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Tiny MIGHTY Satellites

Briefcase-size craft have become game-changers in space exploration.

It took less than 24 hours for things to go wrong. CAPSTONE, a spacecraft no larger than a microwave, had vanished from the radio waves. For the controllers back on the ground, the silence was a problem. Without radio communications, they had no way to command the craft — and no way to correct its path toward the Moon.

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) was a CubeSat, a class of ultra-small satellite, and researchers had intended to use it to prove the stability of a new orbit around the Moon. NASA was hoping that it would thus pave the way to something far more ambitious: the Gateway, a lunar space station that could one day host astronauts preparing to walk on the Moon.

Yet as CAPSTONE failed to respond to repeated messages, those dreams suddenly seemed at stake. Fortunately, time was on the controllers' side. CAPSTONE was on a stable trajectory and carried enough fuel to recover, should it miss the planned correction maneuver. They were confident, too, that the spacecraft had deployed its solar panels, giving it enough power to stay alive while they troubleshot the problem.

▲ **CAPSTONE** A team member installs solar panels on the CAPSTONE spacecraft. Despite multiple mishaps, the little satellite successfully reached the Moon in late 2022.

DOMINIC HART

In the end, that time proved enough. Engineers regained communications within days, successfully executing the maneuver as planned. To blame, they realized, was a software bug triggered by a badly formatted command, which had left the radio unresponsive and the satellite uncontrollable. The satellite's own automatic recovery processes cleared the fault, enabling the craft to continue its journey. Four months (and another mishap) later, in November 2022, the spacecraft arrived and became the first CubeSat to orbit the Moon.

Necessity Is the Mother of Invention

The concept of small spacecraft like CAPSTONE first emerged in the 1990s. At the time, the idea that they would one day venture to the Moon, or even beyond, would surely have seemed ridiculous. They were intended as mere teaching aids, a way for two professors — Jordi Puig-Suari (then California Polytechnic State University) and Bob Twiggs (then Stanford University) — to give their class hands-on experience with designing and building satellites.

Normally this design process took years, with a price tag stretching into the tens of millions of dollars. Even getting satellites off the ground was expensive. Launch costs at the time started at $5,000 per kilogram, and many satellites weighed several tons. What was needed, they realized, was a kind of minimalist satellite, something small, cheap, and lightweight — something that a master's student could put together in two years, with time to spare before graduation.

The result was the CubeSat: a small box, measuring 10 centimeters (4 inches) per side, containing only the most essential ingredients for survival in space. As long as they kept the basic dimensions of the cube, students were free to fill the satellites with whatever equipment they wanted. They could even stack the cubes, building up larger CubeSats from individual units.

Crucially, Puig-Suari and Twiggs also designed a simple deployer for their CubeSats. This box could carry any CubeSat

BON VOYAGE Three Japanese CubeSats deploy from the International Space Station. They tested various university-built instruments, including a drag chute to help deorbit spacecraft faster.

PEGGY WHITSON

on almost any rocket. It also meant that CubeSats didn't need an expensive dedicated rocket. Instead they could hitch a ride, taking advantage of space unused by larger satellites. When a group of six CubeSats launched in 2003, they rode on the Russian Rokot-KM, soaring into space with three far larger satellites. Later launches would do the same, using rockets as diverse as the Falcon 9, India's PSLV, and even the gigantic Space Launch System.

Before long, CubeSats caught the imagination of entrepreneurs, who realized the satellites offered a way to overcome the high-cost barrier to launching a space business. One could, for example, kit out a dozen or so CubeSats with cameras, put them in orbit, and begin selling imagery of the world below. Companies like Planet Labs and SkyBox Imaging (later sold to Planet) did exactly that, building up constellations of dozens, then hundreds, of satellites. Others employed them to monitor the atmosphere, to track aircraft and ships, and to hunt for smugglers and illegal fishing vessels.

A handful have even been used for astronomy, turning their sensors toward the stars instead of toward Earth. One, the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA), demonstrated technologies for exoplanet surveys. It became the smallest spacecraft to detect a planet around an alien star. Another, HaloSat, mapped X-ray radiation from across the sky, enabling researchers to probe the galactic halo around the Milky Way.

There is, however, a catch. CubeSats may be capable, but they are also notoriously unreliable. One study by NASA, published in 2019, concluded that for every five CubeSats launched before 2017, two had failed in their mission goals. A significant proportion of CubeSats appear to be dead on arrival, never checking in with their operators after reaching space.

