

Satellite Radar Interferometry



*From hundreds of kilometers away in space,
orbiting instruments can detect
subtle buckling of the earth's crust*

by Didier Massonnet

Tectonic plates creep silently past one another; glaciers flow sluggishly down mountains; ground level slowly rises and falls. The geologic forces that shape the surface of the earth usually act with such stealth that most people remain entirely unaware of them. But then the sudden break of a geologic fault or the explosive eruption of a volcano occurs in a populated area, and the devastation instantly makes thousands frighteningly aware that the solid earth is indeed prone to motion.

To better understand and, perhaps, forecast such catastrophic events, scientists have labored to measure the ongoing bending and stretching of the earth's crust. For this task, they have employed instruments of many types, from simple surveyor levels to sophisticated electronic positioning equipment. With all such methods, a person must travel to the site that is to be evaluated to set up some sort of apparatus and make observations. Yet this commonsensical requirement, as it turns out, is not an absolute prerequisite.

In 1985 I carried out a study—then an entirely theoretical exercise—that showed a way, without putting any equipment at all on the ground, to monitor the deformation caused by tectonic forces. At that time scientists had used satellites and aircraft for many years to construct radar images of the land below, and I envisioned that, with some additional tricks, these same devices could detect the subtle shifts that the surface of the earth undergoes. I immediately tried to convince geologists of the value of this endeavor, but most of the people I approached remained dubious. Measuring ground motion of only a few millimeters from hundreds of kilometers away in space seemed too miraculous to be feasible. Fortunately, I

was able to persuade my employer, the French Space Agency, to allow me to pursue this exciting prospect.

It would take years of diligent work, but my research group, along with other investigators around the world, has succeeded in carrying out what seemed quite fantastic to most scientists just a dozen years ago. My colleagues and I have used a new technique, called satellite radar interferometry, to map geologic faults that have ruptured in earthquakes and to follow the heaving of volcanic mountains as molten rock accumulates and ebbs away beneath them. Other researchers have harnessed radar interferometry to survey remote landslides and the slow-motion progress of glacial ice. Former skeptics must now concede that, miraculous or not, radar satellites can indeed sense barely perceptible movements of the earth's surface from far away in space.

Helpful Interference

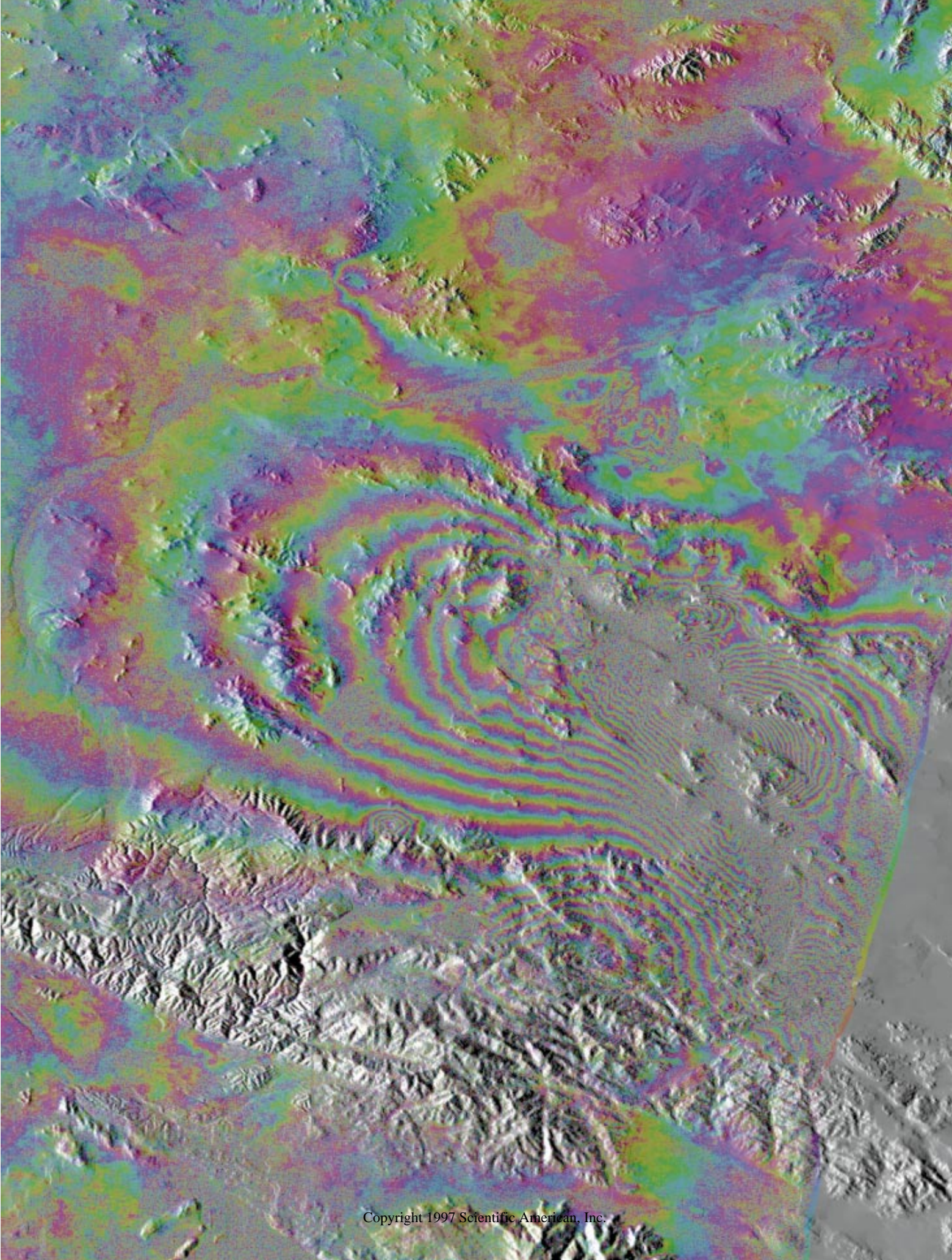
Although the dramatic successes of satellite radar interferometry are quite recent, the first steps toward accomplishing such feats took place decades ago. Soon after radar (shorthand for *radio detecting and ranging*) became widely used to track airplanes using large rotating dish antennas, scientists devised ways to form radar images of the land surface with small, fixed antennas carried aloft by aircraft [see "Side-Looking Airborne Radar," by Homer Jensen, L. C. Graham, Leonard J. Porcello and Emmett N. Leith; *SCIENTIFIC AMERICAN*, October 1977]. Even thick cloud cover does not obscure such images, because water droplets and ice crystals do not impede the radio signals. What is more, aircraft and orbiting satellites fitted with radar antennas can take these pictures equally well during

