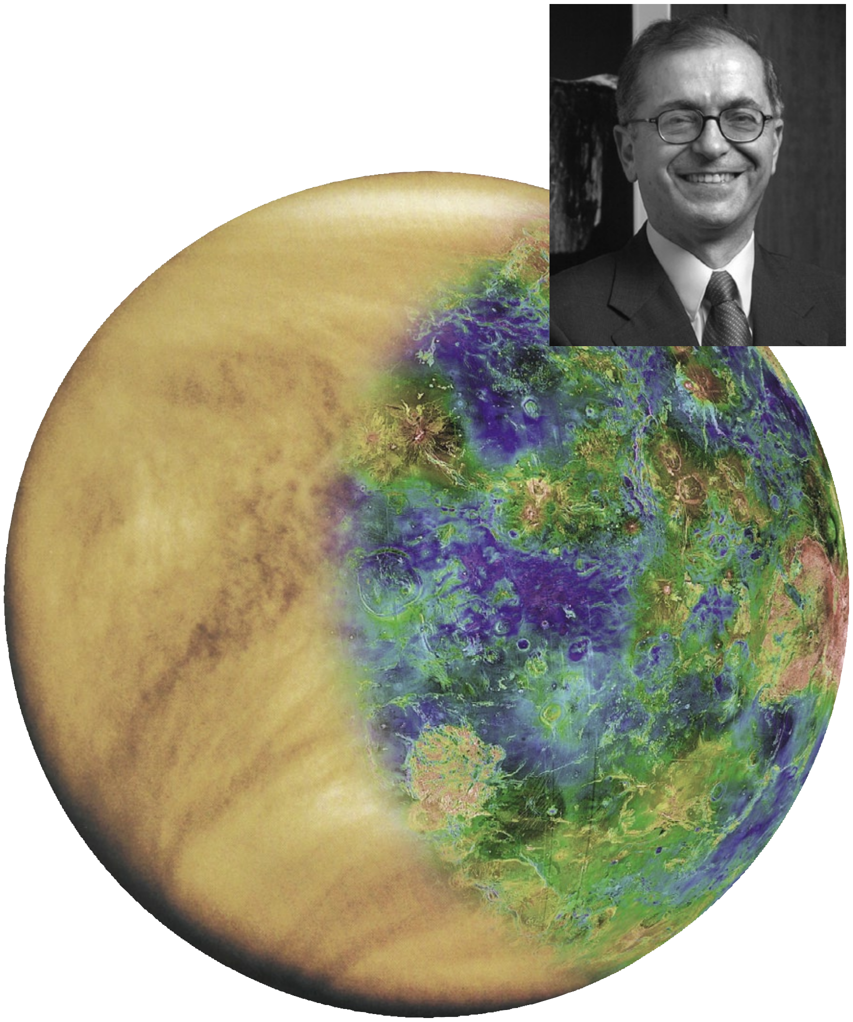
What Lies Beneath

by Douglas L. Smith



An ultraviolet image of Venus's clouds as seen by JPL's Pioneer Venus Orbiter in 1979 is "peeled" away to reveal Venus as mapped by more than a decade of radar investigations culminating in the Magellan mission. The colors are keyed to elevations, from blue basins to red mountains. Inset: Elachi was a member of Magellan's science team.

"I have never received in my life a paycheck which didn't have Caltech on top of it," laughs Charles Elachi, professor of electrical engineering and planetary science and director of the Jet Propulsion Lab. "You could say I'm a lifer." Elachi will have been at Caltech for 40 years come this fall, and in his tenure has helped explore Venus and a moon of Saturn, headed three projects that were flown on the Space Shuttle, and shepherded to maturity a technique that has revolutionized the earth sciences. He arrived as a grad student in 1968, earned his MS in electrical engineering in 1969, and got a summer job at JPL in 1970. "And one of the group's supes [JPL slang for supervisor] said, 'Well, gee . . . you look like you know something about electromagnetic waves. We're just starting to look at a Venus mission to image the surface with radar. Would you be interested?' And I said, 'Sure, that's great.'"

