InSAR Deformation Time Series for an Agricultural Area in the San Luis Valley

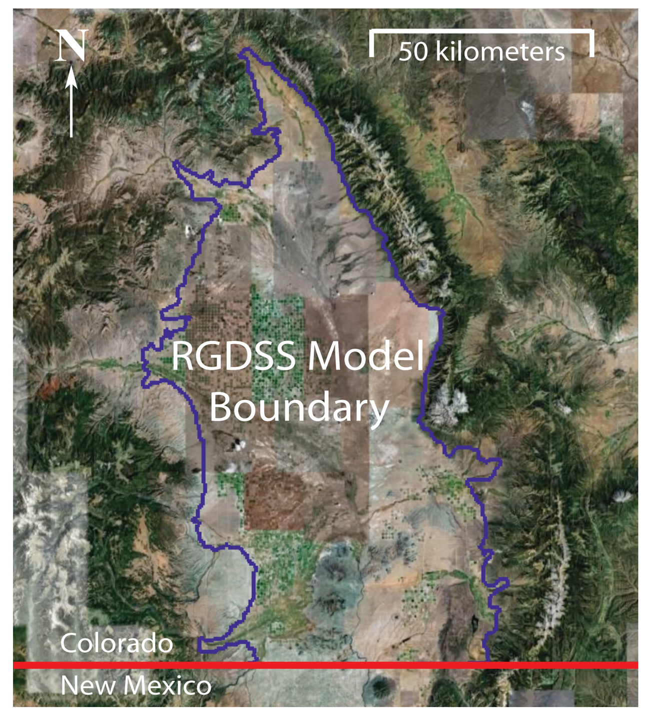
Jessica Reeves[1], Rosemary Knight[1], Howard Zebker[1], Willem Schreüder[2], Piyush Shanker Agram[3] and Tom Rune Laukness[4]
[1]Dept. of Geophysics Stanford University, [2]Principia Mathematica, [3]Dept. of Electrical Engineering Stanford University, [4]Northern Research Institute Tromsø Norway
jesser@stanford.edu

1) Motivation: Challenges in Water Management

The San Luis Valley (SLV) is an 8000 km² valley located on the northern side of the Colorado-New Mexico border. The valley has a vibrant agricultural economy that is highly dependent on the effective management of the limited water resources. The Rio Grand Decision Support System (RGDSS), a Colorado-state-funded project, is in charge of the analysis and administration of water resources in the SLV. The RGDSS currently includes a hydrogeologic database and a MODFLOW finite-difference groundwater flow model. Despite an extensive dataset the model is not now able to accurately predict hydraulic head values over the entire SLV.

It is critical that the RGDSS incorporate sufficiently spatially dense data to be able to characterize the heterogeneous, time-varying behavior of the groundwater system in this large-scale model. We show here that Interferometric Synthetic Aperture Radar (InSAR), a remote sensing method, can provide these data. We hope to use these data to better constrain large hydrogeologic models.

The high-altitude, desert landscape of the San Luis Valley. The Great Sand Dunes National Park is in the foreground and the Sangre De Cristo Mountains are in the distance.



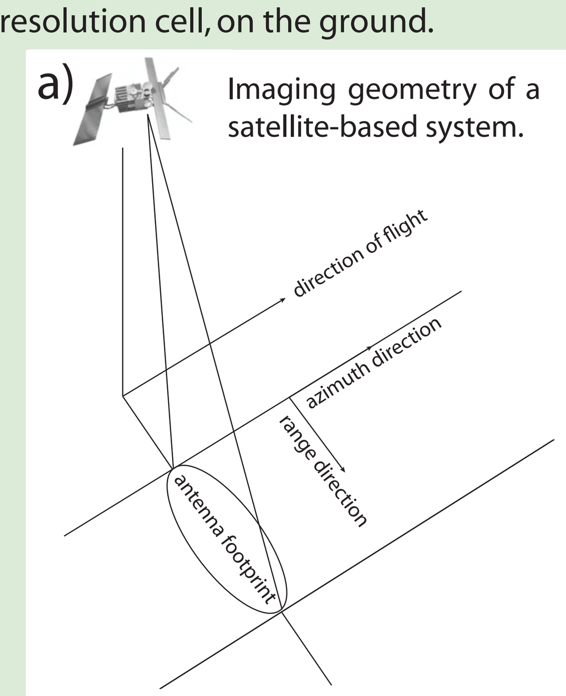
The extent of the San Luis Valley as defined by the RGDSS.

