# Results of InSAR analysis in Yolo County


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March 2, 2017 WRA Technical Committee

# Overview

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- Overview of Interferometric Synthetic Aperture Radar (InSAR) processing
- Issues encountered and analysis strategy
  - Data availability

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- InSAR total deformation estimates from ALOS and ENVISAT data
- Comparison with GPS survey data
- Comparison of InSAR time-series vs other data sources
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- Cost comparison of InSAR vs GPS-based surveys
- Recommendations

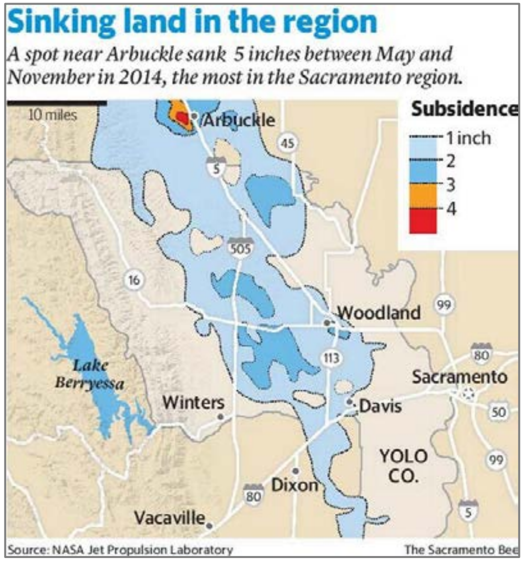
# Approach

# Project Objectives

This project was designed to assess how satellite-based techniques influence stakeholders' understanding of subsidence in Yolo County, and appropriate policy responses.

As part of this overall study, Stanford undertook a geophysical study with the following specific objectives:

- Estimate total subsidence in Yolo County from InSAR data from 2002-2005, 2005-2008, and 2008-2012.
- Characterize any seasonal surface deformation signal(s) observed in Yolo County, including magnitude, timing, and spatial distribution.
- Compare observed surface deformation patterns to known geologic features.
- Compare observed surface deformation patterns to both spatial and temporal patterns of estimated water use, including irrigation and groundwater pumping.



# Project Objectives

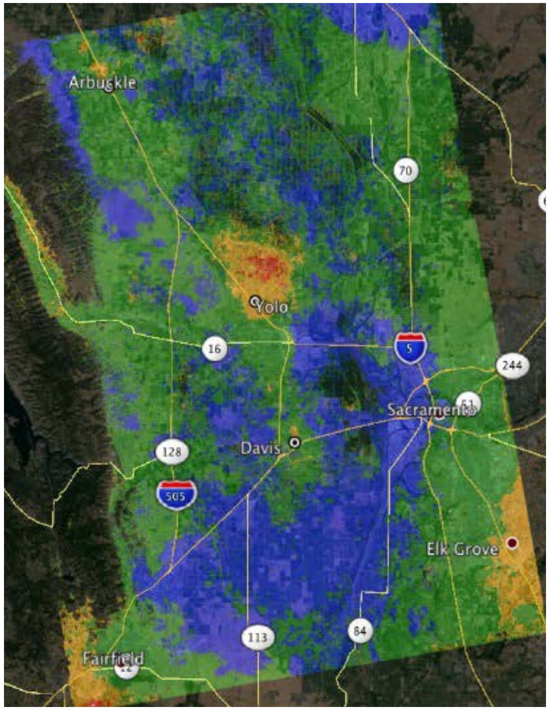
Ultimately, the intention of this project is to help the stakeholders of Yolo County better understand:

- Magnitude, timing, and spatial distribution of subsidence within Yolo County.
- Potential relationships between observed subsidence and use/management of water and groundwater resources.
- How InSAR may be used as a technique to monitor and assess subsidence, and how this technique may compliment and/or improve upon traditional techniques based on surveying GPS stations.

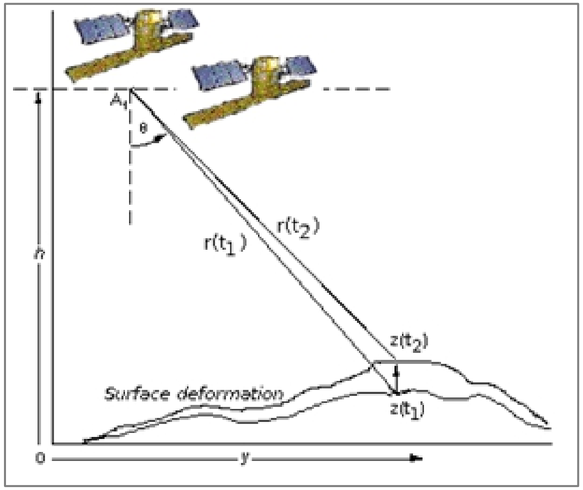

Image: USGS

# InSAR

- **In**terferometric **S**ynthetic **A**perture **R**adar
- Satellites utilizing precision radar measure reflections from the ground surface at different times
- If the position of the ground has changed during the time between measurements, the travel time of the reflection also changes, resulting in a phase difference between the two measurements
- Ground deformation can be calculated from this phase difference




Credit: Farr et al., 2015




Credit: GGOS, adapted from European Space Agency

# InSAR Processing

Processing of InSAR data can be quite an involved process, and generally includes:

- Identification and acquisition of the available satellite images (scenes) in the study area/timeframe.
- Geometric corrections to those images to account for angle of incidence, shifts in satellite position between scenes, and other factors (co-registering the scenes).
- Identification of areas on the surface that act as good reflectors, resulting in good amplitude and coherence, called persistent scatterers.
- Generating an image of the estimated phase difference between scenes, as an interferogram.
- Converting the interferogram to an estimate of relative vertical ground movement (unwrapping the interferogram)

# InSAR Processing

Each of these steps will influence the quality and/or uncertainty of the final result.  For example:

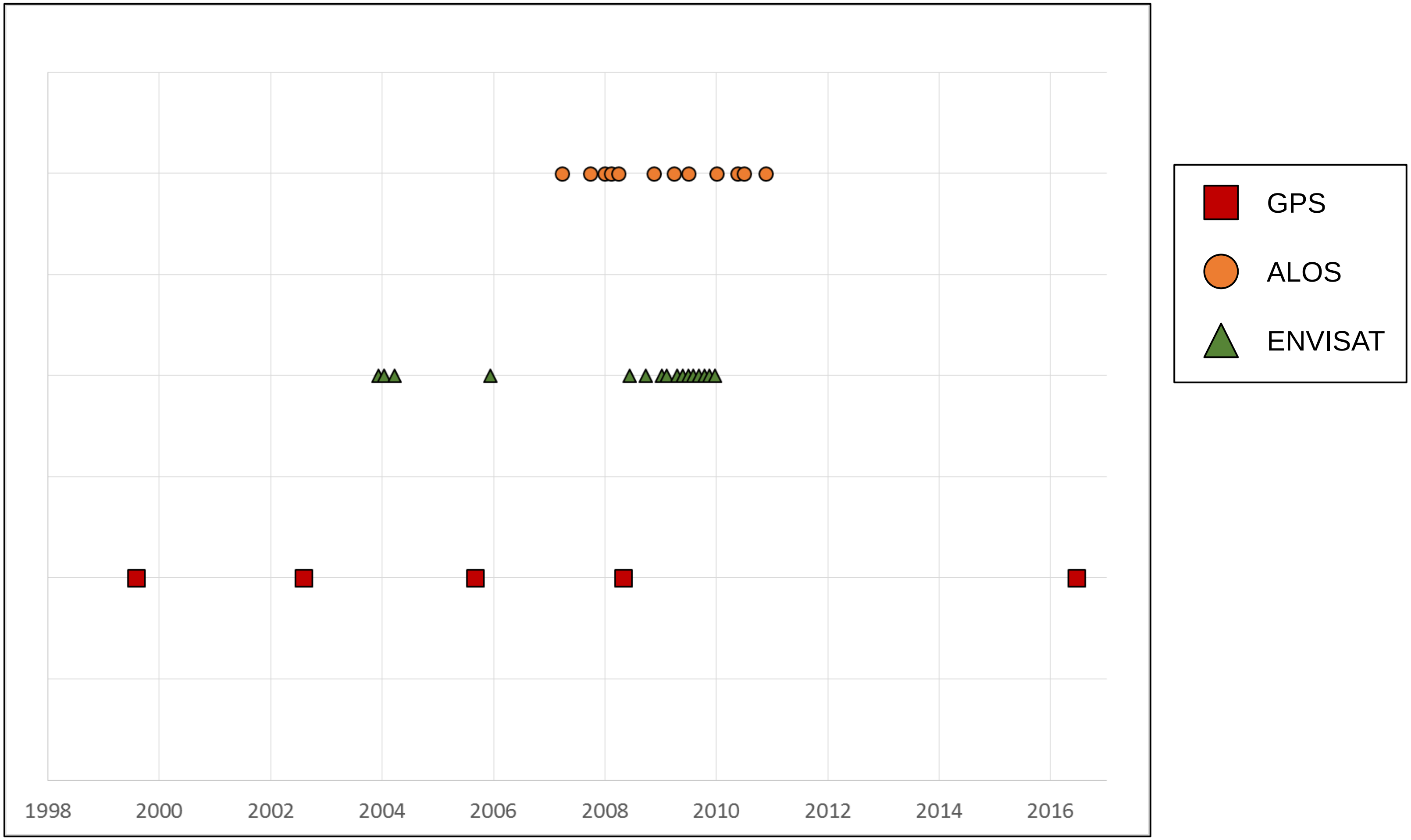
- Having a low number of scenes over the study area within the analyzed timeframe will make co-registering the scenes and unwrapping the interferograms more difficult, because more significant changes may have occurred between scenes.
- The quality of the Digital Elevation Model (DEM) used during the geometric corrections can lead to artifacts in the result, if its resolution is not sufficiently fine.
- Persistent scatterers can be sparse in some areas.  The best persistent scatterers are often:
  - Buildings, roads, and other fixed, flat infrastructure
  - Sparsely vegetated areas, or areas with unchanging, low vegetation

# Issues Encountered: Data Availability in Yolo County

- Data for the study period (2002 to 2012) were acquired by two different satellite missions, ENVISAT and ALOS, each requiring different processing routines.
  - ALOS scenes were available over Yolo County at regular intervals from early 2007 through late 2010.
  - ENVISAT scenes were available over Yolo County from late 2003 through the end of 2009, but it was found that there were no ENVISAT scenes available in 2006 or 2007 and very few scenes from late 2004 through 2005.

