INGENUITY ON MARS:
The Little Copter That Could
PAGE 12

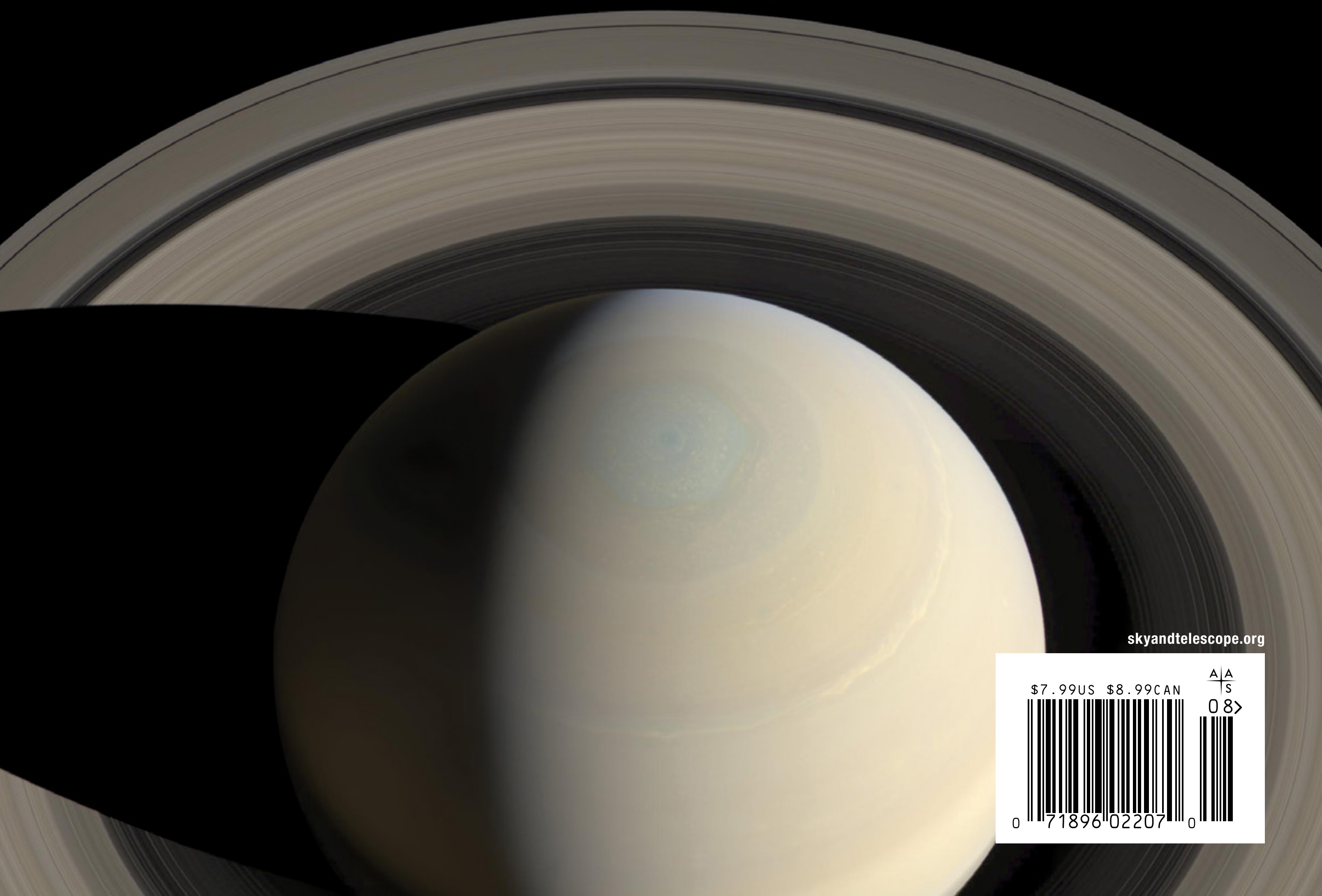
AUTOMATION:
The Future of Astrophotography
PAGE 60

LUNAR OBSERVING:
Ghost Craters on the Moon
PAGE 52

SKY & TELESCOPE
THE ESSENTIAL GUIDE TO ASTRONOMY
AUGUST 2022

DISCOVERING
Saturn's Ring Spokes

Page 28



skyandtelescope.org
$7.99US $8.99CAN
08
0 71896 02207 0

TO THE SKIES The Martian helicopter took this image from a height of 10 meters (33 ft) during its sixth flight. The image looks west toward the Séítah geologic unit.

