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on the cover

Buzz Aldrin's boot print on the surface of the Moon. Fifty years ago, on July 20, Apollo 11 made history when Neil Armstrong and Aldrin became the first humans to step onto another world. Now NASA has plans to go back by 2024. *[NASA]*

On the FAST Track

A giant radio telescope in China displaced thousands of people during its construction. But now it's complete, and it could change our view of the cosmos forever.

By Steve Murray

The Five-hundred-meter Aperture Spherical Telescope (FAST).
[National Astronomical Observatories, Chinese Academy of Sciences]

Tianyan ("the eye of heaven") is open and astronomers are excited about what it's seeing. The Five-hundred-meter Aperture Spherical Telescope (FAST)—the world's biggest radio astronomy dish—is demonstrating its enormous potential, even while its commissioning tests are still underway.

FAST astronomers reported some of their initial results earlier this year in Science China Physics, Mechanics & Astronomy and Research in Astronomy and Astrophysics. Their studies include analyses of abnormal emission shift events, frequency-specific pulse profiles, a study of rotating radio transients and the status of a large-scale sky survey of neutral hydrogen (HI).

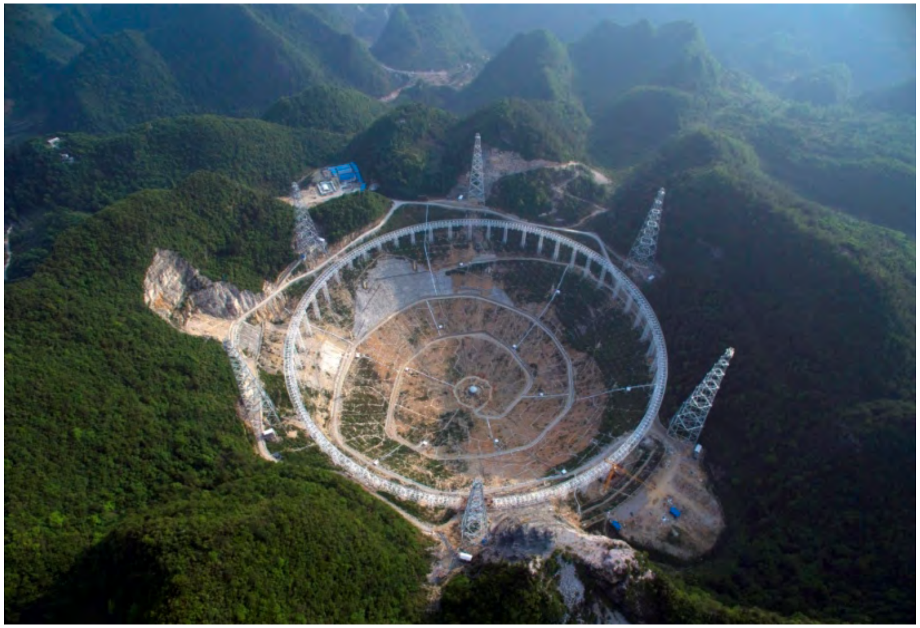
Chinese scientists have big plans for the instrument, including support to pulsar timing arrays and to the search for exoplanets. The first FAST pulsar discovery occurred in August 2017, only ten years after project funding was first awarded and, as of July 2019 its pulsar discovery count was up to 85. Astronomers around the world are watching its progress closely. "They're getting some amazing results for such an early-stage telescope," says George Hobbs, lead for the Parkes Pulsar Timing Array project at the Australia Telescope National Facility. "FAST is already getting involved in millisecond pulsar timing, and their instrumentation and setup and science cases are all thought out."

The FAST concept began taking shape in 1994 when attendees at the General Assembly of the International Union of Radio Science began discussing ideas for a next-generation radio telescope. Those plans later evolved into the Square Kilometre Array, an approach that didn't include China's technical concepts. The country nevertheless decided to press on with their *own* world-class instrument. Funding for FAST was awarded in 2007 and telescope construction began in 2011.

Scientists chose a site for the telescope about 1,100 miles (1,700 kilometers) from Beijing. A limestone depression among the karst hills of southwest China's Guizhou Province, known locally as Dawodang, offered natural topography that would reduce construction costs. Its remoteness and sparse population also promised to minimize electromagnetic emissions that could interfere with radio astronomy work. "Sparse" didn't mean "empty," however, and 65 villagers living near Dawodang were moved about 9 miles (15 kilometers) away in 2009. Later, nearly 10,000 residents living within 3 miles (5 km) of the site were also moved to ensure a radio quiet zone around FAST. The resettlement costs of $269 million far exceeded the $180 million spent on actual telescope construction.

