GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 17, PAGES 3215-3218, SEPTEMBER 1, 1998

Rapid subsidence over oil fields measured by SAR interferometry

Eric J. Fielding, Ronald G. Blom, and Richard M. Goldstein

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Abstract. The Lost Hills and Belridge oilfields are in the San Joaquin Valley, California. The major oil reservoir is high porosity and low permeability diatomite. Extraction of large volumes from shallow depths causes reduction in pore pressure and subsequent compaction, forming a surface subsidence bowl. We measure this subsidence from space using interferometric analysis of SAR (Synthetic Aperture Radar) data collected by the European Space Agency Remote Sensing Satellites (ERS-1 and ERS-2). Maximum subsidence rates are as high as 40 mm in 35 days or > 400 mm/yr, measured from interferograms with time separations ranging from one day to 26 months. The 8- and 26-month interferograms contain areas where the subsidence gradient exceeds the measurement possible with ERS SAR, but shows increased detail in areas of less rapid subsidence. Synoptic mapping of subsidence distribution from satellite data powerfully complements ground-based techniques, permits measurements where access is difficult, and aids identification of underlying causes.

Introduction

Ground subsidence is a major worldwide hazard. One recent estimate placed the annual cost of subsidence damage and mitigation within the U.S. alone at over $100 million [*National Research Council*, 1991]. Relatively slow subsidence caused by the natural process of sediment compaction is widespread but seldom causes problems on human timescales. More rapid subsidence of the ground surface is usually attributable to human activities, such as the extraction of fluids from beneath the surface. Fast local changes in land elevation and associated surface strains can cause damage to structures that is costly to replace or repair, and can also greatly increase flooding potential.

Rapid ground subsidence over areas of petroleum and gas extraction has been observed previously [*Mayuga and Allen*, 1970; *Pratt and Johnson*, 1926; *Vanhasselt*, 1992]. The effects are most noticeable on a coastline where a small elevation decrease may cause inundation, first described over an oilfield near Houston, Texas [*Pratt and Johnson*, 1926]. Parts of the city and port of Long Beach, California, suffered major problems due to rapid (up to 0.75 m yr^{-1}) land subsidence related to extraction of oil from the underlying Wilmington oil field [*Mayuga and Allen*, 1970]. Problems were caused both by inundation and by horizontal strains on the sides of the subsidence bowl. Subsidence over petroleum extraction zones can also cause significant damage to extraction infrastructure itself, including expensive well failures. In this paper, we report subsidence rates as high as 40 mm in 35 days or an annual rate of > 400 mm yr^{-1} in two California oilfields.

Traditional measurements of land subsidence are made by detailed surveying and tide gauges. Recently, GPS (Global Positioning System) surveys and tiltmeters have been used. All of these techniques: (1) measure changes in locations of a limited set of benchmarks, (2) require a large number of individual observations to map the subsidence distribution, (3) require ground access, and (4) are generally costly to acquire.

Synthetic Aperture Radar (SAR) images can be combined using interferometric analysis to measure surface deformation remotely [*Gabriel et al.*, 1989]. An advantage of SAR interferometry (IntSAR) is that it can provide a geographically comprehensive map of the deformation, with a sampling rate far more dense than the most detailed surveys. One disadvantage is that SAR interferometry only measures one displacement component, but the operating satellite systems are most sensitive to vertical motions, which is appropriate for subsidence. While most applications of IntSAR todate have been to study nearly instantaneous deformation due to earthquakes and rapid motion of glaciers, gradual subsidence and uplift of the earth's surface have also been measured [*Briole et al.*, 1997; *Carnec et al.*, 1996; *Fruneau et al.*, 1996; *Galloway et al.*, in press; *Lu et al.*, 1997; *Massonnet et al.*, 1997; *Peltzer et al.*, 1996; *Vadon and Sigmundsson*, 1997](also M. van der Kooij, Atlantis Scientific, unpublished, 1997). Here we demonstrate interferometric mapping of rapid surface deformation related to petroleum extraction.

The Lost Hills and Belridge oilfields are located in western Kern County, California, on the west side of the San Joaquin Valley (Figure 1). The major oil reservoir in both fields is diatomite [*McGuire et al.*, 1983]. The extraction of large volumes of fluid, aided by hydrofracturing, from diatomite formations located at shallow depths (about 700 m below the surface) in Lost Hills and Belridge fields, causes a reduction in the pore fluid pressure, resulting in significant compaction of the reservoir rocks under the weight of the overburden. A subsidence bowl forms at the surface [*Bondor and de Rouffignac*, 1995; *Holzer and Bluntzer*, 1984; *Martin and Serdengecti*, 1984]. Subsidence at the South Belridge field was first noted in the 1980's [*Bondor and de Rouffignac*, 1995; *Bowersox and Shore*, 1990].

