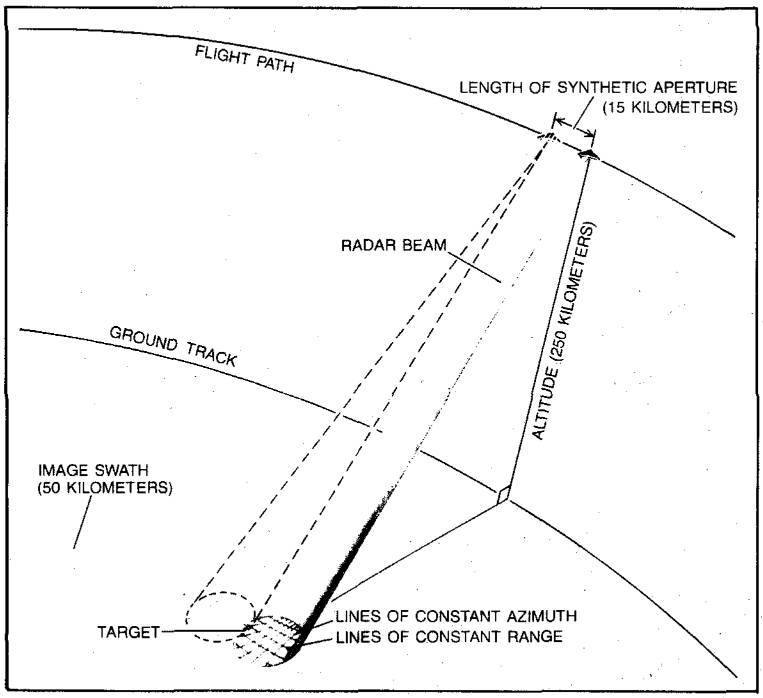
Seeing under the Sahara: Spaceborne Imaging Radar

by Charles Elachi

OUR EYES are sensitive to only a very narrow band of the electromagnetic spectrum. But in the last few years instruments launched into orbit around the earth have been viewing the earth at wavelengths beyond the visible and providing some richly detailed and often surprising images of the earth's surface, because the waves in different parts of the electromagnetic spectrum have different properties that determine what the instrument will "see." Landsat sensors operate in the visible and near infrared, while Seasat and the space shuttle Columbia have carried imaging radars, which "see" beyond the far infrared with the still longer microwaves. The Shuttle Imaging Radar (SIR-A) on Columbia sent back some particularly startling images of southern Egypt, revealing an unknown geomorphology buried beneath the eastern Sahara Desert — ancient river valleys and dry stream beds indicative of a much different past climate.



The Shuttle Imaging Radar (SIR-A) synthesized a 15-kilometer-long antenna by using the shuttle's motion along its flight path to put its 10-meter antenna in a series of locations and by then combining the signals coherently. The two-dimensional radar image is resolved by measuring its range (how long it takes the echo of the microwave pulse to return to the sensor) and its azimuth (determined by the Doppler shift, or change in frequency due to the relative motion of spacecraft and target).

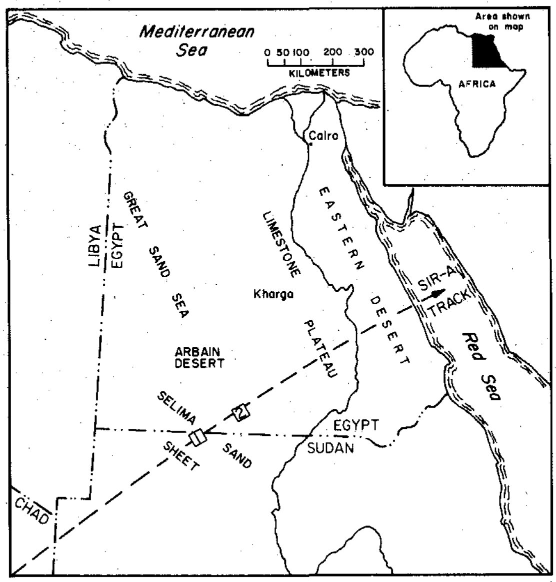
A radar instrument sends out microwave pulses that bounce off a target and echo back. In one dimension, the imaged scene can be resolved by measuring how long it takes the echo to return to the sensor. Doppler shifts of the echoes, the change to higher or lower frequencies, determine the resolution in the other dimension. So if we process and analyze all the information (time delay and spectral content) in the signals, we end up with a two-dimensional image. Differences in the radar backscatter are a function of the slope and roughness of the target and of its electrical properties. Radar waves are attenuated by the electrical properties of moist soil, but very dry sand would theoretically let the radar signal pass through a sand cover. In the eastern Sahara where it rains only about every 50 years, the sand is about as dry as soil can get, and the radar waves could probe through a sand layer a few meters thick.