"It's a matter of time, resources, and experience," says Michael Swartwout (Saint Louis University), who maintains a detailed database of CubeSats. Many small satellite designers, he argues, have to be willing to sacrifice performance for cost — a consequence of limited budgets and time pressures imposed by shared launches with fixed deadlines. "If you don't have the opportunity to delay the launch," he says, "you often end up doing the final check-outs after launch."

Since those check-outs often reveal unexpected problems, CubeSats must be designed to be reparable in orbit. Problems like those encountered by CAPSTONE, he says, can be fixed as long as the spacecraft is ready for it. In some cases that means uploading new software; in others, it means making sure the spacecraft can stay safe even if something doesn't work

◀ **CAREER LAUNCHER** CubeSats have given students and early-career scientists hands-on experience with building satellites. From top to bottom: A NASA intern works on the Advanced Electrical Bus, which launched in 2018 to test a new high-wattage electrical system; St. Louis University students work on a satellite that launched in 2013 to test a tiny infrared camera; CalPoly students test the Planetary Society's LightSail satellite, which in 2015 demonstrated the feasibility of using sunlight to propel tiny spacecraft.

NASA / GRC / BRIDGET CASWELL; ST. LOUIS UNIV.; CALPOLY: THE PLANETARY SOCIETY (3)

as expected. Unfortunately, it also means accepting a higher chance of degraded performance or even failure.

Still, despite these drawbacks, CubeSats have revolutionized the way universities, companies, and researchers survey our planet and the galaxy around us. Though they are risky, they are cheap. They can thus host experiments and technologies that might otherwise never find their way into space.

Until recently, however, that revolution has been constrained to a few hundred miles high. As CubeSats venture farther from Earth, might they soon change the way we think about exploring the solar system, too?

Next Stop: Mars

An early glimpse of how the future of planetary exploration may look came in 2018. That year a pair of CubeSats — MARCO-A and MARCO-B — lifted off with NASA's Insight, a lander heading to Mars. Guided by their internal navigation and propulsion systems, they flew toward the Red Planet. As they did, they became the first CubeSats to leave Earth's realm and head into deep space.

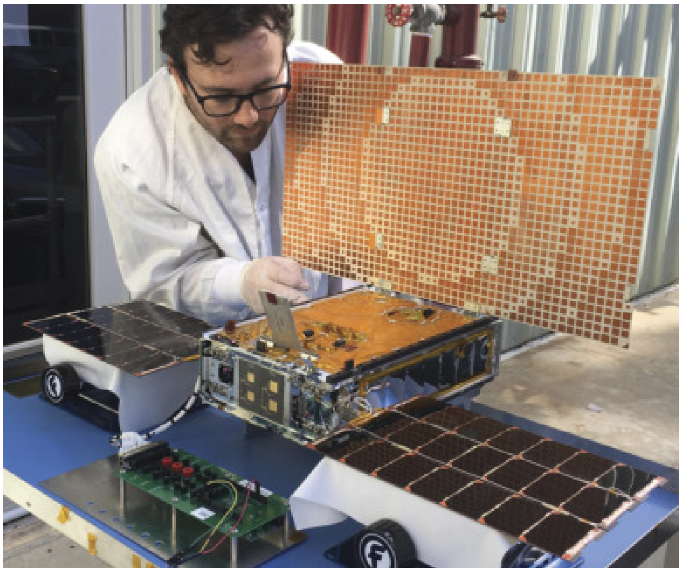
As CubeSats go, the MARCO satellites were sophisticated beasts. Each was six units in size — that's to say, made of six basic cubes stacked in a rectangular shape. They were equipped with propulsion systems, allowing them to steer their way towards the Red Planet. Both also deployed large antennas, enabling them to send messages to Earth and receive instructions back.

Despite this sophistication, however, the MARCO CubeSats were still small, weighing some 14 kg (30 pounds) each. NASA, aware that CubeSats do not always operate as planned, especially when far from Earth, sent two. At least one, they hoped, would survive all the way to Mars. If it did, then the CubeSat would help relay data from Insight's descent to the Martian surface, transmitting signals back to Earth across 157 million kilometers (97.5 million miles) of space.

In the end, that caution proved unnecessary: The pair reached Mars without major issues, showing that CubeSats are capable of interplanetary flight. They were able to relay data from Insight, giving operators an almost (bar the speed-of-light delay) real-time view of the landing. And for reasons probably more symbolic than practical, MARCO-B snapped a picture of Mars as it flew past.

That, then, was a success. Operators kept contact with both CubeSats in the weeks after the Mars flyby, downloading as many data files and images as they could. As they drifted farther from Mars' orbit, NASA started thinking about other targets, checking to see if any asteroids happened to lie along their trajectories.

