Monitoring Ground Deformation from Space

Introduction

Scientists at the U.S. Geological Survey (USGS) are using an exciting new tool to detect, measure, and monitor subtle changes in the shape or relative position of the Earth's surface. By bouncing signals from a radar satellite off the ground in successive orbits and looking at the differences between the images, interferometric synthetic aperture radar (InSAR) can detect small differences in the distance between its position and the ground as the land surface moves—whether up, down, or sideways. InSAR shows spatial patterns of deformation in remarkable detail and, in combination with ground-based monitoring, gives USGS scientists unprecedented insight into a wide range of earth science processes.

How InSAR Works

Detecting changes in the position of the Earth's surface requires two radar images of a selected area taken from approximately the same position in space but at two different times. In figure 1, the radar signal is shown as a wave, and different segments are marked with different colors to emphasize the shift in position of the reflected wave. Uplift of the ground surface has occurred between the first and second pass of the satellite, and so the total length of the return signal for the second pass is very slightly shorter than for the first pass.

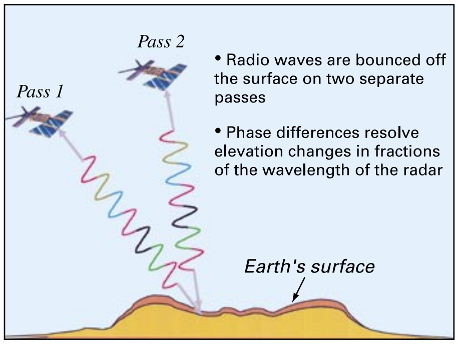

Figure 1. Diagram showing how radar interferometry detects uplift of the Earth's surface. Both the distance between the satellite positions and the amount of uplift (red layer) are exaggerated for clarity. Modified from Zhong Lu, USGS, written commun., 2004.

Interferometry is based on processing the pair of images to map out the differences in the reflected signals over the area. Because the area covered by the two radar images is typically a square 50 or 100 kilometers (km) on a side, this method allows scientists to look at deformation over large areas.

Reading an Interferogram

The amount and pattern of deformation in an interferogram are shown by using the range of colors in the spectrum from red to violet. Figure 2 shows an interferogram documenting subsidence in the Santa Clara Valley of California (upper image) and a shaded-relief map (lower image) correlating the color bands with the deformation pattern.

This and many other interferograms use the convention where moving from red to violet in the pattern indicates that the ground at the center has moved closer to the satellite (uplift). In the Santa Clara example, the color bands change in the reverse order, indicating that the center has subsided. This shift corresponds to 3 centimeters (cm) of subsidence over a distance of roughly 8 km. Interferometry thus detects very small changes in the elevation of the Earth's surface and resolves the exact shape of those changes.

The subsidence seen in figure 2 is a consequence of seasonal ground-water pumping that occurred from January to August 1997. This kind of surface-displacement map enhances the ability to monitor and manage subsidence caused by the compaction of aquifer systems (see Galloway and others, 2000).

Deformation at Volcanoes

Decades of experience in monitoring active volcanoes, such as Kilauea in Hawaii, have led scientists to realize that the movement of molten rock (magma) underground can be tracked by monitoring deformation of the surface of the volcano. An unexpected result of doing systematic InSAR analysis for volcanoes in Alaska and in the Western United States is the discovery that some long-dormant volcanoes are actively deforming and may erupt eventually, although they currently exhibit little activity.

