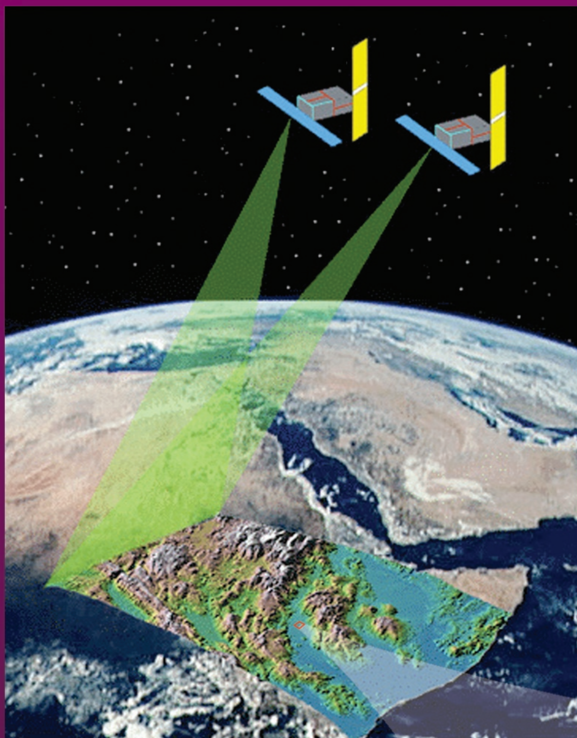
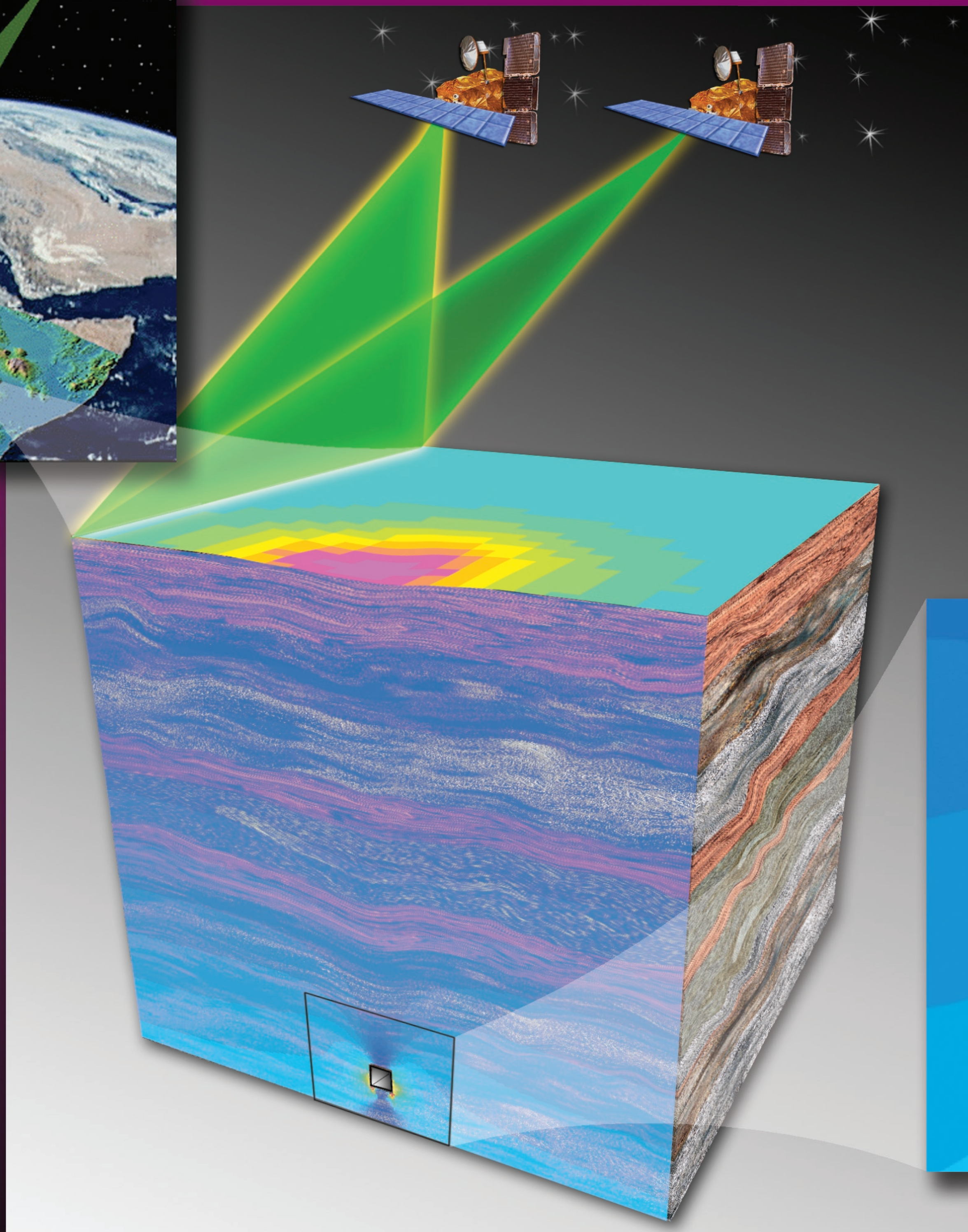
Monitoring