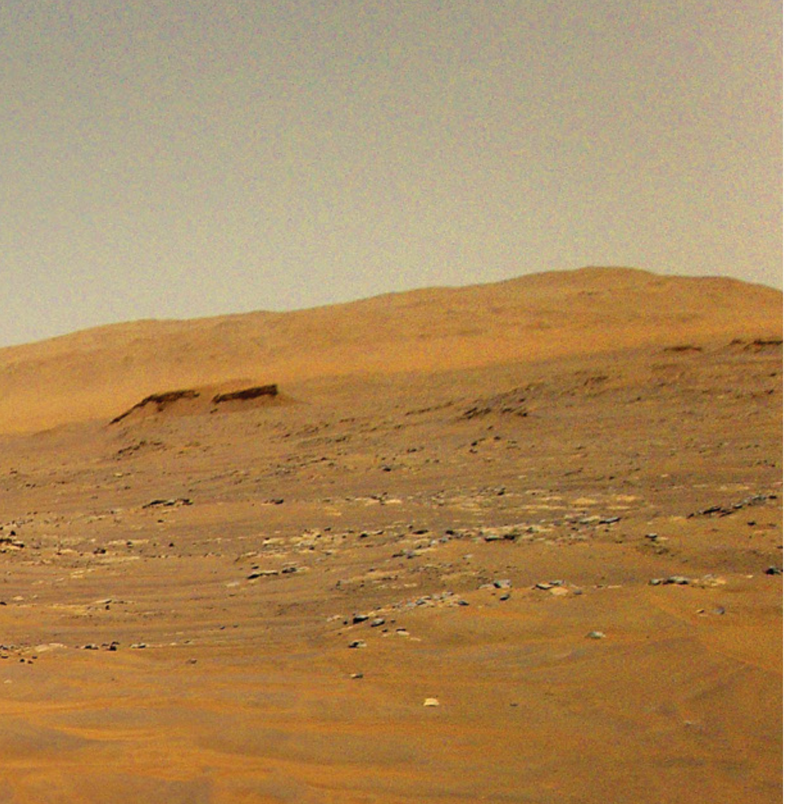
Flying with INGENUITY on Mars

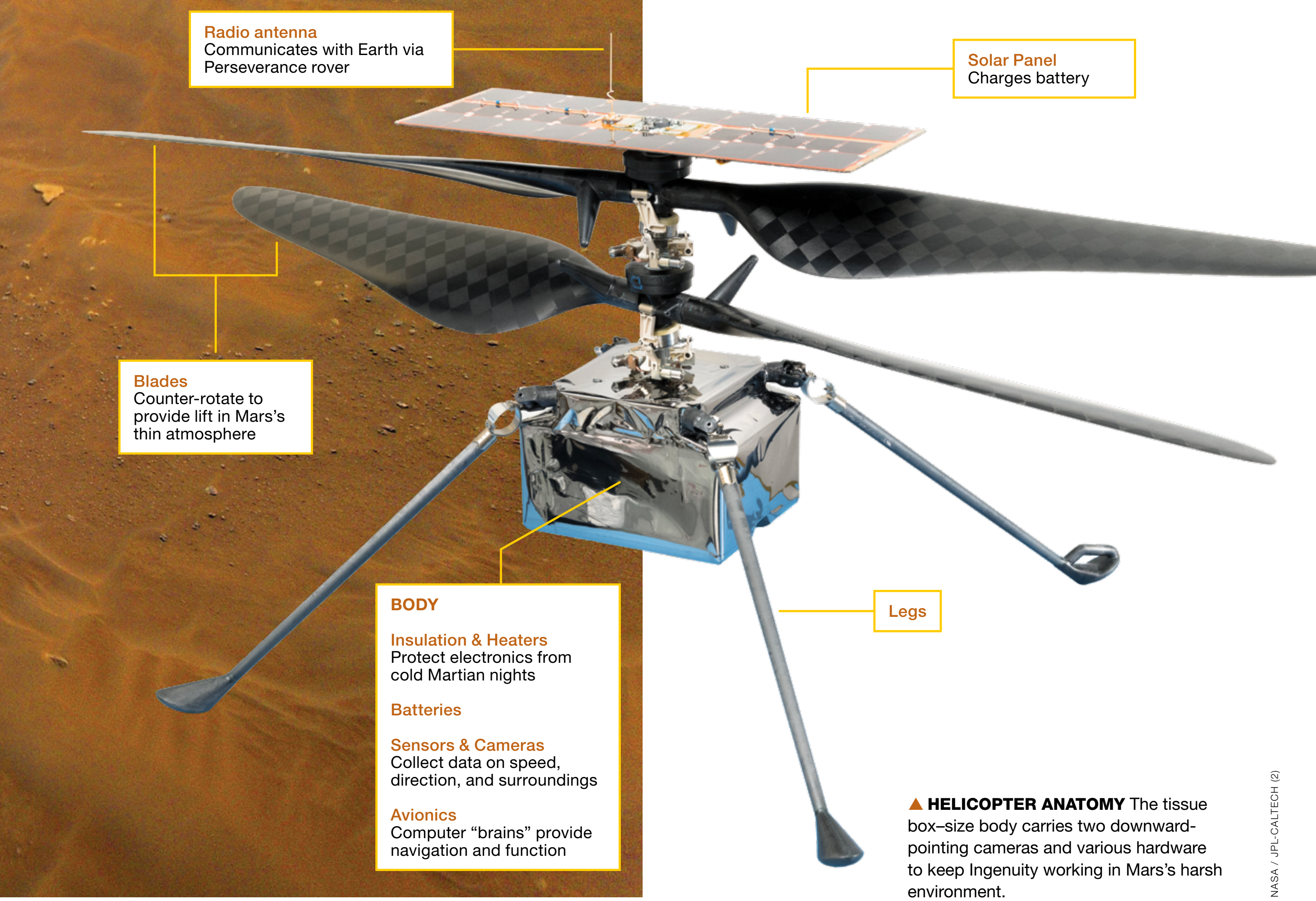
It's thanks to bold creativity and tenacity that a small rotorcraft is now exploring the Red Planet.

“What science could you do with a helicopter on Mars?”

