OPERATION: MARS ANTENNA

In a marriage of brute force and millimetric precision, a vital communications link in the Deep Space Network has just undergone a major repair. The giant Mars dish—so named because its first job, in 1966, was to track Mariner 4 after its flyby of the red planet—has relayed commands to, and data from, every earthly emissary to have ventured beyond the moon. As the most sensitive antenna available, it was also crucial in bringing the Apollo 13 astronauts home. But 44 years of operation—more than double its projected 20-year lifespan—have taken a toll on the bearings that allow it to aim its radio beam precisely at a spacecraft the size of a VW Beetle more than 10 billion kilometers away.

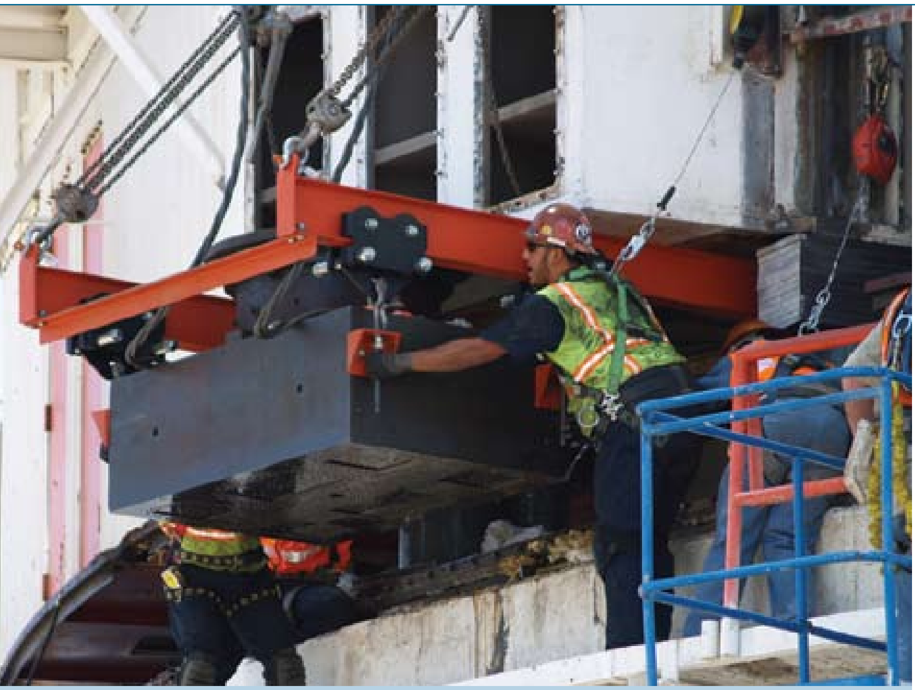
Officially known as Deep Space Station 14, the 70-meter antenna sits in a shallow valley at JPL's Goldstone complex deep in the Mojave desert between Los Angeles and Las Vegas, where it is shielded from as many of humanity's interfering radio signals as possible. The dish and its substructure, including the two-story corrugated steel building that houses the drive motors and some of the signal-processing equipment, weighs about 3,000 metric tons—more than a herd of 500 elephants.

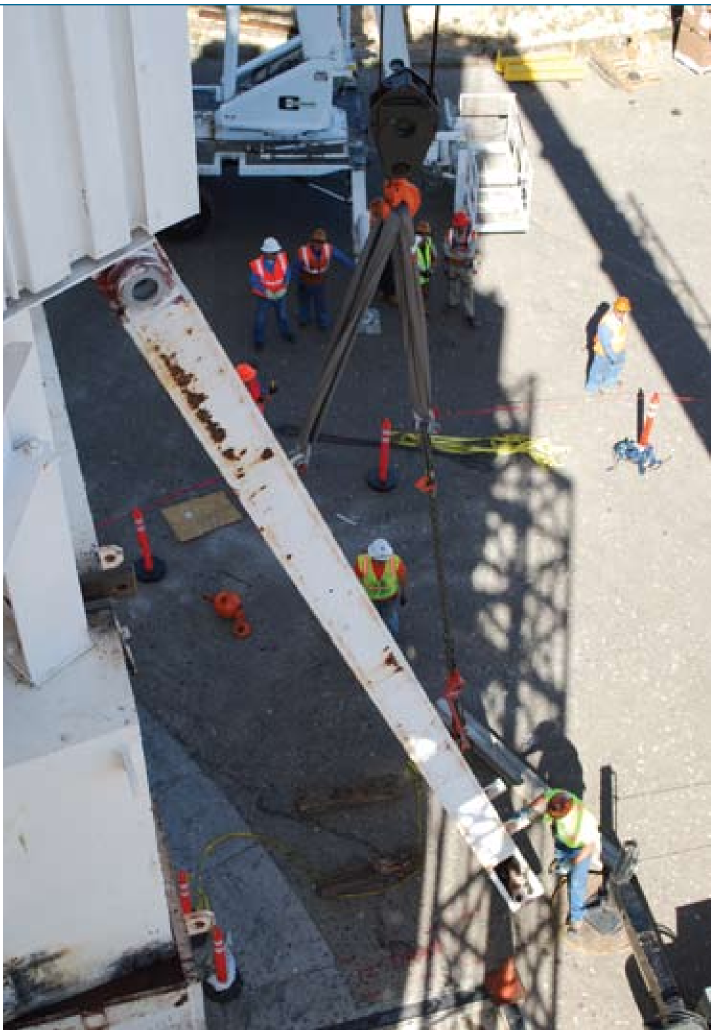
The entire assembly, as tall as a 20-story building, rests on three steel support pads. These pads are part of the hydrostatic bearing on which the antenna rotates, and they glide on a quarter-millimeter film of oil atop a 24-meter-diameter steel ring called the runner. The runner, in turn, sits on a 10-meter-tall pedestal. Tiny trickles of oil would seep through the runner's joints and drip off its edges, deteriorating the cement-based grout below. As the grout softened, the runner would develop "waves," so a team of four technicians would spend eight to 10 hours a week inserting shims under the runner to keep it level.

Work began in March to replace the runner, the grout, and the elevation bearings that allow the dish to tilt from the zenith to the horizon. The elevation bearings were done first—a sort of warm-up job, as this merely involved lifting 1,800 tons of dish off its mounting. Next, the crew used the same hydraulic jacks to raise the entire 3,000-ton colossus five millimeters—enough clearance to ease out the old components and install a thicker runner with tighter joints on new oil-resistant, epoxy-based grout.