# Issues Encountered : Data Availability

- Available scenes from ALOS and ENVISAT, along with dates of ground-based GPS surveys:

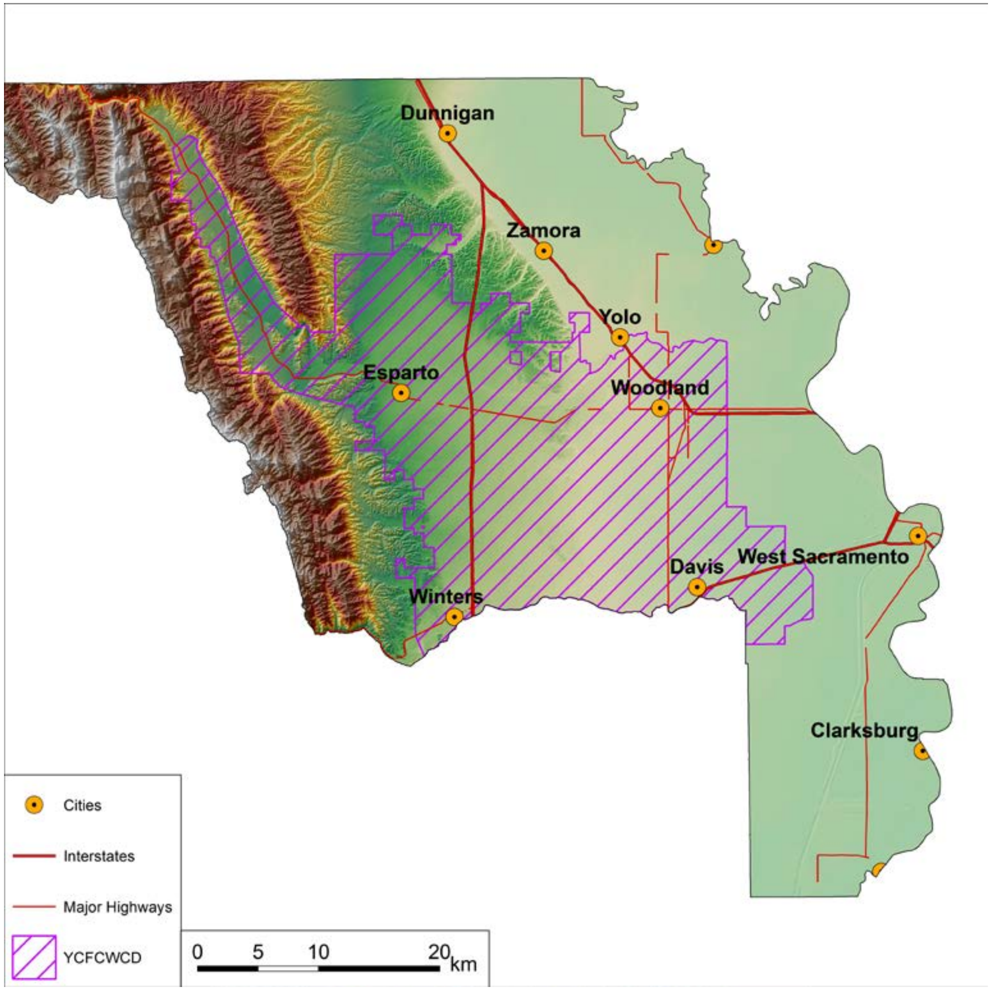


# Approach

- Given the available data, it appeared that concentrating on the ALOS data would yield the best results, and formed the core of our analysis.
  - The frequency of ALOS scenes will also be more indicative of the data available from current satellite missions.
  - Given that the current drought cycle began in 2007, which coincides with the first available ALOS data, the nearly 4 years of ALOS data from 2007 to late 2010 should be representative of the influence of drought conditions on subsidence in this area.
  - ALOS data will be compared to the GPS-survey data taken in 2008.
- ENVISAT data were also processed. These data could provide an indication of the change over a longer time period, however due to the less frequent sampling, results have higher uncertainty and cannot be divided into the discrete time periods set out in the study objectives.

# Results

# Yolo County



Dunnigan
Zamora
Yolo
Esparto
Woodland
Davis
West Sacramento
Winters
Clarksburg
Cities
Interstates
Major Highways
YCFCWCD
0
5
10
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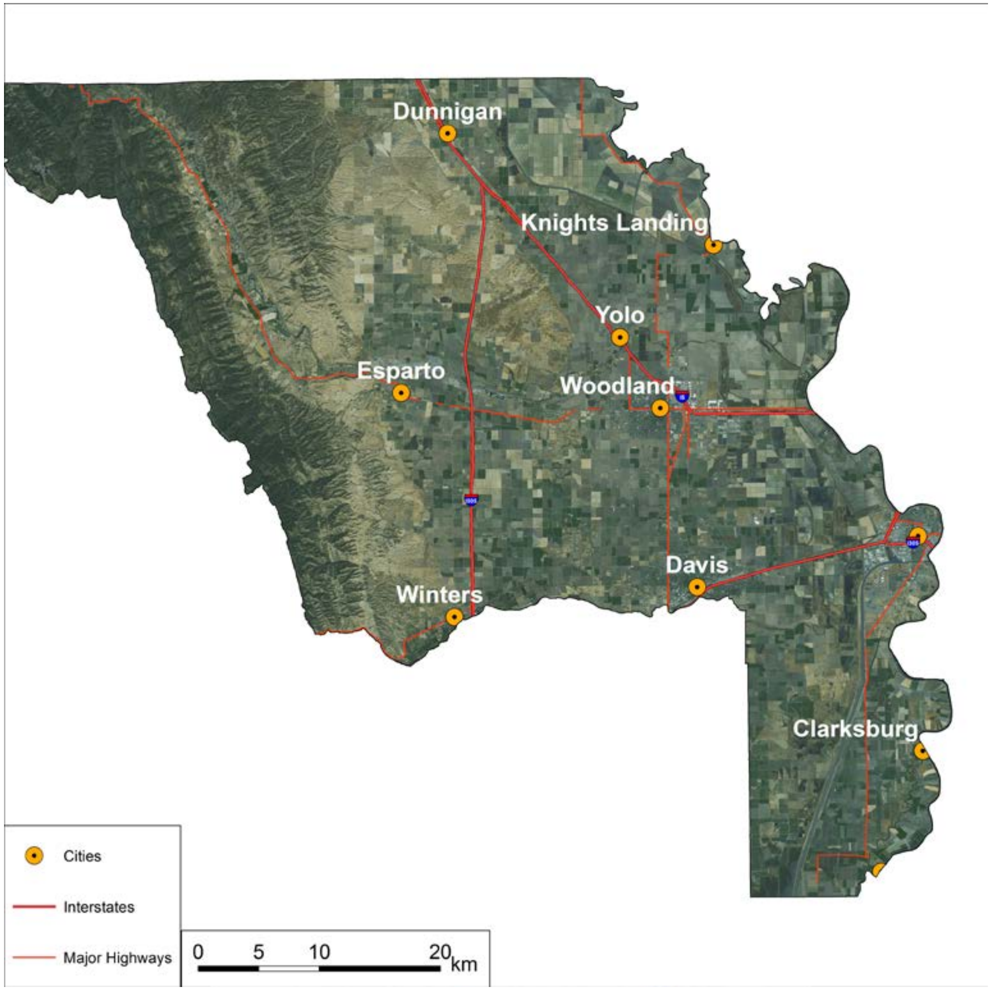
km