Robotics expert and aerospace systems engineer Bob Balaram (Jet Propulsion Laboratory) posed that out-of-the-blue question to his JPL colleague Matt Golombek back in the fall of 2013. After “a momentary and slightly stunned silence,” Matt, a planetary geologist and project scientist for the Spirit and Opportunity rovers, thought back to when Opportunity was exploring the 800-meter-wide (half-mile-wide) Martian crater Victoria in the late 2000s. The rover team had needed to spend nearly a year driving from promontory to promontory along the rim, mapping the crater’s topography and exposed outcrops at high enough resolution to be able to eventually drive down into it. Had the rover carried some sort of scouting drone, like a helicopter equipped with cameras, it “could have collected superior stereo images of the crater walls from inside the crater — where the rover could not go — in just a few sols,” Matt says.

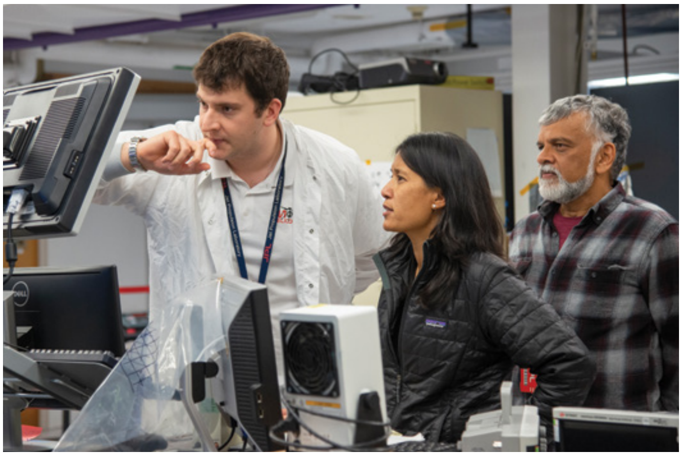
JPL robotics experts like Bob had been working up ideas and prototypes for powered flying vehicles on other worlds

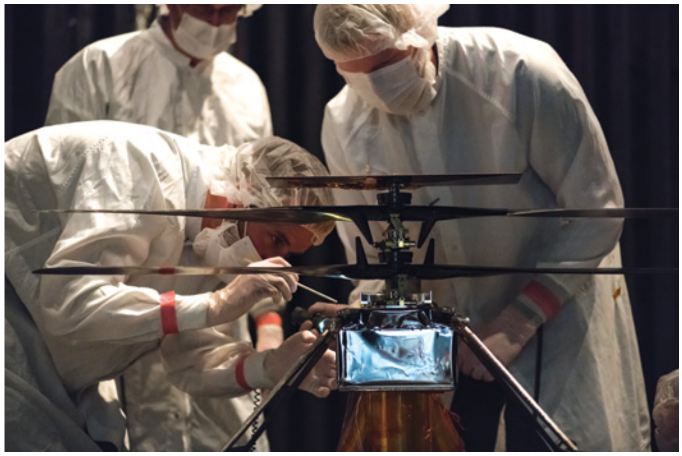




▲ **HELICOPTER ANATOMY** The tissue box–size body carries two downward-pointing cameras and various hardware to keep Ingenuity working in Mars’s harsh environment.

NASA / JPL-CALTECH (2)





▲▶ **DO THE HUSTLE** *Left:* Flight test leader Teddy Tzanetos, MiMi Aung, and Bob Balaram (from left to right) observe a flight test inside JPL's Space Simulator in January 2019. *Center:* Team members attach a thermal film to the helicopter's fuselage in February 2019. *Right:* Engineers attach the helicopter to the rover's belly in August 2019.

for some time. Given that, and realizing that both the pace and the amount of science could be substantially enhanced with the help of a flying scout, Matt led a 2014 proposal to include a "Mars Helicopter Scout" on NASA's upcoming Mars 2020 rover mission. That JPL team included, among others, Bob as chief engineer and planetary missions camera expert Justin Maki as the imaging lead.

NASA didn't select the proposal to be part of the mission's scientific payload, opting instead for cameras, spectrometers, and environmental sensors to fly on what would eventually be named the Perseverance rover. But the fact that an advance scout could potentially enable significantly more and better science — by providing geologic context, identifying key outcrops for future analysis, and collecting 3D images to help improve driving — was not lost on the NASA officials putting the mission together. Nor was it lost on then-JPL Director Charles Elachi, who persistently and energetically continued to advocate to NASA Headquarters that they find a way to add such scouting capability to the mission. Elachi also helped direct some internal JPL research and development funding toward the idea, to continue work on the design.

Elachi's persistence and internal investments paid off in 2018, when NASA decided to include JPL's helicopter scout as a separately funded "technology demonstration" mission. Carried to Mars on Perseverance's belly, the helicopter was tasked with proving that controlled, powered flight by a remote-controlled robotic vehicle was possible on a planet hundreds of millions of kilometers away.

So began the adventure of doing what no one had done before: flying on Mars.

Make Haste

Time was short: The heli had to be mounted to the underside of the rover by the summer of 2019, in preparation for the rover to be fully tested that fall and then shipped to Cape Canaveral in early 2020 for its launch that summer. That left less than 18 months to build a working flyer — the blink of an eye compared with a typical NASA project schedule.

The small design and test team had to be nimble, working quickly and efficiently within a large and relatively risk-intolerant government organization that is not particularly well-known for being quick or efficient. The team shared similarities with JPL's earlier Sojourner rover team, Justin tells me, which labored back in the 1990s when he started his career at JPL to design the first wheeled vehicle that would drive on Mars. Both projects were technology demonstrations that had a "Skunk Works kind of team," he says, referring to a division at the aerospace giant Lockheed Martin: a small group operating semi-independently within a much larger infrastructure, trying to solve unprecedented and high-risk engineering problems.