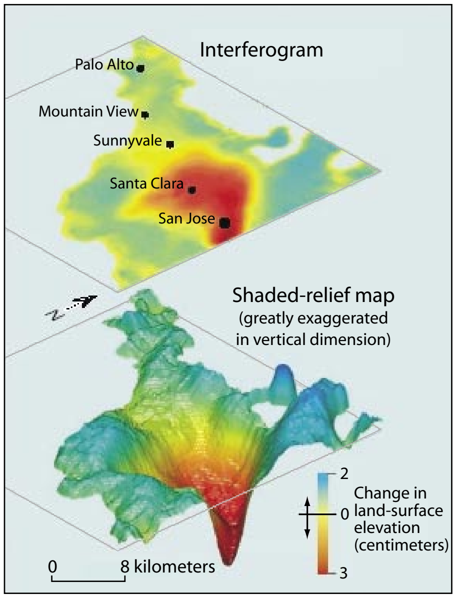

Figure 2. Interferogram (upper image) of the Santa Clara Valley, Calif., showing patterns of subsidence (with local uplift) that occurred from January to August 1997. The shaded-relief map (lower image) translates the color-zonation pattern of the interferogram into three-dimensional topography. Vertical dimension is greatly exaggerated. From Galloway and others, 2000.

Figure 3 shows an InSAR-defined area of uplift near the cluster of volcanoes known as the Three Sisters, in central Oregon. This deformation, which does not lie directly beneath any volcano, is in an area where the most recent eruption occurred 1,500 years ago. Uplift of the ground's surface, which began in 1997, reached 15 cm at the center of the bull's eye pattern in 2001. Subsequent Global Positioning System (GPS) monitoring shows that uplift continues at a steady pace, suggesting that the uplift is produced by upward movement of magma (intrusion). The InSAR pattern places the depth of intrusion at 6–7 km (Wicks and others, 2002).

Because of the observed uplift, the USGS installed seismometers, GPS stations, and gas-monitoring equipment in the area to check for other signs of volcanic unrest. At first, the new seismometers detected no earthquakes in the area of uplift. In March 2004, however, a swarm

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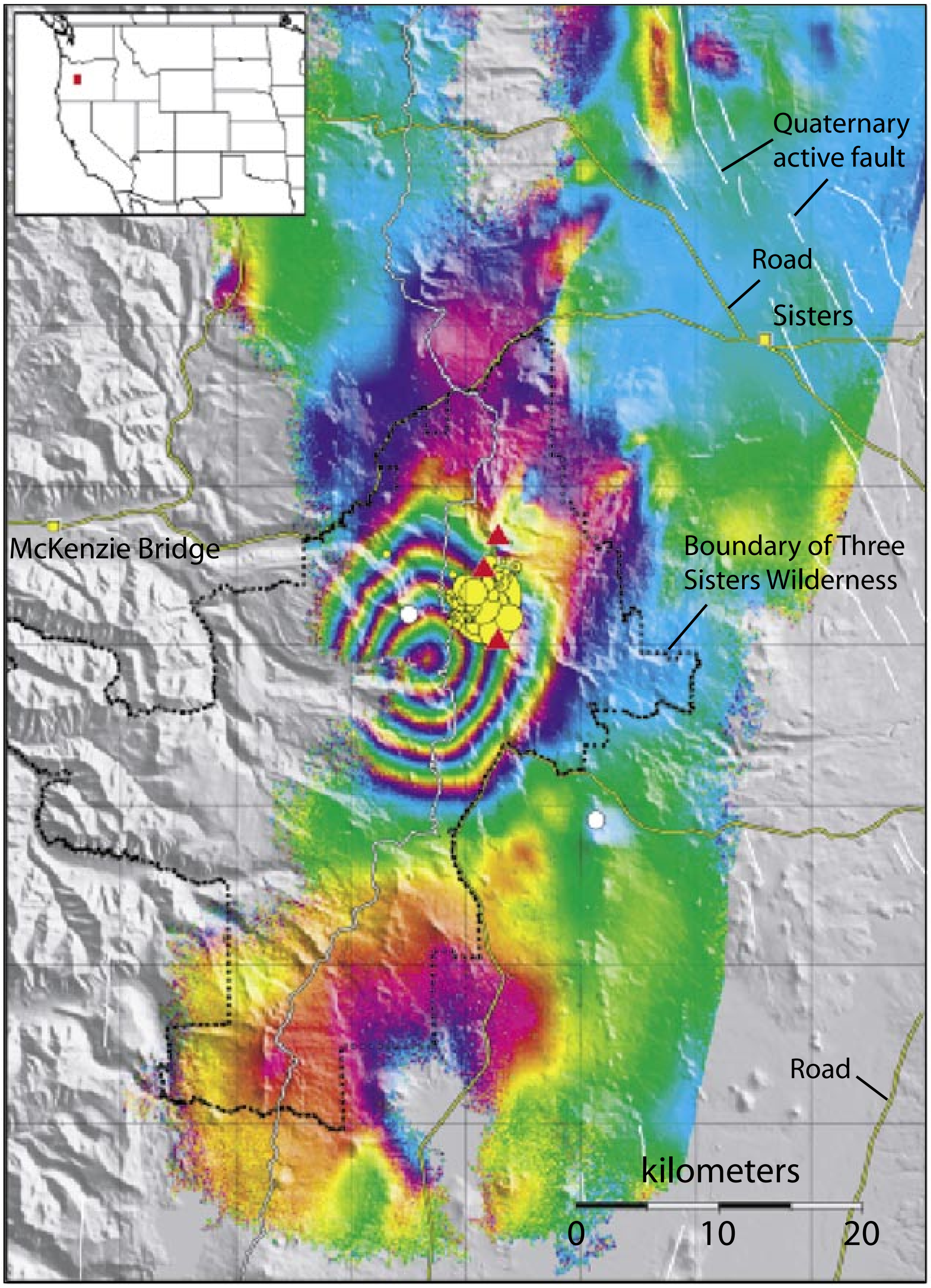