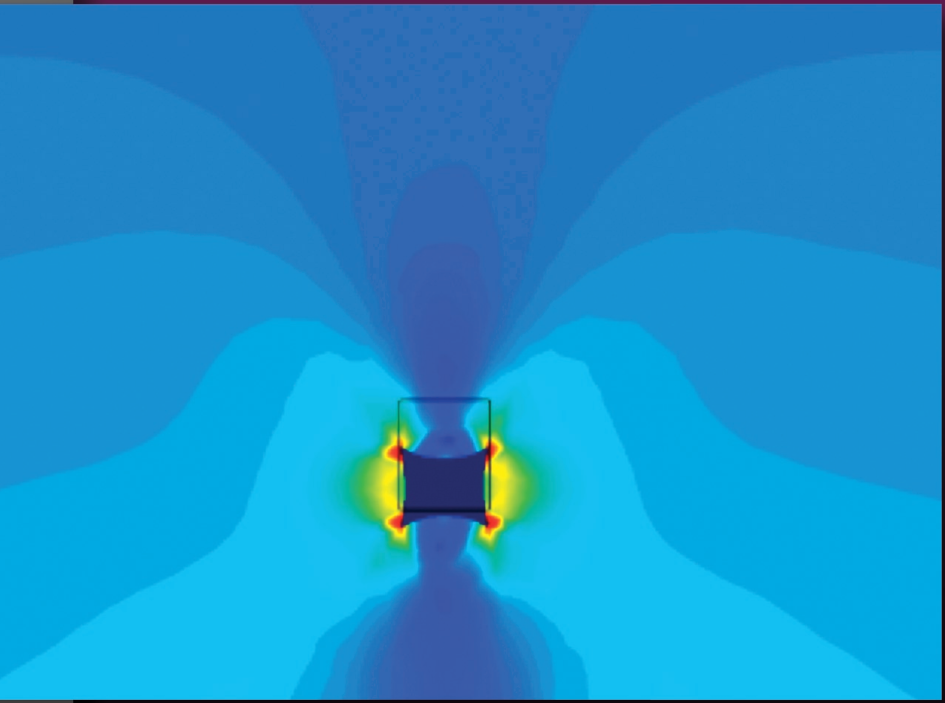
(top) Radar images are taken from a satellite making a repeat pass over an area of Earth's surface. (*Image courtesy of Howard Zebker, Stanford University.*) (center) By analyzing these images, researchers can detect surface changes caused by an underground cavity (shown), a clandestine nuclear explosion, or an environmental hazard. (right) Researchers can also run simulations to characterize deformation.

Earth's Subsurface from Space

A new application of radar technology is helping scientists detect very small subsurface changes.

SINCE 1945, when U.S. scientists conducted the first nuclear test, Trinity, nations have been signatories to a series of treaties designed to reduce the scope of tests and eliminate nuclear testing. For example, the Limited Test Ban Treaty in 1963 banned tests in the atmosphere, under water, and in space, and the Threshold Test Ban Treaty in 1976 established a yield limit of 150 kilotons (150,000 tons of TNT) for underground testing. The Comprehensive Test Ban Treaty (CTBT), signed in 1996, banned all nuclear tests.

Although the U.S. has not ratified the CTBT, it has a significant effort aimed at monitoring worldwide for nuclear explosions. Detection and identification of seismic events is one of the primary monitoring methods. Concern about the possibility of concealing a nuclear test by deliberately minimizing its seismic signals has led to an interest in developing tools that can complement standard seismic monitoring techniques and increase the precision of detecting, identifying, and characterizing underground explosions.



One such method is the use of radar images from satellites. Laboratory geophysicist Paul Vincent is leading a team that is applying a radar imaging technology to detect near-vertical surface deformations measuring less than 1 centimeter caused by underground disturbances.

Called interferometric synthetic aperture radar (InSAR), the technique can be used to monitor Earth's surface from space and possibly detect clandestine underground nuclear tests. InSAR has become a standard tool for mapping changes to Earth's surface caused by earthquake faults; glaciers; and oil, gas, and geothermal reservoirs. Livermore's Laboratory Directed Research and Development Program provided the initial funding for applying InSAR to deformation problems, and the Department of Energy (DOE) is sponsoring ongoing InSAR research.

For decades, DOE has funded Livermore research to monitor underground nuclear testing. Vincent says, "The challenge with monitoring is not only in detecting signals from small nuclear explosions down to a very low magnitude but also in discriminating them from nonnuclear events, such as earthquakes and mining explosions." More than 100,000 earthquakes similar in seismic magnitude to a small nuclear explosion occur in the world every year. Many of these are disregarded because of their depth or similarity to other events known to be nonnuclear, such as mine blasting. However, many others are not so easily identified. By combining seismic techniques developed over the past 40 years with InSAR images, Livermore researchers hope to increase international confidence in monitoring for underground nuclear testing.