Then-JPL systems engineer MiMi Aung also joined as proj-

LAB PHOTOS: NASA / JPL-CALTECH (3); TIME SERIES OF FIRST FLIGHT: NASA / JPL-CALTECH / ASU / MSSS

FIRST FLIGHT On April 19, 2021, Ingenuity lifted itself into the thin Martian air. These snapshots are from the movie Perseverance's Mastcam-Z took as the helicopter spun up its rotor blades, rose to 3 meters, rotated, hovered, and then touched back down.

ect manager, bringing her expertise with spacecraft-to-spacecraft communications technologies as well as knowhow from having led JPL's Guidance, Navigation, and Control Sensors section. MiMi describes the helicopter team's journey from the initial concept through design and testing as starting with a basic question: Is it possible to build and fly a helicopter on Mars at all? The team members took a fast-paced — yet also incremental and systematic — approach to answering the question, starting with prototypes and engineering models that they operated remotely inside JPL's "space simulator" thermal vacuum chamber, set up to simulate Mars with its thin and cold carbon dioxide atmosphere.

To achieve lift in an atmosphere with a pressure comparable to 80,000 feet above Earth's surface (where existing helicopters can't fly), they realized that they would need a super-lightweight fuselage and large, specially shaped rotor blades that could spin about 10 times faster than what is needed for terrestrial helicopters. They brought fans into the testing chamber to add wind, making flying even tougher but more realistic. They worked out how to communicate back and forth with the rover, essentially creating a mini local Wi-Fi network between the heli and its rover "base station." And they figured out how to enable the helicopter to fly autonomously: Relying on its own cameras, computers, and other systems, the craft has to make decisions in real time about how to stick to the flight plan, including adapting to changing conditions like wind gusts.

The team did its own research as well as leveraging ideas from the terrestrial robotic drone community. The only break the researchers would get was from Mars's weak gravity — about a third of Earth's — which would make it a bit easier to lift the solar panels, rotors, and landing gear, not to mention the computers, batteries, electronics, heaters, cameras, accelerometers, and laser altimeter housed inside the fuselage.

All of that work had to be done with the clock ticking and with the team knowing that any major test failure or other mishap could derail their ride to Mars. The team referred to itself as WENDY, for "We're Not Dead Yet," Matt says, because NASA only gave them a little bit of money at a time, tied to a deliverable that then led to the next short-term funding with a new deliverable. "So we never knew if we would actually get to the launch pad."

But they had their eyes on the final prize. "Our team really, really wanted to get to fly the helicopter at Mars," MiMi says. "As a result, as we accomplished each major milestone, we dared not celebrate fully — we had the attitude of 'not yet, not yet' at each step."

The resulting helicopter design is both familiar and alien. The dual lightweight, carbon-composite rotor blades each span 1.2 meters (almost 4 feet) from tip to tip. They counter-rotate nearly at the Martian speed of sound in order to generate the required thrust. (A similar rotor spinning on Earth could lift more than 50 times as much mass, according to JPL's Håvard Grip, Ingenuity's chief pilot.) The fuselage is a relatively simple box a little smaller than a typical toaster and coated with Kapton film for thermal control. Rather than wheels or skids like most helicopters, this one's landing gear consists of four flexible, 38-cm-long (15-inch-long) angled legs made of tapered carbon-fiber tubes, with golf club–like feet designed to prevent the legs from digging into soft soil. Springy hinges at the legs' tops help soften the shock of landing. Power comes from six lithium-ion batteries inside the fuselage that are trickle-charged during the daytime by solar

Helicopters 101

Aircraft fly thanks to the inverse relationship between air's speed and pressure: The higher the speed, the lower the pressure. The curved top and flat bottom of aircraft wings force air to flow over the top faster than it does over the bottom, which causes suction and lifts the craft higher. An airplane zooms through the sky to move enough air over its wings to fly; a helicopter does the same thing by spinning its rotor blades.

NOTABLE FIRSTS

John Stringfellow's "Bat"

DATE: June 1848

LOCATION: Chard, England
FUEL: steam
DURATION: unknown
CRAFT WINGSPAN: 3 m (10 ft)

CLAIM TO FAME:
first powered flight

Wright Flyer

DATE: Dec. 17, 1903

LOCATION: Kitty Hawk, North Carolina
FUEL: gasoline
DURATION: 12 seconds
CRAFT WINGSPAN: 12.3 m (40.3 ft)

CLAIM TO FAME:
first crewed powered flight

Ingenuity Helicopter

DATE: Apr. 19, 2021

LOCATION: Jezero, Nili Fossae region
FUEL: solar
DURATION: 39 seconds
CRAFT WINGSPAN: 1.21 m (3.97 ft)

CLAIM TO FAME:
first powered flight on Mars

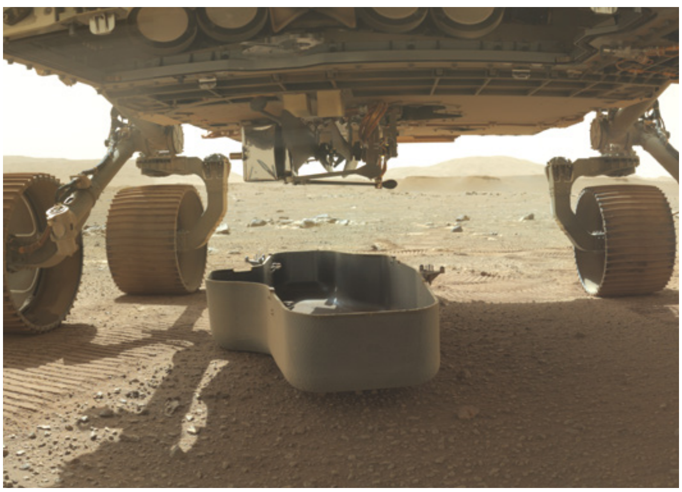
panels that the heli wears like a stationary hat on top of the rotors. The heli's small, omnidirectional radio antenna is mounted atop the solar panel. The entire vehicle has a mass of only about 1.8 kg (4 pounds), which weighs around the same on Mars as a 28-ounce can of tomato sauce does in your kitchen cupboard.