The resolution of an image depends on the ratio of the operating wavelength to the size of the sensor aperture or, in the case of radar, the length of the antenna. Since the wavelength of microwaves is several orders of magnitude greater than that of light (SIR-A's signal had a 24-centimeter wavelength), the antenna necessary for adequate resolution in imaging would have to be enormous. This problem has been solved in much the same way that radio astronomers with very long baseline interferometry (VLBI) create an antenna with a baseline of many thousand kilometers by combining the signals from an array of antennas in different locations around the world. In what is called synthetic aperture radar we don't actually use an array of antennas but rather take advantage of the fact that the antenna is moving, using the motion of the satellite to put the antenna in different locations and then combining the signals coherently, thus synthesizing a long aperture. The signal from the antenna in one position on the flight path is added to the signal from the next position on the flight path and so on a couple of thousand times. So even though our antenna for the first Shuttle Imaging Radar was only 10 meters long, we actually had an antenna effectively 15 *kilometers* long.

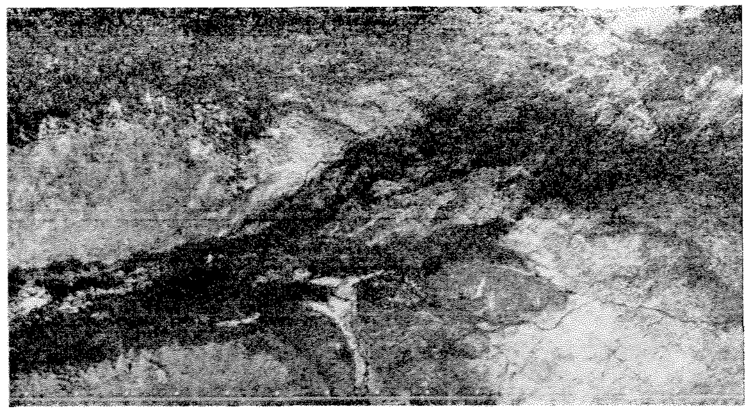
Because the shuttle could travel 15 kilometers in two seconds, we had to have stable clocks to be able to combine all the information precisely. We also needed a powerful computer to coherently add together the hundreds of millions of bits per second from the radar echoes to generate an image. Since the fastest computer available is still too slow to handle this rate of data processing in real time, we used optical holographic techniques in SIR-A to combine all the signals and generate the radar images.

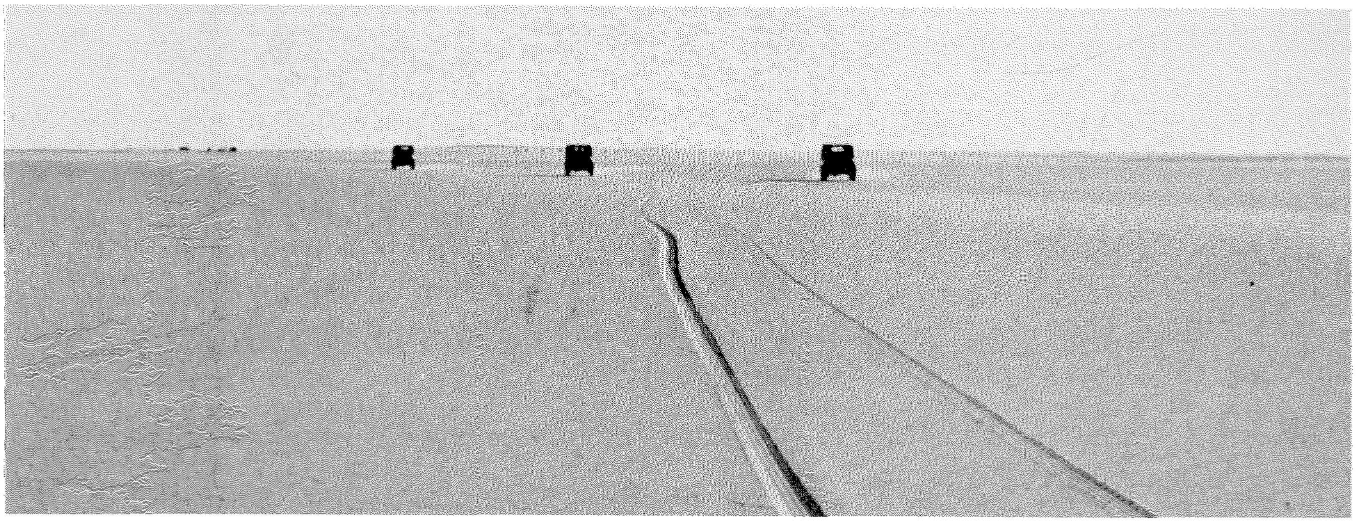
SIR-A flew on the second shuttle flight in November 1981, the first one to carry a scientific payload. When we picked up the film after the landing and took it back to JPL, everyone on the project stayed up all night working — developing the original film, processing it on an optical correlator, and developing the resulting film to get the image. At 6 a.m., when the first one emerged successfully (it was over Australia), we had a big champagne celebration.

