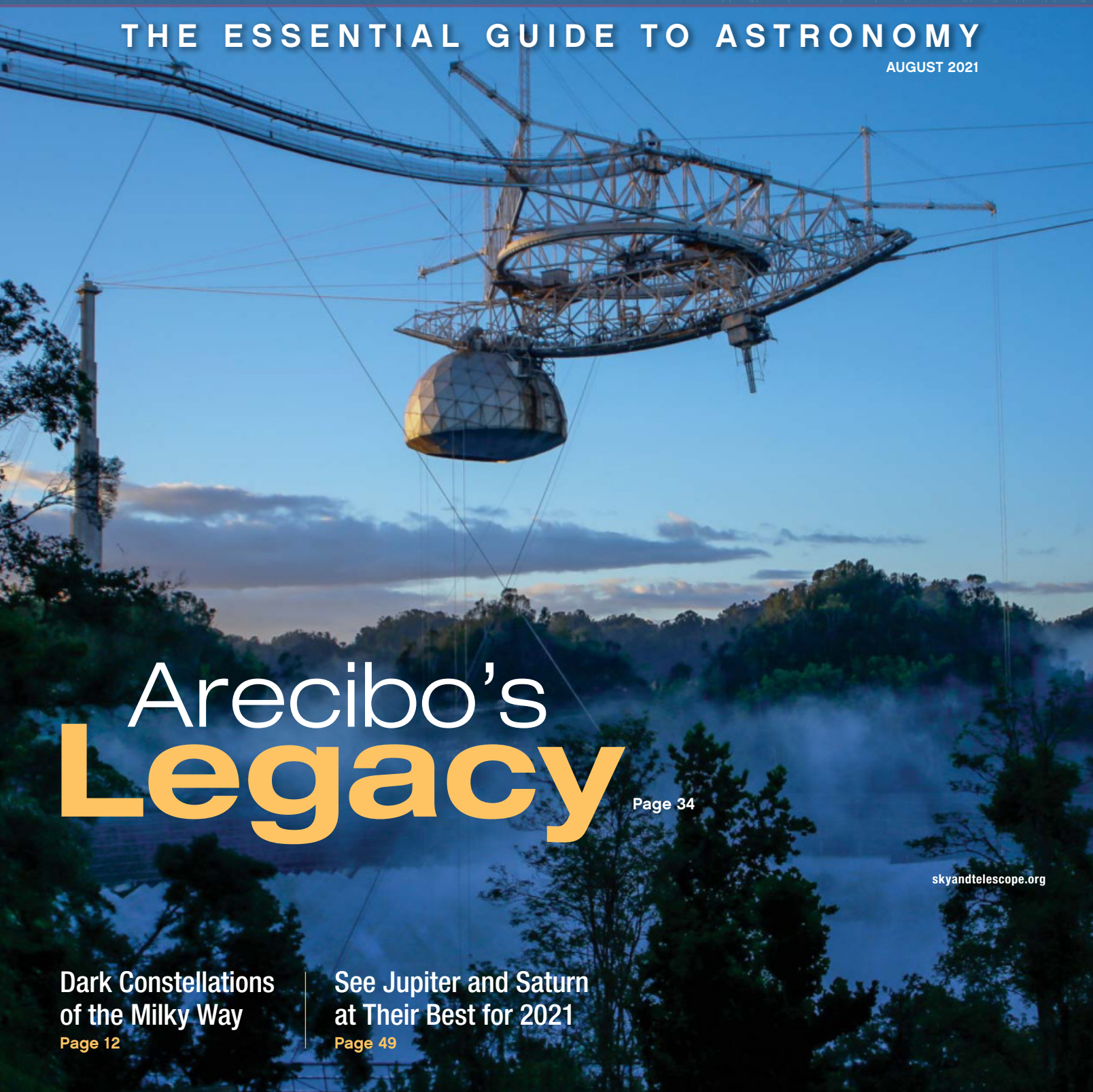
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

AUGUST 2021



Arecibo's Legacy

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Arecibo's Legacy

The tragic loss of the iconic radio telescope abruptly ended more than a half century of science and inspiration.

▲ **BEFORE THE FALL** This panorama from the visitor center's observation deck shows the telescope's instrument platform (with Gregorian dome), two of the three suspension towers, and part of the dish, all surrounded by the Puerto Rican jungle.