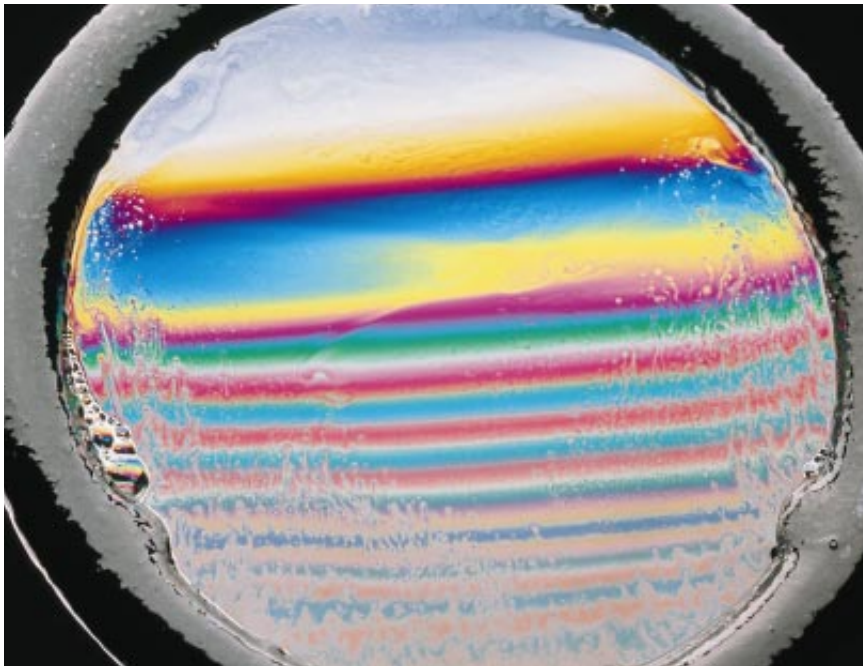
the day or night, because the radar provides, in a sense, its own light source.

But the distinction between radar imaging and conventional aerial photography is more profound than the ability of radar to operate in conditions that would cause optical instruments to falter. There are fundamental differences in the physical principles underlying the two approaches. Optical sensors record the amount of electromagnetic radiation beamed from the sun (as countless independent light waves, or photons) and reflected from the ground. Thus, each element of the resulting image—called a pixel—is characterized by the brightness, or amplitude, of the light detected. In contrast, a radar antenna illuminates its subject with "coherent" radiation: the crests and troughs of the electromagnetic wave emitted follow a regular sinusoidal pattern. Hence, radar instruments can measure both the amplitude and the exact point in the oscillation—called the phase—of the returned waves, whereas optical sensors merely record the quantity of reflected photons.

A great benefit arises from measuring phase, because radar equipment operates at extremely high frequencies, which correspond to short radio wavelengths. If a satellite radar functions, for

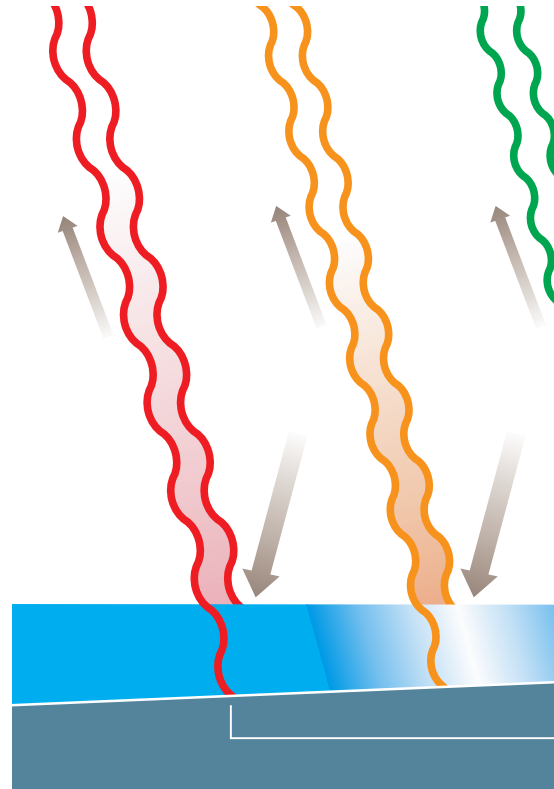
INTERFERENCE FRINGES (*colored bands at right*) obtained from a sequence of radar scans by the ERS-1 satellite (*above, left*) show the deformation of the ground caused by an earthquake near Landers, Calif., in 1992. Each cycle of interference colors (*red through blue*) represents an additional 28 millimeters of ground motion in the direction of the satellite. The radar interference caused by the mountainous relief of the area (*black-and-white background*) was removed to reveal this pattern of ground deformation.