Once completed, the helicopter was carefully folded up, origami-like, and stowed on the underside of the rover's body in August of 2019. A lightweight, deployable debris shield covered it to protect it from the spray of pebbles and dust expected to be kicked up by the descent system's exhaust plumes during landing.

All the scout needed now was a name. In April of 2020, just three months before launch, Alabama high school student Vaneeza Rupani won NASA's nationwide contest to name the helicopter. She proposed Ingenuity. As she wrote in her contest entry, "Ingenuity is what allows people to accomplish amazing things, and it allows us to expand our horizons to the edges of the universe."

Fingers Crossed

Perseverance and Ingenuity launched on an Atlas V rocket from Cape Canaveral Air Force Station in Florida on July 30,



▲ **SHIELDS DOWN** Perseverance dropped the debris shield protecting Ingenuity on March 21, 2021, and peeked under itself with the WATSON camera on its robotic arm to take this image.

NASA / JPL-CALTECH / MSSS

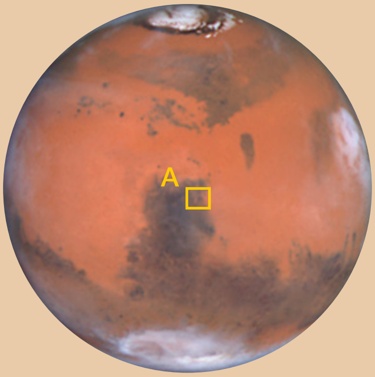
2020. After an uneventful cruise, the pair made a safe, gentle landing on the rocky and sandy floor of Jezero Crater on February 18, 2021. The fact that much of the final assembly, testing, and launch activities, as well as the preparations and practice for all operations on Mars, proceeded — in NASA speak — "nominally" while the world was in the grips of the COVID-19 pandemic is a true testament to the dedication and professionalism of the many thousands of people who made it all happen.

Once on the ground, the Perseverance rover team set about assessing the geological and environmental characteristics of the landing site and testing the rover's systems. The Ingenuity team, meanwhile, spent the early mission days working with rover scientists and engineers to identify a safe, football-field-sized "airfield" where the initial heli flights could be conducted. The Mastcam-Z team, which I lead as principal investigator along with Justin as deputy PI, eagerly participated in the photographic hunt for the right place to fly.

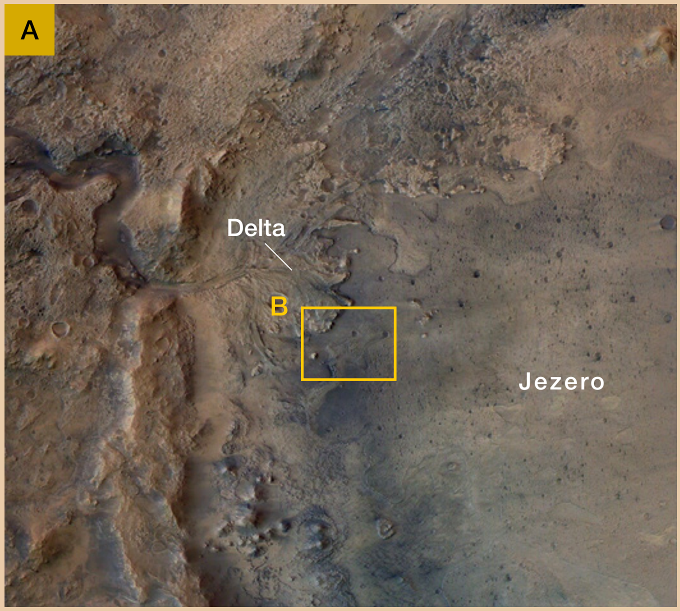
Perseverance's Octavia E. Butler landing site is in a relatively flat part of the crater floor. Using orbiter and rover images, the teams identified a nearby area that was large and rock-free enough to serve as a safe airfield. After checking out the rover's wheels and other systems needed for driving, Perseverance headed out. Along the way, the rover dropped the heli's protective debris shield onto the ground and took inspection photos of the folded-up helicopter using the arm-mounted WATSON camera. Once the rover arrived at the airfield, the teams began the many-sols process of slowly unstowing the helicopter and then gently dropping it the remaining 10 cm (4 in) to the surface. On April 3, 2021, Ingenuity finally "landed" on Mars.