ANGEL TRUJILLO / GETTY IMAGES

Disasters such as earthquakes and hurricanes are common in Puerto Rico. Only about 180 by 60 kilometers (110 by 40 miles) in extent, the small island lies 1,600 kilometers southeast of Miami, far from any major landmass. The Atlantic Ocean beats against its northern shores, and the placid Caribbean strokes its southern coast. Despite the dangers, Puerto Rico is a popular tourist destination and home to 3.2 million U.S. citizens, a resilient and diverse population long proud of the world-famous 305-meter (1,000-ft) radio telescope at Arecibo Observatory.

But at 7 a.m. on December 1, 2020, their resilience was severely tested. At that moment the support cables above the dish snapped, and the 900-ton antenna platform suspended above the dish plummeted into it in a mangled mass of steel. The crash triggered a nearby seismograph accustomed to recording small (and some not so small) earthquakes from the collision between tectonic plates in the region.

Senior telescope operator Israel Cabrera was a witness. "I do not have the right words to explain my pain when the platform collapsed," he recalls. "Just to hear the cable threads ripping like gun shots and see the platform coming down — it was a lot to take." He and other staff members watching all started to cry. They had dreaded this moment. "I feel this loss in [a] very emotional way," says Cabrera. "Now, just looking every time I come to work, I can see the ghost of the platform, but it is not there anymore."

Planetary scientist Edgard Rivera-Valentín (Lunar and Planetary Institute) was born in Puerto Rico and had been an integral part of the observatory scientific staff. He emphasizes that the loss isn't merely scientific. "It is cultural. Over the past 57 years, the telescope has woven itself into the Puerto Rican culture and has become a symbol of science and excellence in Puerto Rico. A symbol of our hopes and dreams to improve, to grow, and to achieve. A symbol of inspiration. So, you can imagine the angst I and my island felt witnessing its collapse."

The observatory is located south of the city of Arecibo, some 80 km west of San Juan. When my wife and I worked there as astronomers, it used to take us 35 minutes from our residence to navigate the winding road and the 167 bends in its last few miles. After you received a friendly greeting at the guard gate, you entered what might have been one of coziest spots on Earth to do your work. Nestled in a narrow valley between 30-m-high, densely vegetated cliffs, sturdy concrete and cinder-block buildings housed telescope operations, electronics, administration, staff scientists, visiting scientist quarters, and a cafeteria. Although the dish itself hid behind the foliage, from the control room windows you could see the enormous antenna platform suspended only about 240 m away, as if hovering in midair. At night the jungle came alive with the cacophony of coqui tree frogs calling to one another

ARECIBO OBSERVATORY / NASA / NSF

among the background sounds of countless other creatures.

What was it like to observe with this awesome structure? Consider the scene in late July 2020, when, following a precautionary shutdown due to Tropical Storm Isaias, the planetary radar team fired up the radio transmitter and nursed their receiver and computers back to life, just in time to catch the passage of the potentially hazardous asteroid known as 2020 NK_1. Within hours the researchers calculated its orbit and concluded that at its closest approach this century, in 2043, this asteroid will pass harmlessly at a distance of 2.5 million miles. That meant scientists could remove it from the list of potential future impactors managed by NASA's Center for Near-Earth Object studies.

"It is very exciting to have a successful observing run like this," says observatory scientist Flaviane Venditti as she recalls her experience. "We felt that what we did was meaningful."

But now the meaning has gone. After she woke up and heard the news on that fateful day in December, her brain didn't register it for several hours. "I was in a mix of denial and shock. It was only hours later when a minute of silence was requested during a virtual call with more than 100 Arecibo users and friends that it really hit me. The telescope had died. That was when I went from denial to mourning."