RICHARD MEGNA Fundamental Photographs

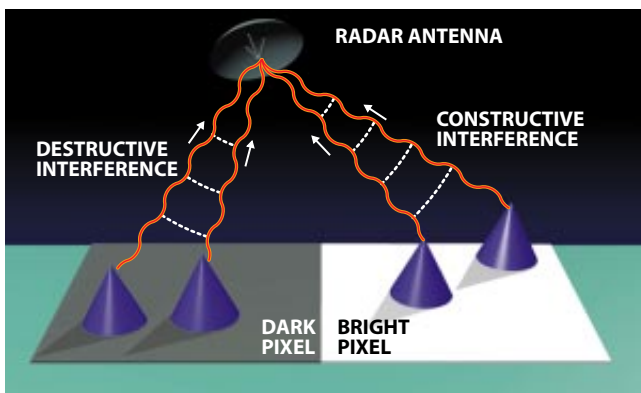
SOAP FILM of tapering thickness can separate light into its component colors (*above*), each of which corresponds to a particular wavelength of electromagnetic radiation. A fringe of one color shows where the light rays of that wavelength reflect from the top and bottom surfaces of the thin film and combine constructively (*right*).



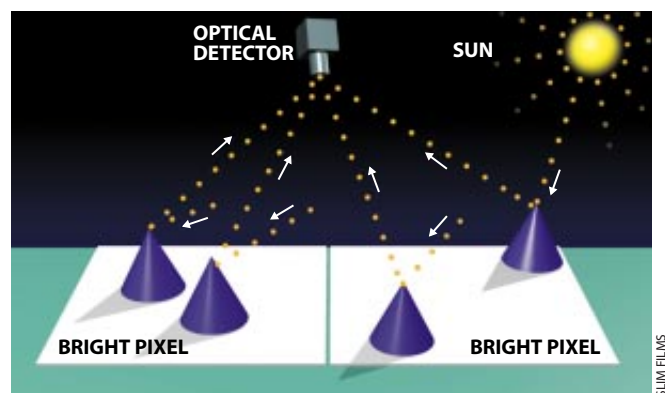
instance, at a frequency of six gigahertz (six billion cycles per second), the radio signal will travel earthward at the speed of light for only five centimeters during the tiny amount of time the wave takes to complete one oscillation. If the distance from the radar antenna to a target on the ground is, for example, exactly 800 kilometers, the 1,600-kilometer round-trip (for the radar signal to reach the earth and bounce back up) will correspond to a very large—but whole—number of wavelengths. So when the wave returns to the satellite, it will have just completed its final cycle, and its

phase will be unchanged from its original condition at the time it left. If, however, the distance to the ground exceeds 800 kilometers by only one centimeter, the wave will have to cover an additional two centimeters in round-trip distance, which constitutes 40 percent of a wavelength. As a result, the phase of the reflected wave will be off by 40 percent of a cycle when it reaches the satellite, an amount the receiving equipment can readily register. Thus, the measurement of phase provides a way to gauge the distance to a target with centimeter, or even millimeter, precision.

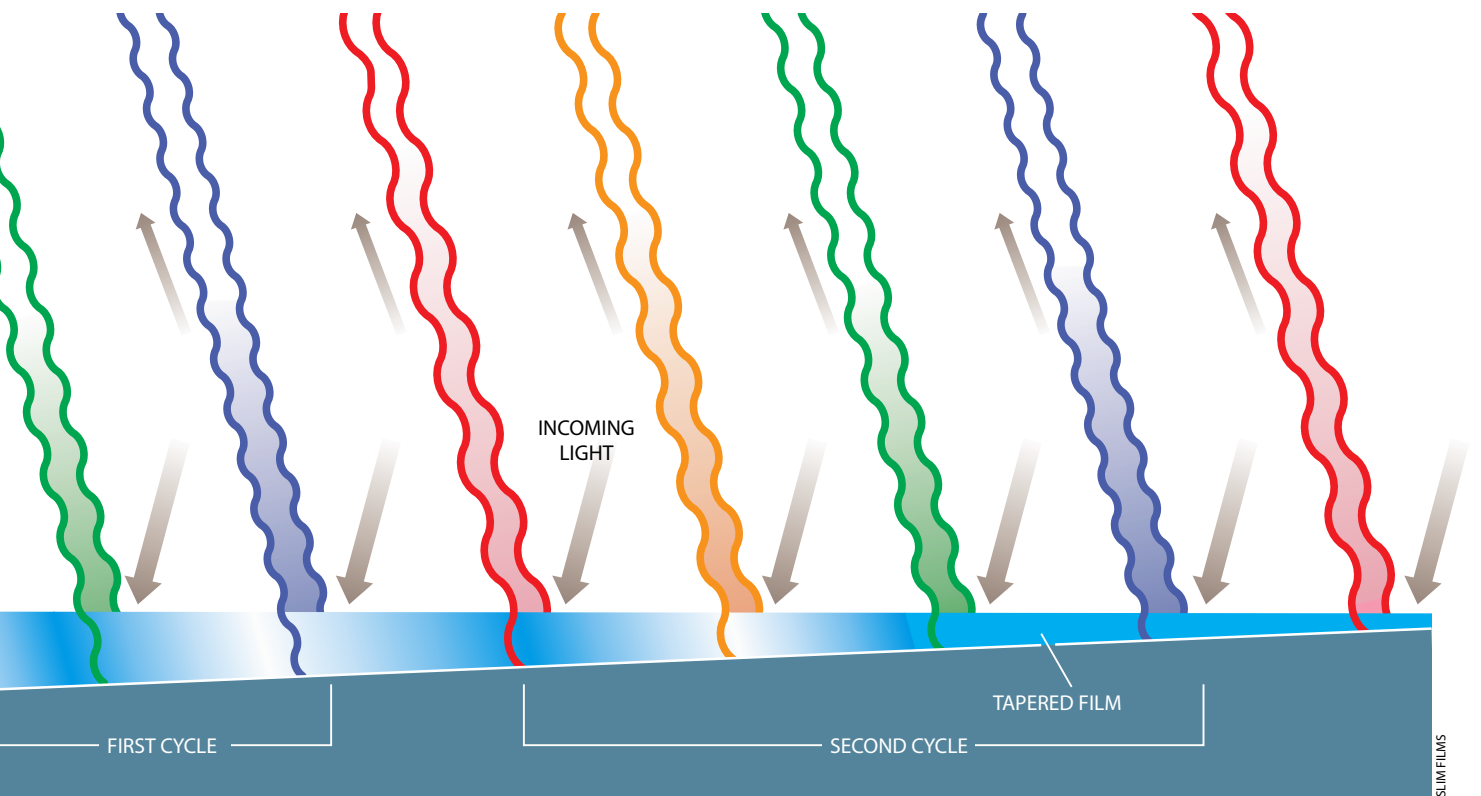
Yet for decades, most practitioners of radar imaging completely overlooked the value of phase measurements. That oversight is easy to understand. A single pixel in a radar image represents an appreciable area on the ground, perhaps 100 square meters. Such a patch will generate multiple radar reflections from the countless small targets contained within it—scattered pebbles, rocks, leaves, branches and other objects—or from rough spots on the surface. Because these many radar reflections will combine in unpredictable ways when they reach the antenna, the phase mea-



