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ANTENNAS stationed at NASA's Deep Space Network Goldstone Complex work with two other complexes around the world to communicate with over 40 space missions.

Oversubscription of the Deep Space Network (DSN) has officials concerned about data loss by space science missions. The radio antenna array, operated and managed by the Jet Propulsion Laboratory, is designed to command, track, monitor, and conduct experiments with spacecraft; it currently juggles communications with over 40 space missions from nearly 30 countries. (See "The Deep Space Network at 50," by Joseph Lazio and Les Deutsch, Physics Today, December 2014, page 31.)

Without the DSN, rovers couldn't roam on Mars and *James Webb Space Telescope* (*JWST*) images would never leave the observatory. The network is up to 40% oversubscribed, leaving many missions unserviced at a time when the rate of new launches is increasing. By the 2030s, excess demand on the DSN is expected to reach 50%, according to an audit that NASA's inspector general released in July. Even as demand increases, the DSN budget has decreased by tens of millions of dollars over the past decade.

The DSN consists of three deep-space-communications facilities evenly spaced over the globe to provide around-the-clock communication. They are located in Goldstone, California; Madrid, Spain; and near Canberra, Australia. Each site has a 70-meter antenna that can track spacecraft tens of billions of kilometers away and varying numbers of 34-meter antennas, for a total of 14. The smaller antennas can be combined to strengthen weak signal reception and increase data rates.

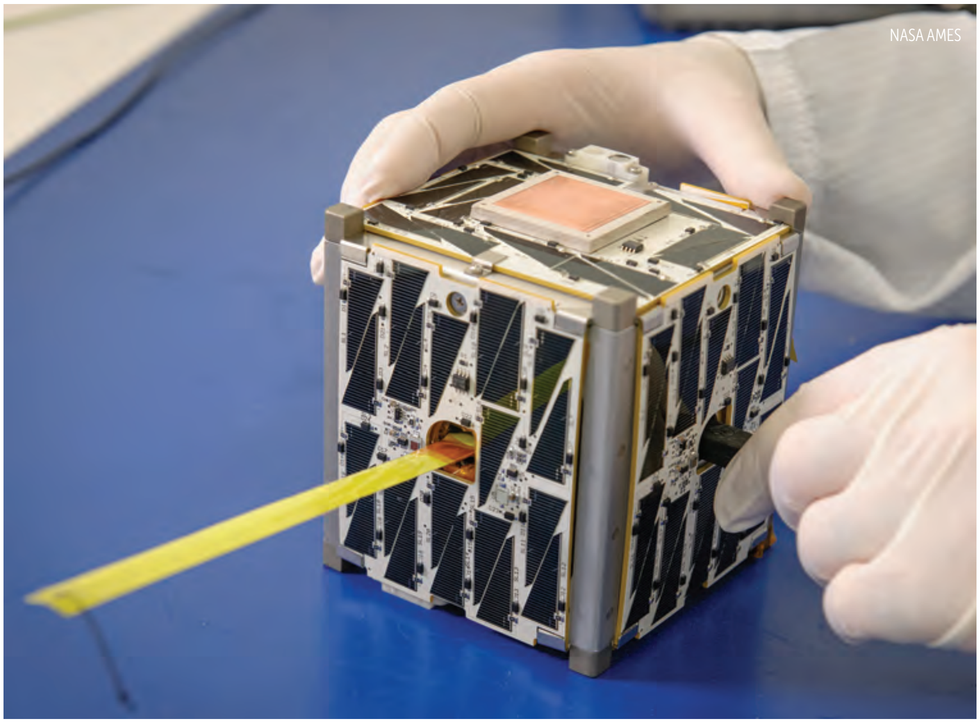
As Earth rotates and a craft rises above the horizon at a site, a mission can begin its scheduled communication pass with a DSN antenna. During a pass, operators can receive telemetry, perform radio science experiments, and track and monitor the craft. They also downlink data to Earth. If a spacecraft is still communicating with the DSN when it sets on the horizon at one complex, an antenna at another one will pick up the signal. When the mission has completed its pass, another mission will hop on the antenna. Typically, an antenna can talk to one spacecraft at a time. But a technique called multiple spacecraft per aperture has been applied to communicate simultaneously with a few Mars missions.

The DSN talks to craft that range in distance from 16 000 kilometers away to beyond the solar system. The network still communicates with *Voyager 1*, the farthest spacecraft from Earth. *Voyager 1* was launched in 1977 and is currently more than 38 billion kilometers out. The farther away a craft is, the larger the antenna it needs.