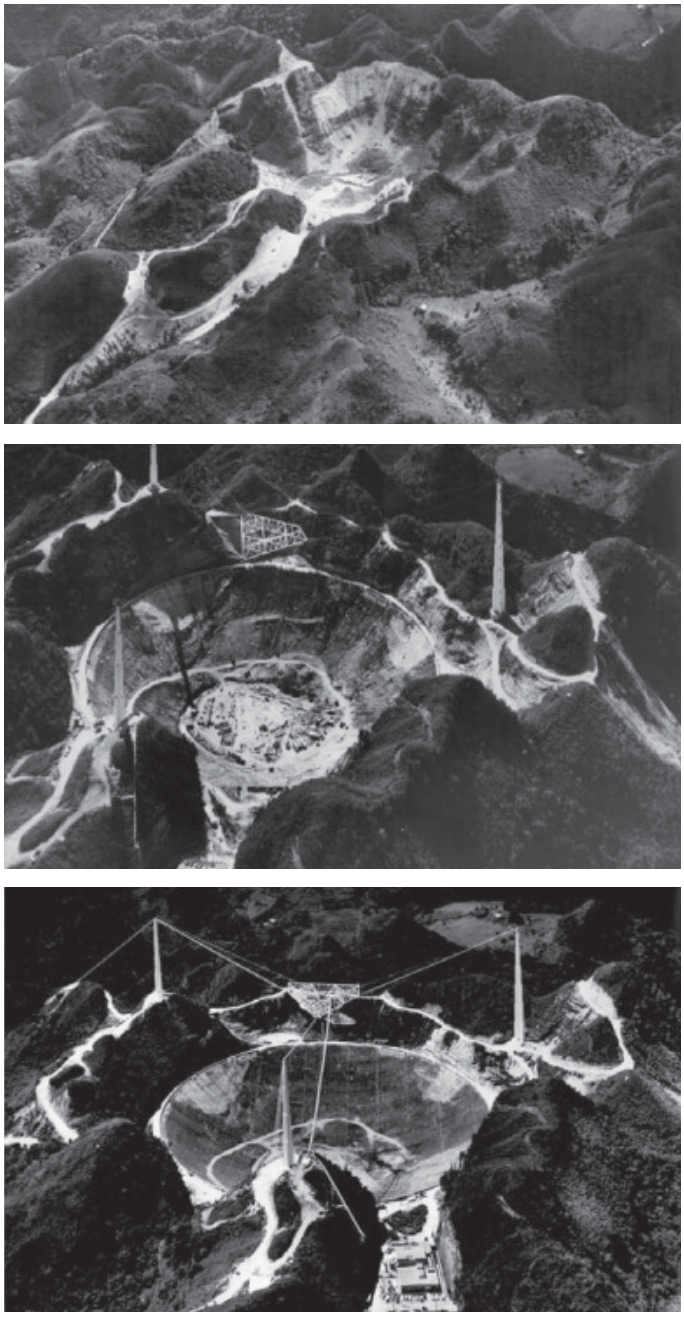
▲ **NO THREAT** Arecibo observations at the end of July 2020 enabled astronomers to confirm that the asteroid 2020 NK_1 will not strike Earth for at least the next 200 years. The object is several hundred meters across.

From Pulsars to Asteroids

Engineers completed construction of Arecibo's great dish in 1963. Originally, defense agencies funded the observatory, but after only a few years the National Science Foundation (NSF) became its steward, joining with NASA in the 1970s to undertake a massive upgrade. A second overhaul in the 1990s smoothed the dish's nearly 40,000 aluminum surface panels to 2-mm accuracy, enabling it to observe at frequencies as high as 10 GHz. Although the dish itself was immobile, astronomers could point at different parts of the sky by moving the instruments on the overhead platform into different positions, thereby catching radio waves reflected off the dish from the target.

The 30-meter-wide Gregorian dome was added to the instrument platform in the second upgrade. It essentially converted the dish from its spherical shape into a paraboloid, focusing the radio waves from space to a single point instead of them coming to a focus along a sequence of points in a line. The upgrade also enabled astronomers to smoothly change between receivers at different frequencies: Mounted on a turntable inside the dome, the desired receiver could be moved to the focal point and brought into action at the flick of a switch. This instrument platform is what plunged into the dish, ending more than a half century of science.

Arecibo leaves an amazing scientific legacy — arguably, no large radio telescope in the world can match its list of key discoveries. Over the decades, astronomers utilized its radar instruments to measure the rotation of Mercury (3 rotations for every 2 orbits of the Sun) and to find that the rotation of Venus beneath its cloudtops is retrograde, spinning backwards compared to its orbit. In 1968, observers used the big dish to measure the frequency of the Crab Nebula pulsar (33 milliseconds — significantly shorter than other pulsars found at the time), and in 1974 Richard Hulse and Joseph Taylor discovered the first-ever binary pulsar. Careful monitoring of the binary's ticking demonstrated the two dead stars were slowly spiraling toward each other at the rate predicted if the system were emitting gravitational waves, then still only hypothetical. That discovery earned the pair a Nobel Prize in 1993, an honor with which no other large, single-dish radio telescope has ever been associated.