Figure 3. Interferogram showing the area of uplift (1997–2001) at the Three Sisters volcanoes (red triangles), in the Cascade Range in central Oregon, based on European Remote Sensing Satellite imagery. In March 2004, a swarm of more 300 small earthquakes (yellow circles) occurred near this center of uplift. White circles, Global Positioning System stations. From Charles Wicks, USGS, written commun., 2004.

of 300 small earthquakes occurred, having epicenters just to the northeast of the center of the uplift shown in figure 3. This example shows how using InSAR to prospect for deformation at otherwise unmonitored volcanoes helps USGS scientists design more efficient and effective monitoring networks for volcanoes in the early stages of unrest.

Other U.S. volcanoes where there is InSAR-documented deformation include several volcanoes in the Aleutians (Okmok, Akutan, Westdahl, Fisher, Kiska, Makushin, Seguam, and Aniakchak), plus Peulik Volcano on the Alaskan Peninsula, Long Valley caldera in California, and Yellowstone caldera in Wyoming. InSAR results for Yellowstone were given by Brantley and others (2004). The most complete set of data exists for Westdahl, where a series of interferograms records a decade of continuous deformation, with deflation during the 1991–92 eruption, followed by steady reinflation (Lu, Masterlark, and others, 2003). Ideally, volcanologists would like to use this technique to look at all volcanoes worldwide to see if they are deforming.

InSAR's greatest strengths are that (1) it can be applied to extremely remote and otherwise unmonitored volcanoes and (2) it gives scientists an areal image of the deformation field, not just deformation at a series of points on a map. The main limitation, aside from the limited stream of imagery (currently only two satellites are operating), is the difficulty of seeing through vegetation to the ground beneath. This problem is especially acute for the many active volcanoes in the tropics.

A Different Wrinkle—Deformation Associated with Earthquakes

InSAR-detected deformation at volcanoes is considered to be predominantly vertical, as it involves either (1) swelling as magma intrudes or a hydrothermal system pressurizes or (2) subsidence caused by magma withdrawal during an eruption, depressurization, or thermal decay of a hydrothermal system. For many earthquakes, however, most of the deformation observed is horizontal and happens along the fault on which the earthquake occurs. Because InSAR can detect movement only toward or away from the satellite, other sources of information are needed to characterize the offset if both horizontal and vertical movements occur.

Figure 4 shows deformation fields associated with two large earthquakes that occurred in Alaska in October and November 2002. In each case, the interferogram is based on a pair of images—one taken before and one soon after each event. In each case, there are large paired lobes showing deformation across the fault. The symmetry of the paired lobes suggests that the motion was predominantly horizontal, a hypothesis consistent with ground observations.