Interferometric Observations

We have measured ground subsidence at Lost Hills and Belridge from space using interferometric analysis of SAR data collected by the European Space Agency Remote Sensing Satellites (ERS-1 and ERS-2). The ERS-1 and ERS-2

Paper number 98GL52260.
0094-8534/98/98GL-52260$05.00

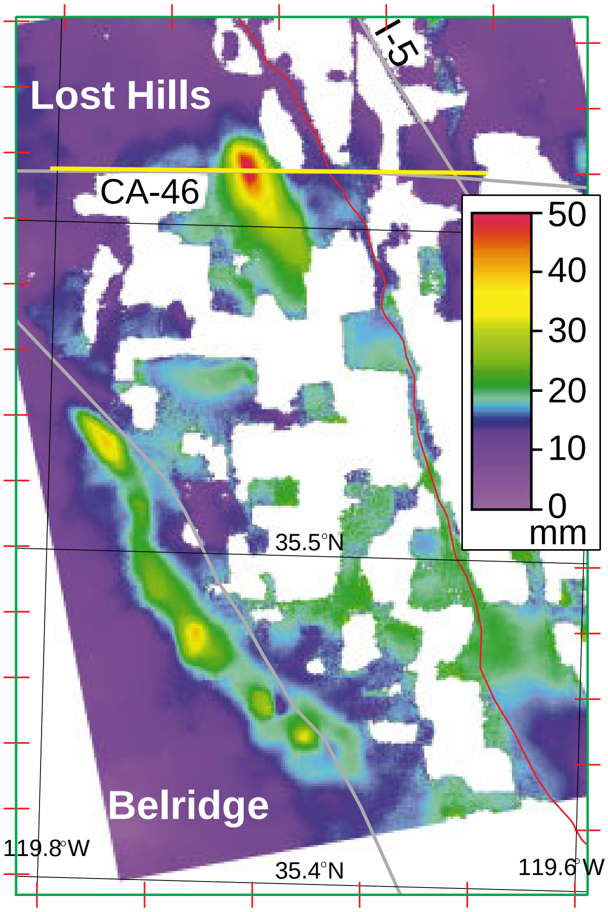

Figure 1. The 35-day ascending ERS interferogram with phase converted to range change in satellite line-of-sight direction and geocoded. Colors show relative apparent motion of surface, with the yellow and red areas moving away, hence downward relative to dark purple areas. Overlays show major roads (gray lines) and California aqueduct (red line). Irregular areas in white are regions where the phase could not be reliably unwrapped, due to decorrelation. This is primarily in agricultural fields where the ground surface has been significantly modified by plowing or crop growth. Note > 40 mm of subsidence over Lost Hills in 35 days.

satellites have SAR instruments that operate in C-band at a wavelength of 56.56 mm. The normal orbital cycle is 35 days, but the ERS-2 satellite orbit follows ERS-1, passing the same point one day later. We produced interferograms from ERS-1 and ERS-2 SAR image pairs with time separations ranging from one day to 26 months, from both ascending and descending orbits (see Table 1).

We corrected the interferograms for the phase signature due to orbital separation and earth curvature, but we did not remove the very small topographic phase component. The topographic contribution to phase over the oilfields is negligible, because there is < 30 m of relief in the Lost Hills and even less at Belridge and because the IntSAR pairs have very small orbital separations or baselines. The ambiguity height or amount of elevation that will cause one fringe of phase change of these pairs (Table 1) highlights their low sensitivity to elevation. Topographic maps show up to 30 m (100 ft) of relief for Lost Hills (north of the subsidence bowl). This relief corresponds to a maximum of $\sim 54°$ of phase or

