made valuable contributions to CALIPSO, and their efforts are also acknowledged. A. Clarke also contributed to CALIPSO through initial model development.

Additional detailed information about CALIPSO and an extensive photographic archive may be found at the following Web sites: http://www.ems.psu.edu/~elsworth/projects/calipso/ and http://comp.uark.edu/~mattioli/research/CALIPSO/Intro.html.

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InSAR Permanent Scatterer Analysis Reveals Ups and Downs in San Francisco Bay Area

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Using new analysis techniques of space-based radar data, surface deformation features caused by various tectonic, geomorphic, and hydrologic processes are imaged in the San Francisco Bay area of California. Uplift is due mainly to sub-mm/yr tectonic upheaval related to slip along and interaction of the complex array of San Andreas transform system faults, while seasonally recharging aquifers account for tens-of-millimeters rise. Observed downward motions are caused by seasonally depleting aquifers, active deep-seated landslides, and rapid settling of unconsolidated sediments and man-made fill alongside the San Francisco Bay.

Synthetic aperture radar interferometry (InSAR) from Earth-orbiting spacecraft has revolutionized the field of crustal deformation research since its first geophysical application about a decade ago [*Massonnet et al.*, 1993]. During the last 10 years, InSAR has been used to study a wide range of surface displacements related to active faults, volcanoes, landslides, aquifers, oil fields, and glaciers, to name just a few, at a spatial resolution of less than 100 m and centimeter-level precision [see *Massonnet and Feigl*, 1998; and *Bürgmann et al.*, 2000a for reviews of the InSAR method and applications]. The temporal resolution is limited by the approximately monthly repeat time of satellite flyovers. Due to the viewing geometry of the radar satellite (the beam along which distance changes are measured is oriented at ~23° off vertical), InSAR is particularly sensitive to vertical deformation, but cannot detect displacements parallel to the orbit track. Severe limitations to the InSAR method remain, especially decorrelation of surface scatterers due to vegetation or other surface change processes, incoherence caused by large satellite orbit separations between the two image acquisitions used to make an interferogram, and noise from signal delays in the Earth's atmosphere.

A new approach, the permanent scatterer method (PS) [*Ferretti et al.*, 2000; 2001] has been introduced to improve the ability to determine millimeter-scale displacements of individual features on the ground using all data collected over the target area by a SAR satellite (such as the European Space Agency's Earth Remote Sensing, ERS-1&2 spacecraft, on which this study relies). As long as a significant number and density of independent radar-bright and radar-phase stable points (i.e., permanent scatterers) exist within a radar scene, and more than about 15 SAR acquisitions have been collected, displacement time series and range change rates can be calculated [*Colesanti et al.*, 2003]. The PS method can measure surface motions at a level of < 1 mm/yr and can resolve very small-scale features, including motions of individual scatterer targets not previously recognized in traditional SAR interferometry over the San Francisco Bay area [e.g., *Bürgmann et al.*, 2000b].

From 1992 through 2000, 49 images of the ~100 x 100-km frame centered over the San Francisco Bay area have been collected by the two ERS satellites. Previous work using standard interferograms has focused on regional surface deformation associated with slip on the Hayward fault [*Bürgmann et al.*, 2000b] and time-dependent land subsidence and uplift from water table changes in the Santa Clara Valley [*Schmidt and Bürgmann*, 2003]. Here, an independently processed analysis of ERS SAR data using the PS method is presented that reveals spatially and temporally complex patterns of surface motions in the area, which are indicative of active tectonic, hydrologic, and geomorphic processes. The ability of the technique to precisely monitor the motion of individual buildings, utility poles, outcrops, or other radar-bright objects over a wide region provides measurements of surface motions at 115,487 points using the 49 data acquisitions (Figure 1). Using even more advanced algorithms, it should be possible to find about 5 times more PS that have reliable coherence in the target frame. Gravity-driven surface processes, such as settling of unconsolidated sediments and landsliding, are found to be taking away what tectonics is slowly constructing.