The most important new information conveyed by InSAR is that deformation occurred over a much larger area than the swath of land along the faults. The epicenter for the Nenana Mountain earthquake (fig. 4*A*) lies at the west end of its strain centers, suggesting that strain was propagating to the east. This strain propagation helped trigger the much larger Denali earthquake (fig. 4*B*), farther east along the same fault (Lu, Wright, and Wicks, 2003). The strain lobes for the Denali earthquake lie almost entirely to the east of its epicenter, extending far out of the range of the interferogram. This pattern is consistent with the direction of propagation of ground breaking (red lines in fig. 4*B*) during the earthquake.

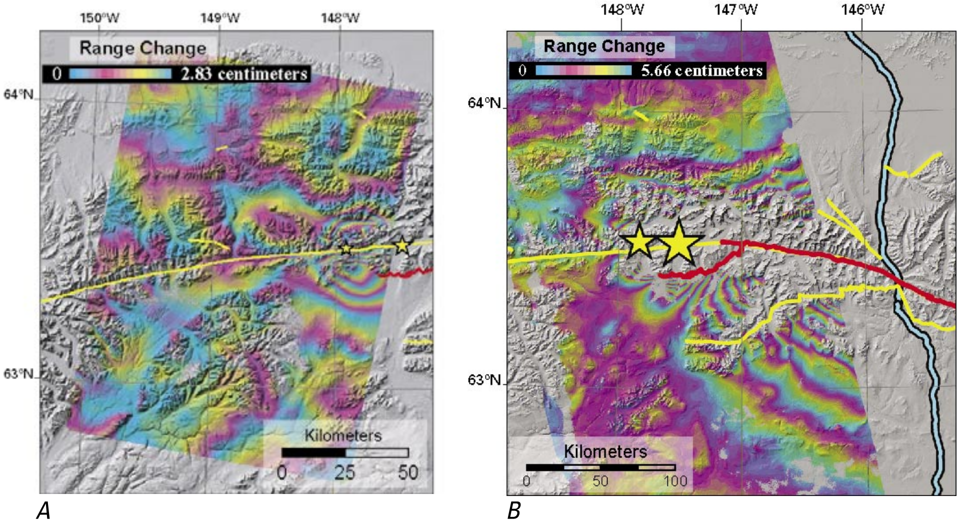

Figure 4. Interferograms showing deformation fields associated with the Nenana Mountain and Denali earthquakes (epicenters at small and large stars, respectively). *A*, Magnitude 6.7 Nenana Mountain earthquake (October 23, 2002) and paired deformation lobes north and south of the fault. Based on Radarsat images taken on August 16, 2002, and October 27, 2002. *B*, Magnitude 7.9 Denali earthquake (November 3, 2002) and extensive deformation. Note that each color band (fringe) has twice the value assigned in figure 4*A*. Based on Radarsat images taken on October 29, 2002, and November 22, 2002. Yellow lines, faults; red lines, ground breaks. From Lu, Wright, and Wicks, 2003.

Much of the off-fault deformation probably occurred after the earthquakes, as the Earth's surface caught up with deformation that had begun at depth and propagated very rapidly along the fault surfaces involved. If scientists are able to demonstrate, from sufficiently frequent InSAR analysis, that some of this strain actually occurs before an earthquake, then this new technique may eventually lead to a means of forecasting earthquakes for some fault systems.

InSAR and GPS

The Los Angeles, Calif., area is an important target for USGS research because this heavily populated and highly developed metropolis is very active tectonically. The geology of the Los Angeles area is complicated, with many active faults and other structures. For these reasons, the USGS and its partners (including the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF)) have installed an extensive network of GPS stations called SCIGN (Southern California Integrated GPS Network) to help monitor and understand ongoing tectonic activity in the area (see the USGS Earthquake Hazards Program Web site http://earthquake.usgs.gov/products/factsheets.html#west).