2) Background: Introduction to InSAR

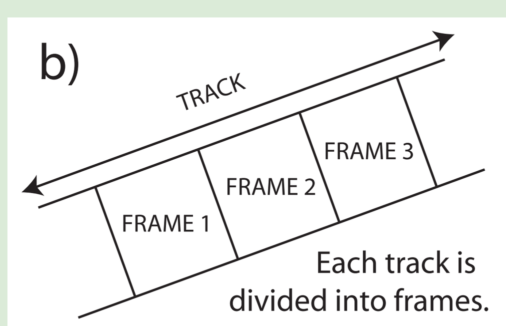
Synthetic Aperture Radar (SAR) is a microwave imaging system that utilizes a radar system to transmit and receive electromagnetic (EM) waves with wavelength λ. The area of the ground illuminated by the transmitted EM waves is the called the antenna footprint, Image a).

As the satellite orbits Earth, the antenna footprint moves along the ground, so that a track of data is collected, Image b). Each acquisition of data for a given track and frame is referred to as a SAR scene. Each pixel in a SAR scene stores a complex number that describes the amplitude and the phase of the EM wave reflected from the corresponding area, referred to as a resolution cell, on the ground.

a)



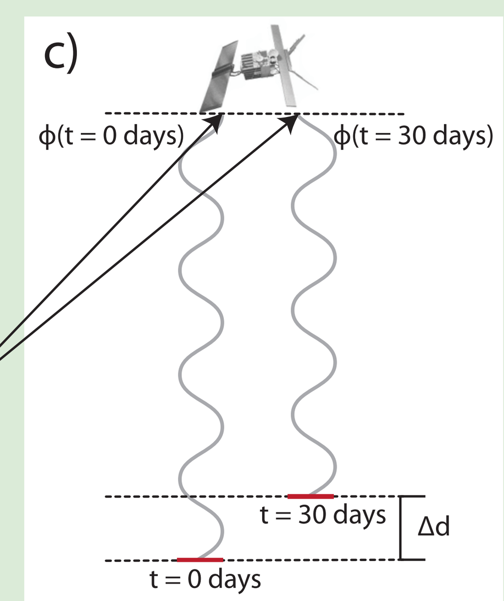
b)



The phase ϕ measured at two different times can be used to get a measure of the elevation change of the ground, Δd.

Δd is the parameter of interest in our study.

c)



The difference in phase (Δϕ) between two SAR scenes, Image c), is stored in an image called an interferogram.

$$\Delta\phi = \Delta\phi_{def} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{n}$$

where $\Delta\phi_{def}$ is due to deformation of the ground
$\Delta\phi_{topo}$ is due to errors in the satellite orbit
$\Delta\phi_{atm}$ is due to atmospheric effects
$\Delta\phi_{n}$ is due to phase noise

We must determine and remove $\Delta\phi_{topo}$, $\Delta\phi_{atm}$, and $\Delta\phi_{n}$ in order to obtain $\Delta\phi_{def}$.

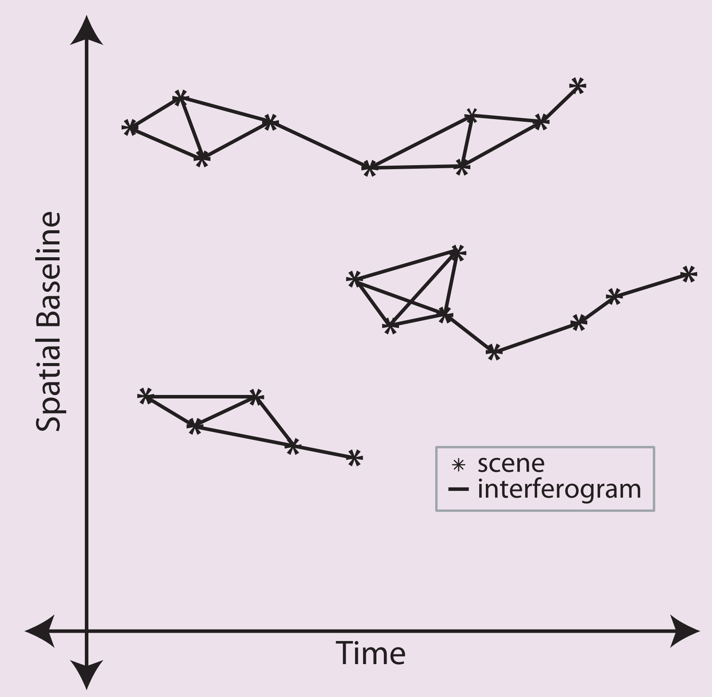
We assume that the transmitted signal is a pure sinusoid such that a change in phase has a linear dependence on the elevation change Δd (multiplied by two for two way travel).

$$\Delta\phi_{def} = 2\pi/\lambda\ (2\Delta d) = 4\pi\Delta d/\lambda$$

Therefore $\Delta\phi_{def}$ is known within modulo 2π radians; this is called the wrapped phase. The wrapped phase must be determined absolutely, a process known as unwrapping, in order to provide meaningful information about Δd.