As it talks to far-flung spacecraft, the Mars dish also measures the distance to them, providing vital data to the navigation teams. Changing the dish's height by more than a few millimeters would void these calculations. The new runner is seven inches thick to the old runner's five, so, in one final engineering challenge, the hydrostatic bearing pads had to be removed and machined down to compensate.

The project, two years in the planning, had a set-in-cement deadline: the dish had to be back on line by early November, in time for JPL's rendezvous with comet Hartley 2. They made it. —*MW/DS*





OPPOSITE PAGE

Top left: Sometimes low-tech fixes keep high technology in business. Stainless steel shims, fabricated to an accuracy of 0.0001 inches, keep the runner level.

Top right: One of the three hydrostatic bearing pads that slide along the runner as the giant antenna rotates on its pedestal.

THIS PAGE

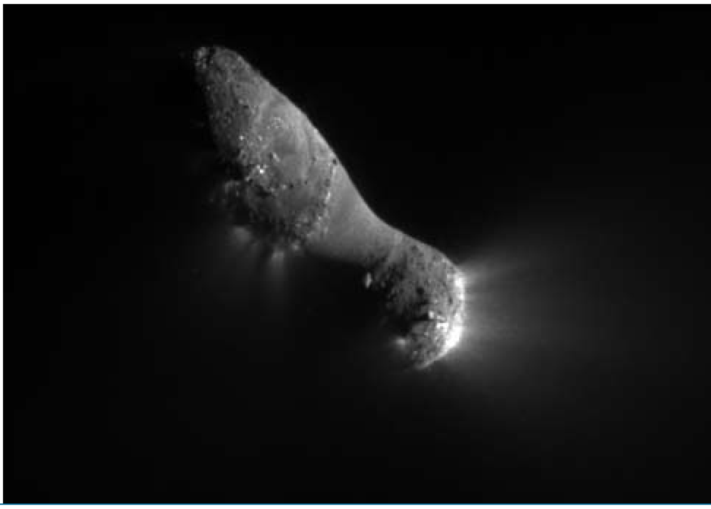
Top left: A crane lifts one of 11 new runner segments to the top of the concrete pedestal. Once there, segments were maneuvered into position on air bearings, on which they floated like pucks on an air-hockey table.

Top right: JPL engineer Tim Sink checks the levelness of the sole plates that will support the runner segments. The laser leveling was done in the cool of the night to minimize any thermal-expansion errors due to the July heat. The grout was mixed and poured at night for the same reasons. With daytime highs routinely over 100 degrees Fahrenheit, the night shift was a plum assignment.

Middle left: Removing the hydrostatic bearing's pads was as easy as opening a kitchen drawer—if your drawers weigh 6,400 kilograms each, that is.

Middle right: Workers prepare to install one of the three support legs that took the weight of the antenna once it had been jacked up off the runner.

Right: JPL's EPOXI mission took this look back at comet Hartley 2 on November 5 at a distance of 849 kilometers. The comet's nucleus is about two kilometers long and about 0.4 kilometers wide at the "neck" in the middle. Hartley 2 is the smallest, most active comet yet visited by a spacecraft, and EPOXI's observations are the most detailed yet made. The jets appear to be a mixture of carbon dioxide and dust, suggesting that chunks of dry ice in the comet's interior are vaporizing from the sun's heat.



HAVING A BLAST

In 2007, soon after landing at Naha Airport on the island of Okinawa in Japan, a Boeing 737 started spewing fuel from a puncture in its right-wing tank. As the fuel flowed onto the hot engine, it ignited, causing several explosions as flames engulfed the plane. Fortunately, everyone evacuated in time and no one was hurt.

Of course, planes, trains, and automobiles don't generally burst into huge fireballs whenever they're near a heat source, whether it be a spark or a lit cigarette—despite what Hollywood might lead you to believe. But clearly, exploding fuel is a hazard, and understanding how it ignites allows engineers to develop the proper safety regulations to minimize danger.

Postdoc Sally Bane (PhD '10), working with Joe Shepherd (PhD '81), Johnson Professor of Aeronautics and professor of mechanical engineering, is analyzing how a spark can ignite flammable gas. She's discovered that these spark-ignited explosions are a lot more complicated than previously thought, and her results bring much-needed updates to safety standards that are decades old—and, in some cases, based on data that are flat-out wrong.

For decades, engineers have determined the likelihood of a spark-ignited explosion in an aircraft by using a number called the minimum ignition energy (MIE). Each type of fuel or vapor has its own MIE value, and if a spark's energy is below that value, then nothing should ignite. The problem, however, is that the MIE is based on data from old experiments, some from more than 60 years ago. Even though the numbers have been updated over the years, no one has ever gone back and reevaluated the original experiments in depth. The original data from the 1940s are still cited today, Bane says.

As an expert in explosions, Shepherd was recruited in 1996 by the National Transportation Safety Board to help figure out why TWA Flight 800 crashed into the Atlantic just 12 minutes after takeoff from New York's JFK Airport (see "Learning from a Tragedy," *E&S* No. 2, 1998). During the investigation, some of Shepherd's experiments showed unforeseen variability in spark-ignited explosions—even with a spark below the MIE, the fuel sometimes still blew up. However, he didn't get a chance to explore the issue further until Bane came to his lab as a graduate student in 2005.

According to Bane, performing this kind of experiment is difficult and time-consuming, and since there hadn't been any obvious reason to doubt the old MIE data, people were content with the existing information. It took her five years to design, build, and run her experiments, which are among the most rigorous ever done.