InSAR data for the Los Angeles basin cover at least part of the area monitored by the SCIGN array (fig. 5). There are few other places on Earth where both InSAR and time-continuous GPS deformation data overlap, allowing a direct comparison of the data. The comparisons possible for the Los Angeles basin demonstrate that the two methods produce quantitatively similar results. The data also complement each other; continuous GPS monitoring provides continuity in time, whereas InSAR shows the pattern of spatial deformation for the area.

What has been learned from monitoring deformation in the Los Angeles area? First, SCIGN and InSAR data reveal seasonal fluctuations in ground-water levels caused by ground-water pumping, as well as deformation caused by pumping of oil and gas (Bawden and others, 2001). To decipher ongoing tectonic activity, scientists must be able to remove the signal of these more surficial processes from the overall deformation signals. A further benefit, especially of InSAR, is that monitoring allows scientists to see previously unrecognized faults or other potentially seismogenic subsurface structures and to better define the subsurface position of known structures. A more detailed analysis of the information in figure 5 was given by Bawden and others (2003).

What Kind of Synthetic Aperture Radar (SAR) Is Best?

The interferograms shown in figures 2–4 of this Fact Sheet were generated from pairs of images from the European Remote Sensing Satellites (ERS; launched by the European Space Agency) or from Radarsat (launched by the Canadian Space Agency). The sensor on these satellites is C-band radar, which has a wavelength of 5.66 cm. Unfortunately this relatively short wavelength is not ideal for looking at many kinds of natural surfaces and is hindered by vegetation.

L-band SAR, which has a significantly longer wavelength of 23.53 cm, is better suited for interferometry, especially in vegetated areas; however, there is no L-band satellite operating at present. The only significant L-band archive is the imagery obtained by the Japanese Earth Resources Satellite JERS–1, which was operated by Japan from 1992 to 1998. USGS scientists, drawing on this archival imagery, as well as C-band ERS imagery, created two interferograms for Akutan Volcano in the Aleutians (figs. 6 and 7).

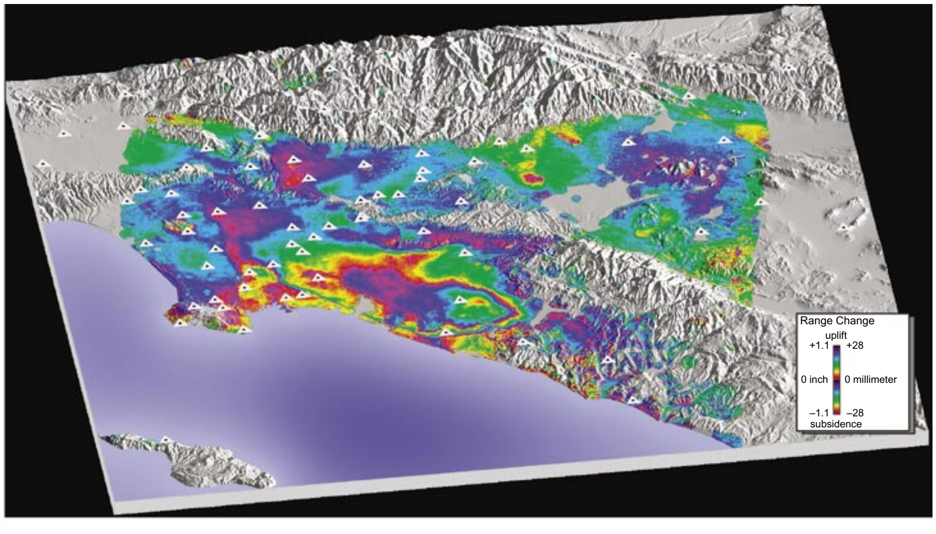

Figure 5. Interferogram showing deformation in the Los Angeles basin, from April 1998 to May 1999, draped over shaded-relief map. Based on European Remote Sensing Satellite imagery. Triangles, Global Positioning System stations. Modified from Bawden and others, 2001.