3) Proposed Technique: SBAS Analysis

Small Baseline Subset (SBAS) analysis produces a **high quality interferogram time series** by selecting interferograms with a small spatial baseline and a short temporal baseline between scenes. By doing so we are able to maximize the number of coherent pixels for each interferogram. The phase of each coherent pixel over time gives the history of its elevation change.



A spatial baseline vs. time plot. All scenes with a spatial and temporal baseline below a set threshold are connected by an interferogram. Each group of connected scenes is known as a small baseline subset.

The thresholds are selected so that all scenes are connected to a subset and all subsets overlap in time. As long as these subsets overlap in time we can combine them via a Singular Value Decomposition (SVD) (Berardino et al., 2002).

What do we mean by high quality InSAR data?

A high quality interferogram contains a large number of coherent pixels.

$$\Upsilon = \frac{\langle S_1 S_2 \rangle}{\sqrt{\langle S_1 S_1^* \rangle \langle S_2 S_2^* \rangle}}$$

where ϒ is the coherence (0 to 1)
‹ › denotes the expected value
S is the SAR scene
S^* is the complex conjugate of the SAR scene

An interferogram is coherent/well correlated, if many of the pixels have coherence near 1; or we can say that it is incoherent/decorrelated, if many of the pixels have coherence near 0.

Some factors that affect coherence: Signal to Noise Ratio (SNR), spatial baseline (distance between satellites during acquisition), and temporal baseline (time between satellite acquisitions).

If the number of scenes we have is N+1, and the number of interferograms we create is M:

$\Delta\phi^T = [\Delta\phi_1,...,\Delta\phi_M]$ — M equations, the change in phase measured for M interferograms

$\phi^T = [\phi(t_1),...,\phi(t_N)]$ — N unknowns, the phase at the time of each scene acquisition

$\Delta\phi_j = \phi(t_{Aj})-\phi(t_{Bj})]$, $j = 1,...,M$ — A linear system of equations

$\mathbf{A}\phi = \Delta\phi$ — In matrix form

We solve for ϕ which is relative to the first scene, when t=0. This becomes $\Delta\phi_{def}$ and we can solve for Δd as a time series relative to the first scene.

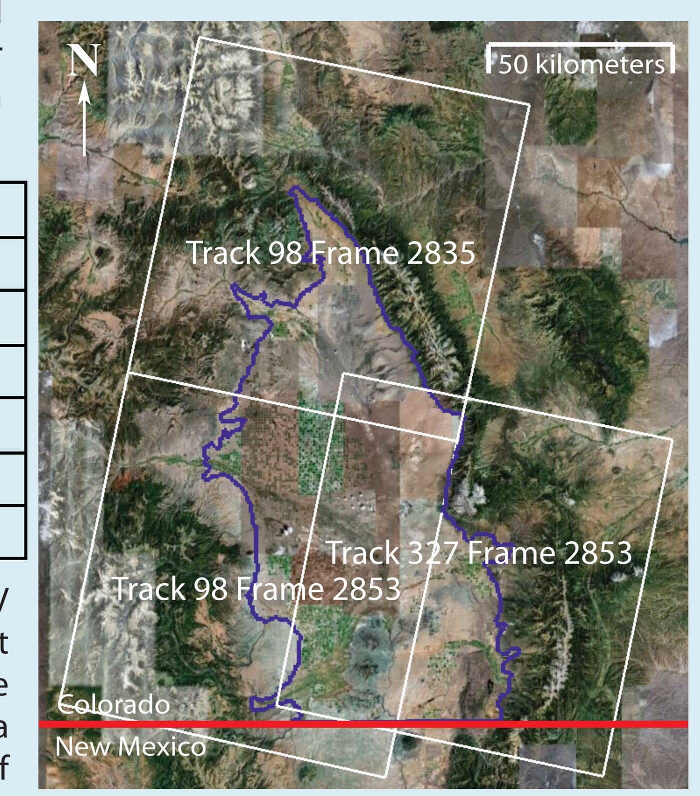
SBAS analysis was implemented via the Generic SAR (GSAR) software package developed by Norut (Lauknes, 2004).