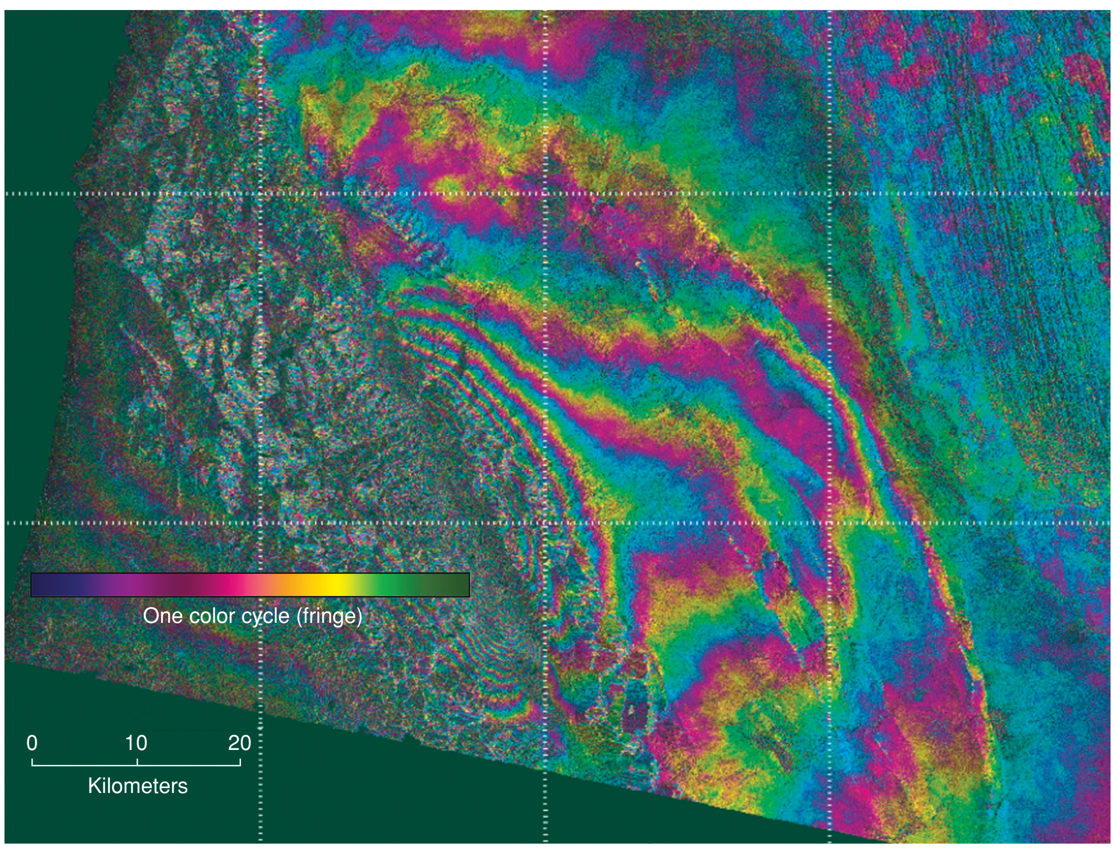
Advances in Radar Technology

In 1978, the National Aeronautics and Space Administration (NASA) launched its Earth-orbiting remote-sensing satellite, Seasat, which was designed to gather information about Earth's oceans. Seasat was the first satellite to use a new type of radar technology, called synthetic aperture radar (SAR). A SAR system "synthesizes" a large antenna by collecting a series of radar pulse returns as the satellite moves along its flight track, which results in increased image resolution. Because a moving SAR antenna can collect radar returns in two directions (range and azimuth), two-dimensional (2D) images can be constructed.

SAR has advantages over other remote-sensing techniques. For example, SAR provides its own illumination in the form of microwaves, so it can image any time of day or night without the need for sunlight. The wavelengths of the microwaves range from 1 to 30 centimeters, which are much longer than those of visible or infrared light. Thus, SAR's longer wavelengths can penetrate cloudy conditions that are opaque to visible and infrared instruments. Also, SAR satellites provide a map view of entire swaths of Earth's surfaces.

SAR's microwave signals or pulses—transmitted at 1,700 times per second—are Doppler-shifted as they are reflected back to the antenna. That is, waves in front of the satellite register a higher frequency, or positive Doppler shift, and waves behind the satellite register a lower frequency, or negative Doppler shift. The Doppler shift registers as zero for ground regions (pixels) directly broadside of the antenna at acquisition time. The zero Doppler allows for the correct placement of each radar return echo along the flight path (azimuth) direction. Researchers use the zero Doppler associated with each azimuth return to construct a 2D SAR image.

Each pixel in a SAR image is represented by a complex number from which the magnitude and the phase can be



This interferogram is based on two radar images taken from the same viewing angle at different times. The fringe pattern shows surface displacement from an earthquake that ruptured up to the surface. Each fringe (a cycle through all of the colors) represents 28 millimeters of near-vertical surface displacement. By counting the number of fringes from the outer edge of the interferogram toward the center of the fringe pattern, scientists can determine the total deformation.

calculated. The magnitude represents how much power from the original transmitted pulse is reflected back to the antenna from a given ground pixel. The phase, or fractional wavelength of the echo, can be used to extract range information similar to what can be obtained from conventional radars, but SAR data are much more precise.