By A. Ferretti, F. Novali, R. Bürgmann, G. Hilley, and C. Prati

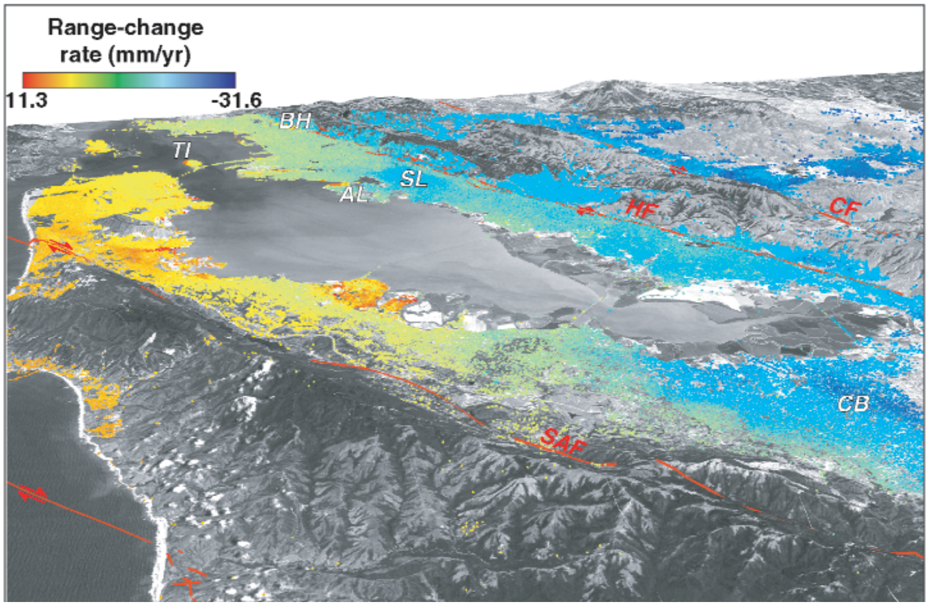

Fig. 1. A three-dimensional view of the 115,487 PS data points and LandSat imagery draped over the topography of the Bay region. The color of each point indicates its measured velocity toward or away from the ERS SAR satellite flying toward 193° and looking down from the east at a look angle of ~23°. SAF, HF, and CF denote the locations of the San Andreas, Hayward, and Calaveras faults, respectively. CB, SL, AL, TI, and BH show locations of the Cupertino and San Leandro basins, Alameda, Treasure Island, and the Berkeley Hills, respectively. Range change rates gradually vary across the region due to elastic strain accumulation about the major plate-bounding faults, but step abruptly across the Hayward fault, which slips aseismically along its surface trace (see Figure 2). Finally, large subsidence rates due to settling are observed alongside San Francisco Bay such as on Treasure Island and in Alameda.

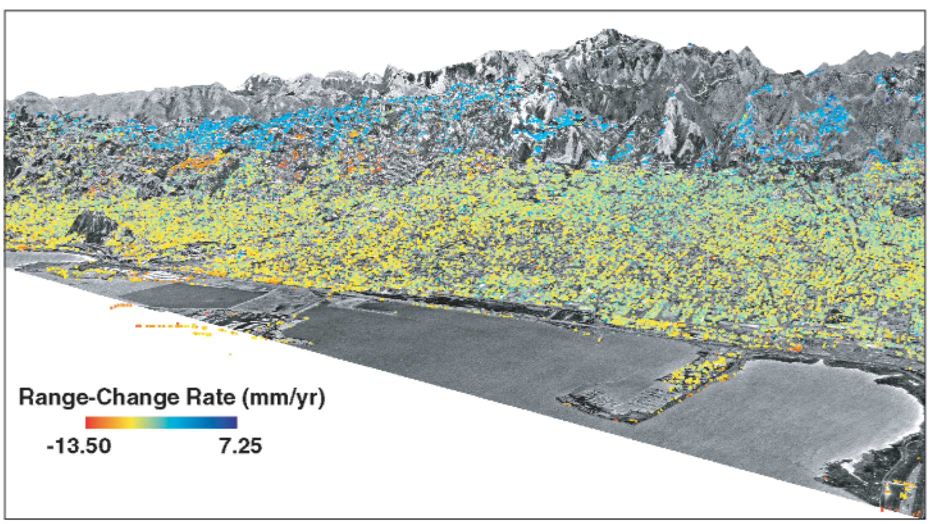

Fig. 2. Close-up of PS range-change rates over the Berkeley area, drawn on an ortho-rectified aerial photograph. Note the sharp offset across the Hayward fault consistent with ~4.6 mm/yr of strike-slip and 0.4 mm/yr of east-side-up, dip-slip faulting. Zones of high range change increases (indicated by red colors) suggest that previously recognized landslides in the Berkeley Hills currently move at rates of up to ~50 mm/yr.