RADAR REFLECTIONS (*red lines*) from a pair of nearby objects can interfere constructively (*right*) or destructively (*left*). Minor differences in geometry can therefore give rise to large changes in the amplitude of the pixels in a radar image.



OPTICAL REFLECTIONS from a pair of objects always produce a similar number of reflected photons (*orange*), regardless of the exact position of the objects. Thus, the brightness of a pixel does not vary with slight shifts in the configuration of reflectors.

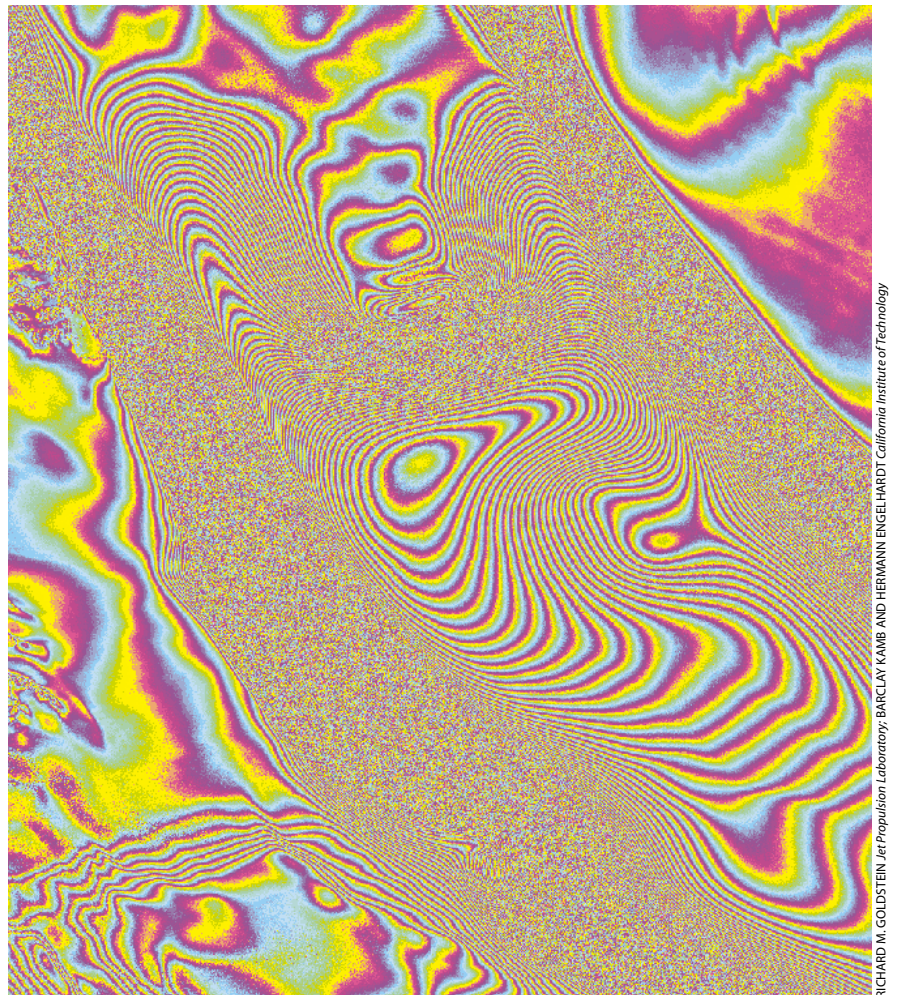


sured for a given pixel seems random. That is, it appears to have no relation to the phase measured for adjacent pixels in the radar image.

The amplitude associated with a given pixel in such an image will, however, generally indicate whether many or few elementary reflectors were present at the corresponding place on the ground. But the amplitude measurements will also have a “noisy” aspect, because the individual reflections contributing to one pixel can add together and make the overall reflection stronger (constructive interference), or they can cancel one another out (destructive interference). This phenomenon in the reflection of coherent radiation—called speckle—also accounts for the strange, grainy appearance of a spot of laser light.

For many years, scientists routinely overcame the troubling effects of speckle by averaging the amplitudes of neighboring pixels in their radar images. They followed this strategy in an attempt to

GLACIAL ICE at the margins of Antarctica flows toward the sea relatively rapidly along confined channels, or “ice streams,” such as the one mapped here using a pair of satellite radar images. Two parallel bands of highly sheared ice (*speckled areas*) mark the borders of the ice stream.



mimic the results of conventional black-and-white aerial photography, and to that end they were quite successful. Yet by averaging amplitudes, they lost all knowledge of the phase of the radar reflections, which unbeknownst to them contained much hidden information.

But that state of affairs did not continue indefinitely. In 1974 L. C. Graham, working at Goodyear Aerospace, first demonstrated that it was possible to take advantage of the phase measured by an airborne radar. Then, in the early 1980s, scientists at the Jet Propulsion Laboratory in Pasadena, Calif., showed that they could extract similar results from the phase measured by SEASAT, the first civilian radar satellite, which was launched in 1978 (but worked for only three months). They did so by comparing two radar images taken from roughly the same position but at different times. In a sense, that exercise was akin to taking two widely separated frames of time-lapse photography. Although the phase itself appeared random every time, the phase differences between corresponding pixels in the two radar images produced a relatively straightforward interference pattern.