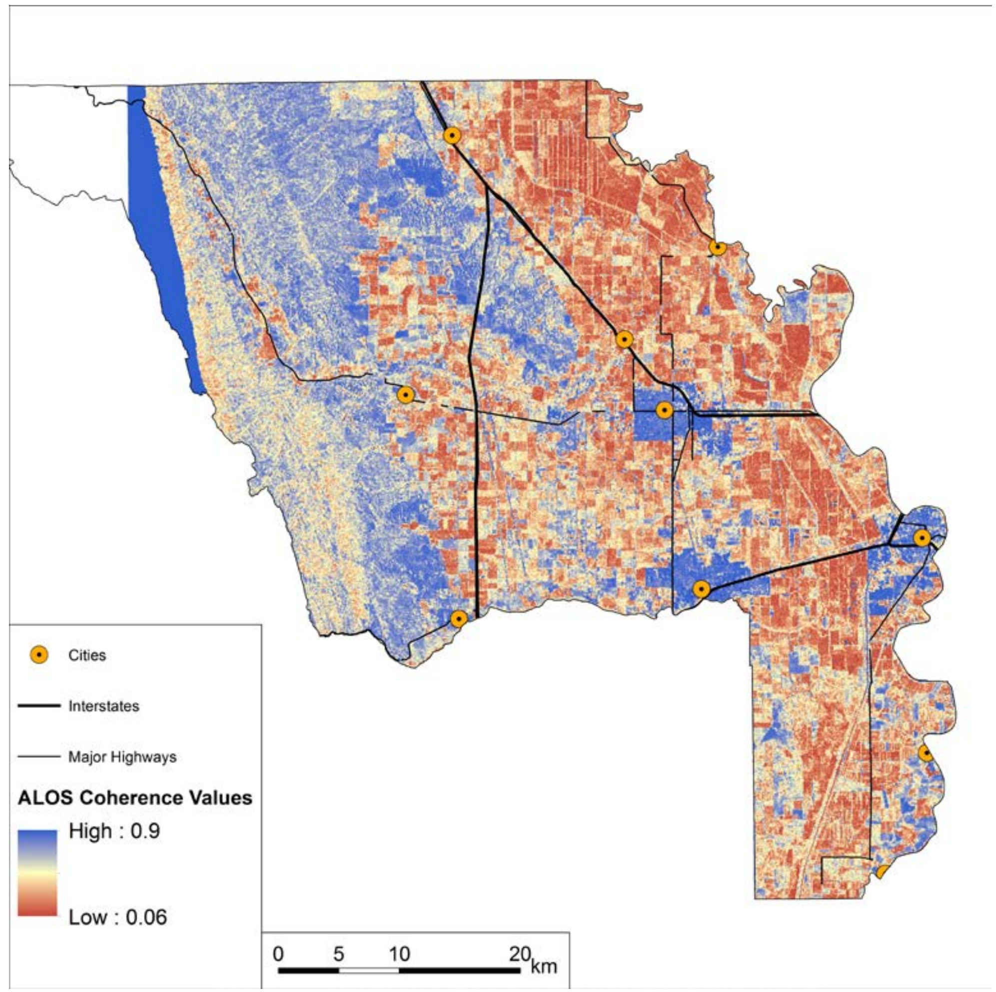
# Yolo County



Dunnigan
Knights Landing
Yolo
Esparto
Woodland
Davis
Winters
Clarksburg
Cities
Interstates
Major Highways
0
5
10
20
km

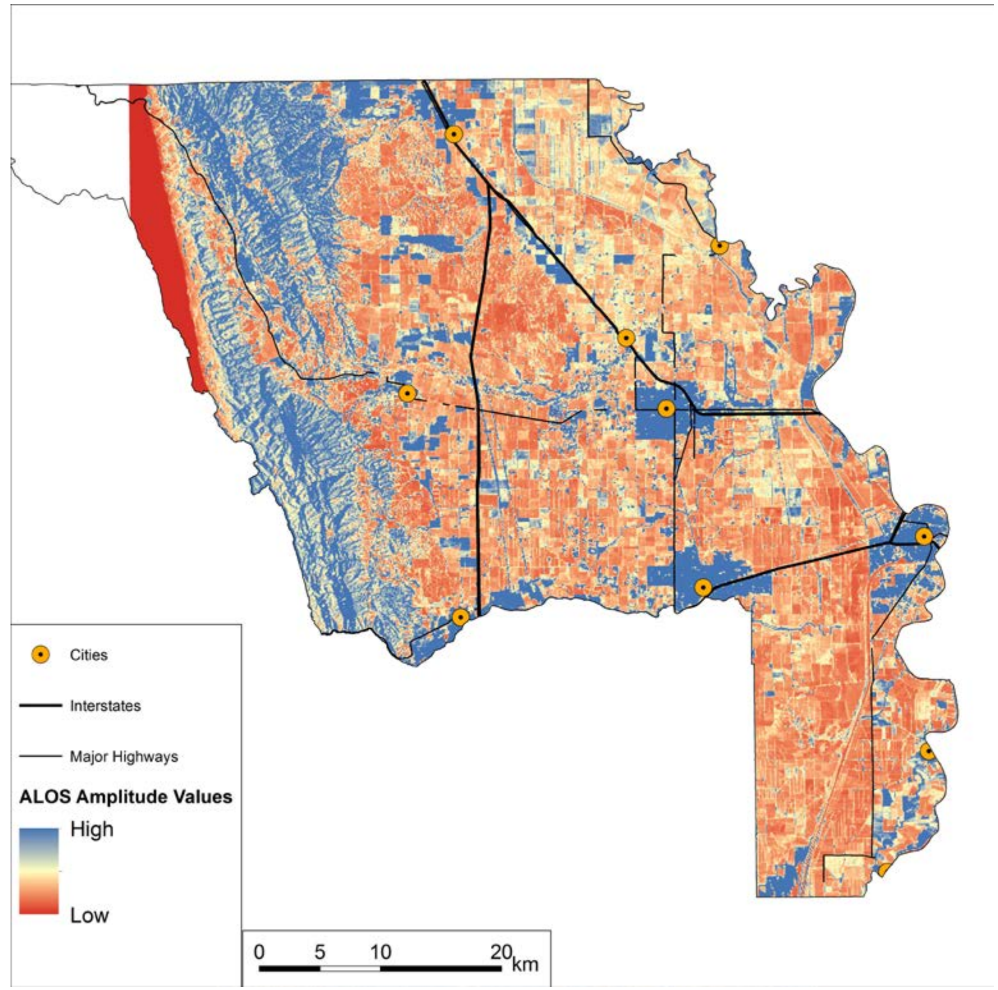
# 2007 to 2011 ALOS data coherence

- Coherence is one measure of the data quality at each pixel in an InSAR scene, with higher values (closer to 1, blue) indicating better-quality data and lower values (closer to 0, red) indicating lower-quality data.
- The best areas in Yolo County for InSAR data quality are the urban areas, with much lower data quality over the main agricultural areas.



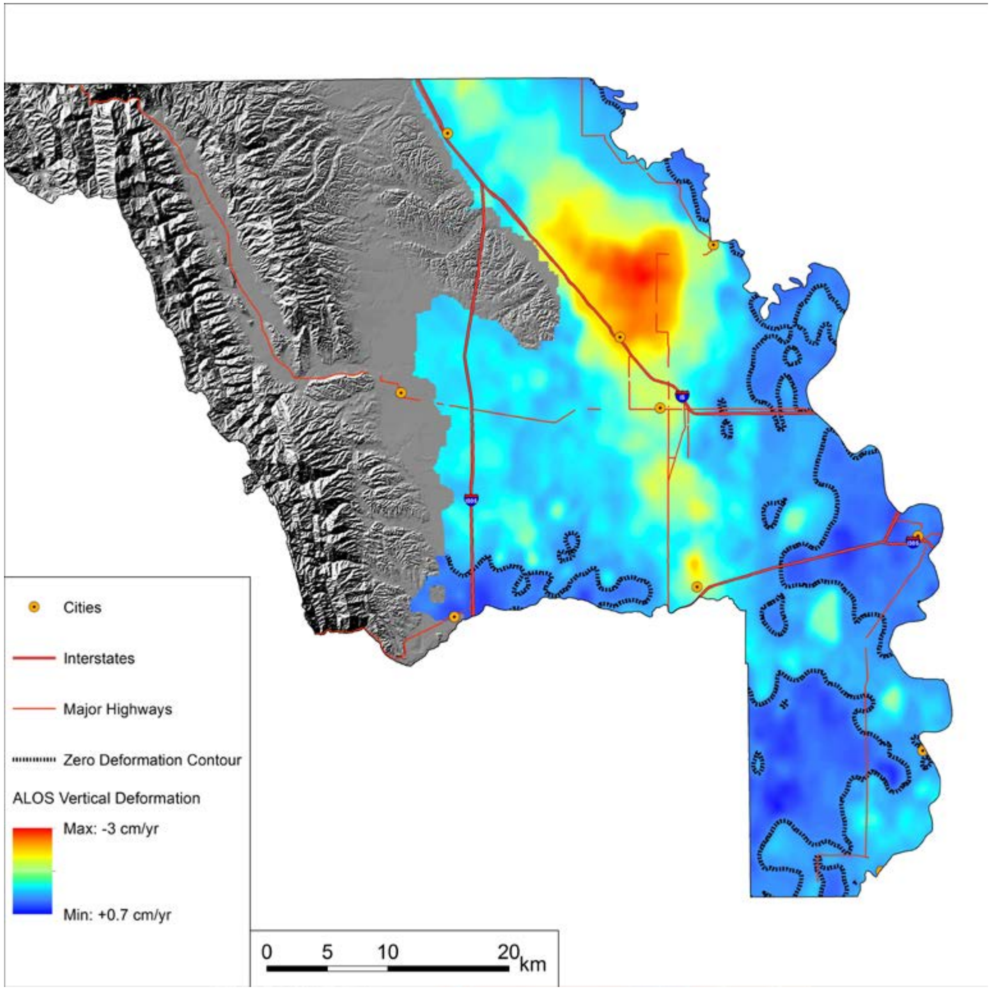
# 2007 to 2011 ALOS data amplitude

- Amplitude is another measure of the data quality at each pixel in an InSAR scene, with higher values (blue) indicating better-quality data and lower values (red) indicating lower-quality data.
- Again, the best areas in Yolo County for InSAR data quality are the urban areas, with lower data quality over the main agricultural areas.