But echoes of "not yet, not yet . . ." were still coming from MiMi and the helicopter team. There were still many steps to perform and systems to check out, including unlocking and testing the rotor blades and testing the communications link with the rover. While the heli team worked to inspect their little aircraft, the rover team moved Perseverance to a viewing location on a rocky plain about 70 meters away — close enough to take good images of Ingenuity using the rover's high-resolution Mastcam-Z cameras, yet a safe enough distance away in case of a flight mishap. The rover would spend several weeks exploring this area — named Van Zyl Overlook,

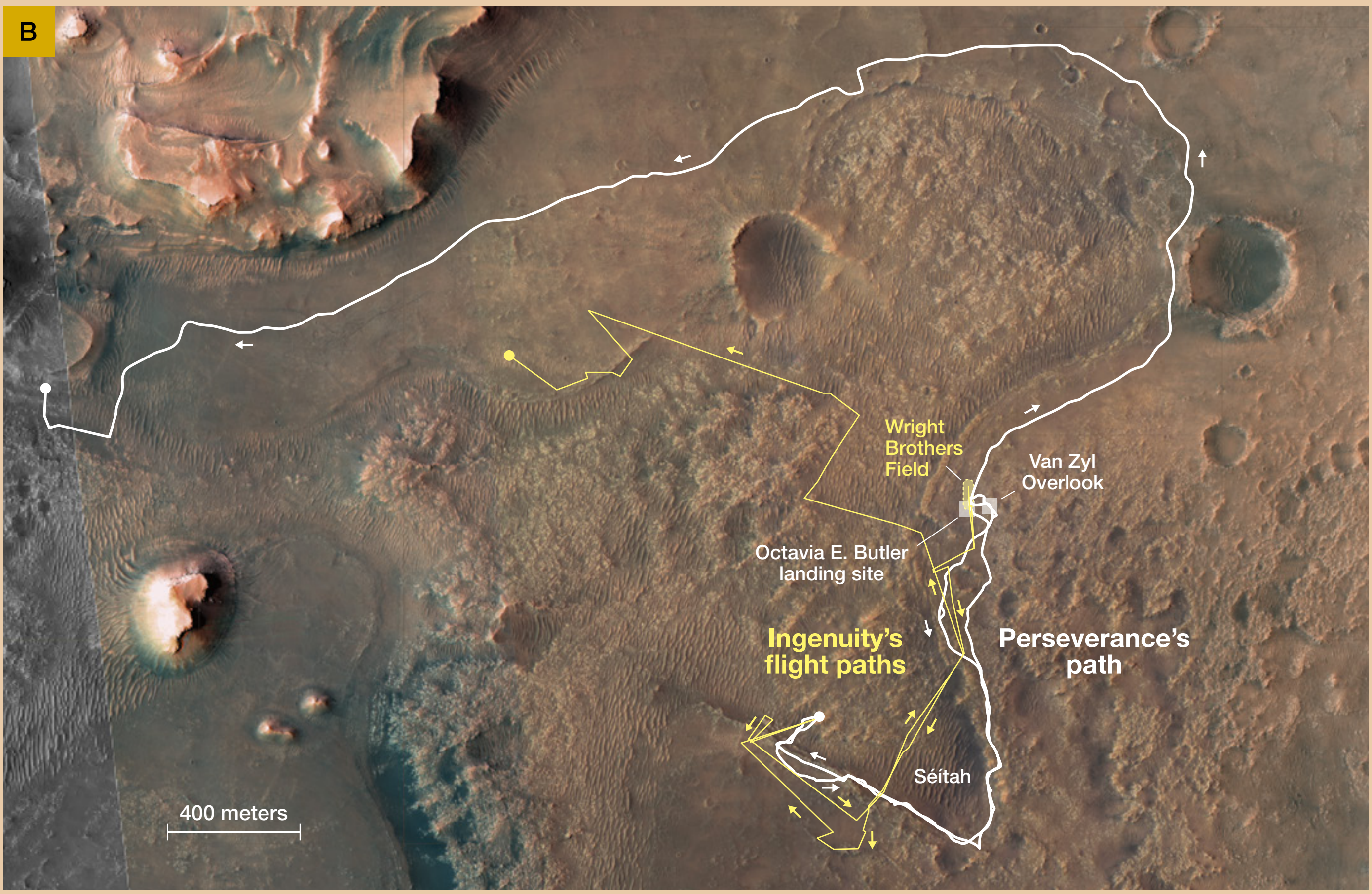
STOCKPILE Perseverance is the first sample-caching mission to Mars. As it trundles across the landscape, the rover drills and stores rock samples. A future mission will collect these samples and return them to Earth.



▲ **LOCATION IS EVERYTHING** Perseverance and its tagalong, Ingenuity, landed in the 45-km-wide crater Jezero, which lies just north of the Martian equator on the boundary between the fractured terrain of Nili Fossae and the ancient impact basin of Isidis Planitia.



▲ **A RIVER RAN INTO IT** An ancient delta along the crater's northwestern edge marks where a long-dry river flowed into Jezero. The delta's sediments would be an ideal place to find chemical or other evidence of microbial life, if it ever existed here.



▲ **TRAILBLAZING** At first, the helicopter kept close to the rover, but flight #9 took it across the treacherous Séítah sands. Subsequent flights explored features beyond the rover's path. As the pair headed for Jezero's delta they followed separate paths, with Ingenuity taking a shortcut across a sandy region that Perseverance had to skirt around. Locations are for May 1st. See where the duo are now at **https://is.gd/whereispercy**.

MARS GLOBE: STEVE LEE (UNIVERSITY OF COLORADO), JIM BELL (CORNELL UNIVERSITY), MIKE WOLFF (SPACE SCIENCE INSTITUTE), AND NASA; JEZERO: ESA / DLR / FU-BERLIN / NASA / JPL-CALTECH; TRAVERSE MAP: GREGG DINDERMAN / *S&T* AND ESA / DLR / FU-BERLIN / NASA / JPL-CALTECH / UNIV. OF ARIZONA after the late JPL space scientist and Ingenuity advocate Jakob J. van Zyl — while always staying within line-of-sight radio contact with the helicopter.