Although the 1,000-foot (305-meter) diameter antenna at Puerto Rico's Arecibo Observatory had reigned as the world's biggest single-dish radio telescope since 1963, that baton was passed in 2016

The Dawodang depression in China's Guizhou Province offered the ideal landscape in which to build FAST. But before construction could begin, the villagers who lived there had to be relocated. *[National Astronomical Observatories, Chinese Academy of Sciences (NAOC)]*



A dish takes shape: Once relocation efforts were completed, construction of FAST began with the assembly of the 1,300-ton cable support network. *[National Astronomical Observatories, Chinese Academy of Sciences (NAOC)]*

when FAST construction was completed. With almost twice the illuminated dish area, astronomers expect that FAST will achieve twice the sky coverage at three times the scan speed of Arecibo, all with greater sensitivity. First light for FAST occurred in September 2016 during its official opening when the telescope observed its first radio source. A two-year commissioning program then began to verify the telescope's physical systems and software performance.

Under the Hood

FAST looks a lot like Arecibo and many of its features are described in comparison to its famous predecessor. The similarities aren't a coincidence. "A few [Chinese astronomers], came out and had a look at Arecibo during the design stage of FAST," notes Robert Minchin a former Group Lead for Radio Astronomy at Arecibo Observatory. Minchin, now a Senior Scientist with the SOFIA Science Center (USRA), adds that "other astronomers from among the Arecibo user community have also been heavily involved with FAST development." Although Arecibo lessons may be reflected in some of the FAST design, novel differences give the new instrument some cutting-edge performance advantages.

The dishes of both telescopes, for example, are made of aluminum panels connected via a network of flexible cables, although FAST components are bigger and heavier: 4,450 FAST panels are used to cover more than twice the surface area spanned by 39,000 panels at Arecibo. The cabling system needed to support the more than 2,000 tons of FAST panels weighs another 1,300 tons.

Because both FAST and Arecibo antennas are installed in karst depressions, tracking requires operators to move the telescope receiver. This means that neither FAST or Arecibo can make full use of their dish areas. The illuminated area of FAST has an effective diameter of 984 feet (300 meters) while Arecibo has an effective diameter of 755 feet (230 meters).

Both FAST and Arecibo antennas have a spherical curvature, but while the Arecibo dish shape is fixed, FAST can reshape part of its dish as a paraboloid in real time. A fixed spherical dish focuses reflected energy along a line, requiring receiver position adjustments to collect it accurately. A paraboloid focuses reflected energy to a point, where smaller adjustments can achieve the same goal.

A system of 2,226 mechanical actuators is attached by cables to points along the FAST panel network to create its paraboloid shape. Each actuator can independently vary the length of its connecting cable by about 18 ½ inches (47 centimeters) and the shape can be adjusted continuously to a tolerance of 0.04 inches (1 millimeters) to maintain accurate tracking. An accurate antenna shape is critical because it sets an upper limit to observing performance. And even