We had collected a large amount of data on the morphology of many regions around the earth; we imaged in 50-kilometer-wide swaths a total of about 10 million square kilometers around the world, about the area of the United States. So it took us several months to develop all the film, which was more than 1000 meters long and weighed 20 kilograms. We developed it in pieces, and the Egypt piece was somewhere in the middle. We finally got to it two months after the mission because we weren't expecting anything particularly exciting from it. Even



The shuttle's path across the eastern Sahara is indicated by the dotted line originating in the lower left corner of the map. The box marked 1 represents the location of the SIR-A image below, which is compared with a Landsat image of the same area (bottom). At lower right in the radar image, channels can be seen that are practically invisible in the corresponding Landsat view. The box marked 2 on the map is the location of the images on page 8.





Although there are no roads in the Arabian Desert, trucks could drive easily across the sand "pavement."

though we knew that penetration through sand was theoretically possible, we weren't looking for it. This was a discovery purely by chance.

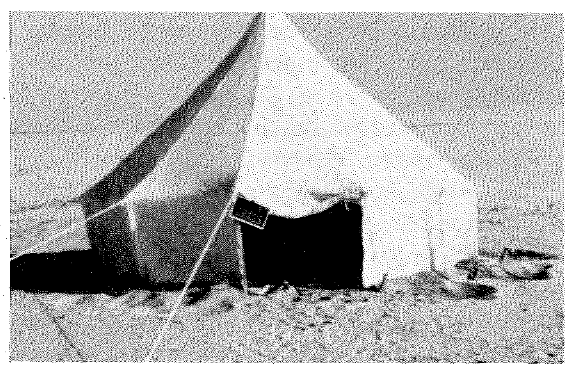
Our first reaction when we saw the drainage channels and valleys on the image was that we had the wrong track, that it was somewhere else, not the Egypt-Sudan border. One of the ten investigators on the team, Carol Breed, a geologist with the United States Geological Survey in Flagstaff, studies sand dunes and deserts all over the world. She had just returned from that area two months before the shuttle flight and swore there was no indication of such channels on the surface; she suggested that we might be penetrating the surface sand cover.

We rechecked our coverage and verified that the image was indeed over southern Egypt. It was kind of a slow process convincing ourselves that the radar had indeed penetrated the sand, but as soon as we realized it, we did some quick calculations and found that theoretically we really could be penetrating 2 to 6 meters. When we realized that we were seeing below the surface, we knew that it was a major discovery for the whole field of earth remote sensing. But the USGS co-investigators and I, as the principal investigator on the experiment, wanted to make sure it was really true. Not only were we curious from a geological standpoint, but our reputations were at stake. So we planned an expedition to Egypt to actually follow the same path as the shuttle to verify whether and how far we were seeing below the sand.

Seven scientists joined the expedition in September 1982: four geologists from USGS, an anthropologist from the University of Pennsylvania, and Ronald Blom and myself from JPL. The Egyptian Geological Survey organized the whole expedition — six jeeps, two trucks, tents, food, water, and everything we would need for two weeks in one of the most barren and desolate places on earth.