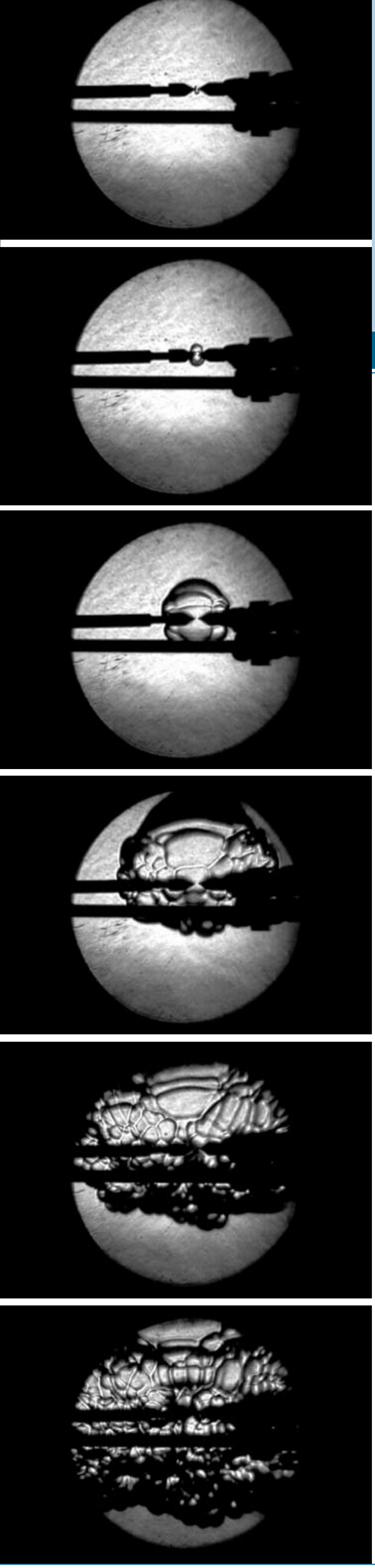
Her explosions range from harmless puffs to tiny fireballs, safely contained in a solid-steel vessel weighing 200 kilograms. Inside the vessel are two pointy tungsten electrodes, separated by a couple of millimeters. Charge builds up in the electrodes, generating a voltage difference that ionizes the gas between them. The ionized gas creates a path for electrons to travel from one electrode to the other, and in just a few nanoseconds, you get a spark. The spark energies that Bane works with are relatively low—as low as 50 microjoules. You would need a million of these sparks to light a 50-watt lightbulb for a second.

A high-speed camera, which can take up to several hundred thousand frames per second, records the spark and any resulting explosion. Bane repeated the experiment for different spark energies and with various mixtures of flammable gases as suggested by the Aerospace Recommended Practices, standards developed by the Society of Automobile Engineers that guide the design and production of aircraft parts. The mixtures contained 5, 6, or 7 percent hydrogen, oxygen, and argon.

Unlike tests that are common in the industry, Bane's are done in a sealed vessel, which means that she knows the gas's composition, temperature, and pressure with a high degree of certainty. Furthermore, Bane says, in other setups, there's no camera that directly observes the ignition. Instead, the only way to tell that there's been an explosion is to watch whether a piece of foil, which is across an opening in the vessel, pops up—or, if the blast is violent enough, bursts open.

Bane discovered that there isn't a single MIE value for a given flammable mixture; there's no single energy that sets the threshold for whether an explosion is possible. Instead, she found, whether or not a certain spark ignites the gas is an exercise in probabilities, rising and falling with the energy of the spark. To be sure, at some point, the energy is too low and an explosion is impossible. But it's not as cut and dried as people had thought.

In the case of the 7 percent hydrogen mixture, Bane's results were roughly comparable to the



Far left: The aftermath of the fire that engulfed a Boeing 737 when leaking fuel was ignited by a hot engine. Fortunately, no one was hurt.
Left: A spark between the two pointy electrodes ignites the 7 percent hydrogen mixture, generating a fireball. It's not as dangerous as it looks—the explosion is small. For comparison, the distance between the electrodes is only a few millimeters. The snapshots are taken at 5, 50, 100, 175, and 250 microseconds.

experiments done by Bernard Lewis and Guenther von Elbe in the 1940s, which gave an MIE of 100 microjoules. She found that at 100 microjoules, the gas had a 10 percent chance of igniting. But for the 5 percent hydrogen mixture, the MIE given was 200 microjoules, while Bane determined that the spark had to be at least 780 microjoules before it even had a 10 percent chance of blowing up. It turned out that Lewis and von Elbe hadn't actually had data for a 5 percent hydrogen mixture back in the 1940s—they had just extrapolated the MIE from data for the 7 percent gas.

This variability is likely an inherent characteristic of spark ignition, Bane says. Even when she kept the conditions as constant as possible, the explosions were never consistent. The spark itself—the channel of plasma connecting the two electrodes—is intrinsically irregular, wavering in shape and motion. Other complexities have been revealed in fluid-dynamic simulations that Bane and graduate student Jack Ziegler have run of the ignition process.

Bane and Shepherd are now working to develop better safety standards with Boeing, which funded the research. Last summer, she expanded her experiments to include kerosene, the type of fuel used in most commercial aircraft. Unlike clean-burning hydrogen, kerosene is a dirty fuel, so after each trial, Bane dons a protective jacket, Kevlar gloves, and goggles before opening the hot vessel to swab out the soot and set up the next experiment.

Bane is finding that it doesn't take much energy to set off kerosene. She was able to ignite kerosene at 60 degrees Celsius with only 0.65 microjoules, while in Shepherd's previous work, it took 40 microjoules to ignite the fuel at 52 degrees. "I anticipate that in future tests I'll be able to ignite mixtures with even lower energies," she says. The ignition of fuel vapor is highly sensitive to temperature change, Bane explains, and her experiment used shorter-duration sparks—about a couple hundred nanoseconds, which is a more accurate simulation of an electrostatic discharge—so the discrepancy isn't a complete surprise. But the fact that it's apparently much easier to ignite kerosene than the test mixtures specified by the FAA has certainly gotten the attention of the folks at Boeing.

Bane says her data can be applied to any situation where there's a tank of fuel and the possibility of a spark—for example, in power plants, in the natural-gas tank that heats your house, or when storing hydrogen gas, which has garnered interest as a clean-burning fuel. But as for smoldering cigarettes blowing cars to kingdom come? "That could never happen," Bane says. Gasoline needs to be extremely hot to ignite, and a cigarette just won't cut it. But it sure looks cool. —*MW*

Watch Sally Bane discuss her work as part of the 2010 Everhart Lecture Series.

A map of the world—or rather the parts the Romans knew or had heard about in 150 CE—from Claudius Ptolemy's *Geographia*.

ON THE MAP

From Neolithic cave painting to Google Earth, humans have used maps to depict, understand, and navigate their environment. Now some of the Caltech Archives' finest treasures on the subject of mapping the earth, the skies, and longitude have gone on display, many for the first time, on the second floor of Parsons-Gates Hall of Administration. The *On the Map* exhibit includes Claudius Ptolemy's 2nd-century map of the known world; Georg Braun and Frans Hogenberg's beautifully illustrated *Civitates Orbis Terrarum*, from the latter part of the 16th century; a 1570 map of Russia by Abraham Ortelius; Johannes Bayer's 1603 *Uranometria*; Johannes Kepler's world map of 1627; a 17th-century planispheric celestial map by Andries van Luchtenberg; prints from Joan Blaeu's 1662 *Atlas Maior*; and first editions of books by Tycho Brahe, Johannes Hevelius, Giovanni Domenico Cassini, and Christiaan Huygens.