In principle, if two sequential satellite images are taken from exactly the same position, there should be no phase difference for any pair of corresponding pixels. But if the scene on the ground changes ever so slightly in the interim between the two radar scans, the phases of some pixels in the second image will shift. Radar satellites can thus track minute movements of the earth's surface.

In the usual presentation, radar "interferograms" produced in this way show ground motion using a series of colored bands, which are meant to resemble the interference fringes produced from a thin film of soap or oil. One complete set of colored bands represents a shift of half a wavelength, because the radar wave must cover the round-trip distance back and forth. For the European satellite ERS-1, a set of fringes marks a change of just three centimeters in the amount of ground motion. Although these fringes record only the component of ground movement that is in the direction of the satellite (or directly away from it), they nonetheless prove extraordinarily useful, because a single radar view can span vast stretches of land that would take years for geologists and surveyors to map in similar detail.

Radar interferometry does, however,

require that the many small reflective objects contributing to each pixel—be they rocks or pockets of vegetation—remain unchanged (so that the random component of the phase is exactly the same for both images). This rather stringent condition creates some bothersome limitations. If the time elapsed between the acquisition of the two images is excessive, the small targets encompassed by each pixel will shift erratically. Leaves can fall off trees; clumps of grass might grow where there were none before; rainstorms may wash out ruts in the ground. Another, even more subtle, problem arises: if the two radar images are taken from different vantage points, the changing geometry will also introduce phase changes.

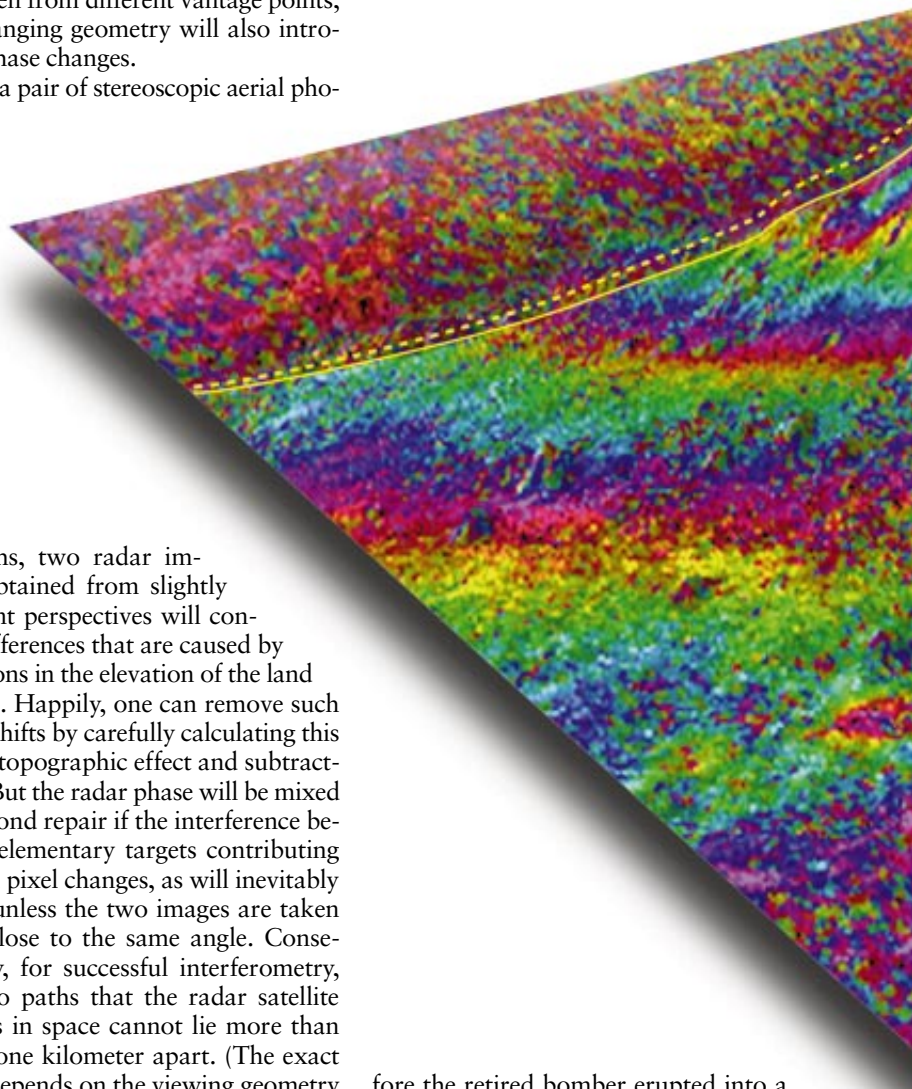
Like a pair of stereoscopic aerial pho-

tographs, two radar images obtained from slightly different perspectives will contain differences that are caused by variations in the elevation of the land surface. Happily, one can remove such phase shifts by carefully calculating this purely topographic effect and subtracting it. But the radar phase will be mixed up beyond repair if the interference between elementary targets contributing to each pixel changes, as will inevitably occur unless the two images are taken from close to the same angle. Consequently, for successful interferometry, the two paths that the radar satellite follows in space cannot lie more than about one kilometer apart. (The exact value depends on the viewing geometry and the particulars of the radar satellite used.) The four radar satellites now in operation—the Canadian Radarsat, the European ERS-1 and ERS-2, as well as the Japanese JERS-1—usually comply with this requirement, although none was designed with interferometry in mind. Aircraft have a much more difficult time flying along the same path