We flew from Cairo to Kharga, an oasis of about 10,000 people, which was the closest we could fly to the Selima Sand Sheet, part of the Arbain Desert (which, in turn, is part of the Eastern Sahara) straddling the border of Egypt and the Sudan. Then we had to drive, starting at 10 a.m. and arriving at midnight. There were no roads, but we could drive 60 mph on the sand because the surface is covered with a thin pavement of pebbles. This very fine, dry sand has accumulated over several thousand years, blown down by the prevailing winds from the Great Sand Sea to the north, and the top layer of pebbles formed a sort of pavement that

(Near right) The author, standing at right, poses for a desert portrait with some of the Egyptian workers. (Center) The sign on the camp tent warns people to keep off the grass. (Far right) Artifacts, such as this arrowhead, from 100,000 to 200,000 years old, were found lying on the desert surface.



doesn't blow into the air even in a high wind. The Arbain Desert is totally uninhabited. It's basically featureless, and the few rocky outcrops look much like the Viking Landers' close-up views of Mars. During the entire ride we didn't see a single piece of grass or anything green. Compared to this, the Mojave Desert is a lush garden. The aridity scale of this region is 200; that means that the capacity of the sun to evaporate moisture is 200 times greater than the amount of moisture coming from rain or condensation. In comparison, Death Valley has an aridity factor of 7.

Life in a scientific camp in the middle of such a desert was not as bad as you might think. Our Egyptian support crew put up all our tents and even made up our beds. It was almost as good as home. We also had a cook, but the food wasn't quite like home. The area was so dry that by the second day all the moisture had been sucked out of the pita bread, and for the next two weeks we ate pita crackers.

Our diet staple was duck; every night we had duck soup and then duck for dinner. The ducks stayed with our cook in the kitchen tent, where he also slept. We asked him how he picked a particular duck for that night's meal, and he told us that he chopped the head off the noisiest one that had kept him awake the previous night. After a couple of days the ducks got very quiet. We were really tired of duck by the time we got back to Kharga two weeks later at the end of the expedition and were eager for a steak or at least something different. But the only restaurant in town had only one item on the menu each night. I'm sure you can guess what it was *that* night.

In two weeks of ducks and digging we did find what we were looking for — evidence that the shuttle radar had indeed seen through the sand surface. A dozen Egyptian workers came with us to dig. For awhile they thought we had gone crazy from the sun, going out into the middle of nowhere and asking them to dig. After they dug these holes, they would see us all

Digging holes in the middle of nowhere (while the scientists photographed) made no sense to the Egyptians.

taking notes and photographs, and then we would go on to the next place and start all over again. Fortunately I know Arabic and could explain to them what we were doing.

It took us a while to accurately locate ourselves when all we could see was sand all over the place. We went to several places where we had seen interesting features on our radar images, and we must have dug about 40 holes. The sand depths in the holes ranged from 0.8 meters to 2.5 meters. In one area the thing we were looking for was the same white limestone that is exposed in a major plateau emerging from the sand to the east of this area, closer to the Nile Valley. In the radar image the exposed limestone looks very bright because it is a rough surface. The sand surface, which is perfectly smooth, should appear dark on the radar, but instead it looks just as bright as the exposed limestone. When our Egyptian workers dug through the sand, they did hit limestone. This convinced us that the radar was reflecting off the limestone bedrock beneath the sand.

We also found hundreds of human artifacts, such as arrowheads and hand axes, just lying on the surface. We weren't the first to make this discovery. Anthropologists have been interested in the area for the last 30 years, puzzled as to how such an inhospitable climate could have supported a population. They had even found cave drawings of domesticated animals. The artifacts we found are from the Acheulian period — 100,000 to 200,000 years old — but ostrich eggshells found by us and previous expeditions have yielded carbon-dated ages as young as 6,000 years. This is very recent even on a human time scale; the pyramids, for example, were built in northern Egypt about 5,000 years ago.