Detecting Subtle Surface Changes

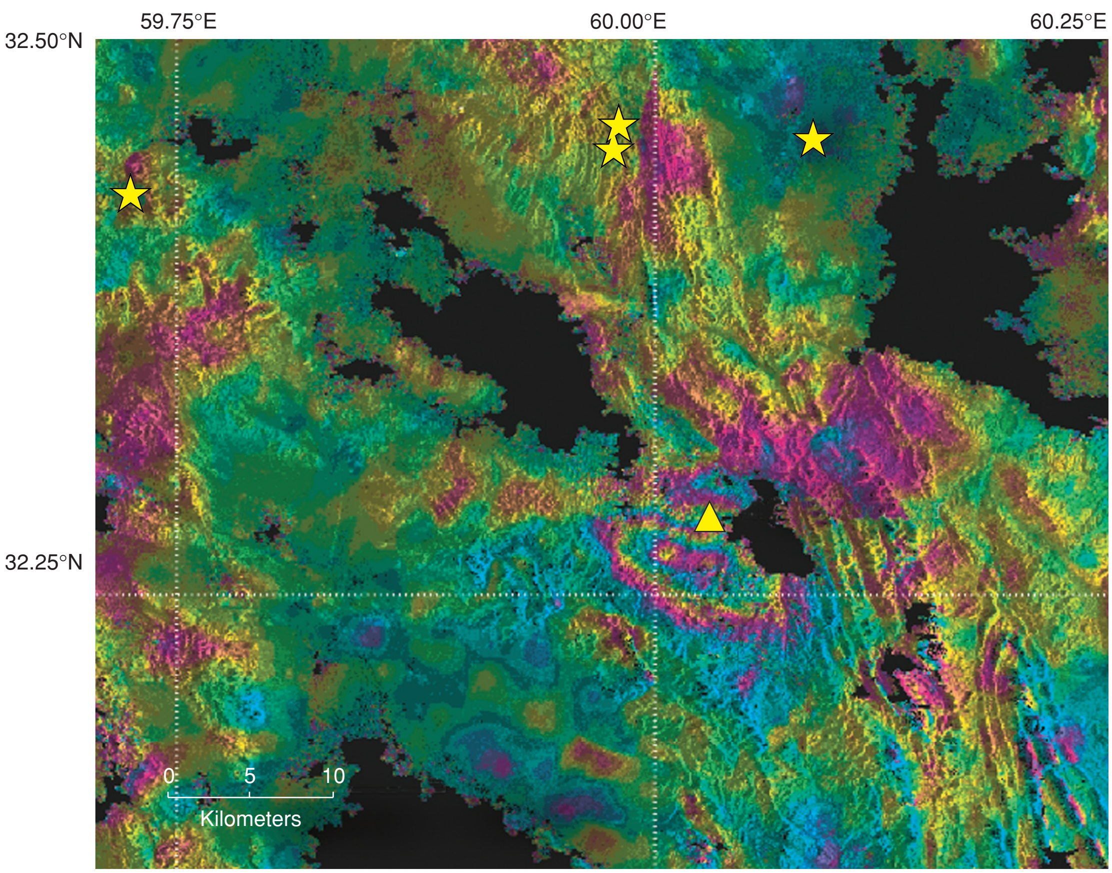
To convert the raw SAR data into maps showing surface deformation (interferograms), Vincent's team uses a combination of open-source and commercial software. Researchers look for common points between two SAR images and line up each of the pixels in a frame. Then they apply algorithms to obtain the phase difference. When two SAR images of the same ground region are acquired from similar viewing angles, the phases of the two images can be interfered (subtracted) pixel by pixel. This process creates interferometric fringes, producing an image called an interferogram. A fringe appears on an interferogram as a cycle of arbitrary colors, with each cycle representing 28 millimeters of near-vertical surface displacement.

Two methods were devised to remove topographic fringes, which can mask surface deformation. In 1993, a French team developed a technique that uses a digital elevation model (DEM) to remove the topographic fringes from an interferogram, leaving only those fringes that are proportional to surface deformation. (A DEM image represents heights above sea level for a particular location.) Also in 1993, the Jet Propulsion Laboratory, California Institute of Technology, developed a method to combine two interferograms of the same region and subtract out the topographical fringes. One (topographic) interferogram is acquired over a short time period to ensure there is no surface deformation. Once the topographic fringes are subtracted, the remaining fringes are proportional to surface displacement plus some atmospheric phase noise.

Today, researchers use both of these methods to create a continuous 2D map of surface displacements over a 10,000-square-kilometer area. By counting (integrating) the fringes on the deformation-only interferogram using a technique called phase unwrapping, they can determine how much the ground has moved, pixel by pixel, to finally form a deformation map. The more the surface has been displaced, the tighter (closer together) are the fringes.