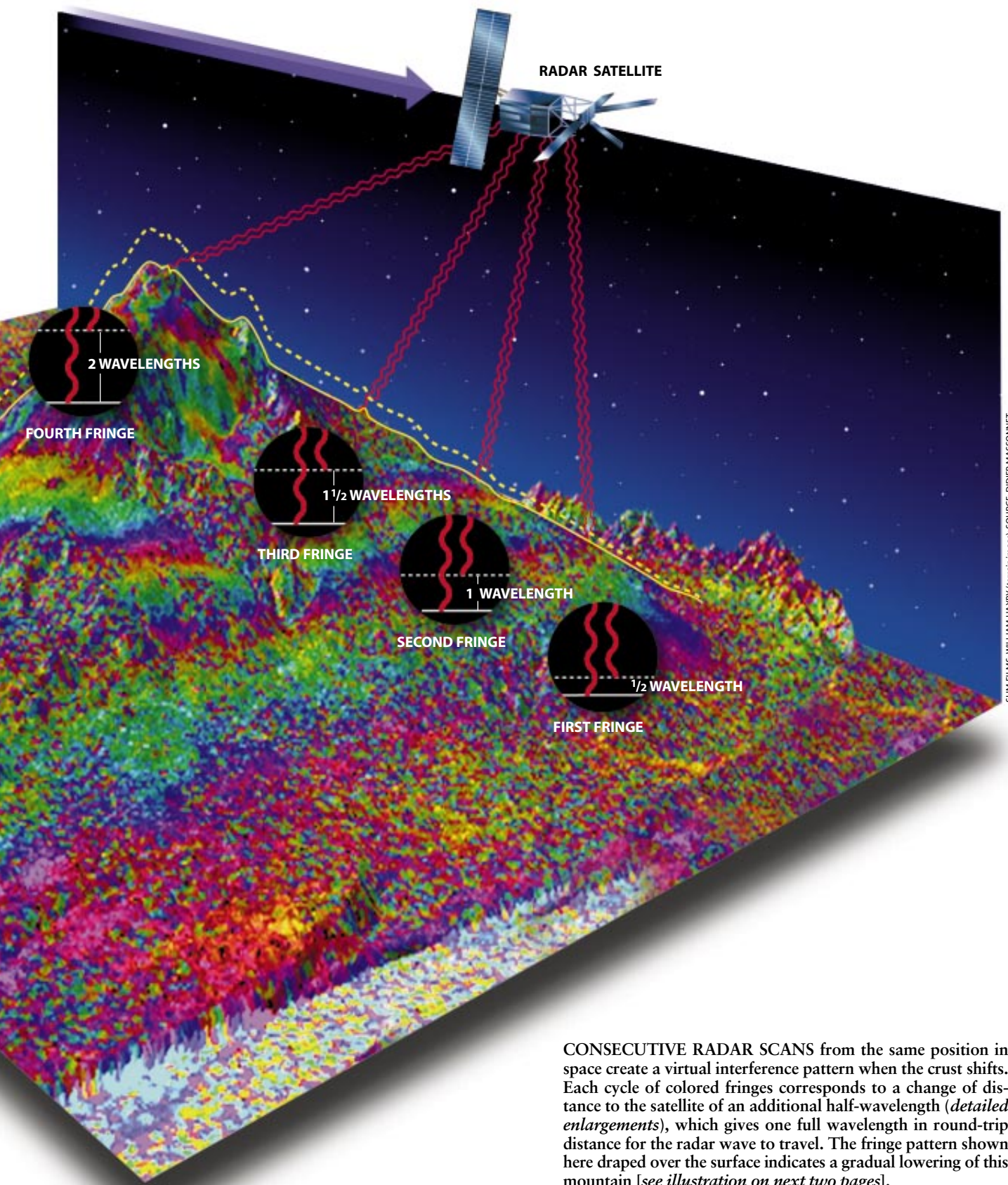
twice, a difficulty I did not fully appreciate when I first began working to prove the concept.

Watching the Earth Move

Shortly after I proposed that radar interferometry could detect tectonic motion, my colleagues and I began experiments to demonstrate the idea using an airborne radar. Our progress was set back severely when the vintage B-17 flying fortress that usually carried our radar crashed on takeoff in 1989. Fortunately, the crew managed to escape be-



fore the retired bomber erupted into a fireball. But we had to start afresh. Rather than adapting our equipment to another aircraft, we attempted to demonstrate our scheme with an airborne radar provided by some German colleagues. Yet we missed our goal, because the aircraft was not able to fly sufficiently close to its previous path. A. Laurence Gray and his colleagues at the Canadian



SLIM FILMS; WILLIAM HAXBY (terrain image); SOURCE: DIDIER MASSONNET

CONSECUTIVE RADAR SCANS from the same position in space create a virtual interference pattern when the crust shifts. Each cycle of colored fringes corresponds to a change of distance to the satellite of an additional half-wavelength (*detailed enlargements*), which gives one full wavelength in round-trip distance for the radar wave to travel. The fringe pattern shown here draped over the surface indicates a gradual lowering of this mountain [see illustration on next two pages].