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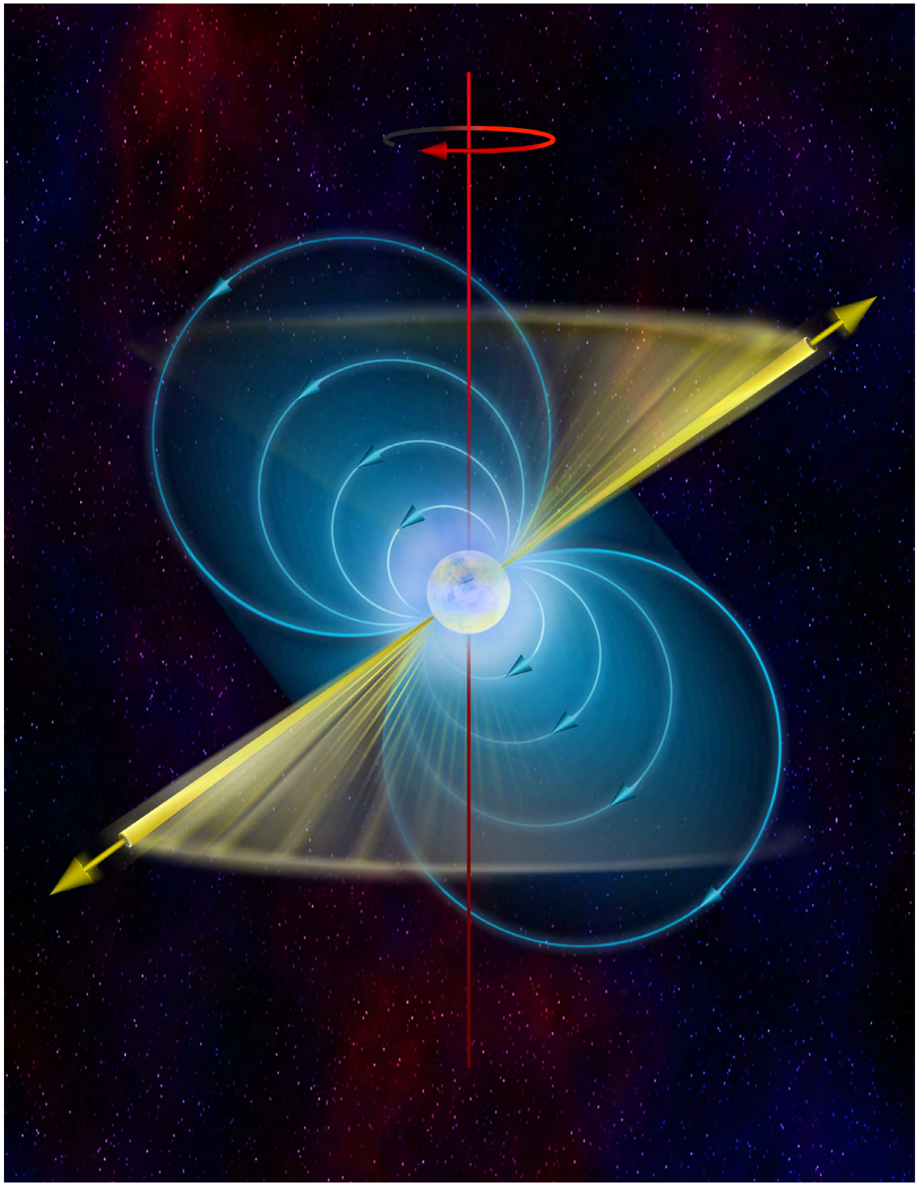
with this level of precision, FAST will have operating limits. "The quality of the dish surface—how perfect the parabola has to be—is directly related to the wavelength of light you're looking at," says Scott Ransom. Ransom is a staff astronomer at the National Radio Astronomy Observatory (NRAO) and works with the Green Bank Telescope in West Virginia. "The reflecting surface can't have any bumps bigger than about roughly 1/50th or 1/100th of that wavelength. If you're going to make a really big dish, it's easier to get the shape right if you're only looking at longer wavelengths. It's difficult and expensive to build to that standard at higher frequencies, which is why FAST will never work much above about 2 GHz."

Both FAST and Arecibo position a feed cabin at their focal points to house the receivers that collect radio energy. The FAST feed cabin is about 43 feet (13 meters) in diameter and weighs 30 tons—a "lightweight" compared to Arecibo's 900-ton feed cabin. Three pairs of opposing cables, anchored by six towers spaced around the rim, suspend the cabin 460 feet (140 meters) over the dish, and can be adjusted to position the cabin to within 4 inches (100 millimeters) across a focal plane diameter of 676 feet (206 meters). The cables can also adjust cabin tilt to accommodate the curvature of the dish surface and a 6 degree-of-freedom Stewart platform—where the receivers are mounted—increases pointing accuracy and compensates for wind-induced vibration.

Cabin positioning and dish curvature for FAST are monitored by a laser system. Over 2,000 prisms are installed across the telescope as laser light targets. The position signals they register furnish real time feedback information to control the telescope and to alert operators to any safety limits during its operation.

The FAST team has used two generations of receivers for the telescope. A low frequency ultra-wideband system was installed in 2016 and has been used primarily for commissioning tests and early



A pulsar is a rapidly-spinning neutron star with a powerful magnetic field. As shown in this diagram, beams of radio waves (yellow) are emitted from the pulsar's north and south magnetic poles, which are offset from the spin axis (red). As it spins, radio waves sweep through our field of view, allowing radio observatories on Earth to register each spin as a flash. *[B. Saxton, NRAO/AUI/NSF]* observations between 270 and 1620 MHz. A narrowband receiver was installed in 2018 and processes beams from 19 individual targets over a frequency range of 1.05 to 1.45 GHz. The new system was designed and built by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) and Hobbs especially proud of their contribution. "We were quite famous for building multibeam receivers," he says, "so when FAST said they wanted a survey receiver, they knew it was technology that worked. In fact, they're very happy with it."

Growing Pains

During early tests, concerns cropped up with the accuracy of the hydraulic actuators used to control the dish shape and with greater-than-expected wear in these devices as a result of continuously adjusting the panels. Issues like these influenced early decisions to conduct the first major scan of the visible sky by FAST, the Commensal Radio Astronomy FasT Survey (CRAFTS). A comprehensive survey could use the extraordinary sensitivity of FAST to generate an enormous volume of new data while engineering control problems were addressed and other commissioning work continued. CRAFTS takes advantage of the wideband 19-beam receiver to make observations for multiple astronomy objectives—such as the search for galactic and extra-galactic hydrogen, pulsars, and fast radio bursts (FRBs)—all at the same time (i.e., commensally).