Ptolemy's map is an early 16th-century version reconstituted from his cartography and geography book, the *Geographia*, published in 150 CE. Ptolemy, a Roman citizen of Alexandria, knew that the earth was a globe—the ancient Greeks had worked it out centuries earlier—but his view of the world extends only from the zero-degree line of longitude off the west coast of Africa (beyond which no sailor had returned to tell the tale) to the 180-degree line through China, and from 60 degrees north latitude to 30 degrees south. He omitted the three-quarters of the globe that was still uncharted, a technique that humans still employ today when mapping unknown terrain such as Saturn's moon Titan, currently under surveillance by JPL's Cassini spacecraft. Cassini's radar views a narrow swath of Saturn's lunar companion with each flyby, and the resulting maps, in which Titan's topographical features are interspersed with black regions for which no data exists, are in some sense Ptolemy's intellectual descendants—JPL's cartographers don't fill the empty space with creations of their own fancy.

Cassini will, in all likelihood, map Titan more rapidly than humans mapped the earth: the Americas, after all, were not discovered by Europe until the late 15th century. But once the Age of Exploration got under way, the exciting accounts of new lands brought back by sailors sparked a renewed interest in geography among prosperous and literate Europeans. Printing presses, invented a few decades earlier, found a lucrative market in catering to the demand for information.

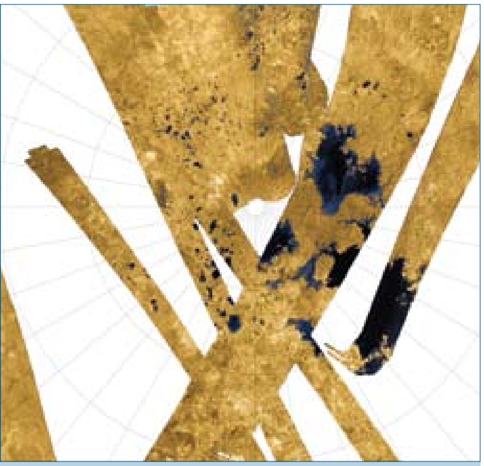
In 1513, the German cartographer Martin Waldseemüller, whose large map of the world (and the first map to use the name "America") had sold well a few years earlier, decided to bring out Ptolemy's *Geographia*. For centuries the Christian world had regarded the ancient geometer as a heretic, and the work was hidden away and forgotten until its rediscovery in the 14th century. Waldseemüller borrowed a manuscript copy, in Greek, from an Italian monastery. The maps were missing, but he reconstituted them, including the world map in the Caltech display, from Ptolemy's extensive topographical list—a compendium of place names and geographical features along with their latitudes and longitudes. (The list was compiled from travelers' reports, and many of the longitudes were wrong—

Anyone comparing a current map of Basel with this 1575 view from Braun and Hogenberg's *Civitates Orbis Terrarum* ("Towns of the World") might think that the Rhine has changed its course over the years. But what's really changed is our notion that maps always have north at the top. In the 16th century, there was no convention for map orientation, and this view is from the north looking south. A compass rose to guide the viewer was also considered unimportant.

or, at best, very bad guesses—which is why the landforms get increasingly distorted the farther one gets from the Mediterranean.)

In the decades that followed, decorative maps and atlases found ready buyers. Some of the finest were produced by the Flemish cartographer Abraham Ortelius, who pioneered the change from the woodcut printing of maps to copperplate engraving, with italic lettering and rich hand-coloring that greatly enhanced the definition and beauty of the prints. When his *Theatrum Orbis Terrarum* ("Theater of the World"), the first true atlas, sold well, he encouraged Georg Braun and Frans Hogenberg of Cologne to produce a companion book of town views and history, the *Civitates Orbis Terrarum* ("Towns of the World").

With its first volume published in 1572, Braun and Hogenberg's ambitious project took an additional 45 years to complete, and Caltech is fortunate to own four volumes from the six-volume first edition. Their scrupulously detailed town plans generally depict buildings and houses from a bird's-eye perspective and are brought to life with drawings of people in local costume carrying out their trades, of animals, and of scenes from history, all accompanied by an account in Latin of the town's situation, population, history, government, commerce, and traditions.



Cassini made this radar mosaic of Saturn's moon Titan. The surface is covered in seas, tinted blue and black.

Today the "armchair traveler" has morphed into the "Google Earther," as more and more people turn to cyberspace to swoop in on houses or the world's cities. Interestingly, Wikipedia's city pages provide almost the same information that Braun and Hogenberg did.

Humans were likely curious about the heavens even before they explored the world: following the daily course of the sun, moon, stars, and planets doesn't involve any traveling. Early astronomers and geographers both used the same surveying instruments, such as quadrants and astrolabes; and both earth and sky maps have equators and poles, latitude and longitude. (The longitude of a star or planet is given by its right ascension, while the latitude is given by its declination.) For millennia, star tables—celestial topographical lists—played an indispensible role in predicting important events in the calendar such as equinoxes, solstices, phases of the moon, and eclipses (not to mention their use in casting horoscopes!), but they were so imprecise that, according to the young Tycho Brahe, "There are just as many measurements and methods as there are astronomers, and all of them disagree."

Accordingly, Tycho (as he is commonly known), a Danish nobleman, made it his life's work to take accurate, systematic observations from a single spot over many years. He persuaded King Frederick II of Denmark to give him the small island of Hven (modern Ven), in the straits between Denmark and Sweden, and to build him an observatory there and provide him with a generous income to fund it. Today's astronomers should be so fortunate!

Tycho named his palatial astronomical research center Uraniborg, the Castle of the Heavens. With accommodations for up to a hundred observers, assistants, and visiting scholars, it was not unlike a modern astronomical research center, save for the alchemy workshop in the basement and the utter lack of telescopes (Tycho was the last major astronomer to survey the skies entirely by naked eye.) He later added Stjerneborg, the Castle of the Stars, an underground observatory with a rotating dome that sheltered his instruments from the buffeting winds that swirled around Uraniborg's towers. A series of lakes provided waterpower for both instrument workshops and a mill that produced paper for publications. Unfortunately, after Frederick's death, Tycho argued with his heir and had to abandon the island in 1597.

Uraniborg, Stjerneborg, and the lakes can be seen on the map of Hven in the Archive's display—a reproduction of a colored engraving by Willem Blaeu from Joan Blaeu's *Atlas Maior*, 1662. The young Willem,

A map of Tycho Brahe's island of Hven (now Ven) from Joan Blaeu's *Atlas Maior* of 1662, showing the observatories Uraniborg and Stjerneborg and the lakes that provided waterpower.