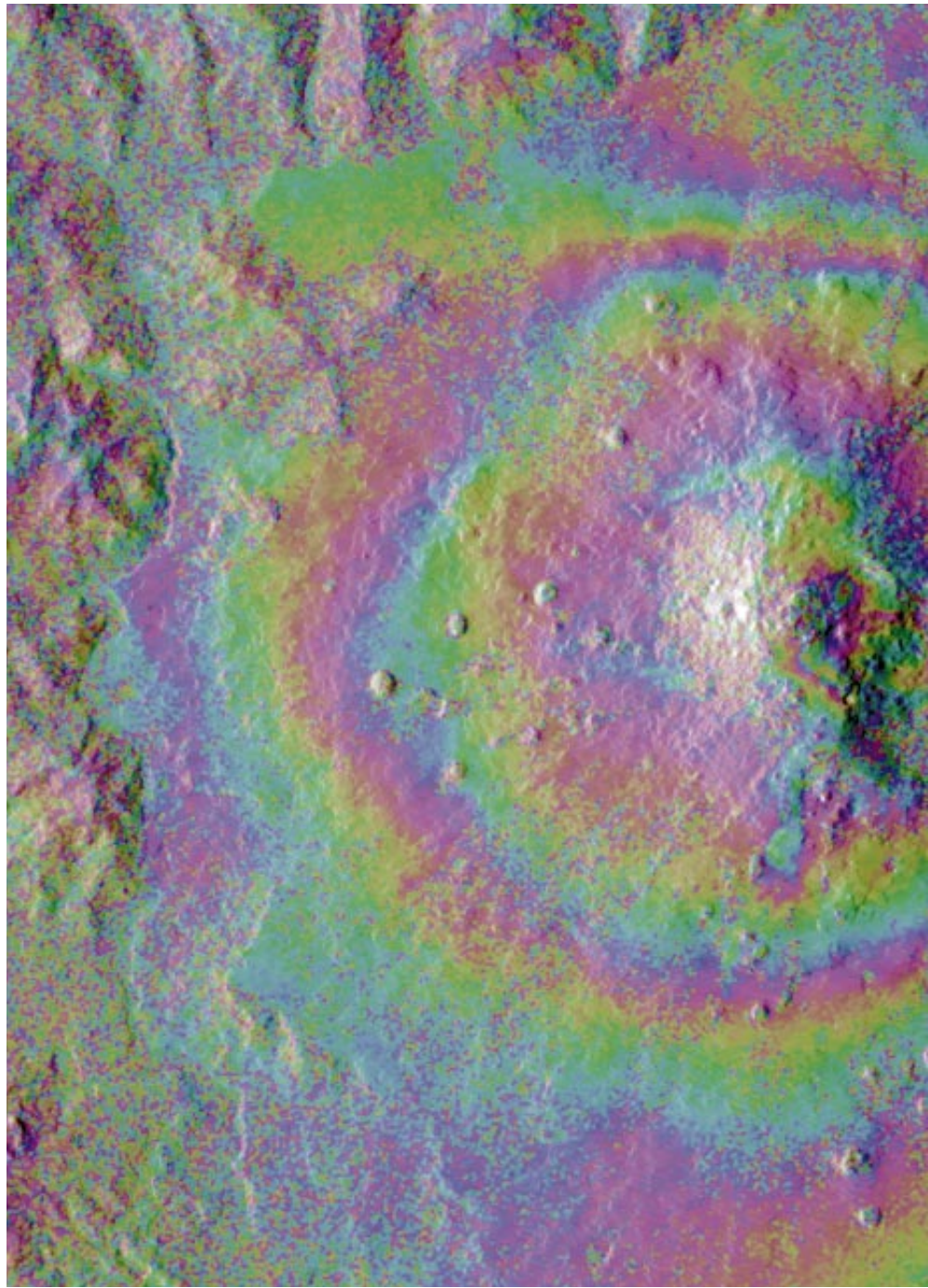
MOUNT ETNA, a volcanic peak in Sicily, subsided as magma drained away below it. An interferogram produced by two radar scans made 13 months apart by the ERS-1 satellite displays four cycles of interference fringes, indicating that the top of the mountain settled by about 11 centimeters during this interval.

Center for Remote Sensing accomplished this tour de force in 1991.

The next year a major earthquake struck near the town of Landers in southern California, and my colleagues and I realized that this desert locale might be an ideal place to test whether a satellite radar could measure the associated deformation of the earth's crust. So we assembled all the radar images of the area available from the ERS-1 satellite and formed several interferograms by combining one image taken before the earthquake with another one taken afterward from approximately the same position. Because the satellite tracks were never identical, the rugged relief in the region affected these interferograms markedly. Yet with the help of a digitized map of elevations, we were able to calculate the topographic contribution and remove it. Doing so unveiled a tantalizingly rich picture of interference fringes. But were these colored bands truly showing what the earthquake had done to the surface of California's Mojave Desert?

To test whether our representation of ground movement was indeed valid, we calculated an idealized interferogram based on measurements that geologists had made for the motion along the main fault. The model interferogram showed a striking resemblance to the radar pattern we found, and that match bolstered our confidence enormously. We were also pleased to see that in some places the fringe pattern revealed tiny offsets on other geologic faults known to be crisscrossing the area. In one case, we detected a mere seven millimeters of motion on a fault located 100 kilometers away from where the quake had struck.

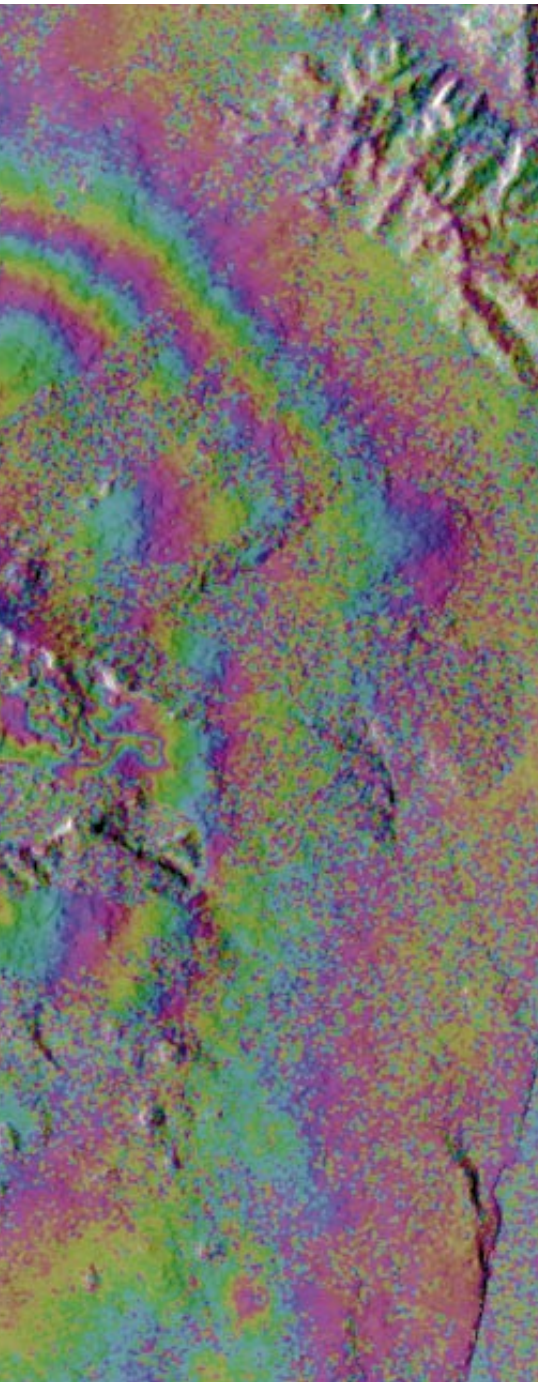
Soon after our study of the Landers earthquake, Richard M. Goldstein of the JPL and his co-workers used radar interferometry to track the movement of glacial ice in Antarctica. They took advantage of an exceptional opportunity presented by the ERS-1 satellite when it passed within a few meters of the path it had followed six days previously. Because the satellite had taken "before"