▲ **CONSTRUCTING A MEGADISH** To build Arecibo Observatory, crews blasted out a pre-existing valley in the Puerto Rican landscape to be the right shape (*top*, December 1960), raised the towers and instrument platform (*center*, November 1962), and suspended a 305-m dish below it (*bottom*, August 1963).

ARECIBO OBSERVATORY / NAIC / NSF (3)

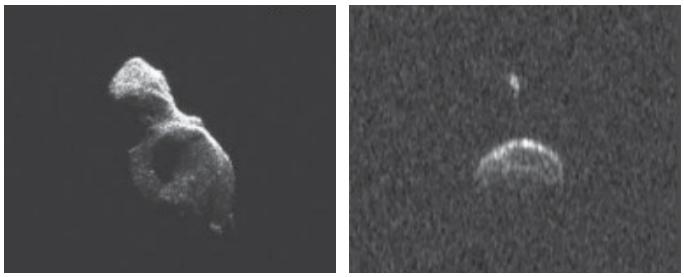
Pulsars continued to play a key role at Arecibo. In 1992 Aleksander Wolszczan and Dale Frail discovered the first planets orbiting a distant star, but that star is a rapidly spinning ball of neutrons — a millisecond pulsar that completes a rotation every 6.2 milliseconds. Dozens of millisecond pulsars, chattering at thousands of times per second, provide very accurate clocks. Before the telescope's collapse, astronomers used it as part of a cooperative project known as the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), monitoring about 80 pulsars on a regular basis using a handful of radio facilities across North America. The NANOGrav team seeks small changes in pulse arrival times that would indicate that Earth is being buffeted by gravitational waves created by pairs of distant supermassive black holes orbiting each other (*S&T:* Jan. 2019, p. 22). Based on how this cosmic surf affects pulsars' signals, astronomers should be able to determine the direction of the waves' arrival.

Early in 2021, the collaboration announced the first hints of a detection of a sea of waves — the *gravitational-wave background* (*S&T:* May 2021, p. 8). But if the team can't confirm the hints using the additional 2.5 years of unpublished data the researchers already have in hand, the loss of Arecibo may delay the work by a couple of years.

Another field hurt by Arecibo's fall is the study of near-Earth objects (NEOs). "Powerful planetary radar systems are very rare," says former observatory scientist Anne Virkki, who headed the planetary radar group until 2021. "The only other active planetary radar in the U.S. is at the Goldstone Deep Space Communications Complex, and it's at least 15 times less sensitive [than Arecibo was] due to its dish size and transmitter power."

Scheduling is also an issue. When a new near-Earth asteroid is detected, it generally wafts past us in a few days. Telescope operators must adapt schedules quickly to catch the object. But Goldstone is in high demand, used as it is for spacecraft communications throughout the solar system. "Their scheduling for asteroid observations is not as flexible as it was at Arecibo," Virkki says.

NEO scientists worry that without the Puerto Rican dish, we are more vulnerable to the inevitable impact of a near-Earth asteroid. In 2019, Arecibo successfully observed more than 120 of these objects, says observatory scientist Sean Marshall, who gives his job description as "defending the planet." In 2020, he and his colleagues withstood earthquakes and tropical storms to observe 58 more, operat-



▲ **NEAR-EARTH ASTEROIDS** These radar images reveal the odd shape of 2014 HQ_{124} *(left)* and the binary 2016 AZ_8 *(right)*. Both 2014 HQ_{124} and 2016 AZ_8's primary member are a few hundred meters wide.

ing through the end of July. "It was exciting to see resolved images of objects that no one had ever seen in detail before," he says.