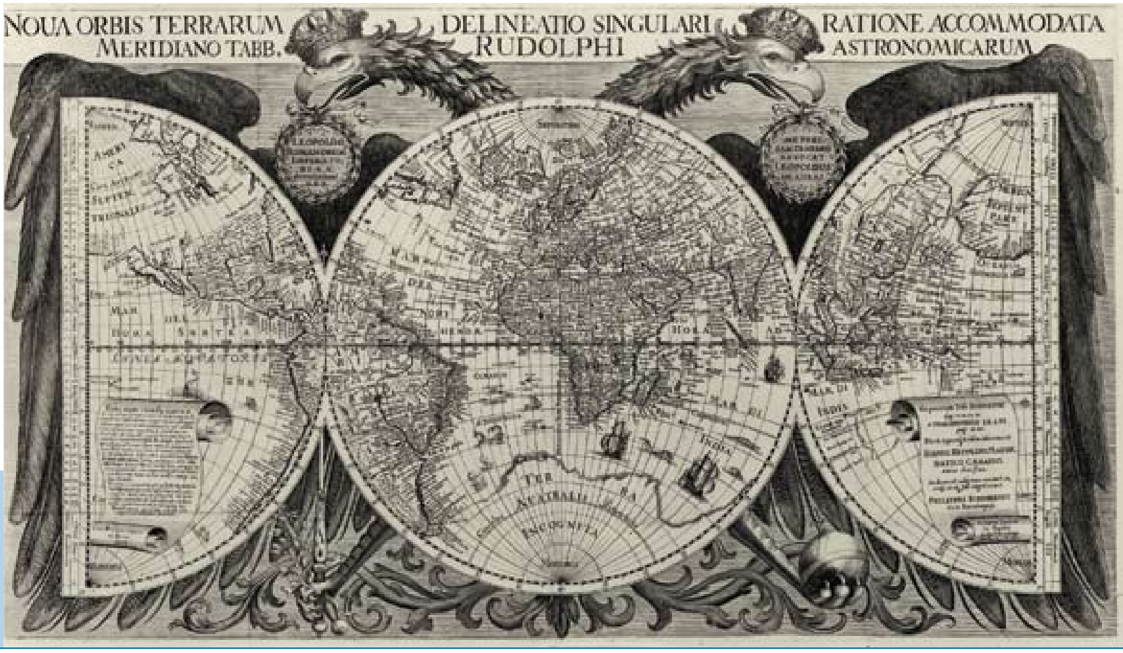
Joan's father, had studied astronomy and globe-making with Tycho, and he went on to run a successful map-publishing business in Amsterdam. Uraniborg was demolished shortly after Tycho's sudden death in 1601, but today we can zoom in on Ven via Google Earth and view Uraniborg's partially restored gardens, the remains of Stjerneborg, and even, faintly, the remains of the lakes.

Tycho's assistant, Johannes Kepler, who would go on to attain some fame in his own right, finished the work by preparing a new set of star tables based on the Hven observations. These he published in 1627 as the *Tabulae Rudolphinae*, or "Rudolphine Tables," in honor of Rudolf II of Austria, Holy Roman emperor and Tycho's royal patron at the end of his life, and Kepler's patron as well. The exhibit includes a photograph of a large world map folded inside Caltech's copy of the *Tables*. The map's unusual projection, comprising one whole hemisphere centered on Europe and Africa, flanked by two half hemispheres, was Kepler's own design. It was probably intended to make it easier for navigators to plot their position by keeping the most-traveled seaways of the Known World contiguous. Kepler's line of zero longitude is centered on Hven. Caltech is fortunate to have this map, as it is rare: the engraver had not finished it when the book was published, and after the astronomer's death three years later, it lay forgotten until rediscovered in 1658.

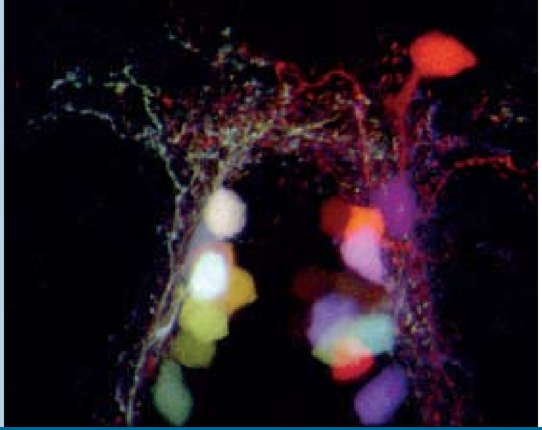
Kepler also tackled the problem of accurately measuring one's longitude, a necessity for any maritime power attempting to become a global presence. But although his method gave useful results on dry land, despite his best efforts, it proved impractical on a tossing deck. Among those who tried to find a better way were Giovanni Domenico Cassini, Christiaan Huygens, and England's first Astronomer Royal, John Flamsteed; books and prints reflecting their work are also on display.

Nowadays, ships, planes, and even cars navigate with the help of satellites, and travelers (almost) always know exactly where they are. Life is safer and easier—but our curiosity about the world around us is as strong as ever. *—BE* E&S

Barbara Ellis is a writer and researcher for On the Map*, which is curated by Shelley Erwin, head of Archives and Special Collections. The majority of the books, prints, and artifacts on display were collected and later donated to Caltech by Earnest C. Watson, founder of the Watson Lecture Series and professor of physics and dean of the faculty at Caltech for many years. The* Tabulae Rudolphinae *are from the Rocco Collection, purchased by trustee Harry Bauer for Caltech in 1955.*



A rare and unusual map of the world designed by Kepler for his 1627 book of star tables, the *Tabulae Rudolphinae*.



Right: Using the "Brainbow" technique, in which neurons are labeled with differently colored fluorescent proteins, the researchers can map out neural circuits in zebrafish larvae. Because the larvae have relatively few neurons and are transparent, they make for a good model organism for studying the neural and genetic systems that regulate sleep.

WHY DO WE SLEEP?

While we can more or less abstain from some basic biological urges—for food, drink, and sex—we can't do the same for sleep. At some point, no matter how much espresso we drink, we just crash. And every animal that's been studied, from the fruit fly to the frog, also exhibits some sort of sleep-like behavior. (Paul Sternberg, Morgan Professor of Biology, was one of the first to show that even a millimeter-long worm called a nematode falls into some sort of somnolent state.) But why do we—and the rest of the animal kingdom—sleep in the first place?