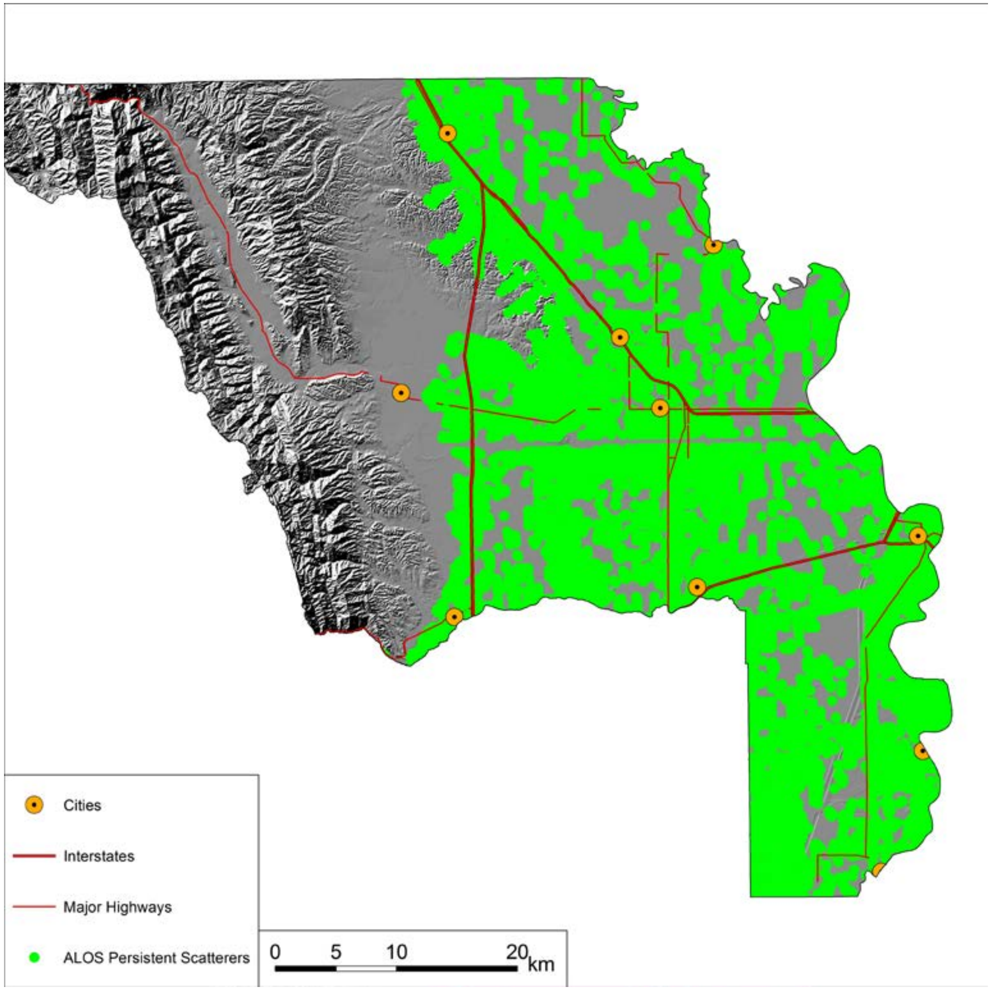
# 2007 to 2011 mean deformation from ALOS data

- Results are expressed here as mean deformation in cm/yr.  Total deformation values are taken as the mean deformation multiplied by the analysis time period (3.65 years)
- Topographic effects in and near the Dunnigan Hills and the approach to the Coast Ranges yielded poor data quality in the western portion of the County
- Maximum deformation of approx. -3 cm/year (-11.0 cm total, red) was seen in the Zamora area.



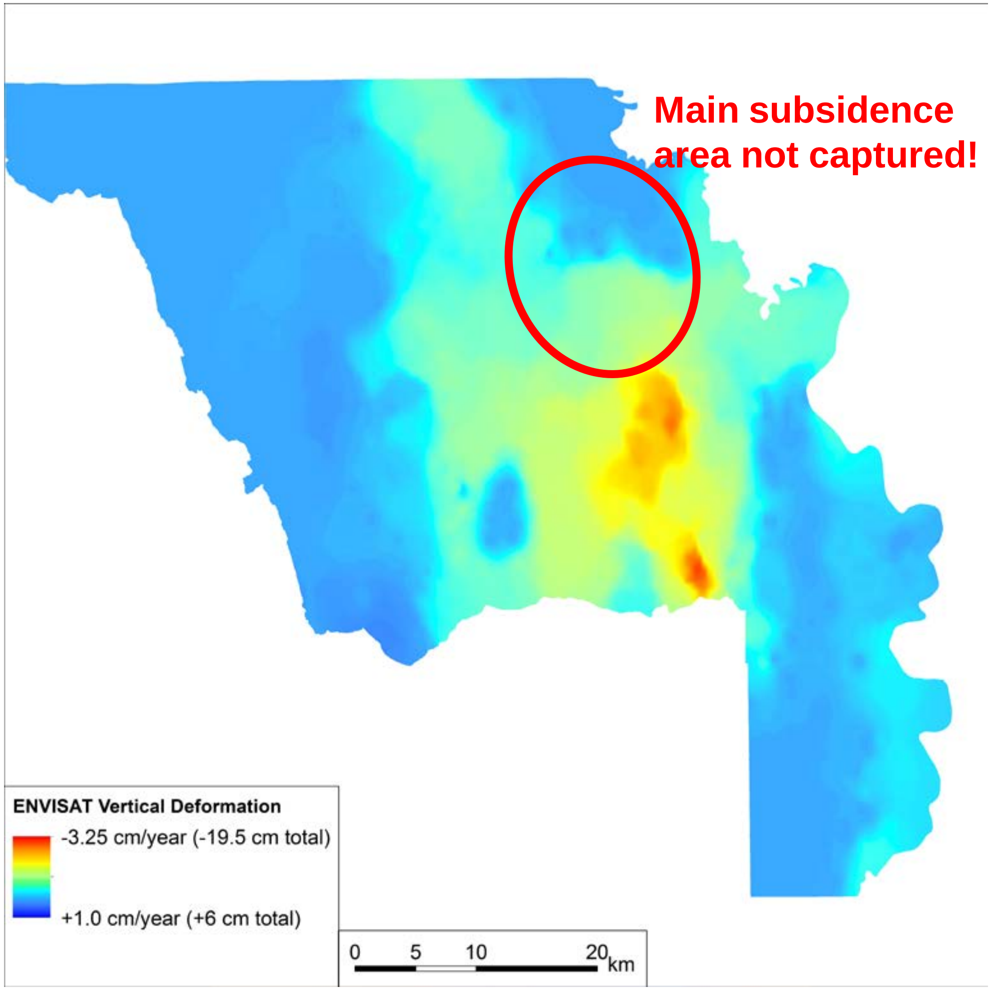
# 2007 to 2011 ALOS persistent scatterers

- Even in the less urban areas, sufficient persistent scatterers were present for a viable spatial interpolation



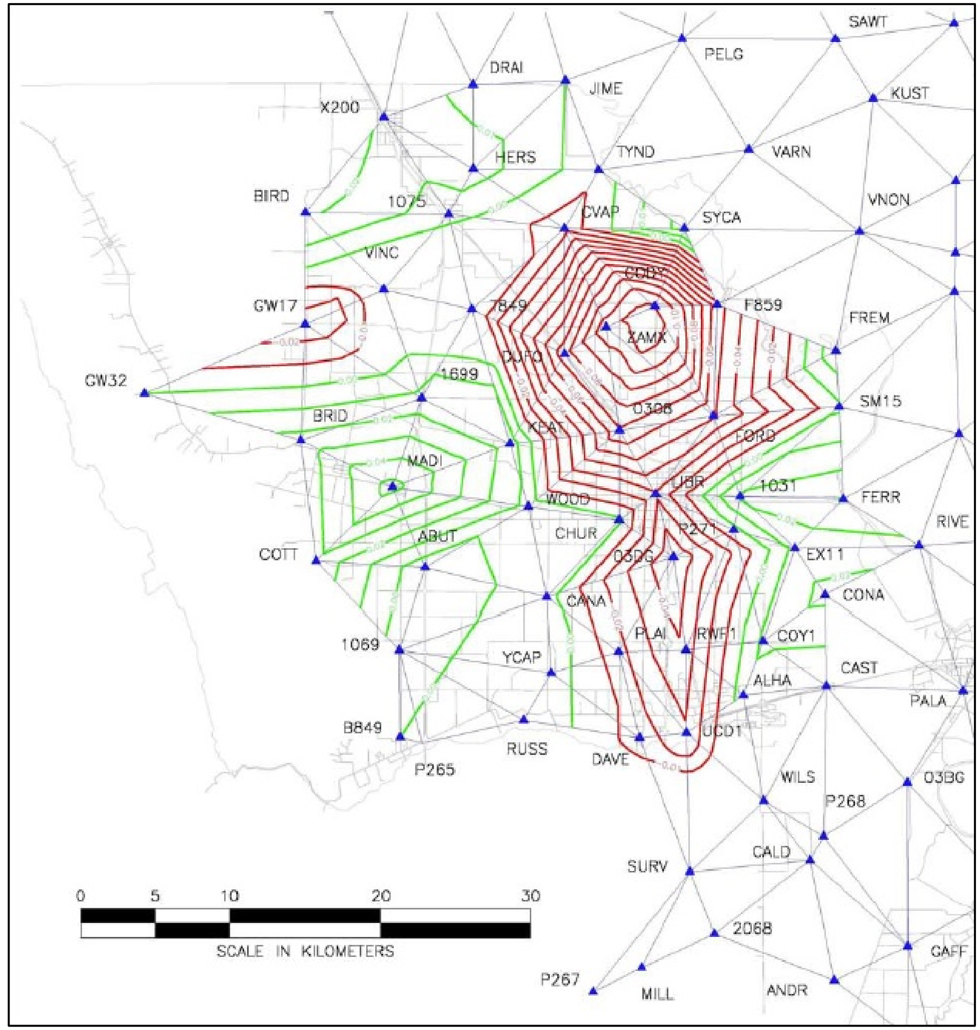
# 2003 to 2009 ENVISAT data lacks sufficient quality

