

InSAR, a tool for measuring Earth's surface deformation

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By comparing phase information from images taken at different times, interferometric synthetic aperture radar can measure terrestrial displacements as small as a centimeter.

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Measurements of changes in Earth's shape provide critical insights into processes of interest to science and society, from subsurface movements of magma; to changes in strain before, during, and after earthquakes; to the motion of ice sheets. Yet even today, vast portions of Earth remain infrequently monitored for deformation, or not monitored at all. And that dearth of information is despite intense efforts and such advances as the global positioning system (GPS).

In the past few decades, scientists have developed the capability to measure centimeter-scale deformation by comparing satellite images taken a few days to a few years apart. That ability has led to a great increase in the percentage of Earth's surface that can be monitored for deformation and in the frequency of such observations. One powerful satellite-based imaging technique, interferometric synthetic aperture radar (InSAR), came into broad use in the early 1990s. It has revolutionized the way scientists see Earth and the evolution of its shape over time.

What is InSAR good for?

Until the late 20th century, measurement of Earth's deformation was necessarily time consuming. Frequently it was perilous because an observer had to be physically present at a dangerous or remote location; the less dangerous but more expensive alternative was to establish an observatory. InSAR overcomes many such practical limitations. With it, one can quickly survey remote sites with areas measuring thousands of square kilometers and achieve a spatial resolution of about 20 m. For example, I was part of a group that could, in a few weeks time, assess the deformation at more than 900 volcanoes in the central Andes. Similar ground-based measurements would have taken years or even decades. In other work, InSAR has observed erupting volcanic craters—without jeopardizing humans or expensive instruments.

Ground measurements from continuously operating GPS stations and other instruments can observe deformation over time scales of seconds. InSAR is complementary to those tools; current satellites can take measurements of much greater areas on a monthly basis. Depending on the configuration of its radar antenna, InSAR can measure a variety of observables including topography, ocean currents, ground moisture changes, and surface deformation from glaciers, earthquakes, and volcanoes. Data obtained with InSAR, in combination with sophisticated location procedures, can help monitor nuclear tests, create better models of the elastic properties of Earth's interior, and assess seismic hazard. A partial list of key discoveries made with the help of InSAR includes

► Dramatic new information revealed by high-resolution maps of deformation before, during, and after earthquakes.

Researchers have used the spatial patterns of deformation in the weeks to years after large earthquakes occurred to place bounds on frictional properties of the fault and the viscosity of the subsurface. InSAR maps have also revealed the importance of postseismic deformation from water movements caused by earthquake-induced adjustments in regional stress fields.

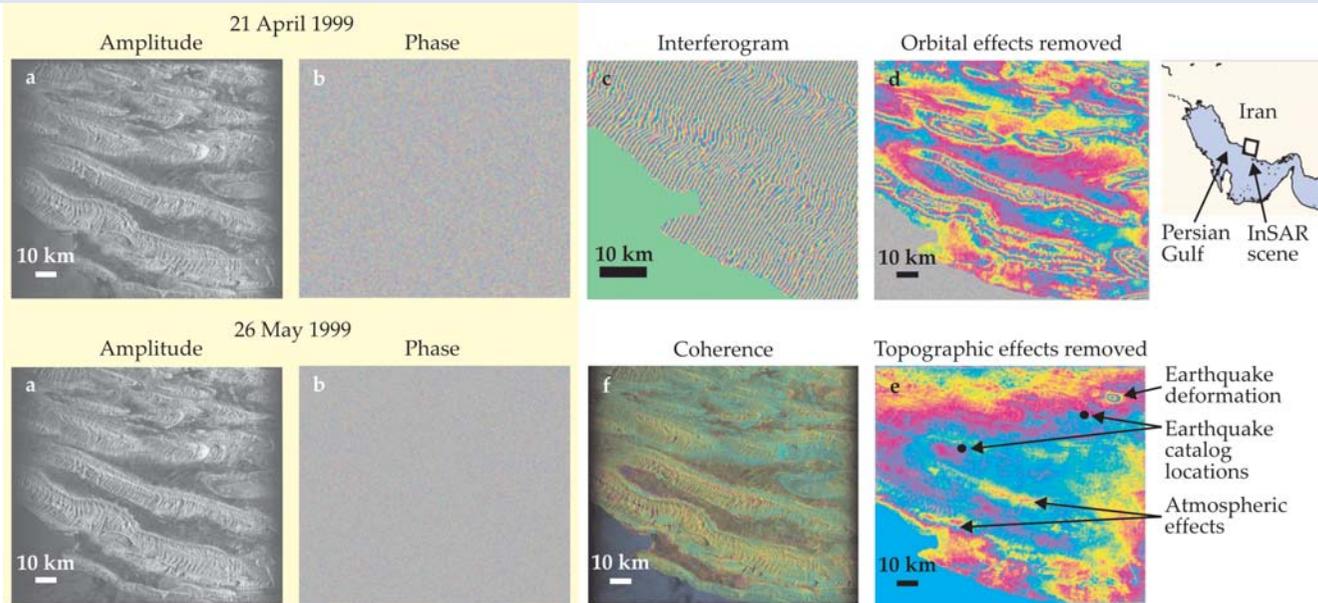
- The locations of certain shallow earthquakes that had been incorrectly determined.
- Magma moving at many supposedly dormant volcanoes.
- Groundwater movements beneath major cities and elsewhere that exhibit complex spatial and temporal variations, in part influenced by human activities.
- Ice sheets that are much more dynamic than previously thought. The dynamism has important consequences for models of sea-level rise.