Venus's terrain cannot be seen directly, because it is hidden by a thick veil of sulfuric-acid clouds. Rough radar maps had been made from Earth that showed continent-sized features, but not much else. One of these had been made by Professor of Planetary Science, Emeritus, Duane Muhleman, using JPL's then-64-meter Goldstone antenna, part of the Deep Space Network, which is used to communicate with far-flung spacecraft. "So I was going to JPL one or two days a week while I was finishing my PhD," Elachi recalls. After being awarded his doctorate in 1971—his thesis being on the propagation of radar waves through periodic media—he joined JPL full-time to work on the Venus Orbiting Imaging Radar. But, he says, "the budget was not that great for planetary missions. So it took a long time to get that mission designed and approved." VOIR, pronounced like the French *voir*, as the project was known in JPL-speak, eventually flew in the 1990s under the moniker Magellan.

While thinking about mapping the arid continents of Venus, Elachi also began using radar to look at Earth's oceans. JPL's Seasat, an oceano-

This 50-kilometer-wide strip of SIR-A data, superimposed on a Landsat simulated true-color mosaic of the Sahara, shows ancient river beds buried beneath the sand.

graphic satellite, carried the first civilian spaceborne imaging radar. This instrument recorded the surface roughness of the ocean—what in layman's terms are called waves—to map wind speeds and directions. The radar also measured the sea-surface height to reveal hidden currents. Warmer water occupies more volume than cooler water, giving the ocean a topography all its own, and of course water flows downhill. Developing the hardware and the analytical techniques for Seasat meant testing the prototypes in a NASA Convair 990—a four-engined jet converted into a research aircraft. "That was a fun period, because I did a lot of flying on the aircraft, going to Alaska, and going to West Africa, particularly Dakar [Senegal]. We were stationed there for like three weeks."

Like all radars, Seasat bounced a microwave signal off a distant object, and calculated how far away it was by how long it took the signal to return. But this radar was in motion—the satellite moving forward, the instrument scanning from side to side. Thus the signal returning from any point on the surface below had its own particular two-component Doppler shift along and perpendicular to the radar's flight path. Since the radar's motion relative to the surface was very accurately known, some fancy but relatively straightforward computer processing could gather up all the echoes from any given point, combine them into a single pixel, and make a detailed picture of the terrain below. This technique is called Synthetic Aperture Radar, or SAR, because the aperture size of the radar camera is the distance it travels while one pixel on the ground remains within the field of view—a synthesis of many radar echoes, in other words.

Unlike an ordinary picture made with visible light, the brightness of each pixel in a SAR image is proportional to its roughness—calm seas appear black, for example, and choppy waves bright gray. On dry land this means that rocky deserts or leafy vegetation will appear brighter than parking lots. The surface's moisture content is revealed as well—the damper the soil, the more brightly it reflects. Perfectly dry sand is actually transparent to some depth, a property that would prove to be more than a thesis chapter.

Seasat flew for a mere three months in 1978, but it demonstrated SAR's usefulness, and has since led to several generations of orbiting ocean-mapping radars called scatterometers.

Bolstered by this success, Elachi, by now in charge of JPL's radar-mapping group, decided that they should try to put SAR on the Space Shuttle, which was to make its maiden flight in 1981. "Those were the days where we used to sit down and draw things on a map," Elachi says. "Not like now. We didn't have all the computers. In 1980, my wife and I bought a townhouse up in Mammoth. We used to take six, seven people, and between skiing, we'd sit down and plan the shuttle orbits. We'd strew all these big maps on the floor and draw by hand where we wanted to take the data and so on."

Elachi proposed a radar so big it would take up a shuttle's entire cargo hold—the bigger the antenna, the sharper its vision. The Shuttle Imaging Radar (later known as SIR-A) rode *Columbia* on its second flight, which lifted off on November 12, 1981, and landed all of two days later due to a leaky fuel cell. "So here I am in my late 20s, having the major payload on the first shuttle flight after the test flight," Elachi remembers. "And a couple of weeks before the launch, the NASA administrator called and said, 'This is the first mission that we have some science on the shuttle, so it'd better work!' So that added a little bit to the drama."