- The main subsidence zone near Zamora is not captured in the ENVISAT results.
- There were the ENVISAT data set had 10x fewer persistent scatterers than the ALOS data set.  This is likely due to the shorter wavelength used for ENVISAT.
- This lack of sufficient data density in both time and space was likely the main factor in this subsidence area being missed.
- Therefore, in this study we are restricted to utilizing the ALOS dataset.



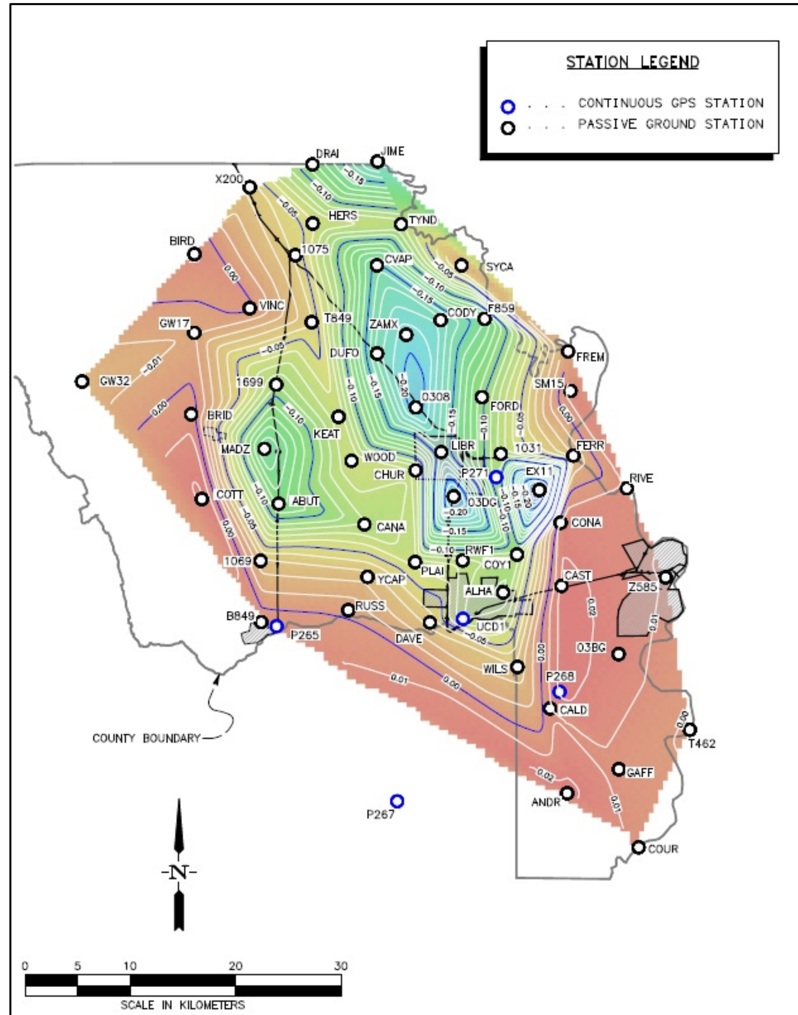
# GPS-Based Approach: Yolo Subsidence Network 1999-2008 Contours

- Results of the 2008 monitoring effort (Potterfield and Frame, 2009)
- Positive (upward) displacement in green, negative (downward) in red
- Total subsidence within Yolo County from 1999 to 2008 ranges from +7 to -26 cm, with maximum subsidence seen in the Zamora area



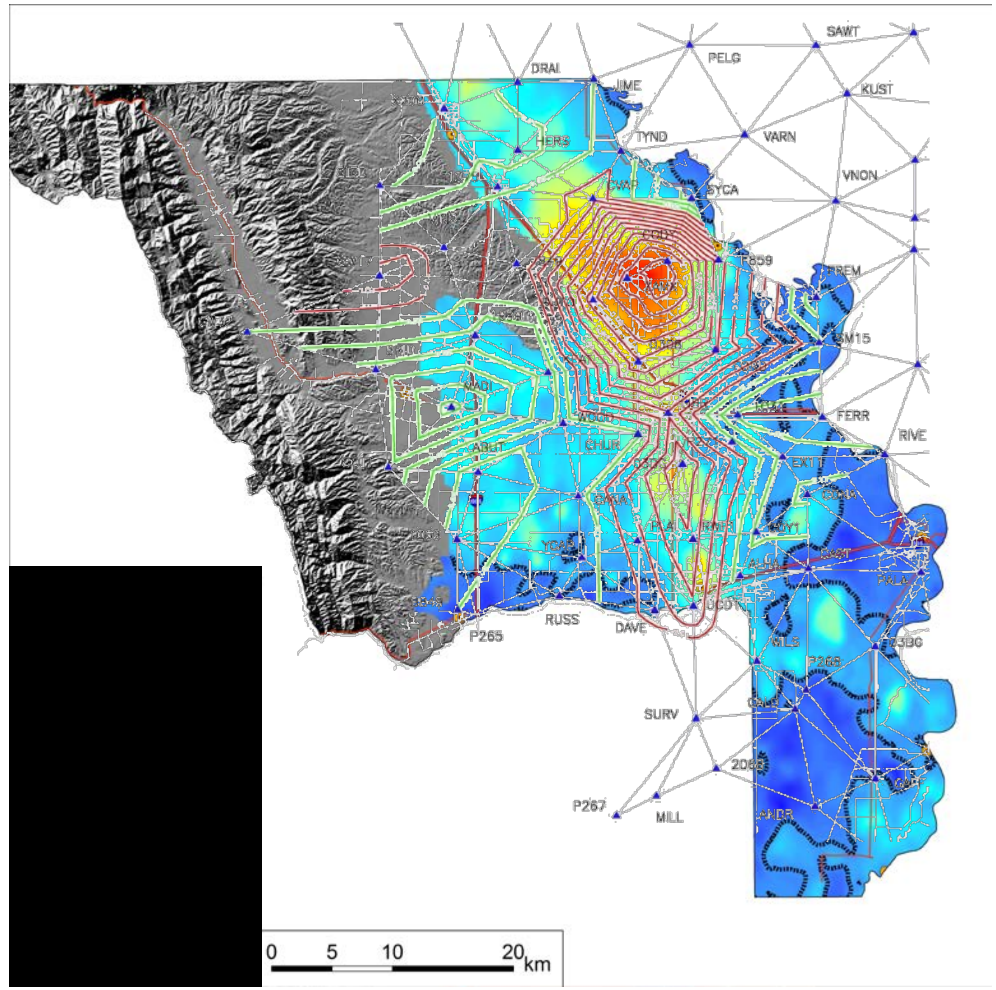
# GPS-Based Approach:
# Yolo Subsidence Network 2008-2016 Contours

- Results of the 2016 monitoring effort (Frame, 2016)
- Positive (upward) displacement in warm colors, negative (downward) in cool.
- Total subsidence within Yolo County from 2008 to 2016 ranges from +8 to -89 cm.