"We spend so much of our time sleeping that it must be doing something important," says David Prober, assistant professor of biology and an expert on how genes and neurons regulate sleep. Yes, we snooze in order to rest and recuperate, but what that means at the molecular, genetic, or even cellular level remains a mystery. "Saying that we sleep because we're tired is like saying we eat because we're hungry," Prober says. "That doesn't explain why it's better to eat some foods rather than others and what those different kinds of foods do for us."

No one knows exactly why we slumber, Prober says, but there are four main hypotheses. The first is that sleeping allows the body to repair cells damaged by metabolic byproducts called free radicals. The production of these highly reactive substances increases during the day, when metabolism is faster. Indeed, scientists have found that the expression of genes involved in fixing cells gets kicked up a notch during sleep. This hypothesis is consistent with the fact that smaller animals, which tend to have higher metabolic rates (and therefore produce more free radicals), tend to sleep more. For example, some mice sleep for 20 hours a day, while giraffes and elephants only need two- to three-hour power naps.

Another idea is that sleep helps replenish fuel, which is burned while awake. One possible fuel is ATP, the all-purpose energy-carrying molecule, which creates an end product called adenosine when burned. So when ATP is low, adenosine is high, which tells the body that it's time to sleep. While a postdoc at Harvard, Prober helped lead some experiments in which zebrafish were given drugs that prevented adenosine from latching onto receptor molecules, causing the fish to sleep less. But when given drugs with the opposite effect, they slept more. He has since expanded on these studies at Caltech.

Sleep might also be a time for your brain to do a little housekeeping. As you learn and absorb information throughout the day, you're constantly generating new synapses, the junctions between neurons through which brain signals travel. But your skull has limited space, so bedtime might be when superfluous synapses are cleaned out.

And finally, during your daily slumber, your brain might be replaying the events of the day, reinforcing memory and learning. Thanos Siapas, associate professor of computation and neural systems, is one of several scientists who have done experiments that suggest this explanation for sleep. He and his colleagues looked at the brain activity of rats while the rodents ran through a maze and then again while they slept. The patterns were similar, suggesting the rats were reliving their day while asleep.

Of course, the real reason for sleep could be any combination of these four ideas, Prober says. Or perhaps only one of these hypotheses might have been true in the evolutionary past, but as organisms evolved, they developed additional uses for sleep.

Researchers in Prober's lab look for the genetic and neural systems that affect zebrafish sleeping patterns by tweaking their genes and watching them doze off. An overhead camera records hundreds of tiny zebrafish larvae as they swim in an array of shallow square dishes. A computer automatically determines whether the fish are awake or not based on whether they're moving or still, and whether they respond to various stimuli. Prober has identified about 500 drugs that affect their sleeping patterns, and now his lab is searching for the relevant genetic pathways. By studying the fish, the researchers hope to better understand sleep in more complex organisms like humans. "Even if we find only a few new genes, that'll really open up the field," he says. The future is promising, he adds, and for that, it'll be well worth staying awake. —*MW*

The pair of colliding galaxies known as the Antennae, as seen by (from left to right) today's visible, infrared, and submillimeter telescopes. CCAT will see the dust-shrouded star-forming regions that the CSO sees, but with Spitzer's spatial resolution.

THE MKIDS ARE ALRIGHT

"Build CCAT!" the decadal survey says. That's the U.S. National Research Council's sixth decadal survey for astrophysics and astronomy, released in August. These surveys predict the greatest scientific opportunities and rank proposed research projects accordingly. The outlined projects offer the best prospects "for making discoveries—both anticipated and unanticipated—for which the next decade will be remembered." CCAT—a telescope initiated by Caltech, JPL, and Cornell that is slated for construction in the high-altitude Atacama Desert in northern Chile—was listed as a top priority for its part in the search for the first stars, galaxies, and black holes.

"The first two billion years of the universe will open up in the next decade," predicts Chuck Steidel (PhD '90), Caltech's DuBridge Professor of Astronomy. "CCAT has a starring role: it is the only telescope that can survey the dustiest and most luminous galaxies in the primordial universe. We expect some big surprises."

Astronomers have wanted a telescope like CCAT since the 1980s, when the Caltech Submillimeter Observatory (CSO) began to reveal dust clouds packed with embryonic stars in nearby galaxies. These clouds look dim or black to optical telescopes, but they blaze in the submillimeter- and millimeter-wavelength light that the CSO and CCAT are designed to see. This light falls between radio waves on the one side and near-infrared and visible light on the other. To see well at these wavelengths—just out of the reach of radio and optical telescopes—completely new cameras and spectrometers had to be developed.

This light may be tough to work with, but it holds the key to understanding galaxy formation. If star-forming regions are thick with dust, primeval galaxies may also be hidden by the dust and gas of their own formation. CCAT will survey huge swaths of sky at great depths, essentially looking back in time by catching photons that have been traveling for more than 10 billion years. Its superb site and 25-meter dish—more than twice as large as the CSO's—are big factors in its observing power. But the real revolution is down in the bowels of the telescope.

It has taken three decades of dogged work, false leads, and lucky breaks to develop the technology for CCAT's wideband spectrometer and its large-format cameras. *E&S* discussed this journey of a thousand steps with Jonas Zmuidzinas (BS '81)—the Kingsley Professor of Physics, Caltech's project scientist for CCAT, and a leader in detector development.

"So far, we have gotten just a small taste of what there is to learn at submillimeter wavelengths," says Zmuidzinas. Studying a submillimeter-bright galaxy often requires three telescopes. You need a submillimeter telescope to find the object, a radio telescope to pinpoint its location, and an optical spectrometer to analyze its chemistry and measure its redshift, which determines its place on the cosmic time-line.

CCAT will be able to do all of these things. Its spectrometer, the next generation of an instrument called Z-Spec, will have unprecedented bandwidth and be able to target multiple objects simultaneously. It will routinely find redshifts for distant, dust-obscured galaxies rich with new stars. Its cameras, using microwave kinetic inductance detectors (MKIDs), are expected to bring the state of the art from a few thousand pixels to many tens of thousands of pixels and beyond. They will capture detailed panoramas of the submillimeter sky.

Caltech and JPL were central to development of the new detectors. That's not because of one or two people—quite the opposite. In this small community, ideas fly from undergraduates to senior researchers to trustees to alumni (don't try to keep track of all the characters that follow!). Here, a good idea can generate the nimble collaboration more typical of a pro sports team—each player, aware of the skills and resources of the others, contributes what he or she can, whether it's a new method, a better production facility, a timely infusion of funding, or a novel design.