What Goes Up...

The tectonics of the San Francisco Bay area is dominated by the San Andreas strike-slip fault system, the major plate boundary between the Pacific and North American plates accommodating about 40 mm/yr of right-lateral motion. The steady gradient in the PS range-change-rate pattern across the region shown in Figure 1 is indicative of the broadly distributed nature of elastic strain accumulation about the major faults in the region that eventually accommodate much of this deformation in large earthquakes. The PS measurement of this strain accumulation field is consistent with independent results from about 3-orders-of-magnitude fewer measurement points surveyed with GPS [*Bürgmann et al.*, 2000b]. The data also reveal a discrete offset across the Hayward fault caused by aseismic fault slip at about 5 mm/yr along its complete length. In addition to the dominant strike-slip faults, thrust faults and earthquakes on such structures play an important role in the deformation of the Bay area and the creation of its rugged landscapes. Such uplift is concentrated in areas of restraining bends and steps along the strike-slip faults. Nonetheless, tectonic rock uplift rates in the San Francisco Bay area are probably less than ~1 mm/yr throughout the region, and thus, have been rather elusive to measure using geodetic investigations. GPS for example, has difficulty resolving vertical motions of rates less than several mm/yr.

As InSAR is particularly sensitive to vertical motions, resolving tectonic uplift by correcting the data for independently measured horizontal motions can be attempted. Along the northern East Bay Hills (Figure 2), which rise between the Hayward and Calaveras strike-slip faults (shown in Figure 1), rock uplift rates are thought to be <1 mm/yr. As the Hayward fault is known to slip aseismically to several km depth [*Bürgmann et al.*, 2000b], any vertical displacement component would also be expected to be localized at the fault, rather than be distributed over a wide elastic strain accumulation zone. The horizontal strike-slip component of fault offset is very well constrained from numerous field measurements [*Lienkaemper et al.*, 2001], with measurements along the northern Hayward fault segment that indicate creep rates have been 4.7 ± 0.4 mm/yr during the last ~ 21 years. The contribution of vertical fault slip to the SAR range-change measurement was estimated by correcting the across-fault range offset for the established horizontal slip values. The first geodetic estimate of active uplift of the East Bay Hills using this method is 0.4 ± 1 mm/yr. Using the same approach of estimating tectonic uplift rates by formally integrating complementary precise measurements (such as from GPS) of horizontal motions with the PS results, it should be possible to resolve sub-mm/yr vertical motions across the whole region.

In addition to the very slow tectonic uplift, the range change measurements reveal a number of regions of quite rapid uplift, including an area near San Leandro and much of the Santa Clara Valley near San Jose. Young sedimentary basins that contain extensive confined aquifers underlie both of these areas. The observed uplift is consistent with previous work showing that recharge and resulting groundwater level rise in the local aquifers resulted in several centimeters of elastic rebound of previously subsiding and compacting basins. Extensive groundwater pumping in the early to mid-twentieth century led to as much as 3 m of land subsidence in the Santa Clara Valley. A combination of reduced reliance on local groundwater (replaced in large part by water transported from the Sierra Nevada), high precipitation in El Niño years during the observation period, and deliberate efforts to recharge the local aquifers contributed to this reversal. Time series of the elevation changes over the Santa Clara Valley show that this uplift pattern is modulated by a strong seasonal cyclic pattern paralleling changes in groundwater levels [*Colesanti et al.*, 2003; *Schmidt*