The rover team also needed to be ready to document the first flight photographically. Several imaging systems on the rover are capable of modest-rate video imaging, including Mastcam-Z. Justin and I had talked many times in the years leading up to launch and arrival about the possibility that we might capture on video the first powered aircraft flight on another world. “How crazy cool would that be?” we both thought.

Our roughly 50-person team practiced taking movies several times by imaging Ingenuity’s blade release and spin tests shortly after deployment, as well as some longer-distance practice sessions from Van Zyl Overlook prior to the first flight. But despite the practice and the checking and double-checking, we were still nervous when it came time for flight #1. Did we point and focus the cameras correctly? Did we coordinate the timing properly with the heli team for the start of the flight and the start of the movie? (Remember, all the commands have to be beamed to Mars in advance.) Could we really fit the thousands of video frames in the camera memory and downlink them back to Earth in a reasonable amount of time?

Finally, on April 19, 2021, the 58th sol of Perseverance’s mission, Ingenuity was ready to fly, and the rover team was ready to support and document the flight. It was programmed to be a simple flight: spin up the rotors, takeoff and hover at a height of 3 meters (9 feet) above the ground, rotate the fuselage by 96°, and then descend to a gentle landing.

And it worked! Total flight time was about 39 seconds, and Mastcam-Z’s two cameras captured it beautifully in both wide-angle and full-telephoto-resolution videos.

The helicopter team had finally realized its dream. “When we saw the altimeter data confirming our successful first flight,” MiMi told me by email, “that was truly the first time that our team actually celebrated fully and 100%!!!”

WRIGHT BROTHERS MEMENTO

In anticipation of Ingenuity’s historic aviation achievement, NASA arranged for a small piece of cloth from the original *Wright Flyer* to be attached to the underside of the Martian helicopter’s solar panel.

▲ **SUCCESS!** Team members rejoice after receiving confirmation of Ingenuity’s first flight.

NASA / JPL-CALTECH

Bird’s-Eye View

Ingenuity’s total flight time was about three times longer than Orville Wright’s first crewed, powered airplane flight at Kitty Hawk almost 118 years earlier. To commemorate the achievement, NASA named Ingenuity’s airfield in Jezero “Wright Brothers Field.” The International Civil Aviation Organization (ICAO) even gave the airfield the ceremonial designation JZRO and the helicopter the official ICAO designator IGY, call sign INGENUITY.

Ingenuity undertook five tech demo flights. The remaining four flights, each more complex than the last, were conducted successfully between April 22 and May 7, 2021. Each was also successfully documented on video by the Mastcam-Z team, along with numerous still photos and time-lapse movies that Ingenuity took with its own cameras. Some of the videos also show Martian dust devils lazily drifting among the background hills, and flights #4 and #5 (and later, #13) show the best examples of how Ingenuity can create its own sort of dust devil, as the blade wash picks up and sweeps dust along its path above the ground. Each flight provided images and detailed engineering data on the helicopter’s height and distance, and the videos document the way the vehicle sometimes had to fight the wind to maintain its stability. It was a real thrill for our team to be part of aviation and film history!

Flights #4 and #5 also have a sound track. Justin had heard the barely audible sounds of the test flights in the thin air of JPL’s simulation chamber, but it wasn’t obvious that we’d actually hear Ingenuity on Mars when Perseverance was hundreds of meters away. Yet once the SuperCam team filtered out the background sounds of wind from the microphone data, the faint, super-low-frequency *thrummmm* of Ingenuity taking off and flying is indeed audible in the videos.

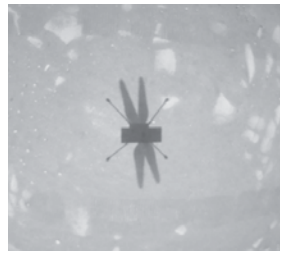
After completing its tech-demo flights, Ingenuity transitioned into a new, extended mission called the *operations demonstration phase*, which is designed to show how an aerial scout vehicle might enhance the rover’s science and driving objectives. Most of these flights have only been documented by the helicopter’s own telemetry and images, as Ingenuity has often been too far away from the rover to resolve well, even using Mastcam-Z.

As of the end of Perseverance’s first year on Mars, Ingenuity had completed 20 flights, including its longest-distance flight (#9) on July 5, 2021, during which it traveled 625 meters across a dune-filled region called Séítah (Navajo for “amidst the sand”) to document an area that the rover could not travel across. Many of these flights have contributed significantly to Mars 2020 mission science, partly because Ingenuity’s 13-megapixel color camera can easily resolve small rocks and other landforms that are both too far away for the rover to see well and too small to be seen at all in orbital images.

For example, helicopter images (and 3D topography derived from those images) over the south Séítah region helped rover drivers carefully plan a route for Perseverance a little ways in to what had previously been thought to be completely untraversable sandy terrain. Scientific analysis of the images also helped the team to identify two compelling outcrops in Séítah where the rover later collected samples, and to forgo collecting samples from another candidate site where the outcrop turned out to be much less exposed than planners had thought based on orbital and rover images. Many of these images have also been used to extend the rover's measurements of the tilts of the layered rocks that appear to form a boundary between Séítah and the rest of the nearby crater floor.