The mission succeeded beyond anyone's wildest dreams, revealing a subsurface network of ancient drainage channels beneath the bone-dry sands of the Sahara. But because the mission was cut short, the carefully planned observational campaign went straight out the cargo-bay door. Recalls JPL's Ron Blom, whom Elachi had hired as the team geologist, "All we could do was take images whenever we went over land. The fact that it happened to be the Sahara was pure serendipity. And when we saw the images, we couldn't believe it. There must have been some mix-up in the labeling—this couldn't be the core of the Sahara, one of the driest places on Earth."

Fortunately, a U.S. Geological Survey crew from Flagstaff, Arizona, happened to be working in Egypt, studying the Saharan terrain as a possible Mars analog. "They knew exactly where they were [on our images], and they had seen hints [of ancient washes] here and there," Blom continues. "But they couldn't get a global picture. And they realized that if they could validate this, they could map the whole Tertiary drainage of the region up to about 6,000 years ago." In fact, the USGS folks had already written a paper on those channels' existence, the galley proofs of which showed up in the desert in September 1982 after Elachi and Blom had joined the Survey party to see just how deep the radar had actually penetrated. Digging holes down to the buried streambeds showed that SAR could see through two meters of parched sand with ease; Elachi would later calculate that depths of up to six meters were theoretically possible under ideal conditions. The USGS paper, needless to say, wound up being substantially rewritten, with the JPL duo being added to the author list. It made the cover of *Science*.

The expedition, supported by the Egyptian government, used Russian jeeps to get around. "The windows didn't roll down," Blom recalls. "They were bolted in; they were designed for Siberia. And of course there was no air conditioning. So first thing every morning you made the choice of either eating dust all day and being semicool, or staying dust-free and roasting."

Wherever the team came across one of the underground washes, they found stone tools scattered everywhere. "You were literally walking on them," says Blom. "It was a deflationary surface, so they were all mixed together, bad for archaeology. But as recently as 6,000 years ago, this had been a savannah, and it had clearly been intermittently inhabited when the climate was favorable." Blom and the others picked up a few as souvenirs, but "I looked around, and there was Charles stuffing bags full of them. He understands intuitively what motivates people, and plays that back to them. He gave the rocks out to everyone at NASA HQ. And behold, SIR-B followed two weeks later."

Elachi is a bit more modest. "Fortunately, that mission worked very well. And within two weeks of that flight, NASA asked me to submit a proposal for a follow-up. And within another two weeks they approved it, which was unusual." SIR-B flew on the *Challenger* on October 5, 1984, and landed seven days later. SIR-B had the capacity to look at the same piece of terrain at multiple angles, improving feature discrimination.

Elachi was still a research fellow at Caltech during this time, spending a day or so a week on campus with Professor of Electrical Engineering Charles Papas, his PhD advisor. He also got an MS in geology from UCLA in 1983 to help him understand what the radar was seeing.

Elachi would soon be given yet another hat to wear. "That was a period of growth at JPL in scientific instruments. We had a number of first-rate, relatively young scientists who were all proposing very successfully, particularly in Earth observations. So all of a sudden, instruments became a big business." In 1987, Elachi was put in charge of all instrument development at JPL and was invited to sit on JPL's executive council.

Meanwhile, Magellan—the spacecraft formerly known as Venus Orbiting Imaging Radar—was ramping up, a scaled-back version having finally been approved. This stripped-down spacecraft had one main antenna, a Voyager spare, to both map Venus and send the data back to Earth. The loss of a second high-gain antenna and the fact that the one they *did* have didn't pivot (another cost-cutter) meant that the whole spacecraft had to rotate itself away from Venus and toward Earth once per orbit to transmit its images. Magellan rode the shuttle *Atlantis* into space on May 4, 1989. By mission's end, the radar had mapped 98 percent of Venus's surface to a resolution of about 100 meters, sharp enough to make out features the size of the Rose Bowl, in 3-D—a better topographic map of the whole planet than was available for Earth at the time.