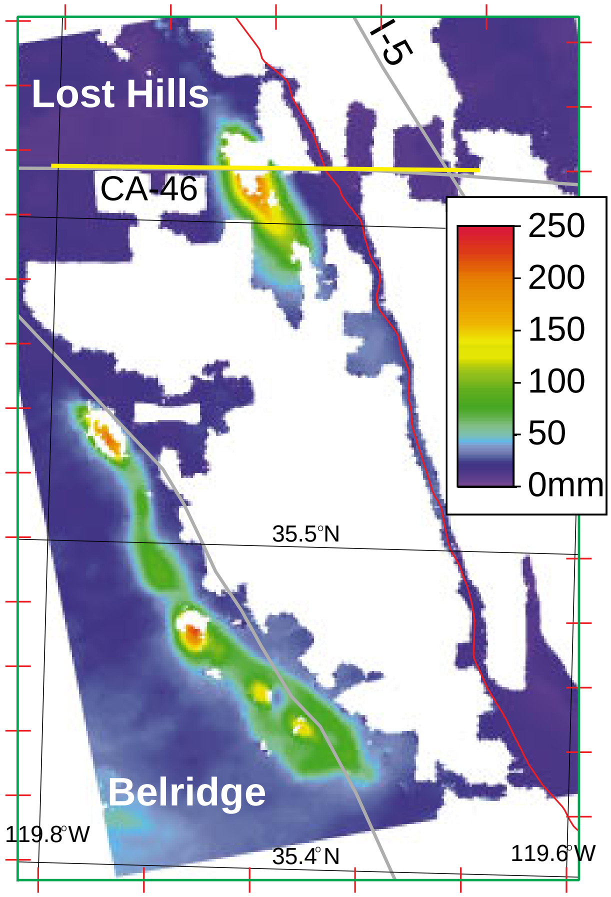

Figure 2. The 8-month ascending ERS interferogram with phase converted to range change as in Figure 1. Note that the subsidence scale portrayed in colors is different, and shows > 200 mm of subsidence. Some areas have subsided too much in 8 months to be resolved. Yellow line along California route 46 (CA-46) shows the location of profile across Lost Hills in Figure 3.

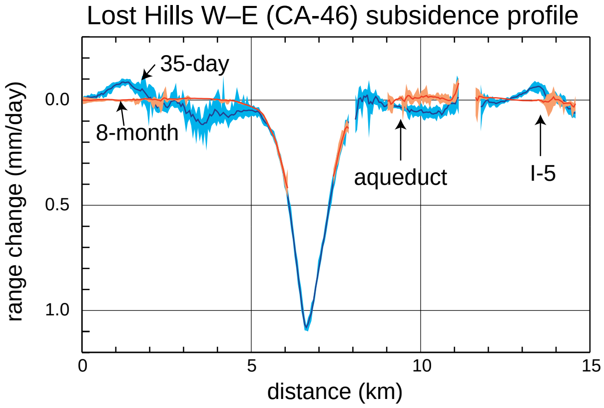

Figure 3. West–east profile through the Lost Hills oilfield with the interferometric phase of the 35-day and 8-month pairs converted to range change and divided by the time interval. The graph shows the variation in values (shaded) across a swath through the interferogram that is 200 m wide and the average values (solid lines). Gaps are places where the phase could not be unwrapped in the agricultural areas on both interferograms and the steep deformation gradients in the center of the oilfield on the 8-month interferogram.

Table 1. Characteristics of Interferograms

Ref. orbit	Ref. Date	Interf. orbit	Int. Date	Elapsed time	B_{perp} (m)[a]	Ambig. height (m)[b]
E1-19690	95/4/21	E1-20191	95/5/26	35 days	~ 20	~ 500
E1-20191	95/5/26	E1-23698	96/1/26	8 months	~ 50	~ 200
E1-23698	96/1/26	E2-4025	96/1/27	1 day	~ 10	~ 1000
E1-9827	93/6/2	E1-21193	95/8/4	26 months	~ 40	~ 250
E2-4347[c]	96/2/18	E2-5349	96/4/28	70 days	5–15	650–5000

[a] Perpendicular component of baseline at mid-swath.
[b] Ambiguity height at mid-swath.
[c] Descending orbits.

< 4 mm of range change [*Zebker et al.*, 1994]. The remaining phase includes the satellite line-of-sight (range) component of surface motion plus changes in radar propagation.

Quantifying and correcting the apparent surface motion due to changes in atmospheric radar propagation delay is difficult because knowledge of atmospheric conditions at the resolution of the radar pixels is unavailable. Phase change is primarily due to changes in tropospheric water vapor distribution [*Goldstein*, 1995; *Zebker et al.*, 1997]. Because the atmosphere is so spatially variable, we sample the atmospheric delays in this area with a Tandem interferogram with a 1-day interval and a short spatial baseline(see Table 1). The observed signal over the flat San Joaquin Valley can be assumed to be almost entirely due to atmospheric delays. Over areas the size of Lost Hills and Belridge, the observed variation is roughly 5 mm of delay, and we expect a similar level of atmospheric effects in the other interferograms. These delays are similar to those estimated by Goldstein [*Goldstein*, 1995] for eastern California. The atmospheric conditions during the two images of Tandem pair may not be typical, but these effects are small compared to the > 40 mm of observed range change over the oilfields.