SIS OPENS THE SUBMILLIMETER

Our story begins in 1979, when Bell Labs' Tom Phillips—now Altair Professor of Physics at Caltech—invented the superconductor-insulator-superconductor, or SIS mixer. The SIS mixer was crucial to the development of radio-style receivers for the submillimeter band, and it is now used in nearly all submillimeter- and millimeter-wavelength telescopes. "It made sensitive high-resolution submillimeter spectroscopy and interferometry a possibility," says Zmuidzinas.

Jonas Zmuidzinas (BS ’81), the Kingsley Professor of Physics and Caltech’s project scientist for CCAT.

An SIS mixer channels photons to a tiny junction made of two layers of superconducting metals, each just a tenth of a micrometer thick, separated by a smear of insulation. Excited by the photons, electrons leap across the insulator by quantum tunneling, generating a measurable current with extremely low noise. John Tucker (BS ’66) developed the theory behind these mixers, predicting that their noise levels could be reduced to the fundamental limits set by quantum mechanics.

Phillips, who had been a visiting associate at Caltech, joined the faculty that year. Once installed in Caltech telescopes, his prototype SIS receivers demonstrated fantastic potential, convincing JPL to dedicate researchers and lab space to the project. The CSO also sped ahead—its SIS receivers caught their first photons in 1987. JPL opened its Microdevices Laboratory in 1988, and the new facility turned physicists’ heads nationwide.

One of those physicists was Zmuidzinas, then a postdoc in Illinois. He was designing ways to force-feed photons to an SIS junction with minimal losses. He had refined a device called a twin-slot mixer, in which two antennas collect light and guide it into microstrips made with superconducting metals.

Zmuidzinas returned to Pasadena in 1990. “Caltech was irresistible. The CSO had recently been completed. The Microdevices Lab had just opened, so there was a beautiful facility for doing this work.” Today, descendents of the twin-slot are used in the Herschel Space Observatory’s spectrometers and in the CSO’s high-frequency instruments.

SPIDERWEBS AND SIN

A few years later, Zmuidzinas focused on the problem of finding distant submillimeter-bright galaxies, which would require a camera with at least a hundred detectors—one per pixel. At the time, the workhorse detectors were germanium bolometers. Bolometers, which are used in both cameras and spectrometers, absorb incoming photons and convert their energy to heat, which an electrical thermometer then converts to a measurable electrical signal. But the devices were laboriously assembled by hand. Zmuidzinas wanted to solve the problem by combining his twin-slot antennas with a new bolometer based on superconductor-insulator-normal (SIN) junctions that had just been invented by a UC Berkeley student. With this approach, the entire detector array could be produced by lithography—no hand-assembly needed!

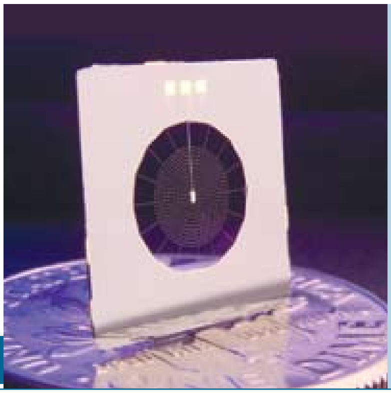
At that time, the late Andrew Lange, then a professor at Berkeley, and his student Jamie Bock were developing the spiderweb bolometer, a refined germanium bolometer in which everything could be mass-produced except the thermometer. The web, less than half the diameter of a dime, was photolithographed, gold-coated silicon nitride. The spider—the thermometer—was hand-placed in the middle. When the silicon backing material was etched away, the spider and web hung in free space, suspended on thin guy lines. Lange began a sabbatical at Caltech in 1994; when he decided to stay, Bock joined JPL as a postdoc. JPL’s Microdevices Laboratory was just what they needed: “They had prototyped the device at Berkeley, but they needed good facilities to make a go of it,” says Zmuidzinas.

Lange, Bock, and Zmuidzinas started down both paths—spiderwebs and SIN—but soon focused on the spiderwebs. They were more of a known quantity, and Lange and Bock wanted to create a working instrument quickly for upcoming experiments. Spiderweb bolometers made cameras faster and more accurate—they had more detectors and needed fewer photons to produce a measurable signal, and cosmic rays and the heat and shaking of nearby equipment affected them less. The 1998 BOOMERanG experiment, co-led by Lange, used them to provide the first experimental evidence that the universe is flat and that the “inflationary theory” is correct (see “An Ultrasound Portrait of the Embryonic Universe,” in *E&S* 2000, No. 3). Similar bolometers are flying on the Herschel and Planck observatories—326 on Herschel and 52 on Planck. They were also used in a 144-pixel camera installed on the CSO in 2002.

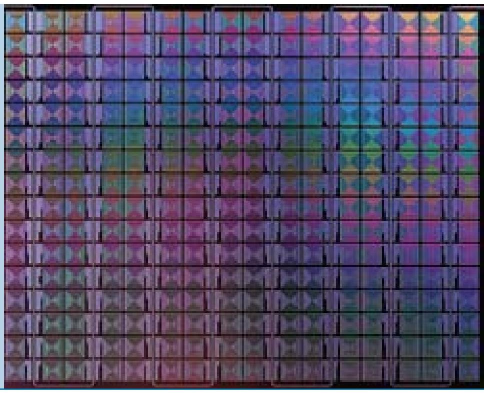
THE MISSING REDSHIFTS

In 1998, a UK team at the James Clerk Maxwell Telescope—located on the summit of Hawaii’s Mauna Kea, just a few hundred yards from the CSO—announced that they had found distant submillimeter-bright galaxies. They had used hand-assembled, thread-suspended, pre-spiderweb bolometers. “It was a brute-force, inelegant solution, but they got there first,” Zmuidzinas says.

The galaxies proved to be very faint and difficult to study at other wavelengths. In particular, their redshifts—usually measured with optical spectroscopy—remained largely unknown.



Left: A spiderweb bolometer sits on a dime. Right: Titanium nitride Microwave Kinetic Inductance Detectors, or MKIDs, of the type under development for CCAT's camera. The active area (pictured) is about a centimeter across, or roughly the size of the chip in which the spiderweb bolometer is suspended, but this MKID has a 16 × 16 pixel array instead of a bolometer's single sensor.



Zmuidzinas started to think about how to make a submillimeter spectrometer with enough bandwidth to measure redshifts for distant galaxies.