Elachi was a member of Magellan's science team, headed by MIT's Gordon Pettengill. "Because of my background in radar, I was mostly making sure that we had the right parameters for the instrument. I looked at how the radar wave would be propagating through the heavy atmosphere of Venus, whether it would be refracted. I and a couple of other resident scientists at JPL worked very closely with the mission people at JPL and the spacecraft people at Martin Marietta [now the

JPL's radar-mapping group crowns Elachi the "Czar of SAR" circa 1979. Front row, from left: Sue Conrow; Annie Richardson; Judy Ribera; Elachi; JoBea Holt (MS '78, PhD '82), the SIR-B project scientist; and Mike Daily. Back row: John Ford; M. Leonard Bryan; Don Harrison; Ladislav Roth; Mike Kobrick, the SRTM project scientist; Vickie Arriola; Andy Gabriel (MS '78, PhD '81), the key developer of the InSAR method; Dee Baker; Blom; and Peter Palluzzi.

"In that period of 10 years, we took spaceborne synthetic-aperture radar from being a curiosity to becoming a credible scientific tool," Elachi beams.

In this SIR-C image, sand dunes are magenta and limestone is green. "Ubar" sits just above the dry wash (light band) at center. Many tracks (red streaks), both ancient and modern, converge on the site from the south, but only one leads out into the desert to the north.

Lockheed Martin Corporation] and the instrument people at Hughes Aircraft, making sure that we had the right wavelength and polarization, the right digitization, the right data deconverters. We were the link between the science team and the engineering team." Although the radar was built by Hughes, it was designed in Elachi's section at JPL; after the launch, his section did the image processing. He was also part of the JPL team that oversaw the spacecraft's construction.

While mapping Venus, Elachi still found time to head the SIR-C mission, the third shuttle radar. SIR-C was packaged with a German-Italian radar called X-SAR that used a different wavelength, which allowed it to see different things—an object reflects radar most brightly when it's about the size of the radar's wavelength. The combo flew twice on *Endeavour*, on April 9–20 and September 30–October 11, 1994. Like SIR-A, SIR-C broke new ground. Or, more accurately, revealed where the ground had been compacted. These passes over the Sahara revealed ancient trade routes through the desert, invisible to the uninitiated on the ground, but betrayed as thin dark lines where millennia of camel trains had trod the sand to firmness. The shuttle's flight path was adjusted to take it over Oman on the Arabian Peninsula, where the "lost city" of Ubar, a key staging area on the frankincense trade route, supposedly lay. T. E. Lawrence, better known as Lawrence of Arabia, called Ubar "the Atlantis of the Sands." In a Koran story very much like that of Sodom and Gomorrah, the wickedness of Ubar's inhabitants moved a fed-up Allah to cause the city to be swallowed up by the earth. And sure enough, the dark tracks converged at a small oasis in the Rub' al-Khali desert (Arabic for "Empty Quarter," and if the locals think it's empty, you *know* it's inhospitable!)—a sinkhole in whose depths archaeologists have since found the ruins of mighty walls, and artifacts dating back to the Bronze Age. (SIR-C's flight was delayed for several years by the *Challenger* disaster, and in the meantime carefully processed Landsat images had given some similar results. The full story of the search for Ubar can be found in *Caltech News*, April 1992.)