4) Available Data: ERS and ENVISAT

There are two satellite platforms that collect data over the SLV: ERS and ENVISAT. The two platforms, both European commissioned, have similar goals for their SAR acquisitions: a sampling rate of one scene per month and large spatial coverage.

Satellite	Track	Frame	# Scenes	Start Date	End Date
ERS-1/ERS-2	98	2853	50	1992	2008
	98	2835	50	1992	2008
	327	2853	23	1995	1999
ENVISAT	98	2853	18	2005	2008
	98	2835	9	2005	2007
	327	2853	29	2004	2009

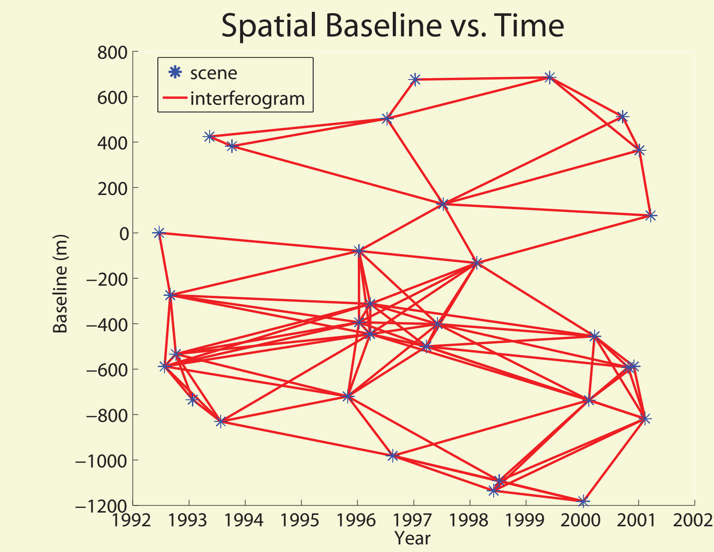
The table shows the number of scenes that were acquired over the SLV by each satellite. The start date/end date is the date of the first scene/last scene acquired for a given track and frame. However, from 2001-2004 the ERS-2 satellite had problems with some of its instrumentation, and no data was collected. For this study we could only use data up until the end of 2000. We acquired raw SAR data from two sources: the Western North American Interferometric Synthetic Aperture Radar Consortium (WInSAR) and the European Space Agency (ESA).



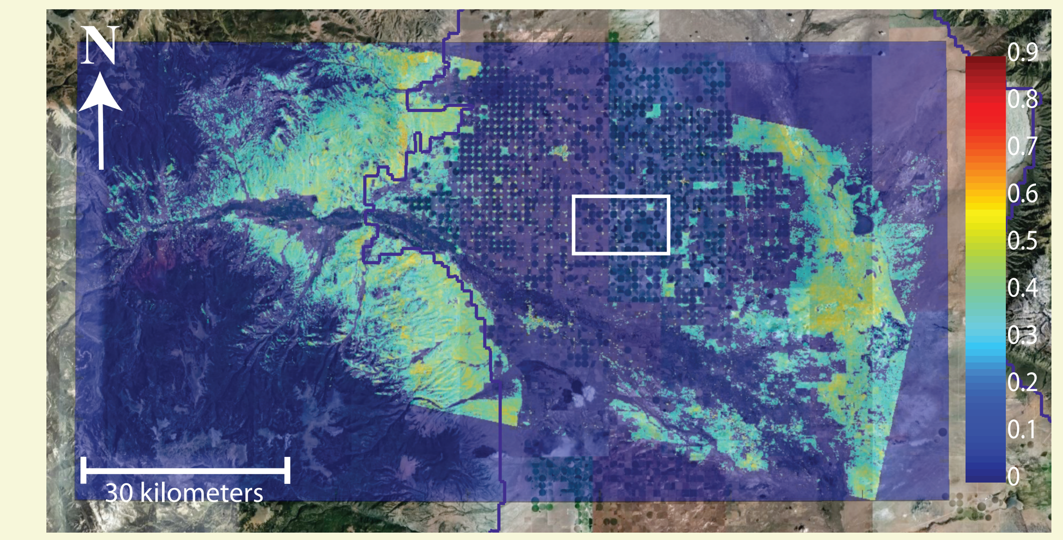
The RGDSS model boundary and the spatial extent of available scenes.