Glen Nagle, the education and public outreach manager at the Canberra site, says the DSN schedule looks like an airport departure board, with its many missions scheduled far in advance and down to the minute. Mission planners at the Space Telescope Science Institute, the Jet Propulsion Laboratory, and the DSN complexes work together to schedule each craft up to a year beforehand. The schedule gets locked in about a month in advance, but can be changed in emergencies. Some spacecraft, such as the *JWST*, have a few passes a day, ranging from two to six hours, says lead mission planner Kari Bosley.

Of the 77 000 hours the DSN supplied to NASA and international partners in 2022, 6732 were devoted to the *JWST*, according to the DSN audit. With 5309 hours, the *Solar and Heliospheric Observatory*, a European Space Agency and NASA spacecraft, was the second largest user. "Recent large missions like the *James Webb Space Telescope* and Artemis have added a significant demand on the DSN as the prime communication link," says Philip Baldwin, acting director of NASA's network services division.

Artemis 1 was a lunar test flight launched on 16 November 2022 that lasted less than a month, splashing down on 11 December 2022. Despite the short flight, it used 1774 DSN hours. One reason the mission consumed so much time on the DSN comes in a Rubik's Cube–sized package: CubeSats. A standard CubeSat measures 10 centimeters on each side and weighs around one kilogram, and up to 24 can be grouped together. They cost tens of thousands of dollars apiece, and that low price tag



CUBESATS, mini-satellites that typically measure 10 centimeters on a side and are often used by students for science experiments, have proved a nuisance for NASA's Deep Space Network. Many of those carried by *Artemis 1* in late 2022 got lost, requiring nearly half of the mission's DSN hours just to track them down.

makes them appealing to universities. CubeSats typically carry out just one or two functions. They might take images of Earth or perform small science experiments, such as measuring Earth's magnetic field.

Artemis 1 launched 10 CubeSats to complete various science experiments. More than half of them lost contact with Earth, and the large DSN antennas were recruited to help find the CubeSats' low-powered transmitters. The CubeSats are "all very experimental in terms of their ability to handle the conditions of deep space," says Nagle. Nearly half of the total DSN hours *Artemis 1* ended up using were to track the lost CubeSats.

Artemis 1 was a test flight, but it garnered priority on the DSN to assess equipment that will be used to ensure the safety of astronauts on upcoming crewed Artemis missions, including the Orion capsule that will carry the crew. "For *Artemis 1*, the DSN provided the only communication link to the Orion capsule as it ventured around the Moon," says Baldwin. "The same will be true for future Artemis missions." Future lunar missions will likely siphon away DSN time from the *JWST* and other missions, and could prevent them from meeting their scientific aims, the DSN audit says.

Even before *Artemis 1* launched, missions had been losing time on the DSN because of excessive demand. Over the last five years, the *Mars Odyssey*, *Voyager 2*, and *New Horizons* each received between 8500 and 15 000 fewer tracking hours than needed. That squeeze has already had a significant impact on NASA's science missions, according to the audit. The missions have faced data loss and at times were unable to send commands, pushing their plans behind schedule.

Fixes falling behind

NASA initiated the Deep Space Network Aperture Enhancement Program in 2010 to accommodate more missions. As of the end of 2022, four of six planned new 34-meter antennas had been constructed. The audit notes that the project is nearly five years behind schedule, and the cost has jumped to $706 million from the original estimate of $419 million. That's apart from the overall DSN budget for operations and maintenance, which shrank from $250 million in 2010 to $213.5 million in 2024. Some aspects of the enhancement project are not expected to be finished until 2029, over a decade behind schedule.

A potential efficiency would be to use higher-frequency signals to increase data downlink rates: What would take days could be reduced to hours with higher frequencies. With data transfers expected to increase 10 000-fold moving into the 2030s, says Nagle, shifting frequencies will help. But more high-power transmitters will be necessary to access those frequencies; the plan to install two 80-kilowatt transmitters contributes $18.1 million to the upgrade's price hike.

NASA is exploring other ways to reduce the DSN load, including expanding the use of tracking multiple spacecraft with single antennas and applying artificial intelligence. Machine learning and AI are already used to help determine when maintenance tasks need to be performed, says Baldwin.

Meanwhile NASA is working with international partners to identify existing antennas that might provide support to the DSN. The agency is designing and building three smaller antennas specifically to assist in the upcoming Artemis missions, and is attempting to procure commercial antenna services to support future Artemis missions, says Baldwin.

Space-communications networks in other countries do not face the same strain as the DSN because they support only their own missions. But a few networks rely on the DSN for their projects. When the Indian Space Research Organisation launched its *Mars Orbiter Mission* in 2013, it used the DSN because India's network only has the capability for lunar distances. The European Space Agency's Estrack network has single antennas in three locations around the world and sometimes leans on the DSN for support.

In sum, says Nagle, the DSN is "a victim of its own success." The communications network has done its job for six decades, he says, but "the strain is showing."

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