CRAFTS is being executed in a "drift scan" mode, using a fixed dish shape and allowing the sky to rotate over the site. The zenith of the receiver is shifted periodically to view a new strip of space, a process that requires about 220 days to complete a single survey, the FAST team plans on performing two such surveys before CRAFTS concludes. Ue-Li Pen is a professor at the University of Toronto and a FAST Fellow—a consultant to telescope staff on a range of science issues. He's also an astronomer with Canada's CHIME (Canadian Hydrogen Intensity Mapping Experiment) Telescope, an instrument that operates exclusively in a drift scan mode, so he appreciates the challenges of completing comprehensive surveys like this. "These telescopes both have unique strengths," he says, "but CHIME has a very wide field of view and sees a lot of sky at once. FAST takes a very long time to survey the sky, but when it does, it's much more sensitive than CHIME."

While many of the early technical problems have since been resolved, as of March 2019, engineers at FAST report that considerable pointing calibration work still needs to be done.

A Bright Future . . . and a Quiet One?

Size matters in radio astronomy. "There are two ways to get a lot of signal," says Patrick Weltevrede. "One is to use a very big telescope, and the other is to stare at the same object for a long time." And FAST is a really big telescope. Weltevrede, who collaborated in a recent pulsar discovery at FAST, is a Lecturer in pulsar physics at the University of Manchester, United Kingdom and has worked with both the Lovell and Parkes telescopes. Scientists anticipate that FAST may discover over 4,000 new pulsars; about 300 of these are expected to have millisecond periods and about 10 percent of them should be stable enough for use in pulsar timing arrays. Observations of the 21 cm (the 1.4 GHz neutral hydrogen, or HI) line—another big goal for FAST—will offer new insights about the formation of the early universe. Currently, the most distant neutral hydrogen detections have been made at a redshift of about $z = 0.2$. Early evolution of galaxies, however, are better examined at a redshift of $z = 0.3$ or larger. Astronomers at FAST are looking to reach out to $z = 0.35$.

If FAST is a boon for world astronomy, however, it's also becom-

While the region offers clear skies, what really matters to FAST is being located in a radio-quiet zone. *[National Astronomical Observatories, Chinese Academy of Sciences (NAOC)]*

ing a boon for the local economy. Although Guizhou Province was not a wealthy part of China when FAST began, people were quick to see a regional business opportunity in the new telescope. Pingtang Astronomy Town, has blossomed with breathtaking speed about 10 miles (16 kilometers) from the FAST facility, with businesses, hotels, restaurants and (yes) telescope tours.

The draw is irresistible. Says Hobbs, "Everyone in China knows about FAST and wants to see it." And scientists at FAST are trying to manage the effects of this popularity. Visitors to the telescope site are capped at 3,000 per day, with strict rules about the use of electronics closer than 3 miles (5 kilometers). But with as many as 10 million visitors a year to the town (based on 2017 tourism estimates), the problem of cell phones, Wi-Fi and other electronic noise may be impossible to control and may become a part of working life for FAST astronomers.

Pulsar Discoveries Await

Although FAST is a new, cutting-edge instrument, with time it will find its place as part of a larger astronomy landscape among other radio telescope and other astronomy science agendas. "It's a very sensitive telescope that can clearly compete with Arecibo in terms of sensitivity," says Weltevrede, "but other instruments around the world will always have important roles to play. The Parkes Telescope, for example, is located further south, and can cover part of the sky that just isn't visible to FAST. Some telescopes can observe higher frequencies, too, where the shape of your dish needs to be very accurate. The Effelsberg Telescope [in Germany], for instance, can observe at much higher frequencies than FAST."

And a lot of radio astronomy research requires those higher frequencies. "FAST has a really big advantage in a huge chunk of pulsar science," says Ransom, "because it's sensitive at the frequencies where pulsars emit most of the energy we can see. But there is a whole bunch of science you can get outside of that range such as looking at pulsars toward the galactic center, where you have to go to high observing frequencies to get through the interstellar medium effects. You can't do that with FAST. As a matter of fact, FAST can't see the center of our galaxy."

Still, FAST represents a big leap in capability, and that means that a big leap is coming in our understanding of the radio universe. "If they continue to improve," adds Ransom, "then FAST will be one of the absolute best pulsar telescopes in the world within the next couple of years. If that happens, the majority of pulsars we know about in say, 5 to 10 years, will have been discovered by FAST. They're going to do some really amazing pulsar science." ✪

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