On one of the flights into Séítah, Ingenuity actually landed right on top of an ancient sand wave. The helicopter's measurements of the feature's unexpectedly low height, gentle slope, and pebbly surface revealed that it is a kind of windblown sand deposit known as a *megaripple*. A megaripple is potentially older than other kinds of sand deposits and could tell us something about ancient winds, because its larger grains make it harder for modern winds to erode and move it.

In a sense, and perhaps surprisingly given the helicopter's relatively short, 30-sol planned mission, Ingenuity has already answered Bob Balaram's original question: What science could you do with a helicopter on Mars? Lots, it turns out. And we are likely only at the beginning of this robot partnership, for NASA has extended Ingenuity's mission through at least September 2022, and the helicopter shows no signs of aging besides some dust.



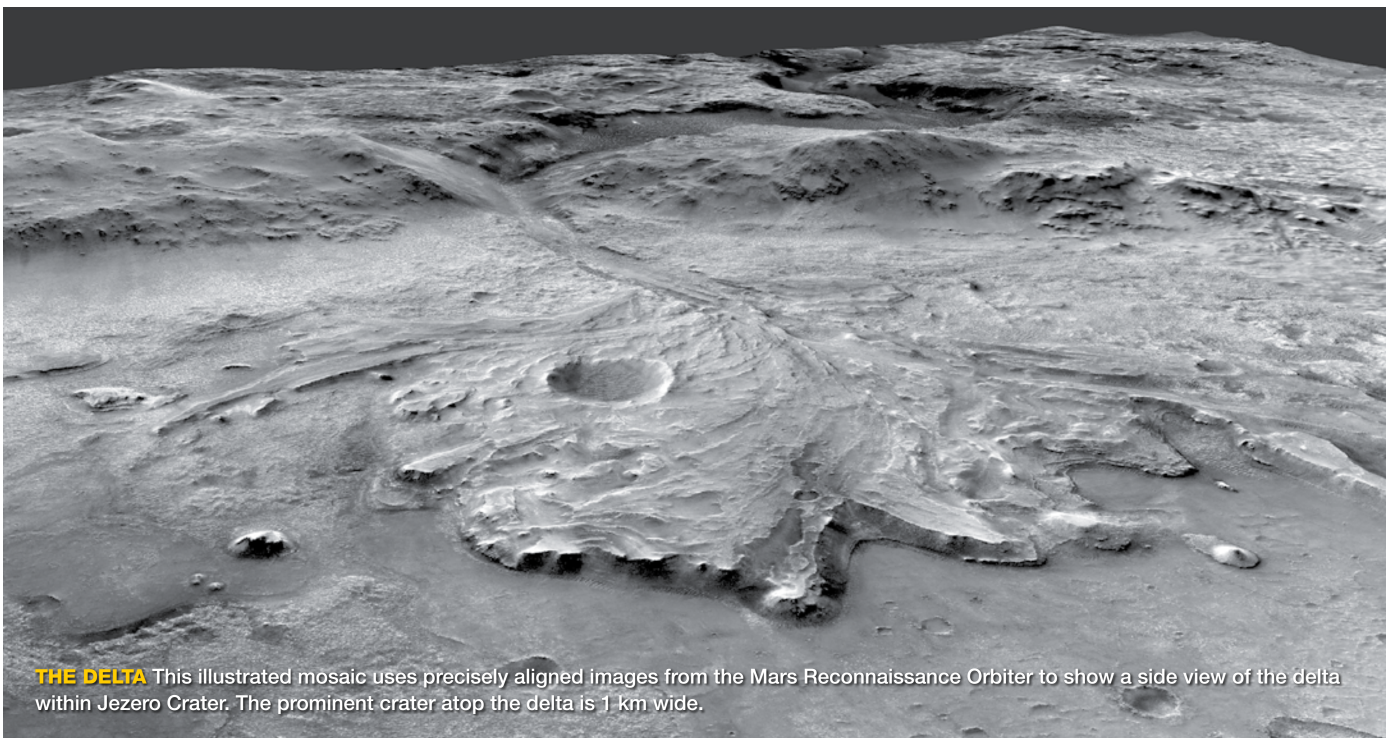
▶ **SHADOW SELFIE** Ingenuity's downward-pointed navigation camera took this image during the helicopter's second flight.

Perseverance and Ingenuity have now arrived at the mission's prime target, Jezero's famous fan-shaped delta. Formed by an ancient river, the delta's cliffs loom 40 meters above the crater floor. Its layered sediments could include lithified mud deposits, which have the potential to preserve ancient evidence for habitable environments and life.

The delta traverse will be filled with boulders, sand traps, and rugged terrain. The first Martian helicopter will have its work cut out for it, helping the rover navigate its way up a river channel. But gone are the days of "not yet, not yet" — Ingenuity's moment has come.

■ *S&T* Contributing Editor **JIM BELL** is a professor and planetary scientist in Arizona State University's School of Earth & Space Exploration. He has been a member of the science teams on every NASA Mars rover mission and two orbiter missions. He has also written nine popular science books, including *Discovering Mars* (2021), coauthored with science historian and *S&T* Contributing Editor William Sheehan.

Follow Ingenuity updates with the team's blog: https://is.gd/helicopterstatus. See Mastcam-Z's Ingenuity flight movies at https://is.gd/helicoptervideos.



THE DELTA This illustrated mosaic uses precisely aligned images from the Mars Reconnaissance Orbiter to show a side view of the delta within Jezero Crater. The prominent crater atop the delta is 1 km wide.