Profiling Seismic Signatures

In their work to monitor globally for nuclear explosions, Livermore researchers have extensively studied

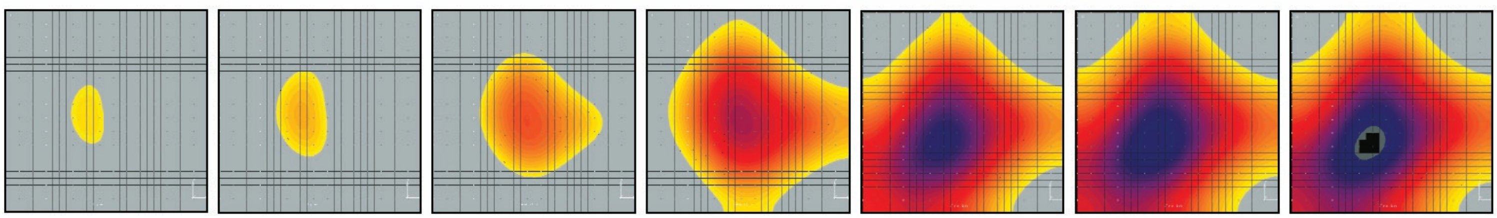


Interferometric synthetic aperture radar (InSAR) can be used to increase the precision of pinpointing the origin of earthquakes. For example, after the April 10, 1998, earthquake in Iran, InSAR (triangle) provided a 20-kilometer correction to the seismic locations (stars) registered by regional seismic stations.

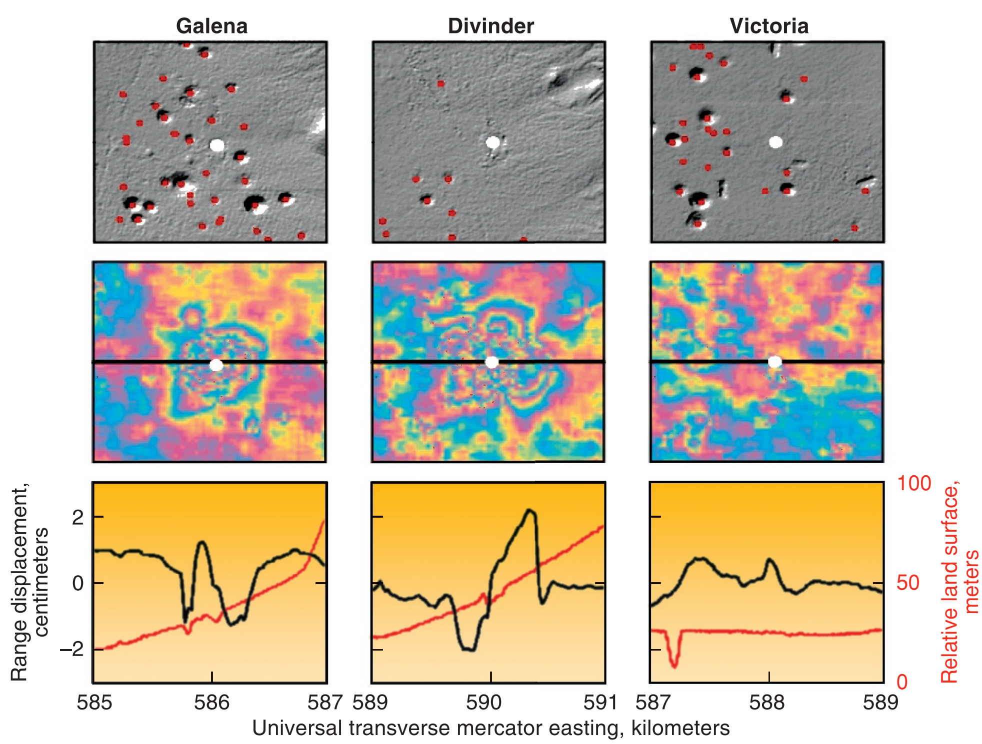
the differences in signatures produced by seismic events. Earthquakes and explosions differ in four important ways. Explosions tend to occur within a few kilometers of Earth's surface and produce spherically symmetric pressure pulses, whereas earthquakes can be many kilometers deep and produce shear slips along faults. The postevent elastic properties of the rocks at the sites of earthquakes and explosions also tend to differ. Finally, explosions have a shorter duration than earthquakes. Laboratory researchers have used these differences to develop a variety of seismic measurements that allow them to identify and discriminate most explosions from the ongoing background of earthquakes.

Seismic instruments can detect seismic waves with amplitudes as small as a nanometer, allowing researchers to pick up medium-size seismic events around the world and very small events at closer distances. Broadband seismic instruments contain a mass kept in place using a force-feedback system. As seismic movement occurs, the instrument measures how much energy is required to hold the mass in place, which is proportional to the ground acceleration.

However, seismic techniques have their limitations. Livermore seismologist Bill Walter explains, "We must sort through many signals to identify those we need to be concerned about. Also, because Earth isn't uniform in composition, signals travel to seismic stations at different speeds. Consequently, it is sometimes difficult to determine the exact origin point for an event without calibration." Seismic events are located by comparing arrival times at different stations of known



Researchers use a finite-element model to calculate forces for individual parts of an area on Earth's surface to predict how long a specific man-made or natural underground structure will take to produce detectable surface deformation under certain geologic conditions.