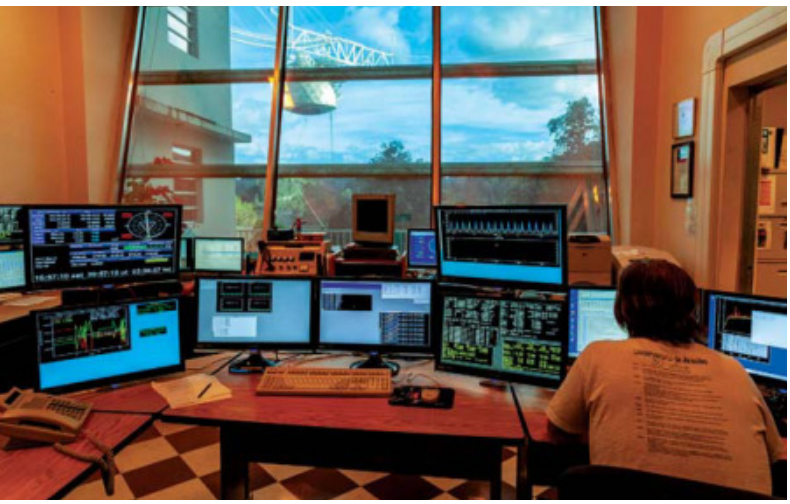
Guarding against the asteroid danger requires knowing as much as possible about objects' orbits and sizes, which requires the mighty radar capability embodied at Arecibo. Now, there is nothing to replace it.

Icon and Inspiration

Puerto Ricans rally in the face of adversity. Following Hurricane Irma in early September 2017, when trees had fallen across the only road along the coast, locals soon went to work clearing the debris with chain saws or machetes they happened to have in their pickups.

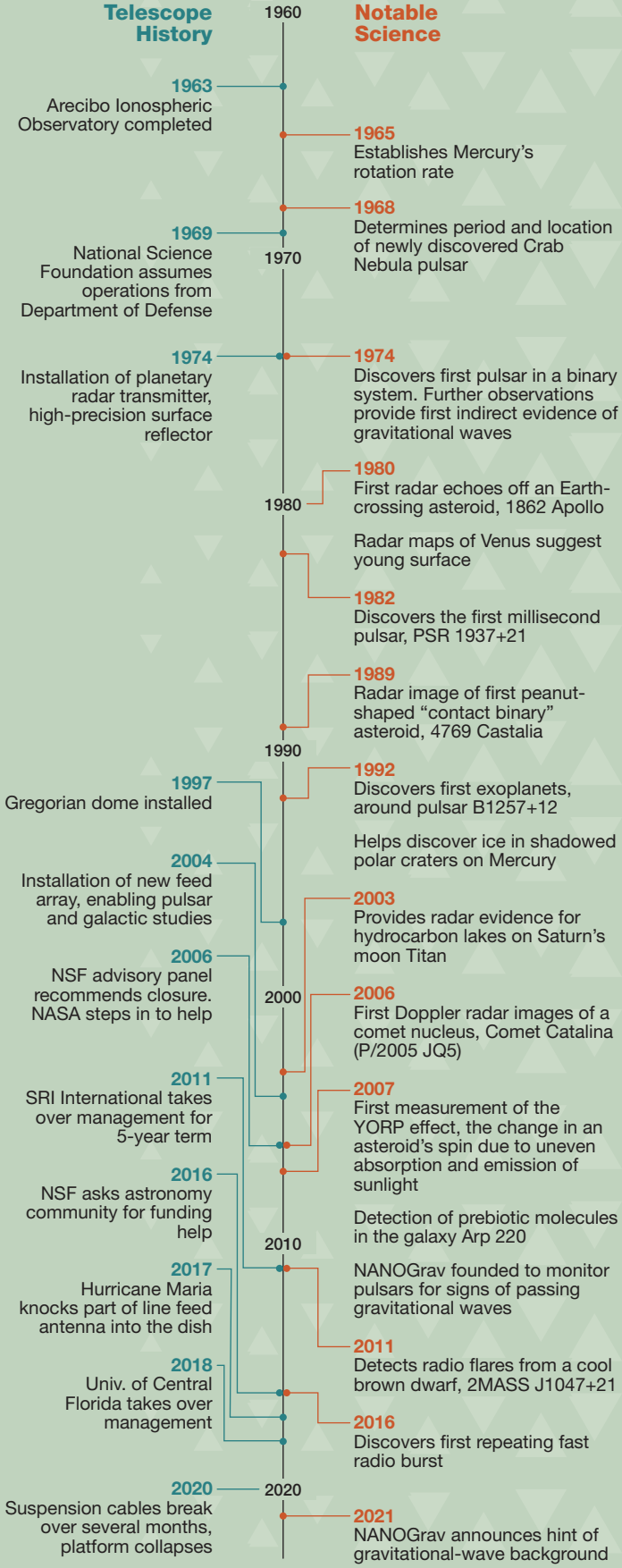
About two weeks later, Hurricane Maria devastated the island. The eye of the storm passed right over the observatory and the city of Arecibo. A half dozen colleagues and I sheltered on site either in the sturdy visiting-scientists building or in offices, together with several dogs and two children. Winds of about 190 kph (120 mph) broke the anemometer on the giant antenna platform and snapped a 70-ft-long antenna, which fell into the dish.

