

## Sentinel-1 Heralds New Era of Satellite Geodesy with Imaging of **South Napa** Earthquake

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The launch of the first satellite in European Commission's Sentinel-1 constellation on 3 April 2014 initiated the countdown to a radical increase in our ability to monitor our dynamic, restless planet. For the first time, radar data will be acquired systematically and frequently over all the tectonic and volcanic areas of the planet. The data will be freely available to the whole community, and the mission has a long duration, with future launches planned to extend the time series to at least 20 years. Here we demonstrate the capability of Sentinel-1 by showing its first tectonic results, which reveal the deformation that occurred during and immediately following the August 2014 **South Napa** Valley earthquake.

For more than two decades, space-based radar satellites have been measuring how the ground deforms with extraordinary precision and spatial resolution using interferometry (InSAR) [e.g. Hooper et al., 2012]. The results have been used to help scientists understand the dynamics of a variety of geophysical phenomena, including earthquakes, volcanoes, landslides, glacier flow and ground subsidence [Burgmann et al. 2000]. Past satellite radar missions were neither designed nor optimised for interferometric analysis, with long repeat times, poor orbital control, haphazard acquisition strategies and, in some cases, commercial pricing policies that have restricted their utility. Sentinel-1A is now operational and by early 2015 will be systematically acquiring data across deforming regions - by this point, we plan to be ready to process the vast quantities of data that will flood in from this extraordinary mission. In 2016, Sentinel-1A will be joined by a second satellite to complete the constellation, doubling the amount of data and halving the revisit time **to 6 days**.

### *August 2014 **South Napa** Earthquake*

The first geophysical event caught in the act by Sentinel-1 was the August 2014 **South Napa** (California) earthquake (Figure 1). The shallow magnitude 6.0 earthquake struck the Napa Valley at 03:20 on the 24th of August (*USGS NEIC*), with the epicentre located just south of the city of Napa (population 77,000). This earthquake is the biggest to hit the San Francisco Bay Area since the 1989 Mw 6.9 Loma Prieta earthquake.

The extent of the ground deformation in the interferogram (Figure 1a) shows that the fault slip in this earthquake matches well the length of the mapped rupture at the surface recorded by scientists from *UC Davis* and also the *USGS* (*also see SCEC event page [response.scec.org](http://response.scec.org)*). The main slip surface in the earthquake was a previously unmapped part of the West Napa Fault **zone**, which is considered to accommodate a minor component of the dextral shear through this part of California [d'Alessio et al. 2005]. The interferogram shows that the southeast-side of the rupture has moved towards the satellite by about 10 cm, whilst the northern portion has moved away by 10 cm. **Typically** near-fault motions in a strike-slip earthquake are horizontal and in the direction of the fault. **However**, away from the fault trace, and particularly near the ends of the rupture, there are significant fault-perpendicular and

vertical motions. **The satellite observations are from a descending track direction travelling north-to-south across the area and imaging Napa from the east, looking in a west-north-west direction (Figure 1a).** On the east side of the Napa North-South fault rupture, the motions are in the same direction with respect to the satellite look-direction, either both towards or both away from the satellite, resulting in a large signal. However, on the western side of the fault, the east-west and vertical motions are resolved in the opposite sense relative to the satellite look-direction, cancelling each other out and explaining the asymmetry seen in the deformation pattern across the fault.

The small surface displacements measured in the interferogram agree with the small offsets measured in the field by geologists surveying the fault rupture, who found displacements in roads and kerb stones of about 10-20 cm [Morelan & Trexler, pers. comm., 2014]. The interferogram also reveals other portions of the fault system that have moved slightly in this event. Sharp lines in the interferogram, known as phase discontinuities, show minor movements on other faults, such as the part of the West Napa Fault **zone** that crosses Napa airport (Figure 1b). On 12 September 2014 a third Sentinel-1 image was acquired over the **South Napa** earthquake rupture. This interferogram (Figure 1c) beautifully confirms the widespread field observations of shallow postseismic afterslip. **The rupture and afterslip were also captured by other satellite (COSMO SkyMed & Radarsat-2) and airborne (UAVSAR) radar systems, offering the chance, combining these various datasets, to build up a relatively dense time-series of the evolution of fault slip.**

#### *New SAR acquisition mode*

Sentinel-1A was launched in early April 2014, but it only reached its final operational orbit on 7 August. The pre-Napa earthquake image was acquired on that day. By comparing it with an image acquired on 31 August, it was possible to create a map of the surface deformation caused by the magnitude 6.0 earthquake using the technique of InSAR [e.g. Hooper et al., 2012]. The actual type of image acquired over this part of California happened to be in “StripMap” mode, similar to the default high resolution mode used by most previous radar satellites. However for Sentinel-1 (Salvi et al., 2012), the default acquisitions over continental areas for the acquisition of radar data will be in a novel mode, known as TOPS (Terrain Observation with Progressive Scans) mode. The TOPS mode has some advantages, the most significant of which is that a 250 km wide image can be acquired at high spatial resolution. This wider swath means Sentinel-1 is the first radar satellite that can revisit the entire land surface every 12 days. On the other hand, the main new challenge introduced by the TOPS mode is that a single product consists of a large number of small, individual but slightly overlapping images. Thus, TOPS data products requires very different processing and data management methods, in comparison to the old SAR acquisition types with a single image per product. Best practices for the optimal handling of TOPS data for geophysical applications is currently an active research topic in the SAR/InSAR community.