5) Results and Conclusions

We illustrate our approach using Track 98 Frame 2853 from the ERS satellites. This area has good spatial and temporal coverage of the valley, with 32 scenes acquired over the time period of June 1992 to November 2000.



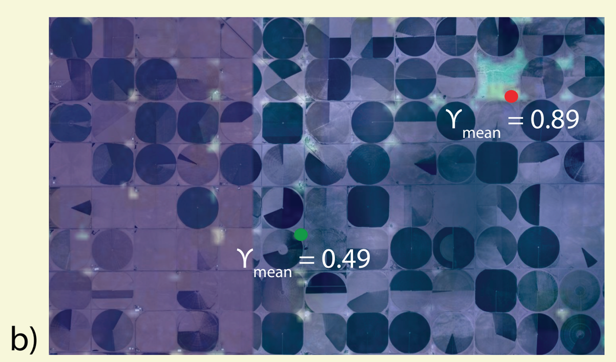
The spatial baseline versus time plot. The maximum spatial baseline between two scenes = 400 m and maximum temporal baseline between two scenes = 2 years; these thresholds produced 89 interferograms.



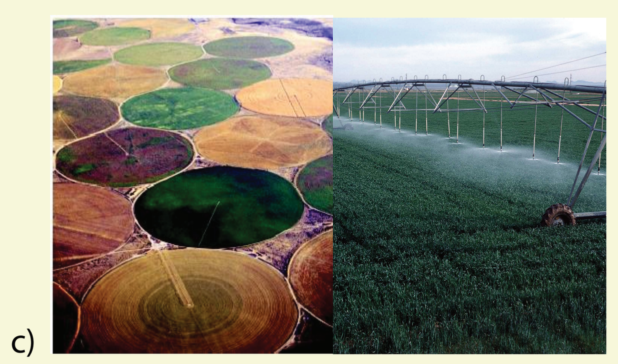
The mean coherence for all the interferograms is shown in the image above (produced by GSAR). Each pixel corresponds to a 50 m by 50 m resolution cell. The white box corresponds to the area in the images a) and b) below.

a)

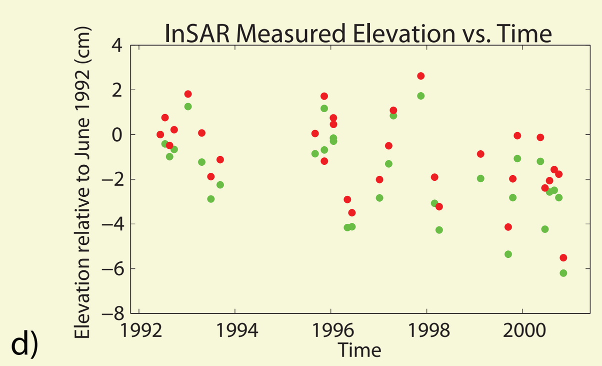
b)



c)



d)



a) A close-up view of the mean coherence overlaid on a Google Earth map.

b) The mean coherence overlay is dimmed and we can see that the higher coherence areas show up within the interstices between the center-pivot-irrigated areas. Two pixels are selected to show an example of the elevation change time series.

c) Photos of the SLV center-pivot-irrigation fields and watering system.

d) The time series of the elevation change for the two pixels in b).

We have derived a time series of the elevation change for over 180 000 coherent pixels in Track 98 Frame 2853; these pixels cover an area of 450 km². This is the first time that InSAR time series data have been used to infer elevation change in an agricultural area.

Ongoing Work

We plan on incorporating the elevation change data from this first frame into the RGDSS hydrogeologic model, along with similar measurements from the other available frames. The incorporation of InSAR data will create a better-constrained hydrogeologic model that can be used to promote sustainable water management and to predict the effects that future climate change may have on the storage of the groundwater system. We also plan on making a time series of the elevation change measured by multiple SAR scenes and platforms, i.e. ERS and ENVISAT. This would allow for more temporal sampling over longer periods of time.

References, Acknowledgments

Berardino, P., Fornaro, G., Lanari, R. & Sansosti, E., 2002. A New Algorithm for Surface Deformation Monitoring Based on Small Baseline Differential SAR Interferograms, IEEE Transactions on Geoscience and Remote Sensing, 40, 2375-2383.

Laukness, T.R., 2004. Long-Term Surface Deformation Mapping using Small-Baseline Differential SAR Interferograms, Masters of Science, University of Tromso, Tromso.

We gratefully acknowledge funding from Schlumberger Water Services which supported this research. We would also like to thank ESA and WInSAR for providing access to the raw SAR data.