Coseismic surface-deformation signals from three underground nuclear tests (white dots) conducted at the Nevada Test Site in 1992 were collected by InSAR over a 14-month time span. The top images show nearby craters (red dots) from other underground tests prior to 1992, which is the first year archived data became available from the European Space Agency's ERS-1 SAR satellite. The color interferograms derived from the InSAR data (middle row) show surface displacement that occurred both during and following the explosions. The profile plots (bottom row) show near-vertical displacement (left scale) and surface topography (right scale).

locations—local and regional. Differences in geology cause variations in travel times that translate to errors in determining the event location. These errors can be reduced by analyzing many seismic sources whose locations are known.

InSAR is providing valuable data to help scientists more precisely pinpoint the origin of seismic events such as earthquakes. For example, InSAR provided a 20-kilometer correction to the origin of a 1998 earthquake in Iran determined by seismic methods.

Modeling Seismic Propagation

To better understand how Earth's surface changes over time after a seismic event, Livermore researchers perform computer simulations. In the late 1980s and early 1990s, Livermore computer scientist and geophysicist Shawn Larsen developed a finite-difference program that is now commonly used in seismic studies. The software, E3D, incorporates three-dimensional (3D) information about the propagation of seismic waves. The program simulates how waves are radiated from an earthquake's source to the surface, at what velocities they propagate, and how they interact with the geology and topography in their path.

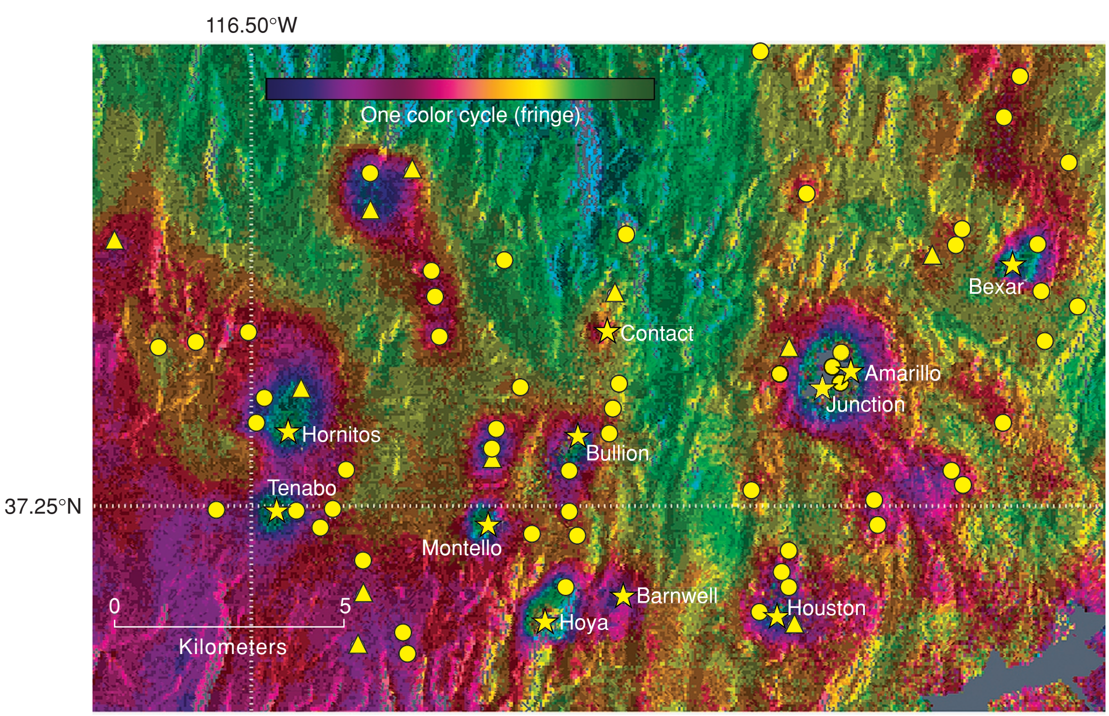
Researchers use another modeling approach for deformation studies called a finite-element method. This method simulates forces, such as gravity and friction, to predict the strain in surrounding rock from an underground cavity as the strain propagates to the surface. Although the code is computationally intensive, it is one of the best tools available to determine how gravity and other forces will affect cracked and stressed rock over time to produce surface deformation detectable with InSAR.

Examining Nuclear Test Explosions

Modeling has shown that for each type of seismic event of a particular magnitude, a distinctive pattern of ground movement is produced that is recognizable in a corresponding interferogram. To better understand surface deformation from underground explosions, in 1999, the team studied coseismic (during a seismic event) and postseismic (after a seismic event) movement using surface-deformation signals from the Nevada Test Site (NTS) that were captured by InSAR over 4 years (1992 to 1996).

Several interferograms were created from raw archived data of the entire test site, collected by the European Space Agency's ERS-1 and ERS-2 SAR satellites beginning in 1992. Underground nuclear tests were conducted at NTS from the 1960s to 1992. Interferograms revealed that postseismic signals can persist for months to years after a nuclear test and that various types of deformation can occur at different rates, depending on the geologic and hydrologic conditions of the explosion area.