But then something curious happened: MARCO-A suddenly stopped responding to controllers. No one has been able to fully establish why. NASA's report on the mission speculates about the nature of possible failures, but it notes that everything looked more or less fine up until the loss of contact. MARCO-B, meanwhile, suffered from a worsening fuel leak, an issue that may have sent it into an unrecoverable spin. Whatever the problems were, they spelled the end for the MARCO mission. The two CubeSats are now lost in space, too small and distant to ever be found.



▲ **MARS-BOUND** An engineer tests the solar arrays on one of the MARCO CubeSats. The pair of satellites flew along behind NASA's Insight lander on its cruise to Mars.

CUBESATS: JOHNSON SPACE CENTER; MARCO-B: NASA / JPL-CALTECH

From Failures to Fleets

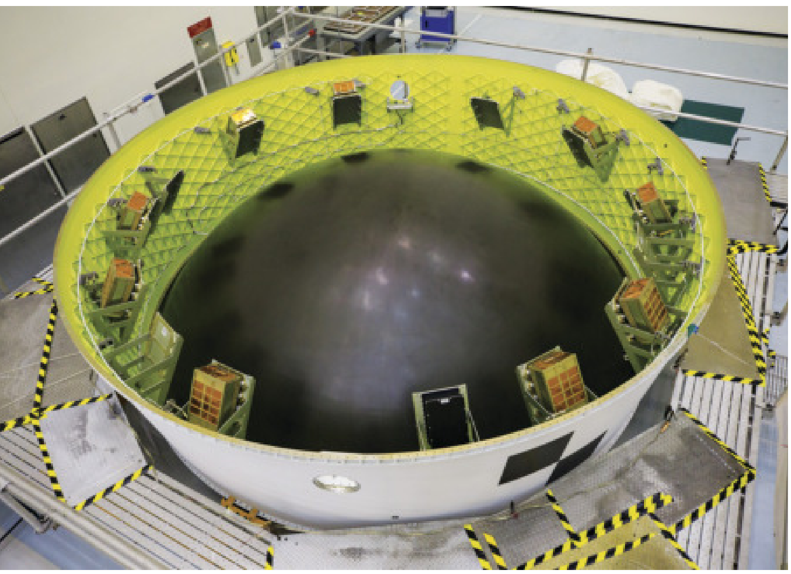
This somewhat sad ending highlights the issues that have haunted many deep-space CubeSats. The Artemis 1 CubeSats — a set of 10 small satellites launched with the Orion capsule in November 2022 — suffered a failure rate as high as 40% (*S&T:* Apr. 2023, p. 10). One — NASA's NEA Scout CubeSat — never responded to its operators' commands. Others suffered component failures or seemed low on power, issues that prevented them from achieving their goals.

NEA Scout, propelled by a solar sail, was intended to fly to the asteroid 2020 GE. Once there, it would have examined the 18-meter-wide (59-foot-wide) asteroid at close range, helping astronomers understand a class of asteroid too small to observe from Earth and never before visited by a larger spacecraft. Omotenashi — a Japanese CubeSat — was supposed to impact the Moon, an event that would have made it the first Japanese spacecraft to reach our natural satellite. Yet it, too, failed, unable to point its solar panels at the Sun long enough to charge its batteries.

Professor Swartwout cautions against taking the lessons of Artemis 1 too harshly. "I would not draw broader conclusions," he says, pointing out that the CubeSats faced battery issues after the long period they spent inside the rocket, repeatedly rolling out to the launch pad and back. Still, he thinks, the reliability of CubeSats, especially as they venture into more dangerous space far from Earth, remains a concern.

Last year at the Interplanetary Small Satellite Conference, Steve Matousek (JPL) painted an optimistic picture. The capabilities of small satellites, he pointed out, are rapidly improving. Propulsion, communications, and satellite lifespans are all benefiting from improving technologies, even as costs fall. Developments in electric propulsion, for example, may enable otherwise impractical deep-space missions.

▼ **ARTEMIS 1 TAGALONGS** An array of CubeSats rode inside the stage adapter between the Orion spacecraft and its giant rocket, the Space Launch System, during the Artemis 1 launch.



NASA / CORY S. HUSTON

He argued that improvements in other technologies — especially in communications, power management, and miniature sensors and instruments — will allow for small-satellite constellations around Mars within two decades.

Small bodies, such as asteroids, comets, or visitors from interstellar space, could be other targets for CubeSat swarms. Currently, Matousek said, we generally have only one viewpoint of these objects as they approach Earth. Ring them with CubeSats, however, and we could see them from multiple angles. We could even survey the moons of the outer planets with CubeSats, supporting the observations of larger, more powerful probes.