How InSAR works

Radar, an acronym for radio detection and ranging, involves the transmission and reception of microwave electromagnetic radiation with frequencies roughly in the range of 10^8 – 10^{11} Hz and corresponding wavelengths of order 1–1000 mm. Radars that image Earth's surface have wavelengths greater than a few centimeters so they can see through clouds and precipitation; they thus can function day or night, no matter what the weather.

To create a radar image, one must determine where the received radar energy interacted with the ground. The two coordinates most often used to describe that interaction point are the range, or distance perpendicular to the radar antenna, and the azimuth, or distance along the flight path. To discriminate ground features in the range direction, one precisely times the returns of radar energy. Features in azimuth are resolved by tracking changes in frequency caused by the Doppler effect. Because many pulses from the radar are combined to create the image of a ground scatterer, the signal processing technique is called synthetic aperture radar (SAR), where the "aperture" includes the motion of the antenna over the many pulses. For a typical civilian satellite, SAR's range resolution is about 20 m and its azimuth resolution is about 5 m.

Each pixel in a SAR image encodes a complex number whose amplitude corresponds to the intensity of the returned radar energy and whose phase represents a fraction of a complete wavelength. The figure shows how a pair of SAR images obtained at different times can be combined to form an interferogram and, with further refinements, yield surface deformation. The amplitude images appear similar to an optical image of the ground, although there are several important differences because the source of illumination is a satellite antenna.



InSAR data may be processed to reveal how Earth's surface deforms with time. These images, from flights of the European Space Agency's *ERS-2* satellite over southern Iran and the Persian Gulf, were taken 35 days apart. Radar returns from the two flyovers yield images with amplitude (a) and phase (b) information at each pixel. The amplitude images show recognizable mountains and valleys, but the phase images look like random noise. The phase *differences* seen in the interferogram (c), however, vary in a regular manner. Two corrections must be applied to the interferogram to account for the slightly different locations of the satellite antenna during the two observations. Orbital effects that would be present for a flat, featureless Earth must be removed (d) but topography must be considered as well (e). Once the corrections are implemented, the remaining phase differences yield surface deformation and show atmospheric variations, particularly in water vapor content, that occurred between observations. The surface deformation seen here is from the 30 April 1999 earthquake in southern Iran, which had been mislocated in seismic catalogs. For successful interferogram formation, the scattering properties of the ground need to be relatively constant between observations so that the coherence of the radar returns is high. Regions (f) of high (green) coherence on land contrast with the low (purple) coherence of the Persian Gulf. Note the absence of interference fringes in panel c over the low-coherence Gulf region. (Adapted from images provided by ESA and Rowena Lohman, Woods Hole Oceanographic Institution.)

The phase in a SAR image is random from one pixel to another because the phase at each pixel is a complicated function of the scattering features located on the surface. However, when the phases from two images are subtracted to form an interferogram, the resulting phase-difference fringes allow one to infer changes in the distance between the ground and the satellite antenna. Each fringe corresponds to a distance change of $\lambda/2$, where λ is the radar wavelength. After removal of effects due to the slightly different locations of the antenna during the two observations, the remaining interferogram should represent surface deformation.

The principal source of noise for satellite InSAR measurements of ground deformation is delay in phase propagation through the troposphere, most often caused by spatial and temporal variations in the water vapor content (see panel e of the figure). In certain areas, independent ground or satellite data can be used to diminish the atmospheric artifacts, but the most globally practical method is to use multiple overlapping observations to better characterize the signal and noise.

InSAR only sees deformation in the line-of-sight direction of the radar beam, which implies that only one component of the deformation can be measured in an individual interferogram. By using multiple satellite passes with different observing geometries, one recovers more than a single component of deformation; that additional information is important for constraining physical deformation models.

Though InSAR systems have provided many new insights, satellites to date have not been optimized for InSAR.

A dedicated satellite able to make frequent and consistent observations could address some large-scale problems in geophysics. Eventually, constellations of InSAR satellites in a variety of orbits, including possibly geosynchronous orbits, could allow near-real-time imaging that would greatly assist the response to natural hazards, and even help anticipate some of them. Beyond terrestrial applications, InSAR missions to Venus, Mars, Europa, or Titan could potentially reveal the myriad deformational processes occurring on those distant objects.

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Additional resources

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- ▶ Several summary reports stressing that InSAR should be a high priority for US funding agencies are available at <http://solidearth.jpl.nasa.gov/insar/index.html>.
- ▶ Information on how to process InSAR data is available at http://www.geo.cornell.edu/eas/PeoplePlaces/Faculty/matt/roi_pac.html. ■