The short spatial scale of the surface deformation at Lost Hills ($\sim 2 \times 5$ km) and Belridge ($\sim 2 \times 15$ km) requires processing of interferograms at the highest possible resolution. Cross-track (range) resolution for the ERS SAR is 7.9 m in slant range $\div \sin(23°) \approx 20$ m on the ground for ERS. Along-track (azimuth) resolution is much higher, roughly 4 m on the ground, so we average 5 pixels in azimuth to give approximately 20×20 m square pixels (see Figure 1). For the longer time intervals (8-months and 26-month interferograms), this resolution is inadequate to resolve the most intense deformation gradients in the oilfields with the 56 mm wavelength of ERS (see Figure 2).

Conclusions

We have used interferometric analysis of spaceborne ERS SAR to map the subsidence of the surface over oilfields in central California. We measure very rapid subsidence rates of up to 400 mm yr^{-1} or > 1 mm day^{-1} (Figure 3), and show the subsidence is largely limited to the petroleum production properties (Figures 1 and 2). In the Lost Hills oilfield, preliminary elastic strain modelling using an implementation of the Okada [*Okada*, 1985] model [*Feigl and Dupré*, in press] indicates a net compaction of 1.7 mm day^{-1} at the center of the subsidence bowl decreasing to 0.6 mm day^{-1} to the south. That much compaction over a total area 0.8×5 km could account for the observed surface subsidence of the 35-day interferogram (Figures 1 and 3). This modeling shows that a volume change of roughly 1.5×10^6 m^3 yr^{-1} in the rock units at depth is sufficient to cause the observed signal for the Lost Hills oilfield. More detailed modelling of the deformation in the fluid reservoirs (e.g., [*Segall et al.*, 1994]) would require data on pressure changes within the reservoir from the operating companies.

Directly mapping the deformation in areas of rapid subsidence (Figure 3) over long time intervals would require a SAR system with a longer wavelength or higher spatial resolution (or both). Another possibility would be to sum multiple measurements over short time periods, which would require a satellite with a tightly controlled orbit that allowed interferograms to be formed between every consecutive pair of orbits.

Interferometric measurements of rapid subsidence over oilfields can provide valuable information for understanding the response of the reservoir and overlying rocks to various petroleum extraction strategies. The ability to map the subsidence distribution from satellite data powerfully complements ground-based techniques and permits measurements in areas where ground access is difficult or expensive. In addition, IntSAR provides an instantaneous measurement that is not possible with campaign-style traditional surveys that take a significant time to complete. The synoptic mapping of deformation with IntSAR is also vital for associating it with the underlying causes. A geodetic point measurement for tectonic deformation in or near an area of subsidence can give spurious results, while an IntSAR map can show the anomalous pattern caused by non-tectonic deformation. This new application of IntSAR should be of interest to the petroleum industry, regulatory agencies, and geodesists.

Acknowledgments. We are grateful to P. Rosen and S. Hensley for the use of their ROI_pac interferometry software, and R. Crippen and K. Burke for helpful comments. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

References

Bondor, P.L., and E. de Rouffignac, Land subsidence and well failure in the Belridge diatomite oil field, Kern county, California. Part II. Applications, in *Land Subsidence,* edited by F.B.J. Barends, F.J.J. Brouwer, and F.H. Schröder, pp. 69–78, IAHS Press, Wallingford, Oxfordshire, UK, 1995.

Bowersox, J.R., and R.A. Shore, Reservoir compaction of the Belridge Diatomite and surface subsidence, South Belridge Field, Kern County, California, *AAPG Bulletin, 74* (5), 616, 1990.

Briole, P., D. Massonnet, and C. Delacourt, Posteruptive deformation associated with the 1986–87 and 1989 lava flows of Etna detected by radar interferometry, *Geophys. Res. Lett., 24* (1), 37–40, 1997.

Carnec, C., D. Massonnet, and C. King, 2 examples of the use of SAR interferometry on displacement-fields of small spatial extent, *Geophys. Res. Lett., 23* (24), 3579–3582, 1996.

Feigl, K.L., and E. Dupré, RNGCHN: a program to calculate displacement components from dislocations in an elastic half-space with applications for modeling geodetic measurements of crustal deformation, *Computers and Geosciences,* in press, 1998.

