# Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California

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**Abstract.** Interferometric synthetic aperture radar (InSAR) has great potential to detect and quantify land subsidence caused by aquifer system compaction. InSAR maps with high spatial detail and resolution of range displacement ($\pm 10$ mm in change of land surface elevation) were developed for a groundwater basin ($\sim 10^3$ km$^2$) in Antelope Valley, California, using radar data collected from the ERS-1 satellite. These data allow comprehensive comparison between recent (1993–1995) subsidence patterns and those detected historically (1926–1992) by more traditional methods. The changed subsidence patterns are generally compatible with recent shifts in land and water use. The InSAR-detected patterns are generally consistent with predictions based on a coupled model of groundwater flow and aquifer system compaction. The minor inconsistencies may reflect our imperfect knowledge of the distribution and properties of compressible sediments. When used in conjunction with coincident measurements of groundwater levels and other geologic information, InSAR data may be useful for constraining parameter estimates in simulations of aquifer system compaction.

## 1. Introduction

Geophysical applications of radar interferometry take advantage of the phase component of reflected radar signals to measure apparent changes in the range distance of ground reflectors, that is, the land surface [*Gabriel et al.*, 1989]. Interferograms, formed from patterns of interference between the phase components of two radar scans made from the same antenna position (viewing angle) but at different times, have demonstrated dramatic potential for high-density spatial mapping of ground surface deformations associated with tectonic [*Massonnet et al.*, 1993; *Zebker et al.*, 1994] and volcanic strains [*Massonnet et al.*, 1995; *Rosen et al.*, 1996]. When the target is the land surface and the antenna is part of a synthetic aperture radar (SAR) platform on an Earth-orbiting satellite, the radar scan may encompass 10,000 km$^2$, and a single picture element (pixel) of the reflected signal may represent an area as small as 100 m$^2$. Mapping programs are recognized as a critical element in efforts to identify and manage subsidence problems [*National Research Council*, 1991], and interferometric synthetic aperture radar (InSAR) has recently been used to map localized crustal deformation and land subsidence associated with geothermal fields in Imperial Valley, California [*Massonnet et al.*, 1997], Long Valley, California (W. Thatcher, U.S. Geological Survey (USGS), written communication, 1997), and Iceland [*Vadon and Sigmundsson*, 1997], and with oil and gas fields in the Central Valley, California (E. Fielding, Jet Propulsion Laboratory, written communication, 1997; M. van der Kooij, Atlantis Scientific Inc., written communication, 1997). We employ InSAR to study a particular case of a global problem, that of regional land subsidence related to aquifer system compaction.

Land subsidence caused by groundwater pumping is due to compaction of aquitards during the time-dependent and typically slow process of aquitard drainage [*Tolman and Poland*, 1940]. Compaction describes the inelastic aquitard or aquifer system compression, reflecting rearrangement of the pore structure under effective stresses greater than the maximum past stress, and is synonymous with the term "virgin consolidation" as used in soil mechanics. Studies of subsidence in the Santa Clara Valley [*Tolman and Poland*, 1940; *Poland and Green*, 1962; *Green*, 1964; *Poland and Ireland*, 1988] and San Joaquin Valley [*Poland*, 1960; *Miller*, 1961; *Riley*, 1969; *Helm*, 1975; *Poland et al.*, 1975; *Ireland et al.*, 1984] in California established the theoretical and field application of *Terzaghi*'s [1925, 1943] laboratory-derived principle of effective stress and theory of hydrodynamic consolidation.

We studied an InSAR interferogram for a groundwater basin in Antelope Valley, Mojave Desert, California (Figure 1), where the U.S. Geological Survey has been collecting geohydrologic and geodetic data for many decades. The interferogram was originally developed by the Jet Propulsion Laboratory (JPL) to study crustal deformation in the Los Angeles area and along the San Andreas fault. We recognized that the small, spatially diffuse displacements detected in Antelope Valley could be related to land subsidence. More than 1.8 m of subsidence attributable to aquifer system compaction in Antelope Valley between 1926 and 1992 had already been measured by traditional surveying methods and the global positioning system [*Ikehara and Phillips*, 1994].

### 1.1. InSAR

When two radar scans are made from the same viewing angle but at different times, a small change in the position of

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