In an optical spectrometer, a grating diffracts incoming light, bouncing it to an array of detectors. The longer the light fans out before it hits the detectors, the more the resolution improves—but the instrument also gets larger. This becomes a serious problem in the submillimeter band, because the wavelengths are about a thousand times longer than in the optical. Hoping to shrink the instrument back down, Zmuidzinas considered confining the light in superconducting circuitry on a silicon wafer, similar to an ordinary printed circuit board. This would address the problem—the metal circuitry would confine the light vertically and also slow it down, reducing the required path lengths considerably. But experiments initiated by undergraduate Chiyan Luo (BS '00) showed that the circuitry would lose too many photons.

Meanwhile, Jamie Bock, by then a JPL research scientist, was also trying to make a better submillimeter spectrometer. He was looking into instruments that bounced light the old-fashioned way, with mirrors and lenses. But they were proving to be unmanageably large, so Zmuidzinas suggested a compromise using a machined-metal version of the superconducting spectrometer.

In 2000, Bock and Zmuidzinas joined forces to develop a new instrument that would draw on each of their approaches, and they were soon joined by Millikan Postdoctoral Fellow Matt Bradford, graduate student Bret Naylor (PhD '08), Hien Nguyen at JPL, and collaborators at other universities.

In Z-Spec, the resulting spectrometer that was first installed on the CSO in 2005, feedhorns funnel light into the 2.5-millimeter gap between two parallel metal plates, each more than a foot on a side. The light hits a faceted, arc-shaped grating, splintering off to be caught by 160 bolometers—variations on the spiderweb concept.

Z-Spec's bandwidth—on par with that of optical spectrometers—is over ten times larger than that of previous submillimeter spectrometers. The instrument recently measured redshifts of several distant, dust-obscured star-forming galaxies discovered with Herschel.

OF SQUIDS AND MKIDS

The story doesn't end with the smashing success of the spiderweb bolometers and Z-Spec. In fact, Lange and Bock's progress on the bolometers had left one box unchecked: "We didn't fulfill the vision of producing large arrays of detectors purely by lithography," Zmuidzinas says. It's a frequent quandary—do you spend more time on a new tool that can scale up, or do you prioritize the ability to do interesting science right away? The spiderwebs had mostly solved the issue of hand-assembly, but placing the thermometers and installing the wiring was still delicate and labor-intensive. In the late '90s, Zmuidzinas returned to the challenge of making a camera with simple wiring and thousands of mass-producible detectors.

Kent Irwin (BS '88) had made progress on this problem, in the meantime, when he found a simple, practical way to make use of superconducting bolometers as a Stanford graduate student in 1995. Called transition edge sensors, his bolometers used strips of superconducting metal films as thermometers. Small temperature changes in the strips reliably yielded measurable changes in resistance, once Irwin drew on the design of stereo amplifiers to keep the strips within a working temperature range. Then, in 1999, in his first job, Irwin and collaborators (including Erich Grossman, PhD '88) developed readout multiplexers using superconducting quantum interference devices (SQUIDs) that simplified the wiring for large bolometer arrays. Arrays of these detectors, incorporating novel antennas inspired by Zmuidzinas's work, are being developed at JPL for studying the cosmic microwave background and for sensitive spectroscopy from space.

It was a breakthrough, but the SQUID multiplexers seemed complicated to Zmuidzinas. The SQUID approach works well for certain applications, but it wouldn't scale up to the large detector count needed for CCAT's cameras. He and JPL's Rick LeDuc discussed the problem at a coffee shop near campus. LeDuc wondered: "Can't we use kinetic inductance somehow?"

This was a lightning bolt for Zmuidzinas. Back in his office, he scanned the literature. Photons absorbed by a superconductor would produce quasiparticles. A quasiparticle population boom would change the superconductor's inductance, which would change the circuit's resonant frequency. Perhaps he and LeDuc could design a lithographed superconducting resonator and use its frequency change as the detect-

If the human eye could see submillimeter light, this is how the skies over the CCAT telescope would look. CCAT will be built atop Cerro Chajnantor in Chile's Atacama desert—at an elevation of 5,612 meters, one of the highest and driest places on Earth. This is essential, as water vapor absorbs submillimeter waves.

able response. Each resonance would be sharp, occupying a narrow range of frequencies. You could tack resonators next to each other on one readout wire, maybe into the thousands. There was no theoretical ceiling for the quality of each resonator.

RESONANT INTERACTIONS

Zmuidzinas and LeDuc shared the idea with Tom Tombrello, Caltech's Kenan Professor and then chair of the Division of Physics, Mathematics and Astronomy. Tombrello spoke with then provost Steve Koonin, who connected him with trustee Alex Lidow (BS '75)—who provided substantial seed funding. "Lidow's gift came at a critical time for us—it allowed us to get the equipment we needed and get set up to do this in the right way," Zmuidzinas says. Prominent researchers from Caltech and JPL, as well as other universities, signed on to the effort. Koonin and Tombrello also talked with JPL's Jakob van Zyl (PhD '86), who helped move the project ahead.

JPL's Peter Day (PhD '93) suggested making the resonators using a structure called a coplanar waveguide, etched from a superconducting metal film deposited on a silicon wafer. In the resulting resonators, the distance covered by the microwaves as they bounced back and forth totaled more than a kilometer!

"They were getting *Q*'s (a quality factor related to path length) of a million-plus," says Keith Schwab, an applied physicist at Caltech. "People in quantum computing and applied physics couldn't believe it. It's had a big impact on our work. And the technology is easy to implement."

Beyond their unanticipated benefits, the new MKID circuits actually *work*. The team has created a camera with 2,304 detectors—it will be installed on the CSO in the fall of 2011. In development are new versions of MKIDs, in which the radiation is absorbed in meandering superconducting strips that also let energy slosh back and forth between inductors and capacitors. They will have *Q*'s in the tens of millions. These MKIDs rely on superconducting titanium-nitride films, a choice suggested by LeDuc. They are very simple, dropping costs and enabling fabrication of extremely large cameras for CCAT.

The invention is also inspiring new applications: Caltech physicist Sunil Golwala is exploring ways to use titanium-nitride MKIDs to detect dark matter, Ben Mazin (PhD '04) is developing optical-wavelength versions for astrophysics, and Zmuidzinas and Day hope to use the material to make a nearly ideal microwave amplifier. These ongoing efforts are supported by the Keck Institute for Space Studies and by the Gordon and Betty Moore Foundation, which also enabled earlier detector work.

"As you can see, you bounce around and it takes a while to land on the right idea," says Zmuidzinas. The instruments at the heart of CCAT will bring decades of work to fruition. Looking back, Zmuidzinas reflects, "There are always such surprising connections. Who would have thought that trying to look for submillimeter galaxies would spark an idea useful in quantum computing? But that's how research works. There are deep, hidden connections among fields. We all learn from each other."

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