A handful of missions, indeed, have already started pursuing this approach. LICIACube, a CubeSat which flew with DART to the asteroid Didymos, is an early example (*S&T:* Sept. 2022, p. 14). When DART smashed into Didymos's small moon, Dimorphos, last year, LICIACube was on hand to photograph the impact, returning a series of images from a distance of under 80 kilometers (50 miles).

HERA, a European follow-up mission to the same pair of asteroids, will carry a pair of CubeSats named Juventas and Milani. They should help HERA survey the asteroid and the impact site with radars and cameras. Afterwards, if all goes to plan, the CubeSats will attempt to land on Dimorphos, relaying their observations back to Earth through HERA.

Interest in these possibilities is becoming more mainstream among astronomers, despite lingering concern about CubeSat performance. In its Decadal Report — an influential publication that directs much of American public spending on astronomy — the National Academy of Sciences gave a cautious nod to CubeSats. It highlighted areas in which CubeSats could benefit astronomers, particularly thanks to the crafts' fitness for rapid response and cheaper missions. CubeSats could reach targets inaccessible to more traditional probes or enable long-term observations of interesting targets — something Earth's telescopes, under high time pressure from astronomers, cannot easily offer. Still, "it remains to be seen," the panel wrote, "whether SmallSats will, in the long run, prove to be an effective platform for a range of astrophysics investigations."

The expendability of CubeSats could also prove an advantage, allowing them to venture into places more expensive satellites dare not go. One proposal, published as part of the European Space Agency's Voyage 2050 mission planning cycle, suggested sending CubeSats through Jupiter's radiation belts. This, a suicide mission surely, could return valuable data from a region too dangerous for bigger probes to enter. Another concept, developed by a team at JPL, envisioned a CubeSat "diving" through Saturn's rings, returning imagery for as long as it survives.

The Next Generation of Explorers

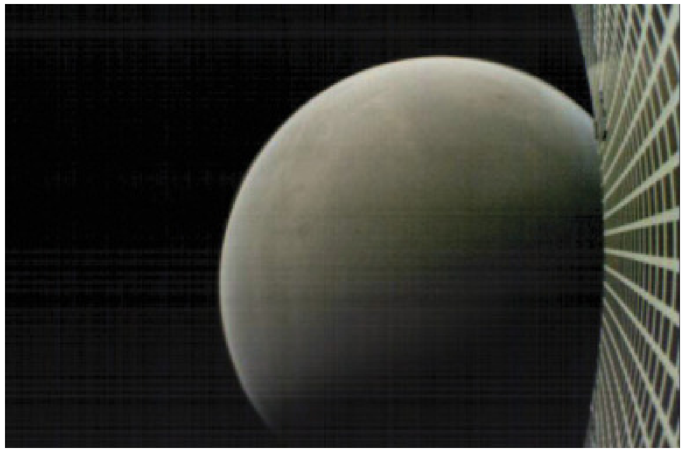
Perhaps the most ambitious plans, however, center on Mars. Despite decades of research and billions of dollars spent on orbiters and rovers, we still lack a clear view of the planet's climate system. Today, just seven active spacecraft orbit the Red Planet: enough to give us daily updates on the comings and goings on Mars, but insufficient to paint a detailed picture of its weather and landscapes (*S&T:* Dec. 2019, p. 22).

Dust storms, for example, often envelop Mars' surface, shrouding the planet for months on end. These hazardous events — they've spelled the end for robotic probes, and NASA fears they may harm future astronauts — appear with little to no warning, sometimes exploding to cover the whole planet, sometimes staying small and quickly fading away. Why? We really don't know.

To find answers, a recent report argued, we need a more dynamic view of Mars. That would mean putting far more satellites in orbit around the Red Planet. Until recently such a project would have come with an extraordinary price tag. Building and running MAVEN, the most recent NASA orbiter to reach Mars, has cost close to $900 million. Multiply that by 10 or 20, and the cost of a constellation looks untenable.