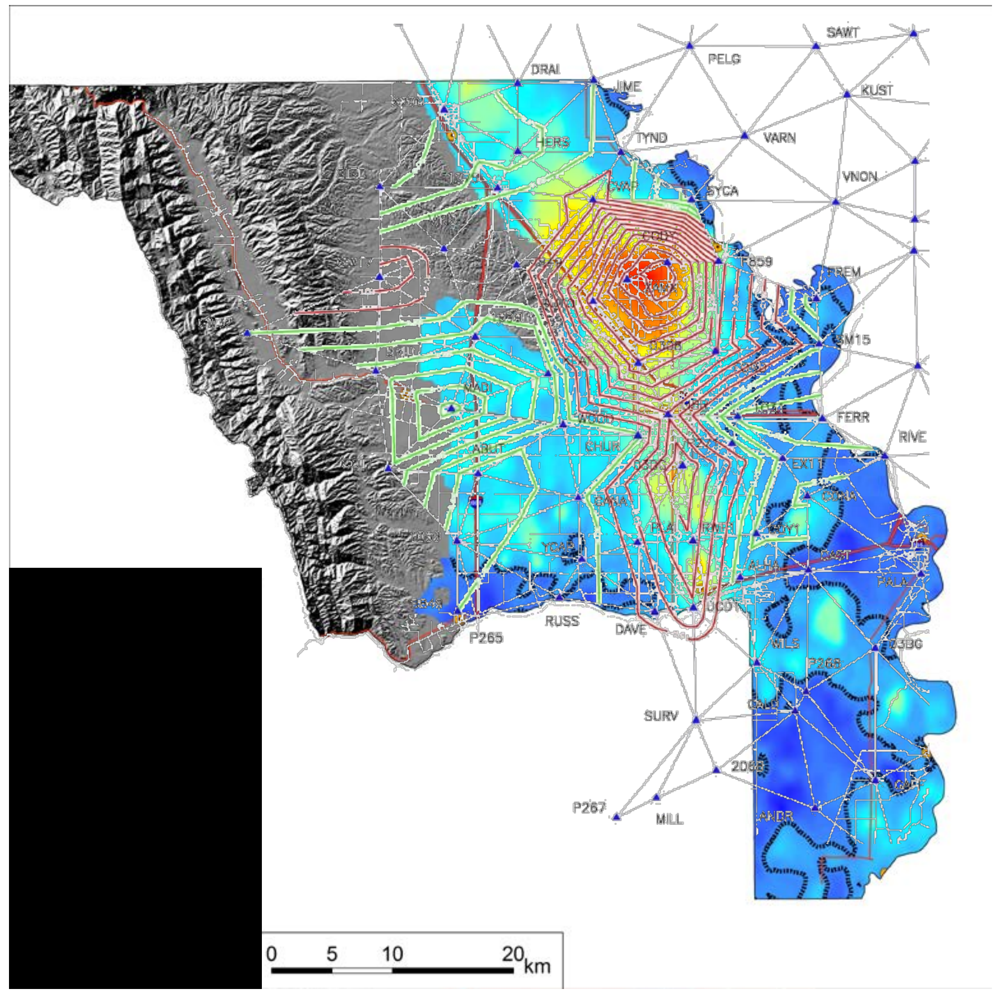
# Comparison of 2007 to 2011 ALOS results to 2008 Yolo Subsidence Network

- There is a strong overall spatial correlation between the contoured data from the 2008 Yolo Subsidence Network survey and the ALOS InSAR analysis.
- The area of maximum subsidence, centered near Zamora, is captured in both sets of results.
- The maximum subsidence rate from 2007-2011 determined from ALOS (-3 cm/year) is consistent with the maximum subsidence rate measured at ground-based survey points.

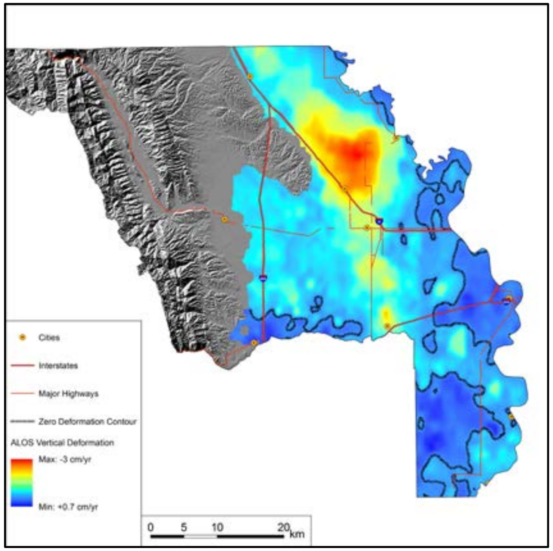


# Comparison of 2007 to 2011 ALOS results to 2008 Yolo Subsidence Network

- The overall trend of increased subsidence, running northwest to southeast along the eastern portion of Yolo County is captured in both sets of results.
- No other areas of significant subsidence were observed.
- InSAR provides finer detail on the exact shape and size of the subsidence-affected areas than the GPS-based survey.
- This ALOS data set includes ~150,000 persistent scatterers, compared to ~70 survey stations.



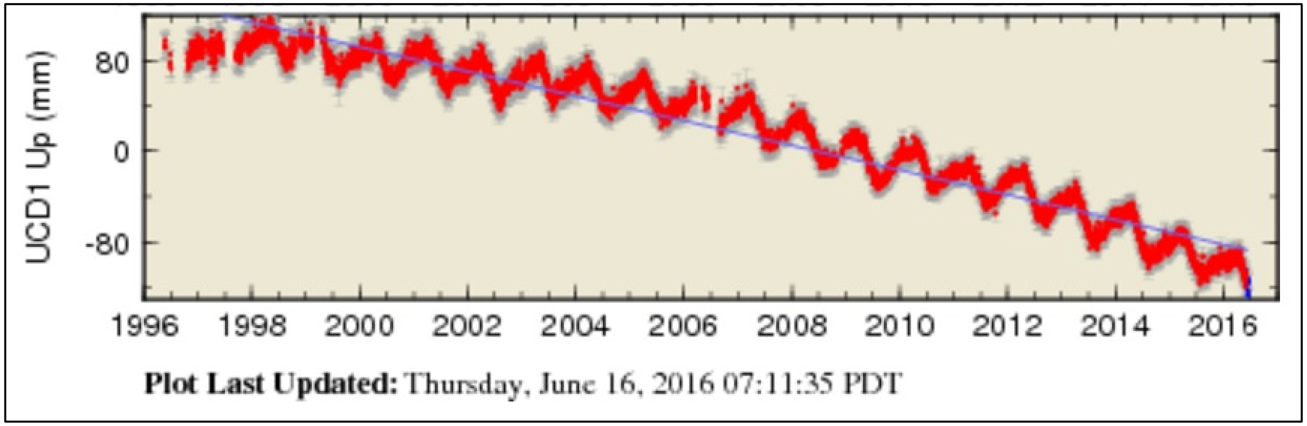
# Comparison of 2007 to 2011 ALOS results to 2016 Yolo Subsidence Network





- The overall trend of increased subsidence, running northwest to southeast along the eastern portion of Yolo County is captured in both sets of results.
- An area of relatively high subsidence at surface station EX11 does not appear in the ALOS data, but may have occurred after 2011.
- The diffuse pattern of very mild subsidence in the central portion of the county is captured in both data sets.

# Continuous ground deformation monitoring at UC Davis



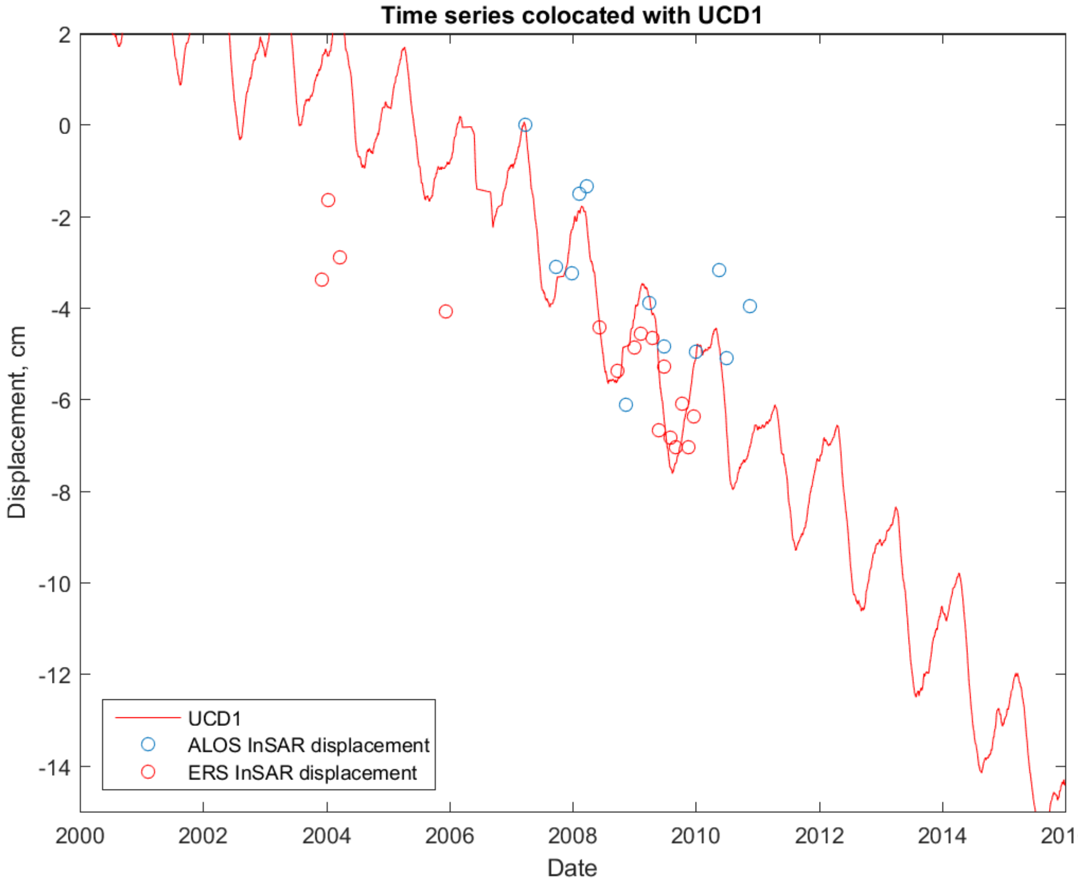

Source: USGS

- "UCD1", a continuously-monitored GPS station, is maintained at UC Davis as part of the Bay Area Regional Deformation network.
- Available data suggest total ground surface deformation of approximately -160 cm from 1996 to 2016.