The majority of the NTS tests produced either an immediate crater or a subsurface collapse minutes to days after the explosion. The most common type of postshot collapse after a nuclear explosion is chimneying, in which the explosion



Postseismic surface-deformation signals captured by InSAR show continued ground subsidence from underground nuclear tests at the Nevada Test Site. The variety of patterns reflect the different subsidence rates, which are affected by the subsurface geologic conditions for each test region. The signals were collected from 1992 to 1996. The stars indicate tests conducted after 1989, and the circles indicate tests prior to 1989. The triangles indicate the largest or deepest tests conducted from the late 1960s to mid-1970s.

cavity migrates upward as blocks of fractured rock fall to fill the cavity below. Such deformation usually takes place in a few seconds. If the chimney reaches the surface, a crater forms.

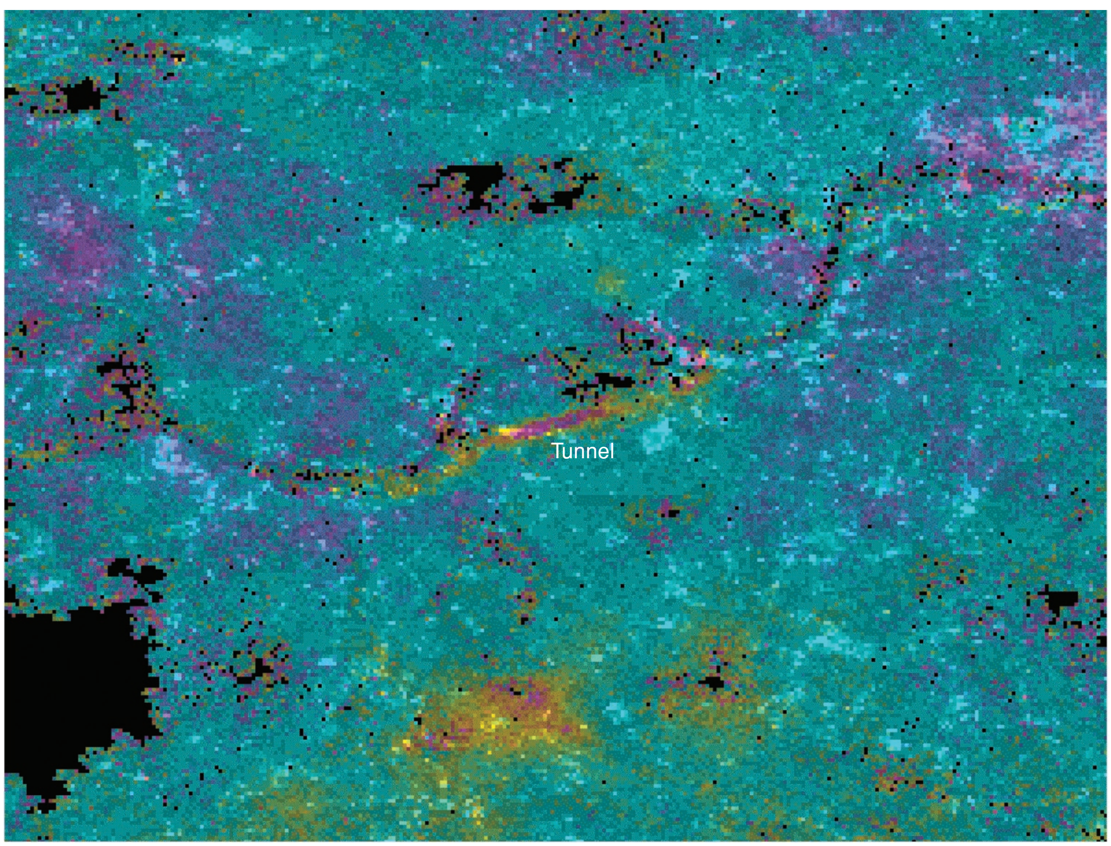
"One of the surprises," says Vincent, "was that the ground where tests had been conducted prior to 1992 is still subsiding." The InSAR data revealed both coseismic and postseismic subsidence signals that extended 1 kilometer or more across the surface, regardless of whether a surface crater was formed from the test. Rates of subsidence varied, although most of the signals indicated that this process occurs relatively slowly. The different rates may be due to several factors, including the number of tests conducted in a specific area. The rate of subsidence was also inversely proportional to the duration of the subsidence, suggesting that in areas with larger or deeper subsidence, the ground may take longer to settle.

The results of the Livermore studies at NTS indicate that InSAR could be used to detect surface deformation associated with underground nuclear explosions detonated at depths in excess of 600 meters. In addition, underground nuclear explosions may not need to be captured coseismically by radar images in order to be detectable. A suspect seismic event that is detected by seismic instruments can be imaged after an event and located to within 100 meters.

Discovering Underground Tunnels

InSAR also has the potential to detect and characterize underground facilities of interest, such as tunnels that might be associated with nuclear test preparations. Underground facilities create voids in the surrounding rock and soil, which often cause the overlying surface to subside. This subsidence is usually extremely small, for example, 1 centimeter of subsidence distributed over an area measuring one to several kilometers wide. Although surface craters and other coseismic surface effects may be detectable using high-resolution optical or other remote-sensing techniques, these broader, more subtle subsidence signals cannot be detected using other methods.

