BACKGROUND REPORT ON SATELLITE RADAR ACQUISITION AND IMAGING

Introduction
Previous technical reports presented evidence for the measurement of land surface "flexure" using differential interferometry (DInSAR). These slight changes in land elevations can be due to changes in the volume of groundwater in regional aquifers (aquifer elasticity). These volumetric changes are due to well field production (ground water extraction) and the spatial rate and timing of ground water recharge. Other ground water related trends in DInSAR anomalies can be determined such as aquifer storativity and permeability, faults boundaries, lag time of aquifer trends and land effects.

In our application, land surface deformation is the result of ground water aquifer elasticity. This elasticity is supported by the aquifer's structural framework made of granular media (sand, silt, clay), air and water. Aquifer elasticity does allow for "land surface flexure" given relatively small changes in the volumetric water and air content. For our purposes, "**deformation**" consists of small land surface inflections termed **inflation** (upward) and **deflation** (downward) measured at the scale of 5 millimeters or greater.

Typically, monitor wells are used to measure and observe changes in water levels in the aquifer due to rates of change in recharge and discharge. These are point measurements and tens to hundreds of these wells and subsequent measurements are needed to adequately observe aquifer pressure changes on a regional scale. Regional aquifer response to large scale pumping is typically assessed with numerical simulation models of the aquifer. These methods demand substantial resource investments. Consequently, the use of DInSAR serves as a cost effective proxy to ground water monitor wells.

The primary focus of this report is to:

1. provide a background of previous local efforts,
2. serve as an introduction to forthcoming reports,
3. provide additional support on the value of this work,
4. provide background information on processes involved in this work, and
5. provide a "pre-contract" archive and description of radar features.

Previous work
The Regional Water Planning Commission contracted the initial investigation of using DInSAR locally in 2004. Dr. Gary Oppliger of the University of Nevada, Reno and Michael Widmer of the Washoe County Department of Water Resources undertook this collaborated work. The final report, "***Washoe County DWR/RWPC cooperative study with Dr. Gary Oppliger of the relation between satellite based radar differential interferometry (D-InSAR) ground deformations and groundwater production and level data in the Truckee Meadows***" was presented to the Commission and accepted on August 3, 2005. This work documented that the use of satellite radar could precisely identify vertical land deformation at the sub-centimeter scale due to ground water

recharge and pumping. It should be noted that most of the investigation centered upon the Truckee Meadows.

Complimentary to this work is technical memo "***The use of DInSAR for aquifer pumping analysis***" dated May 5, 2005, from Michael Widmer to Jeanne Ruefer within the Department of Water Resources. This memo documents the relationship of ground water pumping and land deflation within the Central and South Truckee Meadows. It also describes much of the processing required from acquisition of raw data to construction of deformation grids, briefly described below.

These research works made use of several satellite scenes and interferograms (see below). Acquisitions of these satellite scenes were made from the University and Washoe County. The next section catalogues these images and describes the major features examined. These images represent additional data funded from other sources.

Satellite history- ERS 1/2, ENVISAT 1/2

Historically, the Europeans, Japan, Canada and the United States have launched radar satellites using this technology. Public and private access to data has been limited and the configurations of each of these satellites are not equal such that the data are not interchangeable. For our purposes, the European satellites are preferred.

The first set of radar satellites launched by the Europeans were the ERS 1 and 2. These were functional from 1992 to 2002. Operational problems have rendered these satellites unusable, ERS 1 in 1996 and ERS 2 in 2002. A second set of satellites were launched under the acronym of ENVISAT. These satellites use an improved technology and the data are often referred to as ASAR (Advanced Synthetic Aperture Radar). Satellite scenes from the ENVISAT satellites are not useable with the ERS data.