2014 HQ_{124}: NASA / JPL / ARECIBO OBSERVATORY; 2016 AZ_8: ARECIBO OBSERVATORY / NASA / NSF; OBSERVATION ROOM: ALAN DYER; TIMELINE: TERRI DUBE / *S&T*



▲ **ROOM WITH A VIEW** From the control room, astronomers and students could look out and see the telescope's instrument platform hanging above the dish.

Arecibo's History at a Glance



The Arecibo Telescope

Built into the hills of Puerto Rico, the Arecibo Observatory was a force in radio astronomy for 57 years. But its design left it vulnerable to a harsh tropical climate.

Arecibo, Puerto Rico

Gregorian dome
Added in 1997, the dome focused radio waves onto receivers covering a range of frequencies.

Cable anchor

Tower 8

Instrument platform
The platform weighed 900 tons, stressing the support cables

Line feed
This antenna bounced radar beams off the ionosphere, a mirrorlike layer of charged particles in the atmosphere.

Suspension cables

Failed cables, detail view below

Tower 12

Access catwalk

Tower 4

Karst terrain
Arecibo was built in a sinkhole in a Swiss-cheese landscape of soft limestone rocks. The sinkhole supported the reflector dish and protected it from radio interference.

Reflector dish
A 1974 upgrade replaced a wire mesh with more than 38,000 aluminum panels.

Anatomy of a Failure

On Aug. 10, 2020, an auxiliary cable pulled out of its socket. Then on Nov. 6th, a main cable snapped. In the weeks leading up to the Dec. 1st collapse, staff heard cable wires breaking about once a day.

Snapped main cable

View below

Auxiliary backstay cable

Socket

Main cable

Ruptured auxiliary cable

Main backstay cable

160 wires bundled in main cables, 8 cm thick

Auxiliary cable

Protective paint

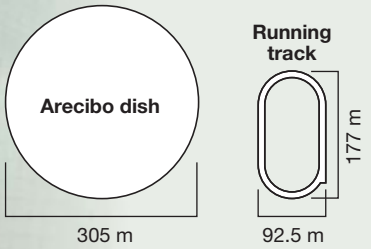
Cable wire

Dry air

Cable protection
To prevent corrosion, cables were painted and air blown through them.

Big Eye on the Sky

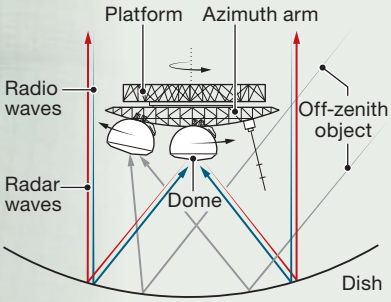
Arecibo was the world's largest radio dish until it was surpassed in 2016 by a radio telescope in China (*S&T:* Feb. 2017, p. 26). Size offers sensitivity to faint objects.



How Arecibo Worked

Radio astronomy

Arecibo's spherical dish allowed it to see objects that aren't directly overhead; the telescope "pointed" by moving receivers on the platform.

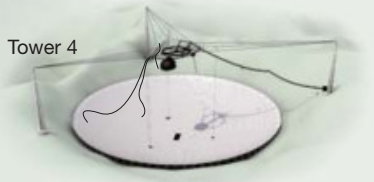


Radar astronomy

In radar mode, the dish turned emitted waves into a collimated beam. The dish caught reflections from targets in the upper atmosphere or solar system.