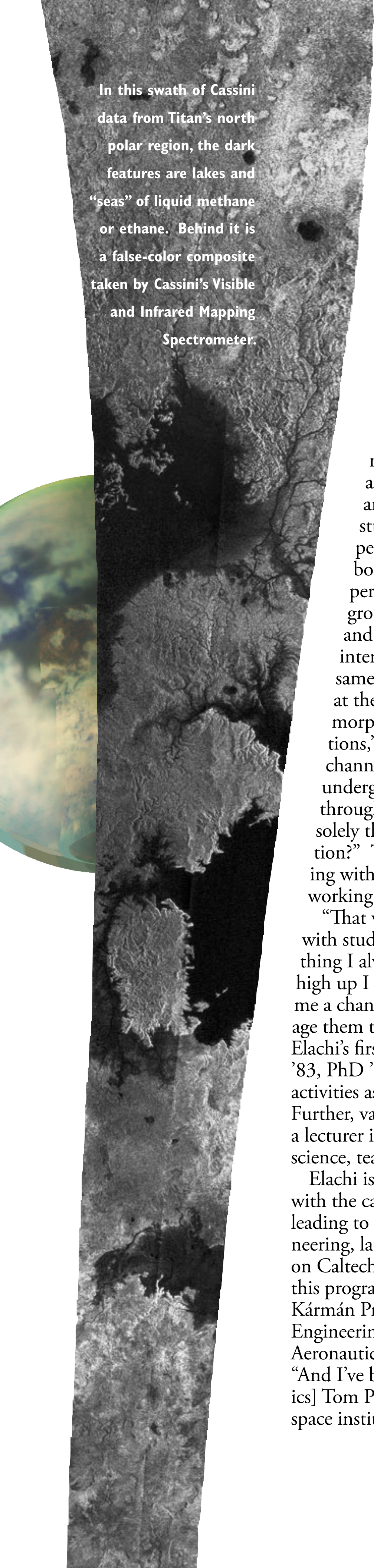
"I leave it up to the archaeologists to decide if it was really the city of Ubar, or some trading post along the way," says Elachi. However, since he was born in Lebanon, the quest had a special resonance for him. As a child, "archaeology was all around me, and everything was thousands of years old everywhere I went. I grew up a few miles from a place called Baalbeck, which has some of the most famous Roman ruins in the Middle East." Elachi has now been to 30 or 40 countries doing fieldwork, he estimates, including a number of archaeological expeditions. "That was fun. I've been to Tibet and western China and Australia and Oman and Arabia and Egypt."

Other team members used SIR-C to do archaeology as well. Diane Evans studied the temple complexes of Angkor Wat in Cambodia; others located lost cities in the Yucatan. More importantly, SIR-C's two flights, five months apart, demonstrated SAR's potential for mapping and monitoring vegetation changes. "In that period of 10 years, we took spaceborne synthetic-aperture radar from being a curiosity to becoming a credible scientific tool," Elachi beams. SAR has caught on worldwide. The Europeans launched their first SAR satellite in 1991 and are now operating their third. The Japanese have launched two, and the Canadians are about to launch their second.

SAR's latest incarnation, called the Shuttle Radar Topography Mission, or SRTM, has finally done for Earth what Magellan did for Venus. SRTM used two antennas to map features in a manner roughly analogous to stereo photography, and rode *Endeavour* on February 11–22, 2000. "The radar effort has gone from being a small group to now a couple of hundred people," Elachi says, "and JPL is probably the world leader in spaceborne imaging radar." Elachi, still boundlessly energetic, oversaw SRTM but was no longer the principal investigator, his managerial responsibilities having started to monopolize his time.

Yet another mission was in the offing. Cassini, which would orbit Saturn, was approved in the early 1990s, and Elachi formed a team to design and build a radar to map cloud-covered Titan, a moon of Saturn thought to have methane seas under its smoggy skies. "So here I was juggling starting Cassini, flying SIR-C, and operating Magellan. And at the same time, I was director for space science and instruments, responsible for all scientific activity and instrument development at JPL. So that was a very busy period, but I was still doing a lot of science at the same time as doing the management."

Elachi had been a lecturer at Caltech since 1982, teaching a very popular class two afternoons a week on the physics of remote sensing. "Arden Albee was my cofaculty, and he used to take the students into the field during spring break, mostly



In this swath of Cassini data from Titan's north polar region, the dark features are lakes and "seas" of liquid methane or ethane. Behind it is a false-color composite taken by Cassini's Visible and Infrared Mapping Spectrometer.

to Owens Valley and the Mojave. He'd show them on the ground how to interpret the images that they'd learned about in class." While Albee was helping the students match what they'd seen from space with what was in front of them, Elachi usually took some much-needed rest.