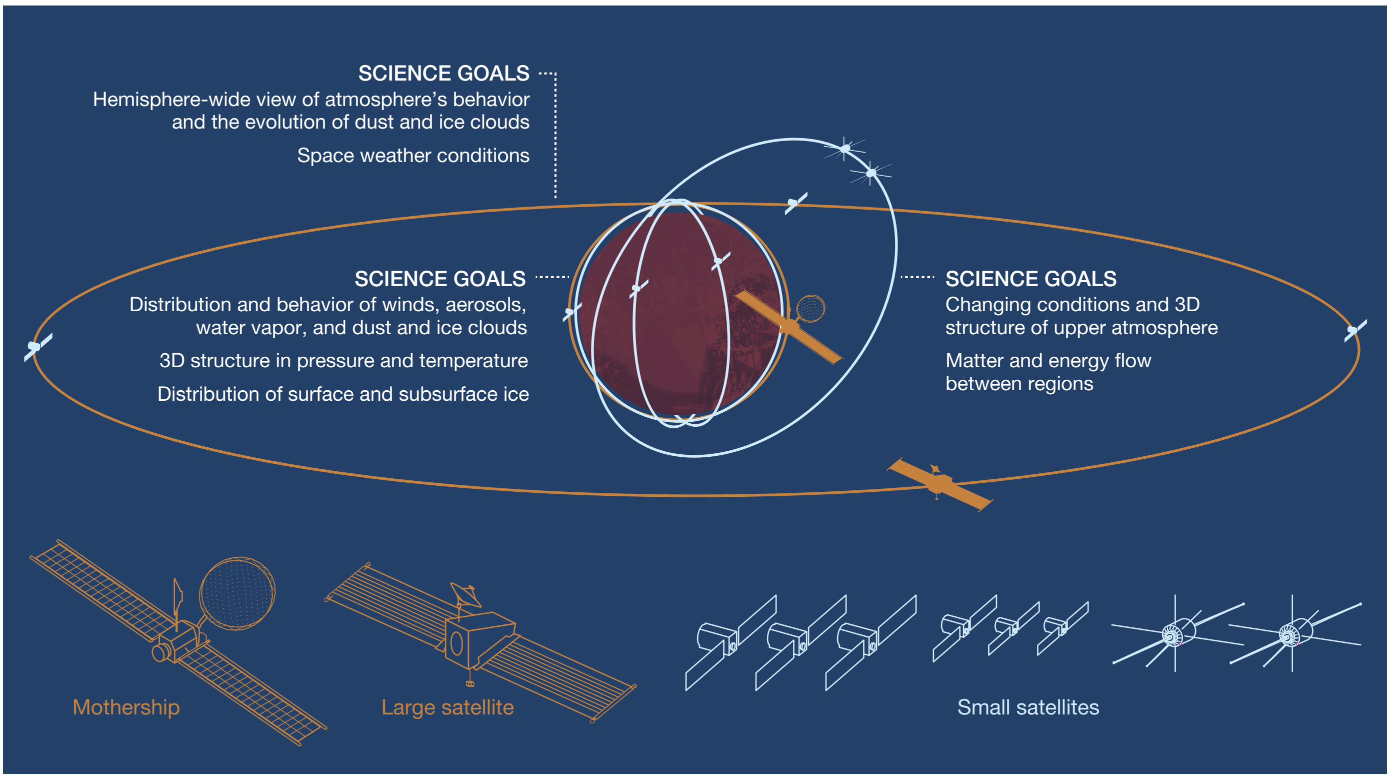
One concept sketched out by NASA, together with researchers from Berkeley and JPL, instead envisions building a constellation comprising a mix of small and large satellites. These would work in tandem to monitor Mars, giving planetary scientists a clear picture of the planet's dynamics for a far cheaper price. In all, the researchers reckon, a constellation of 10 spacecraft would cost around $3 or $4 billion to build, launch, and operate.

Ideas like this, if they ever come to pass, are at least two decades in the future. Yet they show the potential for CubeSats and small satellites to change not just the way we look at Earth, but also at the solar system around us. They promise to open a new era of exploration, giving researchers views of places long considered too risky, difficult, or expensive to explore. They may even, one day, pave the path for humans to venture far beyond Earth.



▲ **PASSING GLANCE** MARCO-B took this image of Mars from a distance of about 7,600 km (4,700 mi) during its November 2018 flyby, while the CubeSat was flying away from the Red Planet.

■ **ALASTAIR ISAACS** is a space missions engineer based in Spain. He has worked on several European satellite projects, including space telescopes and SmallSat constellations.



▲ **MARS FLEET** One mission concept would place 10 satellites of different sizes in three types of orbits around Mars. This arrangement would enable detailed observations of atmospheric conditions on both regional and global scales.

CUBESAT'S IMAGE OF MARS: NASA / JPL-CALTECH; MARS MISSION CONCEPT: BEATRIZ INGLESSIS / *S&T*, SOURCE: R. LILLIS ET AL. / MOSAIC MISSION CONCEPT STUDY 2020