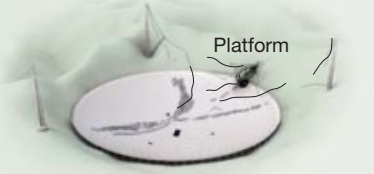
Stages of the Fall

1. After two cables connected to Tower 4 broke, the remaining four shouldered extra loads.



2. On Dec. 1, 2020, those four cables snapped within seconds of each other.

3. The platform crashed through the dish and onto the hillside.



GRAPHIC: C. BICKEL / *SCIENCE*. DATA: RHYS TAYLOR / WWW.RHYSY.NET. FROM D. CLERY "HOW THE FAMED ARECIBO TELESCOPE FELL – AND HOW IT MIGHT RISE AGAIN" *SCIENCE* JAN. 14, 2021 (DOI:10.1126/SCIENCE.ABG5640). REPRINTED WITH PERMISSION FROM AAAS.

Within days, observatory maintenance crews radiated out with heavy equipment to clear area roads of debris. Occasionally a FEMA helicopter landed at the observatory with food and water, and staff quickly loaded up cars and headed out along the byways to distribute the supplies to the community. Locals who lived close to the observatory made daily pilgrimages to draw the delicious water from a tap by the guard gate, pumped from a well on site. We kept the pump running with an emergency diesel generator, and just when fuel threatened to run out, a tanker truck accompanied by a protective police escort arrived to save the day.

But the dish disaster has a very different impact than storms like these do. While the collapse of the telescope did not cost lives, it cannot be quickly rebuilt, and the careers and livelihoods of most of the staff and scientists will never return to normal. Some members of the Arecibo scientific family still can't bring themselves to watch videos of the collapse, even months later. As Christopher Salter, the head of Arecibo's radio astronomy group, puts it, "If a relative of yours were to be run down in a car accident, would you be able to watch a video recording of the event?"

Nor is the observatory's inspirational role in the community something easily replaced. The visitor center (which survived) lured tens of thousands of tourists every year. At the center, hundreds of teachers from all over the island attended workshops in space sciences, biology, chemistry, and nanotechnology. An additional 15,000 students visited the observatory annually, either for day-long visits or to attend the Arecibo Observatory Space Academy for an intense 18-week research program for highly qualified pre-college students in Puerto Rico. Students made the weekly trek from all over the island to attend. In 2020 the observatory also initiated a Girls Educating Girls program, funded though NASA's Puerto Rico Space Grant Consortium, to increase diversity in STEM fields.

Participants in all these programs had an unparalleled close-up view of the antenna platform through their class windows. Luisa Zambrano-Marin (University of Granada, Spain), who is working on her PhD in asteroid studies, recalls the magical times she experienced with students in the summer programs. "You could see in their eyes the impact, the power this telescope had, the meaning and symbolism this structure had. Scientists have come and gone, so have administrators, but locals have always been the literal operators."

Visits to the huge dish changed students' lives. "We had a field trip to the observatory in 2016," says young researcher Marcos Jusino-Maldonado (University of Puerto Rico, Arecibo), "and I decided right then that I would pursue a career in astrobiology, astronomy, and planetary science." Those opportunities are now gone. "Careers in the space sciences are sadly underdeveloped in Puerto Rico," he says. "The observatory was a beacon of hope — perhaps it was possible to work in these fields in our home island. I believe that without the observatory, many local prospective space scientists will not get the motivation and support to reach their potential."

Arecibo's collapse elicited sadness, frustration and some-

BEFORE AND AFTER *Top:* This image of the 305-m Arecibo Telescope shows the dish unharmed, its instrument platform suspended with tables from three towers, called Tower 4, 8, and 12. The visitor center is at Tower 12 (right). The cables of Tower 4 (left) are the ones that snapped on Dec. 1, 2020. *Middle:* When the platform fell, it tore holes in the dish and expanded a gash from earlier in 2020. The series at left shows *(from top to bottom)* the damage as seen from the center of the dish; the destroyed instrument platform and Gregorian dome, seen from the walkway circling the dish; and the dish's underside, which shelters its own ecosystem.