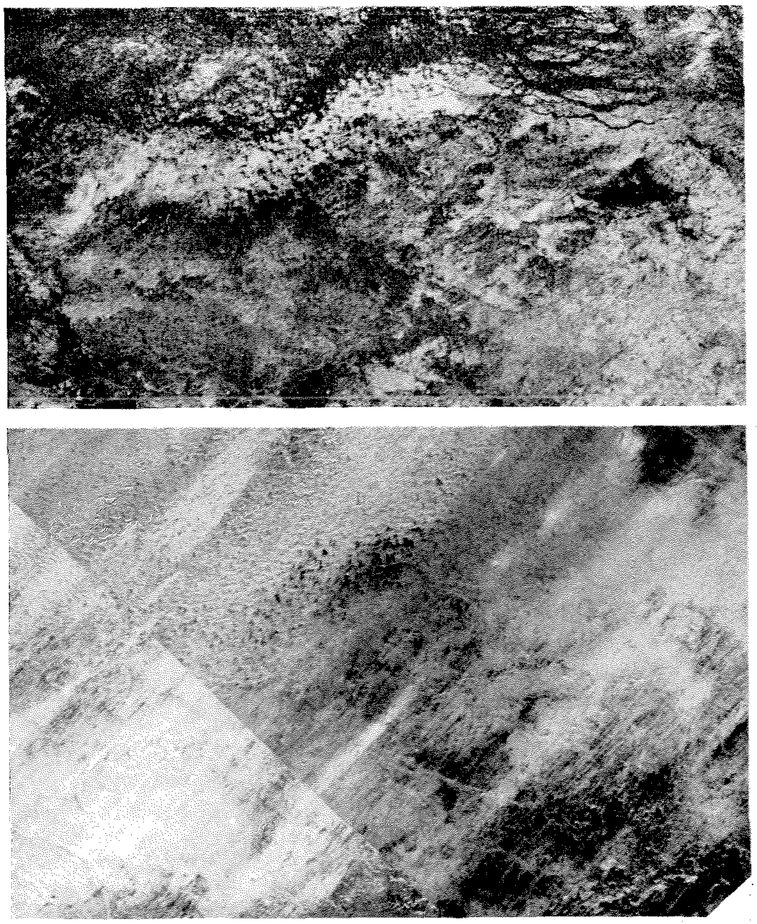
It is now generally thought that over the last

200,000 years the climate has been changing back and forth from very arid desert to a somewhat more savannah-like environment with vegetated areas. During the more hospitable periods, people and animals migrated from central eastern Africa up into the Sudan and Egypt. When it became arid again, all habitation ceased. Our discovery of the buried river valleys, some wider than the Nile, gives strong support to the hypothesis that the climate was indeed less arid in the past.

Another puzzle that our discovery helps solve is why the area is so flat. Usually such flatness is the result of fluvial activity. There *are* dry stream channels running down a large plateau to the west of the Arbain Desert but then disappearing under the sand. Our verification of the continuation of those rivers has helped explain some of the geologic history of the region.

By radar mapping the entire area, we hope to be able to explain much more of the geologic and hydrologic history of this desert region. A complete map could establish the locations of dry lakes and sites of likely ancient habitation, and uncover the evolution of the Nile and its tributaries and the drainage basins of northeast Africa. SIR-A was the first piece of scientific hardware to come back from space on the shuttle, and the same instrument, with a fair amount of modification and retitled SIR-B, will go up again on the shuttle in August 1984 to accomplish this task as well as investigate the radar penetration capability in other arid regions in China, South Africa, and Peru.

The SIR-A image (top) shows a region of drainages in the top right corner invisible to Landsat (bottom). These views are of the Arbain Desert at the site marked 2 on the map on page 5.



About 10 percent of the earth's surface is arid enough to get some radar penetration below the surface. A region doesn't have to be as dry as the Sahara, as we had originally thought. (Actually, radar can see four kilometers through Antarctic ice to the bedrock below and has discovered Mayan canal systems buried in the Guatemalan jungles, but that's another story.) We looked up some older radar images made by Seasat in 1978 of the Mojave Desert, which, as I mentioned before, is a garden spot compared to southern Egypt. And we saw some surprising features that didn't appear on photographs — dikes of harder rock extending beneath the alluvium. Recently a couple of team members went out to this particular site near Barstow and measured the depth of the alluvium at two meters, which is theoretically consistent with tests we had done with some of the drier sand from the Sahara (which, in theory, can be penetrated as far as six meters). Before SIR-B goes up we plan to bury reflectors, which will show up very bright on the radar image, at various depths to see how far below the surface we can see them.

A still more sophisticated instrument, SIR-C, has been proposed to fly in 1987. This one will send out signals at different frequencies, which will penetrate to different depths, and in a sense will be able to peel the different levels like an onion.

Radar is not just earth bound. In 1988 the Venus Radar Mapper mission will carry an instrument very similar to SIR-A to see through the total cloud cover of that planet and give us the first complete high-resolution map of its surface. Saturn's large moon Titan, as revealed in images sent back by Voyager, is also completely surrounded by clouds. Discussions are currently taking place about sending a radar mission to Titan by the end of this decade.

But it has been the technology of the past 20-30 years that has broadened our sight, allowing us to see beyond the small part of the electromagnetic spectrum that evolution allotted us, into the ultraviolet, the infrared, and the microwave, giving us a more complete picture of what's happening around us, a more in-depth understanding of the features of our own planet and, eventually, others. □