Recently, the Livermore team used InSAR to study London's Jubilee rail line, an extension to the city's underground rail system that was joined to its existing line in 1999. The team found a 2-centimeter surface subsidence above the tunnel. Once Livermore researchers have the radar data to create an interferogram, they can use a finite-element model to determine surface-deformation changes from a tunnel or cavity. They first define the size, shape, and depth of the space and then run a simulation imposing a partial collapse on the defined cavity's geometry and depth.



InSAR can be used to detect and characterize underground tunnels and cavities. In a study on London's underground railway system, InSAR revealed a previously undetected 2-centimeter surface subsidence above the Jubilee rail line.

Monitoring Movement in Real Time

Dynamic InSAR, a new technique based on InSAR, can be used to produce interferograms as an event is occurring. "Dynamic InSAR is a more difficult process to perform," says Vincent, "because we can't make the same assumptions when processing the data as we can with before and after images.

Because it can be used to track seismic waves in real time, dynamic InSAR has potential applications not only in national security but also in tracking natural hazards, such as earthquakes, volcanoes, and tsunamis. Vincent says, "Tsunamis travel at subsonic speeds of about 800 kilometers per hour and create less than 1 meter of wave amplitude (height) in open ocean water. SAR satellites orbiting the globe about 11 times per day could be used to track tsunamis in real time, providing an early warning system."

The Livermore team uses raw data obtained from satellites such as the European Space Agency's ERS-1, ERS-2, and Envisat satellites, as well as the Canadian Radarsat Satellite and the Japanese Earth Resources Satellite. An effort is also under way in the U.S. to build and launch an InSAR satellite.

Laboratory researchers think that all explosions, regardless of the terrain under which they occur, leave some surface or subsurface clues. As they use InSAR to refine their skills at interpreting the signatures left by each type of seismic event, the technology will increase its usefulness in national security, environmental hazards, and geologic planning.

—Gabriele Rennie

Monitoring Tsunamis

Interferometric synthetic aperture radar (InSAR) may potentially be used to better monitor tsunamis. A tsunami is a series of ocean gravity waves caused by a high-magnitude earthquake, meteor impact, volcanic eruption next to or underneath the ocean, or large explosion from a man-made detonation. The term "tsunami" comes from the Japanese words "tsu" (harbor) and "nami" (wave).

At their source, tsunamis may measure only 1 meter in height, producing no more than about 1 meter of rolling waves on the ocean's surface. However, tsunamis are long-period waves; that is, their wave crests are far apart—sometimes tens of kilometers on the open ocean. Traveling at subsonic speeds of about 800 kilometers per hour, their long wavelengths allow them to travel across oceans with little loss of energy. When they reach shore, the ocean bottom forces the amplitudes (wave heights) of the tsunamis to increase as much as 10 meters. When tsunamis are traveling in deep oceans, however, their amplitudes are less than 1 meter and are not visible to optical satellites.

More than 80 percent of tsunamis occur in the Pacific Ocean and around Japan. Although they have occurred in other parts of the world, most areas, for example the Atlantic Ocean, lack the subduction thrust faults that trigger tsunamis.

In 1964, a 9.2-magnitude earthquake caused a tsunami in Alaska, killing more than 100 people and causing millions of dollars in damage to property and infrastructure in four countries. This event led the National Oceanic and Atmospheric Administration (NOAA) to establish a federal tsunami warning system for the Pacific Ocean. The NOAA's satellite network and ocean monitoring system gather data from seismic and tidal stations throughout the Pacific to evaluate potential tsunami threats.

The monitoring system includes tidal gauges and buoys scattered around coastlines and on the ocean floor. The buoys are attached to instruments that measure pressure changes and then send the data to the Geostationary Operational Environmental satellites in orbit above Earth. From there, the information is downloaded to computers at a center in Hawaii. The center assesses whether the temblor's location and severity could generate a tsunami. If so, it sends out a warning of an imminent hazard, detailing the wave's predicted arrival at estimated coastal locations within a given time. No system as extensive exists anywhere else in the world.

In the Indian Ocean, the world's third largest, no such buoys and tidal gauges exist. Among the 12 countries threatened by tsunamis in that region of the world, only Thailand has any warning system. Although tsunamis are rare in the Indian Ocean, the tsunami that struck on December 26, 2004, claimed approximately 286,000 lives in 11 nations and caused billions of dollars in damage. The incident demonstrated the need for a warning system in all the vulnerable regions of the world's oceans.

Dynamic InSAR, a form of the technology that can image seismic waves in real time, could be used to complement today's seismic instruments and provide a global tsunami monitoring system. For example, by using two satellites, each traveling around the globe 11 times per day, dynamic InSAR could detect a tsunami's amplitude wave change and track its speed. With this more precise information, decision makers could issue timely, accurate warnings and, thus, help save many lives.

Key Words: Comprehensive Test Ban Treaty (CTBT), digital elevation model (DEM), E3D, finite-element model, interferogram, interferometric synthetic aperture radar (InSAR), International Monitoring System (IMS), nuclear explosion monitoring, remote sensing, synthetic aperture radar (SAR).

For further information contact Paul Vincent (925) 423-8281 (vincent7@llnl.gov).