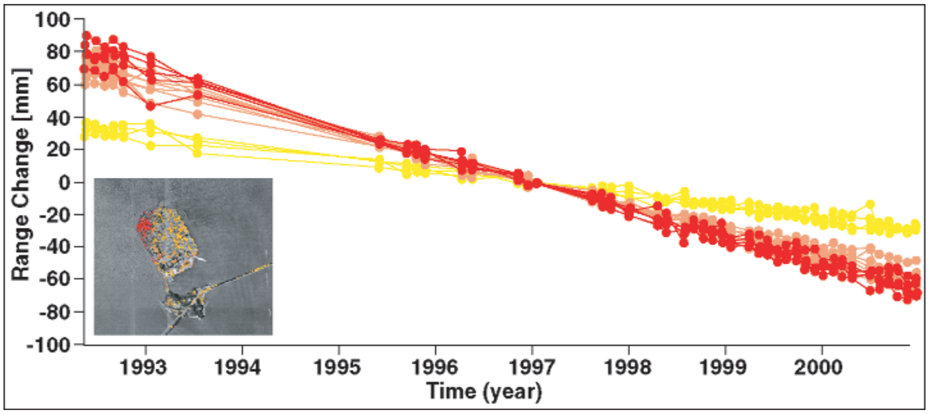

Fig. 3. Time series of 17 individual permanent scatterer points from an area on northwestern Treasure Island that appear to experience very rapid and mostly steady subsidence due to settling of unconsolidated Bay mud and man-made fill. Areas experiencing similarly rapid settling are recognized along much of San Francisco Bay (see Figure 1).

and Bürgmann, 2003]. The spatial resolution and high sensitivity to vertical motions of the SAR range change measurements make it a particularly well-suited tool for the study of surface deformation related to the redistribution of fluids in the subsurface.

...Must Come Down

Tectonic uplift across the Hayward fault zone results in surface topography that is being degraded by various erosional processes, including deep-seated landslides that underlie the populated region. The PS data reveal the degradation of the uplifted hills by slowly sliding (at 27–38 mm/yr with range change projected into the downslope direction), deep-seated landslides in the Berkeley Hills [*Hilley et al.*, 2004]. These landslides are located within developed areas of the Berkeley Hills, and so PS data provide important information about the hazards they pose to businesses and personal property. The PS data reveal changes in slide velocity due to variation in seasonal precipitation, which indicate that saturation of the near-surface groundwater system plays an intimate role in triggering and accelerating these mass failures. In particular, the PS time-series indicate that movement along these slides accelerates during the wet portions of the year and virtually ceases during the dry, summer months. In addition, high-precipitation events such as El Niño greatly enhance the landslides' movement [*Hilley et al.*, 2004]. These observations indicate that the PS method has the potential to characterize the hill slope stability over broad areas at unprecedented resolution. The rich information provided within the PS time series may also be used to study the details of the interplay among precipitation, groundwater flow, and failure of large, deep-seated landslides.

The highest elevation change rates observed are due to settling of developed unconsolidated sediments and anthropogenic fill flanking the Bay. These areas are located over young Bay mud which is the base soil underlying the lowest elevations around the Bay, often overlain by man-made fill to allow for development. Bay mud and fill are prone to consolidation and liquification in earthquakes, leading to surface settlement. The northwest tip of Treasure Island, the Bay Farms division in Alameda, and areas in southeast San Francisco subsided by up to 0.15 m in the 1992–2000 observation period. Figure 3 shows time series of 17 permanent scatterers on Treasure Island that suggest that this subsidence pattern has been quite steady during this time, and does not vary strongly with seasonal precipitation. Points in the northwestern portion of the island show the highest subsidence (Figure 3; red points), while those near the center of the island show significantly less subsidence (Figure 3; yellow points).

When the first SAR interferograms excited the Earth science community 10 years ago, even the more optimistic among us might not have envisioned the degree of precision and detail that new analysis methods of SAR data are now beginning to provide. Over the next 10 years, similarly impressive improvements may lie ahead. Ultimately, the future success of InSAR science will depend on the continued deployment of SAR satellites. This includes, hopefully in the near future, a dedicated U.S. SAR mission focused on surface change and deformation research, which is envisioned as the fourth component of the recently initiated EarthScope program.

Acknowledgments

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