Fruneau, B., J. Achache, and C. Delacourt, Observation and modeling of the Saint-Etienne-de-Tinee landslide using SAR interferometry, *Tectonophysics, 265* (3-4), 181–190, 1996.

Gabriel, A.K., R.M. Goldstein, and H.A. Zebker, Mapping small elevation changes over large areas: differential radar interferometry, *J. Geophys. Res., 94* (B7), 9183–9191, 1989.

Galloway, D.L., K.W. Hudnut, S.E. Ingebritsen, S.P. Phillips, G. Peltzer, F. Rogez, and P.A. Rosen, INSAR detection of aquifer-system compaction and land subsidence, Antelope Valley, Mojave Desert, California, *Water Resour. Res.,* in press, 1998.

Goldstein, R., Atmospheric limitations to repeat-track radar interferometry, *Geophys. Res. Lett., 22* (18), 2517–2520, 1995.

Holzer, T.L., and R.L. Bluntzer, Land subsidence near oil and gas-fields, Houston, Texas, *Ground Water, 22* (4), 450–459, 1984.

Lu, Z., R. Fatland, M. Wyss, S. Li, J. Eichelberer, K. Dean, and J. Freymueller, Deformation of New Trident volcano measured by ERS-1 SAR interferometry, Katmai National Park, Alaska, *Geophys. Res. Lett., 24* (6), 695–698, 1997.

Martin, J.C., and S. Serdengecti, Subsidence over oil and gas fields, in *Man-induced Land Subsidence,* edited by T.L. Holzer, pp. 23–34, Geological Society of America, Boulder, Colorado, 1984.

Massonnet, D., T. Holzer, and H. Vadon, Land subsidence caused by the East Mesa Geothermal Field, California, observed using SAR interferometry, *Geophys. Res. Lett., 24* (8), 901–904, 1997.

Mayuga, M.N., and D.R. Allen, Subsidence in the Wilmington Oil Field, Long Beach, California, U.S.A., in *Land Subsidence,* edited by L.J. Tison, pp. 66–79, Int. Assoc. Sci. Hydrol., UNESCO, 1970.

McGuire, M.D., J.R. Bowersox, and L.J. Earnest, Diagenetically enhanced entrapment of hydrocarbons: southeastern Lost Hills fractured shale pool, Kern County, California, in *Petroleum Generation and Occurrence in the Miocene Monterey Formation, California,* edited by C.M. Isaacs, and R.E. Garrison, pp. 171–183, Pacific Section, SEPM, Los Angeles, California, 1983.

National Research Council, *Mitigating Losses from Land Subsidence in the United States,* 58 pp., National Academy Press, Washington, D.C., 1991.

Okada, Y., Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am., 75* (4), 1135–1154, 1985.

Peltzer, G., P. Rosen, F. Rogez, and K. Hudnut, Postseismic rebound in fault step-overs caused by pore fluid-flow, *Science, 273* (5279), 1202–1204, 1996.

Pratt, W.E., and D.W. Johnson, Local subsidence of the Goose Creek oil field, *J. Geol., 34* (7), 577–590, 1926.

Segall, P., J.R. Grasso, and A. Mossop, Poroelastic stressing and induced seismicity near the Lacq gas field, southwestern France, *J. Geophys. Res., 99* (B8), 15429–15438, 1994.

Vadon, H., and F. Sigmundsson, Crustal deformation from 1992 to 1995 at the Mid- Atlantic ridge, southwest Iceland, mapped by satellite radar interferometry, *Science, 275* (5297), 193–197, 1997.

Vanhasselt, J.P., Reservoir compaction and surface subsidence resulting from oil and gas-production: a review of theoretical and experimental research approaches, *Geologie En Mijnbouw, 71* (2), 107–118, 1992.

Zebker, H.A., P.A. Rosen, and S. Hensley, Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps, *J. Geophys. Res., 102* (B4), 7547–7563, 1997.

Zebker, H.A., C.L. Werner, P.A. Rosen, and S. Hensley, Accuracy of topographic maps derived from ERS-1 interferometric radar, *IEEE Trans. Geosci. and Remote Sens., 32* (4), 823–836, 1994.

E. J. Fielding, R. G. Blom, and R. M. Goldstein, Jet Propulsion Laboratory, California Institute of Technology, Mailstop 300-233, 4800 Oak Grove Drive, Pasadena, California 91109, USA. (e-mail: Eric.Fielding@jpl.nasa.gov)

(Received April 17, 1998; revised June 16, 1998;
accepted June 22, 1998.)