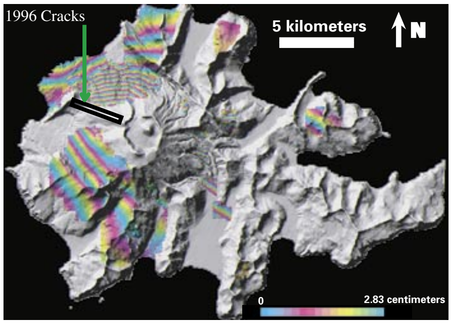

Figure 6. Interferogram showing deformation of Akutan Island (August 1993 to October 1996), draped over shaded-relief map of the island. Based on European Remote Sensing Satellite imagery (C-band radar). From Lu and others, 2005.

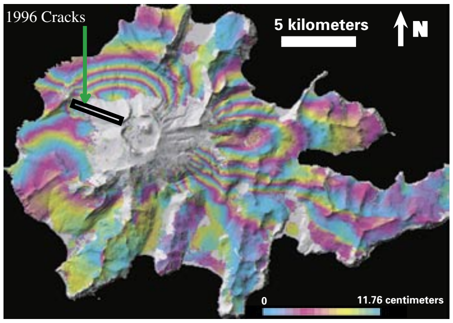

Figure 7. Interferogram showing deformation of Akutan Island (October 1994 to June 1997), draped over shaded-relief map of the island. Based on Japanese Earth Resources Satellite imagery (L-band radar). From Lu and others, 2005.

This pair of interferograms, covering very nearly the same time period, allows scientists to compare InSAR-determined deformation fields for C- and L-band radar over the same target volcano (Lu and others, 2005).

The interferogram based on C-band radar (fig. 6) shows only limited details of the deformation of Akutan Island. Although vegetation can hinder the effectiveness of C-band radar, this is not the case for much of the Akutan image, as the vegetation on the island is sparse (fig. 8) or tundra. Much of the limited coherence results from the nature of the surface material, which in many areas consists primarily of unconsolidated volcanic deposits. This material is unstable on the scale of a few centimeters over a period of years. Only young lava flows and other rock surfaces were stable enough to show coherent deformation (rainbow areas in fig. 6) at the shorter C-band wavelength over 3 years' time.

By contrast, at the longer L-band wavelength, almost the entire surface of the island appears stable enough for the deformation field to be seen (fig. 7). The complexity of the deformation that occurred during the 1996 seismic event is clearly defined. There has been subsidence at the summit and to the northwest of the volcano, consistent with the formation of ground cracks and grabens like the one shown in figure 8, with broader inflation of the flanks on either side. To the east of the volcano is an area of subsidence, which is clearly shown only in the L-band interferogram (fig. 7). USGS scientists have inferred that the inflation was caused by high-level intrusion of a dike, while the subsidence reflects contraction of a deeper source (Lu and others, 2005).

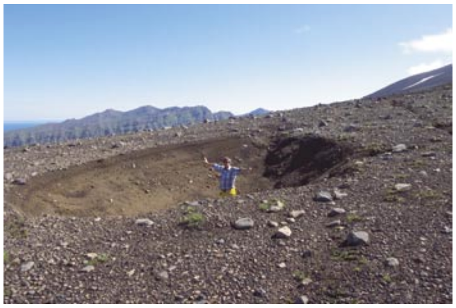

Figure 8. Photograph showing a small graben west of the summit of Akutan Volcano. Note unconsolidated surficial material and sparse vegetation. Photograph by John Power, USGS, August 2001.

Data Acquisition—A Cooperative Interagency Effort

SAR satellites are few in number, and the requirements for collection of repeat images that can be used to generate interferograms are stringent. As a result, useful image pairs, even in large archives of imagery, are not common. The successful applications of InSAR shown here reflect seamless cooperation among several agencies. Some of the ERS data were acquired through the WInSAR consortium, a joint project that includes scientists in both government and academia and is funded by the NSF, NASA, and USGS. Other ERS data, plus the JERS and Radarsat imagery, were acquired with NASA funding through the Alaska Satellite Facility, under cooperative agreements between NASA and the European, Canadian, and Japanese satellite agencies. Further development of this promising technique depends on expanding and strengthening interagency and international coordination in the acquisition of SAR data, including the launching of additional L-band or multiband SAR satellites.

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