Window Into Ground Movement

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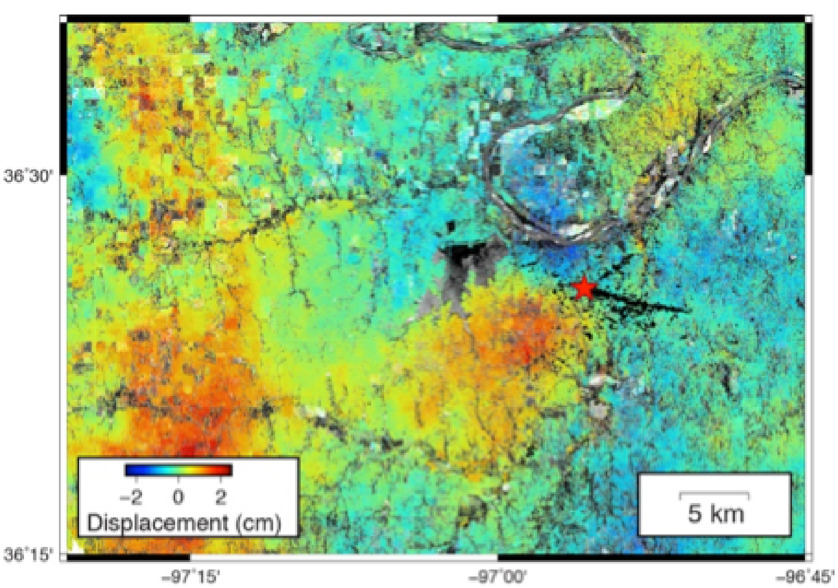
The energy and water needs of the world's population are continuing to grow, requiring new and innovative ways to meet them. The imaging geodesy group at Cornell University uses satellite imagery, including SAR data hosted at the ASF DAAC, to address these problems. Synoptic views of the globe provided by satellite-based remote sensing can aid us in monitoring and characterizing the effects of these efforts, which include significant land-use change as well as transfer of large amounts of fluids that are being extracted from or injected into the subsurface. The pattern of subsidence or uplift is a window into the pattern of fluid flow below – whether the activity is concentrated near the well as expected, or if it jumps into a neighboring region – could be an important indicator of stability or problems to come. The past decade has seen a substantial increase in the number of earthquakes triggered by both injection and production of subsurface fluids, with states in the central United States, such as Oklahoma, now experiencing more earthquakes each year than California. Globally, radar imagery has already been used to characterize the extent of reservoir depletion around oil, gas and water wells [e.g., *Fielding et al.*, 1998; *González et al.*, 2012], with renewed efforts by researchers to understand the complex networks of faults surrounding the areas of exploitation.

The increased rate of earthquakes in regions such as the central United States (Figure 1) brings with it new challenges, particularly since the energy and resource needs of our population are likely to continue to grow. Characterizing the patterns of earthquakes we are experiencing now will help us understand how to anticipate and mitigate future damage. Operations managers at individual well sites, insurance companies and disaster responders all require information about the probabilities of strong shaking and aftershocks after a large event. Even forecasting the expected damage from these new types of earthquakes is not just "business as usual". Analysis of felt shaking reports [*Hough*, 2014] from the Central United States suggests that the distribution of damage from these earthquakes, which tend to be shallower and may have more involvement from fluids within the rock, differs from the damage expected from "traditional" earthquakes, which often occur deep underground. Precise estimates of the location and timing of these earthquakes are needed to understand how they interact with each other and with the perturbations to the subsurface that are driving them.



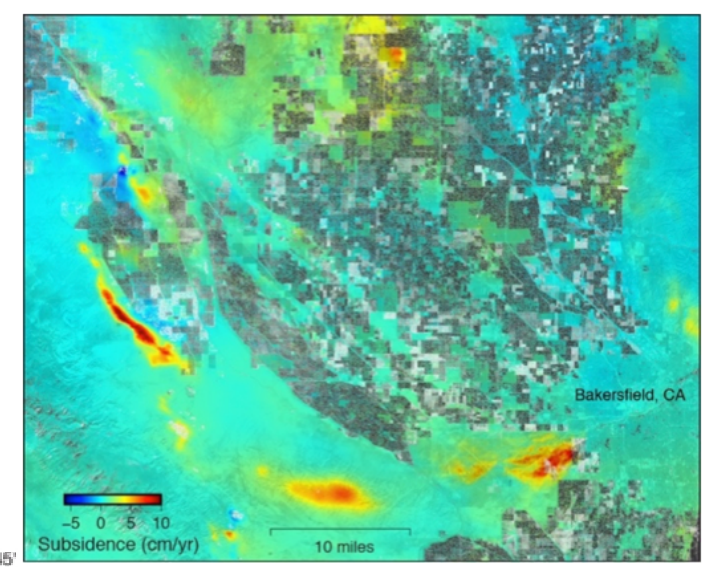


Figure 1: In this example, using SAR data from the European Space Agency's Sentinel-1 platform (downloaded from the ASF DAAC), we can see several cm of displacement over a 10-km-x-10-km region associated with the 2016 magnitude 5.8 Pawnee, Oklahoma, earthquake. The main earthquake location (red star) and aftershocks (black dots) outline a complex pattern that provides insight into patterns of weakness in the subsurface. Also in this image (red band on left) is the signature of a large storm that was present during one of the image acquisitions. When many images are available, such atmospheric effects can be averaged out more effectively to determine the true ground movement.

Figure 2: Rate of ground subsidence in Central California imaged using the European Space Agency's ENVISAT satellite, averaged over the time period 2008-2010 (color), overlain on Landsat imagery (grayscale). Both the results of extraction (red) and injection (blue) can be seen. Patterns in the lower and left of the image are associated with hydrocarbon extractions; large values in the top of the image are associated with groundwater use. Gray areas are regions where the ground surface changed significantly between images, due to crop growth and tilling of fields.

Another type of ground deformation that we explore with SAR imagery is associated with the use of groundwater, particularly in arid regions of the United States. Monitoring changes in shallow aquifer systems and understanding the geologic controls on their basic configuration are rapidly becoming essential challenges as society places increased pressures on water resources. These challenges are present globally in arid regions, with the impacts acutely felt throughout the western United States. Historically, understanding of regional aquifer systems has relied on monitoring wells that are sparsely distributed across impacted areas. Combinations of GPS and InSAR observations [e.g., *Amos et al.*, 2014; *Borsa et al.*, 2014] are now providing a different and complementary view of the patterns of ground-surface displacements associated with injection or extraction of subsurface fluids (Figure 2).

However, InSAR observations cannot be made when the ground surface changes significantly between image acquisitions. Growth of crops, tilling of fields, or trees shedding their leaves are all processes that degrade data quality. The example of induced earthquakes in the central United States shown above (Figure1) is a case where SAR imagery was, fortunately, acquired both before and after the earthquake. Many other earthquakes in these regions have been impossible to study because of the complete lack of data before the event. In recent years, data coverage has improved dramatically, with closer repeats in time that reduce the impact of decorrelation that plagued studies using earlier satellite platforms. This improved data quality comes with the need to understand other factors that contribute to the observed phase delay, such as changes in vegetation, soil moisture and the severe storms that occur frequently in the central United States. Our work at Cornell focuses both on areas with known deformation signals and places that are expected to be fairly stable, so that we can better quantify the impact of these complicating factors. Our goal is to separate out the temporally varying ground displacement signals that may be associated with human activity and seismicity from signals that are solely due to land use change, seasonal variations in vegetation, etc.

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