Elachi was promoted to professor in 2002, the year after he became director of JPL. (The appointment was announced on January 31, 2001, on the 47th anniversary of Explorer 1's launch. "So that was kind of a neat event," he smiles.) He doesn't take on grad students of his own, but he sits on PhD committees and coadvises. Right now, for example, he, Oded Aharonson, assistant professor of planetary science, and grad student Alexander Hayes are studying Titan's hydrological cycle, or perhaps one should say Titan's hydrocarbonological cycle. On Earth, rainwater percolates through rock and soil into underground aquifers. If the water table is high and the topography is low, these aquifers intersect the surface and fill lakes. Does the same thing happen on Titan? "We're looking at the lakes' geographical distribution and morphology, and their subsurface connections," says Aharonson. "There are surface channels, of course, but what's going on underground? Do they drain into each other through subsurface aquifers, or are the lakes solely the product of precipitation and evaporation?" Their work combines computer modeling with analyses of Cassini images, and Hayes is working on a paper for publication next year.

"That was something I always liked, dealing with students," says Elachi. "That was one key thing I always did in my career, no matter how high up I moved into management. And that gave me a chance to pick some of the best, and encourage them to come work at JPL." For example, Elachi's first teaching assistant, Jakob van Zyl [MS '83, PhD '86] is now in charge of all astrophysics activities as a member of the JPL executive council. Further, van Zyl is a Caltech faculty associate and a lecturer in electrical engineering and planetary science, teaching the class Elachi started.

Elachi is also involved in two joint initiatives with the campus. He's helping set up a program leading to a master's degree in aerospace engineering, launched this year, which capitalizes on Caltech's association with JPL. (More about this program, initiated by Ares Rosakis, the von Kármán Professor of Aeronautics and Mechanical Engineering and director of Caltech's Graduate Aeronautical Laboratories, in an upcoming issue.) "And I've been working with [Professor of Physics] Tom Prince on the possibilities of having a space institute on campus—a think tank for what should be done in space science and technology in the future, but also policy discussions. Bring key players from around the world into an academic environment, and think about what should be done in the next couple of decades."

"What I enjoyed in particular is that most of my work was at the crossroad between engineering and science. I had to work with geologists and planetary scientists, atmospheric scientists, orbit people, spacecraft design people, electrical engineers, and that's what makes it fun." Blom thinks this is the key to Elachi's success as director—"JPL is a different animal to different people. The scientists think it's one thing. The engineers think it's another, and the Mars people a third. Everyone sees it differently. But Charles has been immersed in both engineers and scientists, and he knows how each thinks."

Elachi says that "for me now the joy of what I'm doing is really seeing all the young people at JPL carry it on. It looks like in the next decade we'll be launching as many spacecraft as we did in the last decade. We'll be looking for life in our solar system—Mars missions and Europa and Titan. Looking at the neighboring few thousand stars and seeing if there are planets around them. Taking their family portraits. And looking at the cosmic background, looking for gravitational waves, and what dark energy and dark matter are all about. And Earth observation—I started my career at JPL with Seasat, and my goal, before I retire, is to have an operational spaceborne imaging radar flying."

He may achieve this, too—a recent National Academy of Sciences report, setting goals for the earth sciences for the next decade, listed a mission called InSAR as one of the top three priorities. InSAR, for Interferometric SAR, would fly in a polar orbit to give global coverage of the planet and would track the movements of the ground under our feet—bulges that might signal upcoming volcanic eruptions, the stretching and compression of tectonic plates along fault lines that might herald an earthquake, and so forth—as part of a worldwide campaign to assess high-risk natural-hazard areas. InSAR would also measure and monitor ice motions, and keep tabs on the biomass—the amount and types of vegetation—tracking seasonal and longer-term variations to assess the effects of climate change. "It would be a nice bookend. It's been targeted for sometime in the 2012–2015 time frame." □

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