and "after" radar images from virtually the same position, the topography of the glacier did not influence the pattern of fringes, and the resulting picture directly indicated the motion of the ice. That image displayed movement of an ice stream (where flow is relatively rapid) in superb detail.

Having shown its ability to track slipping faults and surging glaciers, radar interferometry had displayed great promise by 1993, and we wondered whether the technique could detect deformation that was even more subtle. So we next

experimented with a set of radar images of the Mount Etna volcano in Sicily. That volcano had been nearing the end of an eruptive cycle during an 18-month period in 1992 and 1993 when the ERS-1 satellite passed over it 30 times. With those many radar images and an elevation map of the area, my colleagues and I were able to produce dozens of interferograms that were free from topographic effects. Some of our results were clearly degraded by changes in vegetation on the flanks of the volcano. (Certain pairs of images used in construct-



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ing these interferograms spanned many months; others encompassed more than a year.) Nevertheless, with the help of researchers at the Institute for the Physics of the Earth in Paris, we were able to follow the deflation of Mount Etna, as the last of the magma erupted and the pressure within the mountain declined. Our radar images showed that Mount Etna subsided by two centimeters each month during the final seven months of eruption. This deformation extended for a large distance around the volcano, suggesting that the subterranean magma chamber was much deeper than geologists had previously thought.

Although Mount Etna is located in one of the best surveyed parts of the world, radar interferometry uncovered surprising revelations (just as it had done by locating minute cracks in the Mojave Desert). The technique should prove even more valuable for studying the hundreds of other active volcanoes on earth that can be viewed using the existing radar satellites. Radar interferometry cannot replace conventional ground surveys, but at the very least it should serve to focus the attention of geologists toward slowly awakening volcanoes as they begin to inflate and become dangerous. This new form of remote sensing also offers a way to monitor volcanic peaks in otherwise inaccessible locales.

As we probe more places, we have come to realize that short-lived variations in the atmosphere and ionosphere can sometimes alter the fringe pattern. Changes in soil properties, too, can induce the interference fringes to shift, even though the ground does not actually move. Such effects can complicate the interpretation of radar interferograms, and we have had to design some clever procedures to discriminate between them and true ground motion.

But looked at more positively, these secondary influences represent features of the earth that are also of inherent interest—and it may prove a boon to some scientists that a radar satellite can map these features in great detail.

More Surprises to Come

What else is in store for radar interferometry? Forecasting specific advances is difficult, but one can safely predict that scientists will find plenty of opportunity to apply this technique all over the world. The four radar satellites currently in operation can scan most of the earth's surface, and Europe, Japan and Canada will soon launch others to add to the fleet of orbiting sensors. My colleagues and I have investigated possible future missions by studying the accuracy that a specially designed satellite could achieve in repeating its trajectory. Such an exact-repetition satellite would be the ideal platform for radar interferometry. The same satellite could also serve to measure surface elevation if its trajectory were purposely shifted in order to create the proper stereoscopic effect. (The National Aeronautics and Space Administration is, in fact, planning a space shuttle mission for the year 2000 to exploit this use of radar interferometry.) In this way, the overall topography of the entire planet could finally be obtained.

Will radar interferometry be able to detect the precursory motions needed for scientists to predict earthquakes and volcanic eruptions? As of yet, no one can say for sure. But in scientific research every new tool brought to bear invariably uncovers crucial facts and deepens the understanding of fundamental principles. Radar interferometry will undoubtedly do the same for the study of the solid but ever restless earth. SA

The Author

DIDIER MASSONNET entered the Ecole Polytechnique in 1979, where he began his scientific training. He later specialized in signal processing and ultimately completed a doctoral thesis on radar imaging at the University of Toulouse. In 1984 he joined the French Space Agency (CNES) but spent his first year at the Jet Propulsion Laboratory in Pasadena, Calif., working with American scientists on data obtained from a shuttle imaging radar mission. He then developed radar processing at CNES. Since 1996, he has been deputy manager of CNES's image-processing division in Toulouse.

Further Reading

RADAR IMAGES OF THE EARTH FROM SPACE. Charles Elachi in *Scientific American*, Vol. 247, No. 6, pages 54–61; December 1982.
MAPPING SMALL ELEVATION CHANGES OVER LARGE AREAS: DIFFERENTIAL RADAR INTERFEROMETRY. A. K. Gabriel, R. M. Goldstein and H. A. Zebker in *Journal of Geophysical Research: Solid Earth and Planets*, Vol. 94, No. B7, pages 9183–9191; July 10, 1989.
SAR GEOCODING: DATA AND SYSTEMS. Edited by G. Schreier. Wichmann, 1993.
THE DISPLACEMENT FIELD OF THE LANDERS EARTHQUAKE MAPPED BY RADAR INTERFEROMETRY. D. Massonnet et al. in *Nature*, Vol. 364, pages 138–142; July 8, 1993.
DEFLATION OF MOUNT ETNA MONITORED BY SPACEBORNE RADAR INTERFEROMETRY. D. Massonnet, P. Briole and A. Arnaud in *Nature*, Vol. 375, pages 567–570; June 15, 1995.