Source: UC Berkeley

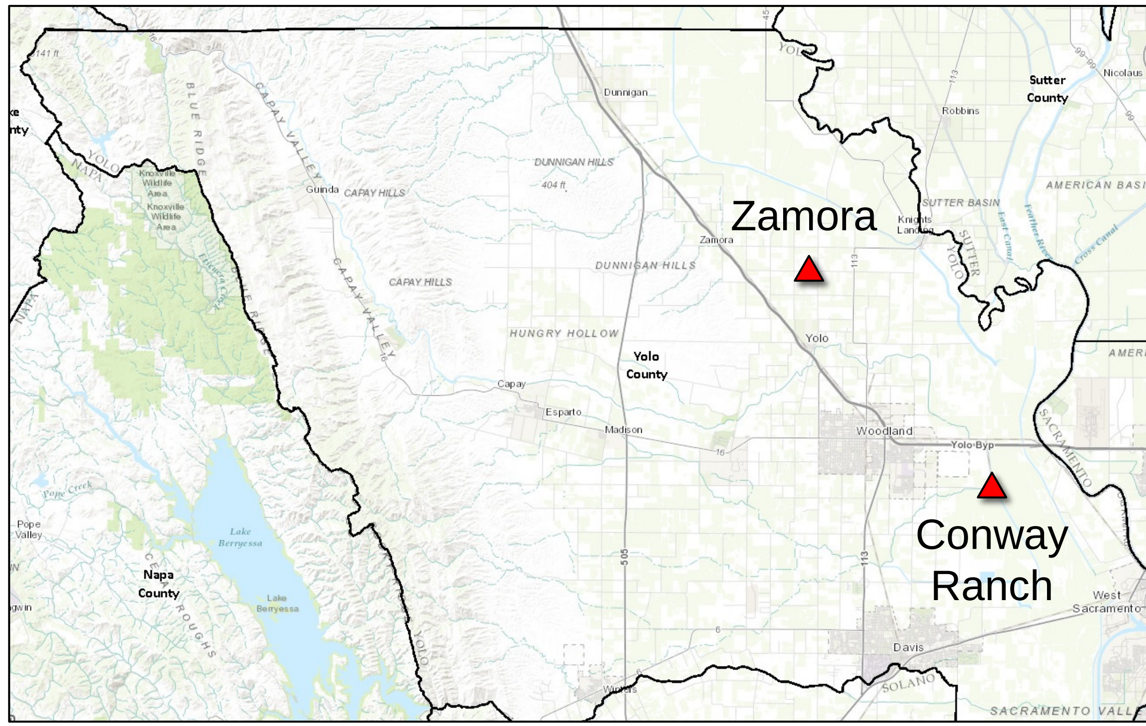
# Comparison of InSAR data to UCD1

- Both ALOS and later ENVISAT data accurately capture the approximate seasonal variation in surface deformation.
- ALOS data capture the trend and mean deformation through the available time period.
- Earlier ENVISAT data do not appear to match UCD1.
- Any individual InSAR deformation estimate includes higher uncertainty than the overall trend in a grouping of estimates.



# Extensometer data from DWR

- DWR has maintained a network of extensometers to assess ground deformation.
- Two of these extensometers are within Yolo County, one near Zamora and the other near Conway Ranch.

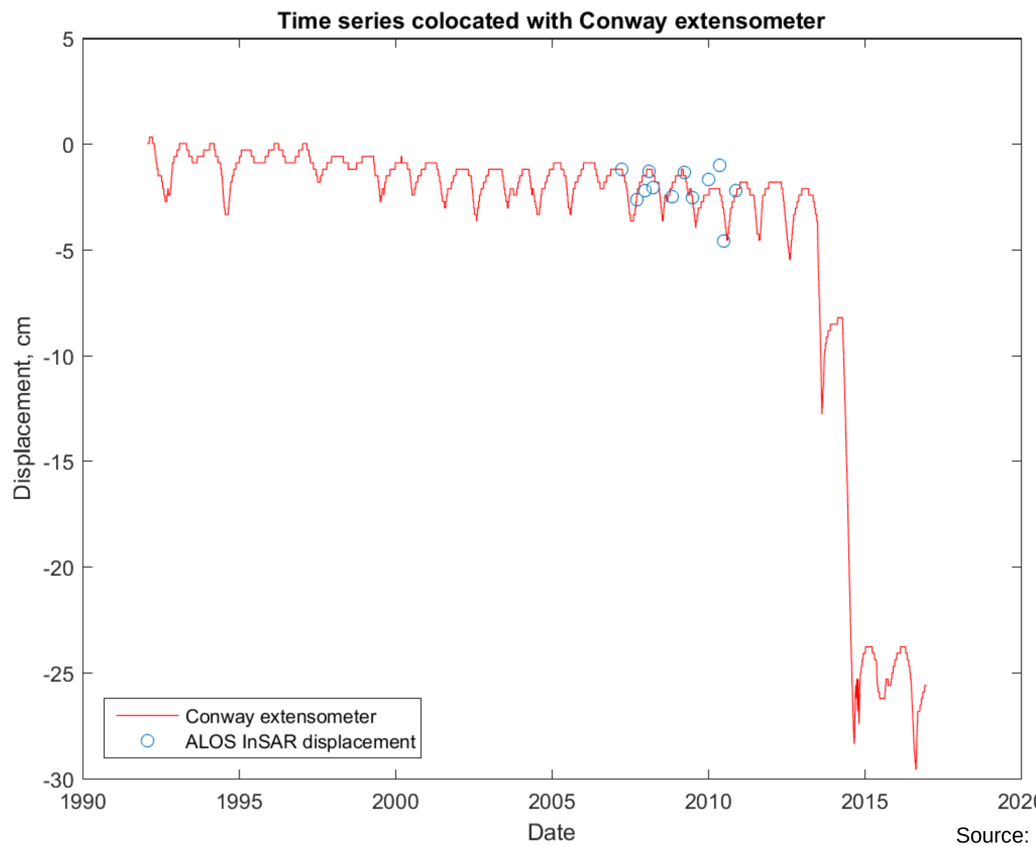



Credit: California Dept. of Water Resources

# Extensometer data from DWR

- ALOS data compares very well with these extensometer data.
- ENVISAT yielded no persistent scatterers in this area for comparison.

Conway Ranch Extensometer (1000 ft depth)

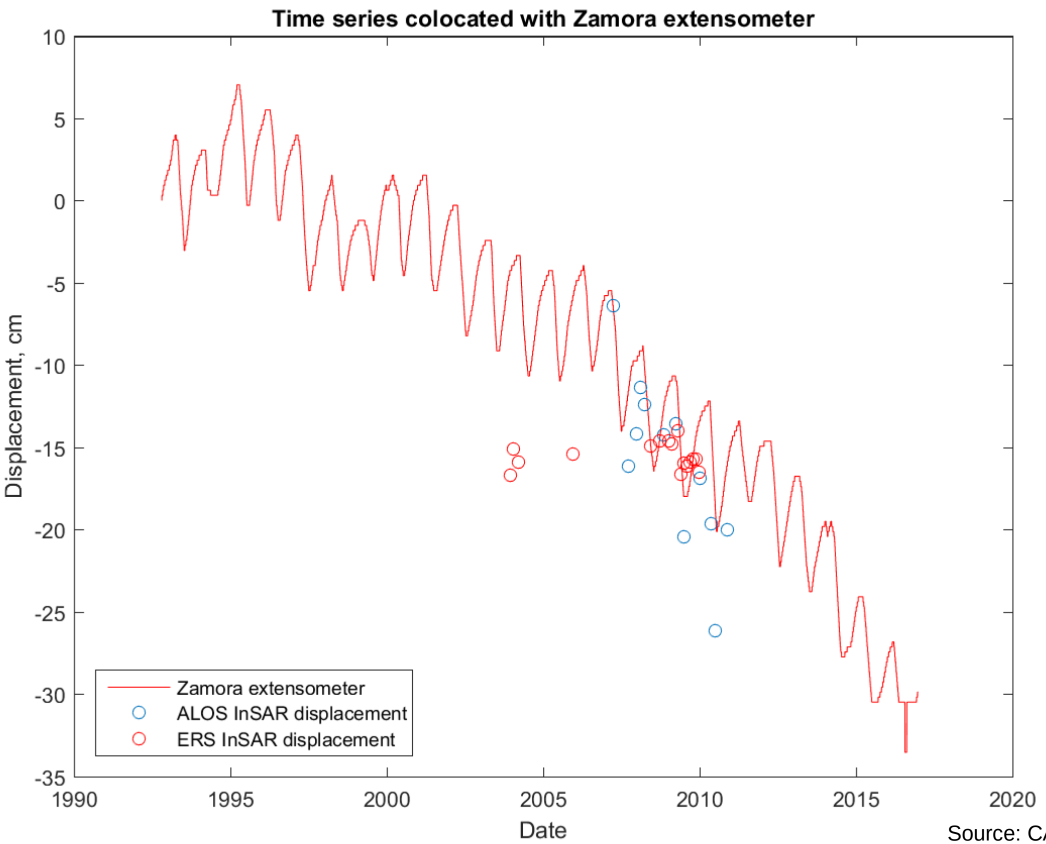



Source: CA DWR

# Extensometer data from DWR

- ALOS data show a similar seasonal signal, but greater overall vertical displacement than the extensometer data. This may indicate that sediments outside the measurement window of the extensometer are compacting.
- ENVISAT data did not compare well with the extensometer data in this location, likely related to the scarcity of data from 2003 to 2007.