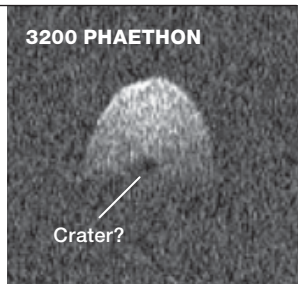
BEFORE: IMAGE COURTESY OF THE ARECIBO OBSERVATORY, A FACILITY OF THE NSF; AFTER: RICARDO ARDUENGO / AFP VIA GETTY IMAGES; CLOSEUPS: MICHELLE NEGRON / NSF (3)

times anger, says Héctor Arce (Yale University), who was born and raised in Puerto Rico. "So many people were proud of Arecibo Observatory. Even non-scientists were proud of this huge and impressive structure, knowing it was maintained and cared for by Puerto Ricans." Arce was one of many inspired to go into science and engineering because of the facility. "Some saw the observatory as a place they could work in Puerto Rico if they decided to go into astronomy or aeronomy. Others were inspired to go into science because they had visited the telescope or had participated in one of their many education programs. The impressive structure was inspiring at many levels."

Rivera-Valentín agrees. "The Arecibo Observatory is a testament to the social impact science and its facilities can have. This social contract, in my personal opinion, makes us responsible to Puerto Rico. In looking forward to the future after this tragedy, I would hope we take the example of inspiration Arecibo gave us and build the next-generation radar telescope in Puerto Rico."

The Future

But what are the chances of building a replacement? At the virtual meeting of the American Astronomical Society in January, the director of the NSF's Division of Astronomical Sciences assured us that Arecibo Observatory would not close. Still, it remains unclear whether the NSF, perhaps in conjunction with NASA, might yet rehabilitate the big dish and its radar and radio astronomy capabilities.



▼▶ **ASTEROID SUCCESS** The happy planetary radar group celebrates the acquisition of radio echoes from asteroid 3200 Phaethon in December 2017. This near-Earth Apollo asteroid is 6.25 km (3.9 mi) across and fortunately poses no threat to Earth. Its debris creates the annual Geminid meteor shower in Earth's skies.

There is also lingering doubt and even resentment about NSF's commitment to support Arecibo. The demise of the telescope on that fateful day did not happen suddenly; it came after multiple cable failures and several years of inadequate funding, as the agency grappled with a flat astronomy budget and burgeoning commitments (see timeline, page 37). As one observatory staff member lamented, "Personally, I'm very disappointed that not enough was done to prevent the collapse when the cables began to show signs of deterioration. Changing the cables a few years ago could have saved the telescope. An investment in maintaining and upgrading it would have been much more cost-effective than building a new one."

What would it take to carry out a reconstruction? The collapse of the 300-ft radio telescope at Green Bank in 1988 presents a sobering parallel. That event occurred in the home territory of Senator Robert Byrd, soon to become Chairman of the Senate Appropriations Committee in Congress. From the start, he insisted that the dish be replaced as soon as possible, and that he would find the money to fund it — which he did. But although the Puerto Rican government has pledged $8 million toward cleanup and replacement planning, the island has no equivalent politician to conjure up the several hundred million dollars needed to rebuild the telescope in whatever form may be decided upon.

The future is thus uncertain. But it is not necessarily dire. A great deal of infrastructure related to the functioning of a large radio observatory still exists at the site. The control room equipment, back-end receivers and computers, and trained staff — all locals — can be drawn upon again. In addition, as Zambrano-Marin reminded me, the radio frequency protections for the Arecibo site, crucial for radio astronomy and ionospheric studies, are still in place. Usually, it takes decades to build such resources and train the staff. Construction of the instrument itself takes just a few years.

The desire to build the Next Generation Arecibo Telescope (NGAT) is strong. More than 2,000 interested parties with worldwide support have already endorsed the outline of its science and technical goals. As this document wends its way through bureaucratic layers on the mainland, it will hopefully stimulate plans to rebuild. If the money materializes, NGAT will make a profound contribution not just to planetary survival and radio astronomy in general, but also to a generation of scientists waiting to happen.

■ Seasoned radio astronomer and author **GERRIT VERSCHUUR** was astronomer emeritus at Arecibo from 2015 to 2018. He's married to astronomer Joan Schmelz (Universities Space Research Association), who served as Arecibo's deputy director during the same years. Their hearts go out to all the staff who made the observatory such a success and who have lost so much.

Read the Next Generation Arecibo Telescope proposal: naic.edu/ao/ngat.

3200 PHAETHON: ARECIBO OBSERVATORY / NASA / NSF; OBSERVERS: COURTESY OF ANNE VIRKKI