### *Future Aspirations & Open Data*

Systematic acquisitions, as well as a free and open data policy, provide new opportunities for routine analysis and operational applications of InSAR from Sentinel-1. In the UK Natural Environment Research Council's Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET; <http://comet.nerc.ac.uk>), we plan to provide processed InSAR results for all the tectonic and volcanic regions of the planet to the research community. This will greatly widen the group of users and scientists which will be able to exploit these previously restricted datasets. When the Sentinel-1 constellation is fully operational, with the launch in 2016 of the identical Sentinel-1B satellite, the average time delay between an earthquake and the first post-event acquisition will be just 1.5 days. We will post interferograms and standard analyses for earthquakes online in near-real time, providing robust information for scientists and responders in the field. At the same time, the regular acquisitions will quickly build into large stacks for each track. We will use these to produce estimates of average surface velocities and time-dependent motions that can be used to assess the slow accumulation of interseismic strain around locked faults. By 2034, there will be a 20 year archive of systematic radar acquisitions from the Sentinel-1 program. We expect that this will have fundamentally changed the way we view our planet, monitor surface processes and analyze time-varying geohazards.

### *References*

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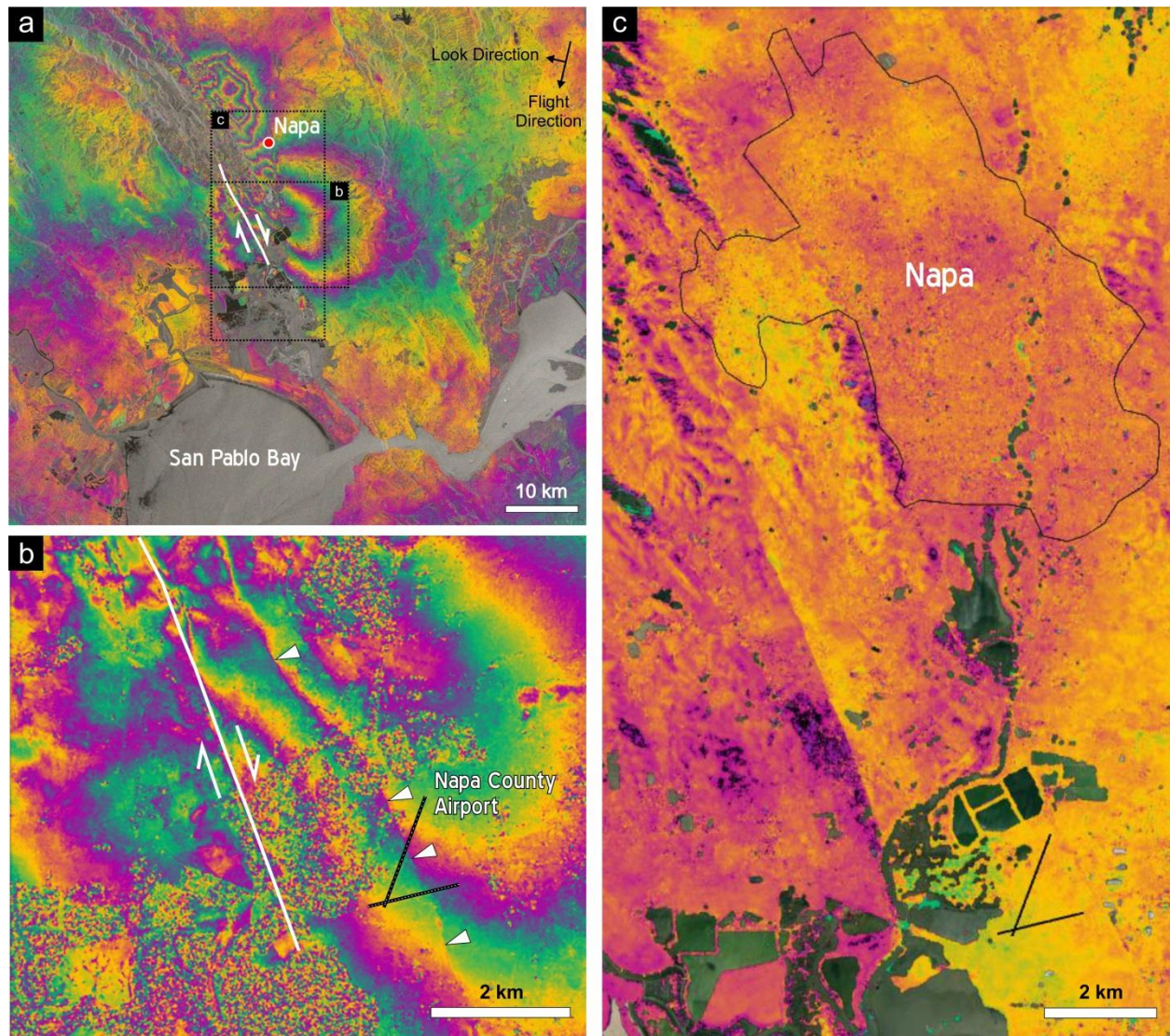


Fig. 1. (a) Sentinel-1A interferogram (07.08.2014-31.08.2014) of the Napa earthquake showing ground displacement contours (2.8 cm) of motion towards and away from the satellite. **The black arrows indicate the satellite flight and look direction.** The deformation pattern follows the surface trace of the rupture mapped in the field by scientists from UC Davis. (b) Enlarged view of the deformation field around Napa County Airport showing both the main rupture to the west of the airport, and a discontinuity in the phase across the runways. (c) Postseismic interferogram (31.08.2014-12.09.2014) showing the fault shallow afterslip discontinuity of about 2 cm. The interferometric results can be downloaded from: [insarap.org](https://insarap.org).