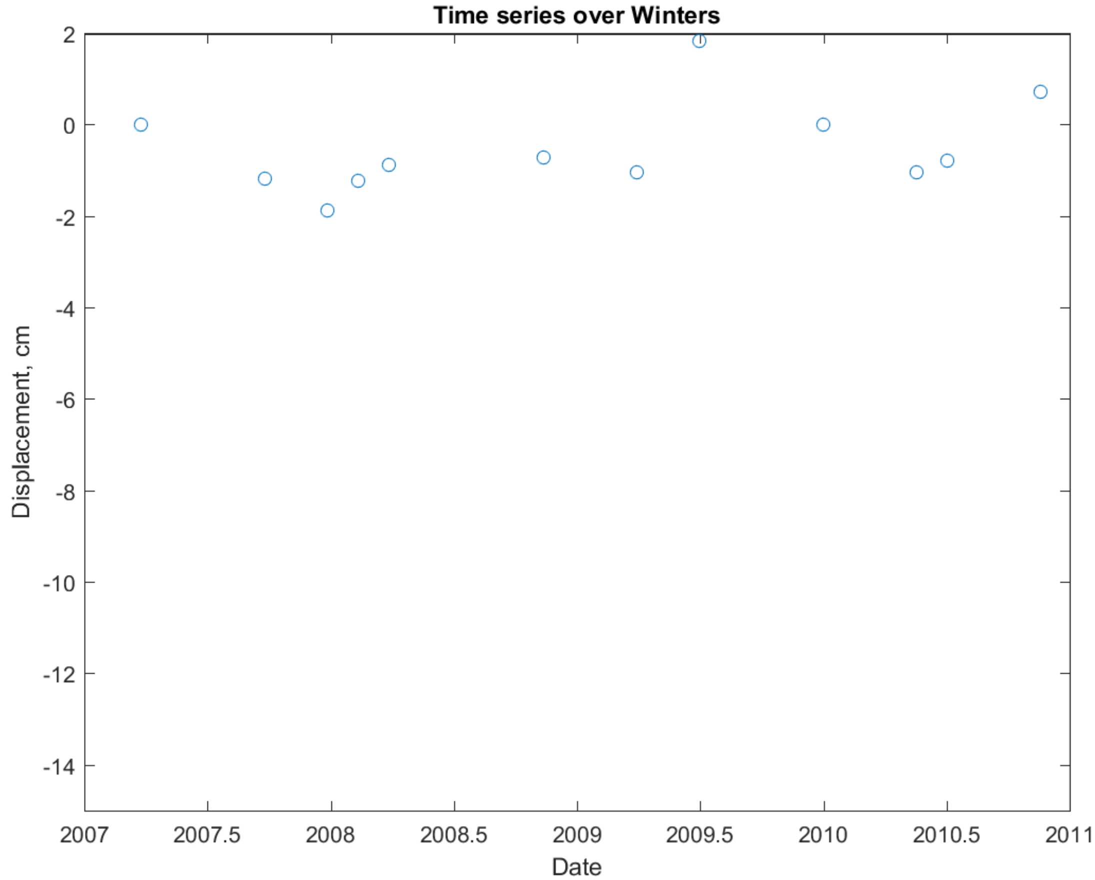
Zamora Extensometer (1000 ft depth)




Source: CA DWR

# ALOS Time-Series for the City of Winters (2007-2011)

- ALOS data show a generally flat trend, indicating little to no subsidence occurred during the 2007-2011 interval.



# InSAR Uncertainty

- In areas with a high density of good reflectors and good DEM control, estimates of ground surface displacement from InSAR are typically on the order of +/- 2 cm or less, and under ideal circumstances can reach millimeter-scale precision.
- Uncertainty increases in areas with a scarcity of persistent scatterers, and precise estimates of uncertainty for specific locations would require computer modelling efforts.
  - However, we estimate that the general uncertainty for the ground surface deformation estimates derived from ALOS data in this study remain within +/- 2 cm.

## Moving Forward

# Data availability

- Going forward, InSAR data comparable in quality to the ALOS data will be available.
- A new satellite mission “Sentinel-1” was launched in 2014, with data collection planned through 2021.
- Sentinel data will be available free of charge, and the mission is designed for approx. 12 days between passes over the same area.
  - Operational constraints can sometimes impact the actual data availability for any given area/timeframe.

Credit: Dick Ireland, European Space Agency

# Obtaining InSAR analyses

- Currently, InSAR analysis can be obtained through sponsored research with USGS, NASA Jet Propulsion Laboratory, or certain universities such as Stanford.
  - There is currently a lack of private consulting firms analyzing InSAR data for subsidence studies.
- We presume, given the level of subsidence in Yolo County, that analysis of ground surface deformation will be undertaken every 3 to 4 years. An InSAR analysis of ground surface deformation over Yolo County over such a time period, with 1 to 2 scenes available per month, will likely require 200 to 250 hours of staff time to complete.
  - At an hourly rate of $150/hr, this corresponds to a cost of $30k to $40k.
  - This cost estimate assumes that data from the Sentinel mission will be available free of charge, and that staff undertaking the analysis already have the necessary code to process Sentinel data.

# GPS-based surveys vs InSAR analyses

- InSAR advantages:
  - The direct cost of InSAR-based monitoring of subsidence is estimated to be approximately half the cost of the current GPS-based surveys.  For comparison, the most recent (2016) round of GPS surveys for the Yolo subsidence Monitoring Network included approx. $74k of direct costs, along with an estimated $190k of in-kind contributions from participating agencies, primarily in the form of staff time.
  - Fitting a curve to InSAR data measured over several years helps remove seasonal effects from long-term subsidence estimates.
  - With a sufficient temporal density of InSAR scenes, the magnitude of seasonal ground surface deformation can be accurately estimated.
  - Analysis of InSAR data can be done at any time after data becomes available, allowing greater flexibility in timing than ground-based surveys.

# GPS-based surveys vs InSAR analyses

- InSAR constraints:
  - For the best possible results, ground-based data (especially continuous GPS stations) are utilized in the processing of InSAR data to avoid unwrapping errors.
  - Certain areas of Yolo County, including the most densely agricultural and those areas with significant topography, had poorer InSAR data quality.  This precluded InSAR deformation estimates for the hilly areas of Yolo County, but sufficient persistent scatterers were still available to generate reliable ground deformation estimates in the low-lying agricultural areas.
  - Some time periods during past satellite missions have had gaps in coverage due to mechanical issues (e.g. ENVISAT).

# Conclusions

- Ground surface deformation in Yolo County, as determined by InSAR analysis of ALOS data from 2007 to 2011, agreed closely with total deformation derived from surface-based GPS in terms of the spatial distribution of subsidence patterns and the maximum rate of observed subsidence.
- InSAR data from the ENVISAT mission is available prior to 2007, but there are very few scenes available in 2006 and 2007, and a smaller number of persistent scatterers in the dataset, making ENVISAT much less reliable than ALOS.
  - In particular, the ENVISAT data did not capture the area of most significant subsidence, near Zamora.
- InSAR analysis of the ALOS data provided an accurate indication of seasonal ground surface deformation, when compared to continuous GPS and extensometer data.
- Equivalent analyses could be obtained for a reasonable cost in the future, using data from the Sentinel mission.

# Recommendations

- Given the positive agreement between InSAR and traditional ground-based techniques and its cost-effectiveness, it is recommended that InSAR be incorporated into the subsidence-monitoring plan for the Yolo groundwater subbasin.
- Areas of Yolo county that are potentially problematic for InSAR include the Dunnigan Hills, the Capay Valley, and the Coast Ranges, however these areas have not shown significant subsidence to date.
- Given the rate and magnitude of observed subsidence in Yolo County since 1999, assessing subsidence patterns with InSAR analysis is advisable at intervals no longer than 3 to 4 years.

# Recommendations

- Ground-based survey work is also still advisable as part of the overall subsidence monitoring plan for Yolo County. However if InSAR-based monitoring continues to provide sufficient spatial and temporal resolution for groundwater management decisions, the ground-based surveys may be undertaken less often, such as every 8 to 10 years.
  - These ground-based surveys could be used as controls on subsequent InSAR analyses and to capture deformation data in the lower-risk regions that are problematic for InSAR.
  - The ground-based surveys will also mitigate against any issues with obtaining data from future satellite missions (mechanical failure, gaps between future missions, etc.).
  - Given the high-quality dataset already generated from the Yolo Subsidence Network, and its general agreement with subsidence rates and patterns estimated from InSAR analysis, future surveys should continue to survey these same stations, if possible.

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# Acknowledgements

Funding for this project is made possible by a seed grant from the Stanford Woods Institute's Environmental Venture Projects program and the S.D. Bechtel, Jr. Foundation.

**Thank You!**