How satellite images are processed to deformation grids

Differential Interferometric Synthetic Aperture Radar, or D-InSAR is a technique whereby two geo-referenced satellite scenes are digitally compared to examine any change in microwave phase from the exact same resolution cells (20m pixels). Another way said is that a radar signal or pulse is focused on the earth and timed from when it is emitted to when it is "bounced back" to the satellite. The time in travel can calculate a distance since the radar pulse travels at the speed of light. The radar pulse actually covers a large swath of the earth's surface (100s of square miles), but is discretized at 20 meter sized cells (or pixels). Then comparing one scene to the next, a difference in distance (as calculated with time or phase change in the electromagnetic signal), at the sub centimeter scale, can be realized per cell or pixel. If the change (or no change) is consistent over a large area, the term "coherency" is used to distinguish useable data.

Changes in distance, with coherent data, will be due to land surface displacement in the resolution cell itself. For example, the effects of tectonic movement or deformation can be imaged in this manner, within limitations. These limitations are usually dictated by extensive changes in land use (i.e. subdivision construction, snow cover, farming activities) and different satellite orbit spacing between when the two images were taken.

While cloud cover is usually not an issue, moderate to large precipitation events can disrupt the usability of the data.

Once acquisition of the raw satellite data is received, a very complicated yet automated processing routine is followed to create a satellite “scene”. Two scenes of the same “exact” area and with the relatively same orbit (generally within 1000 feet) can be digitally compared with a resulting “interferogram”. These are called “pairs” and represent the changes in the land surface over the period of time the scenes represent. These interferogram images or pairs can be difficult to view on a computer screen and require experienced interpretation. Dr. Oppliger has developed a routine to process the interferogram to a “deformation grid”. This grid represents true land surface deformation, if indeed any surface change has occurred. By contouring of this deformation grid, interpretation is relatively easy and comprehended by the layperson. This deformation grid is the final product submitted to Washoe County for cataloguing, archiving and interpretation.

Contract program with UNR

The Regional Water Planning Commission entered into a joint contract with the University of Nevada, Reno and Washoe County Department of Water Resources in October 2006. This contract consisted of the acquisition (by WCDWR), processing (by UNR), cataloguing (by WCDWR), and summarizing deformation grid anomalies found through the use of these satellite radar scenes (by WCDWR). Annual reports are to be presented to the Regional Water Planning Commission. This contract, unless renewed, will expire October 2009. It is projected that acquisition will continue at the rate of one scene per month. As described above, not all scenes will be useable (non-coherent).

Catalogue of scenes, interferograms and grids from ERS 1&2

The Table below lists the data acquired by Washoe County or available from UNR from the European Space Agency’s ERS 1 & 2 satellites. The first column indicates the satellite data that has been processed to a scene. The second column lists the interferograms that have been formed (as pairs) with the two scene dates used to form the interferogram (columns 3 and 4). Finally, the last column lists whether or not the interferogram has been processed to a deformation grid. Washoe County has archived these grids. Future grids can be made from the pairs listed with relative ease.

How to interpret deformation grids- what’s real and what’s not

The focus of this program is related to significant changes in ground water levels as reflected in land surface elevation changes. Lands that have not been developed or have been completely developed make good “reflectors” and it is these lands that are reviewed for slight changes in land surface elevation. Typically, the lands that we are interested are those within wellfields, near the Truckee River or other important water bodies, and near ground water recharge areas. These lands must also overlie important and regionally extensive aquifers.

As discussed briefly above, any large-scale (square miles) change in the land surface will be shown in the deformation grid images. Within our area of investigation this amounts

Table 1
Scenes, interferograms and deformation grids from ERS satellites

ERS1/2 scenes	ERS1/2 Interferogram	Pair	Dates	deformation grid
14-Apr-92	pair 1	21-Feb-97	6-Jun-97	no
10-Nov-92	pair 2	14-Apr-92	11-Nov-93	**yes**
30-Mar-93	pair 5	30-Nov-93	19-Oct-95	**yes**
17-Aug-93	pair 6	30-Mar-93	28-Dec-95	no
30-Nov-93	pair 7	10-Nov-92	11-Apr-96	no
19-Oct-95	pair 8	17-Aug-93	21-Feb-97	no
20-Oct-95	pair 9	17-Aug-93	6-Jun-97	no
28-Dec-95	pair 10	14-Apr-92	19-Oct-95	**yes**
11-Apr-96	pair 11	28-Dec-95	24-Sep-99	no
13-Dec-96	pair 12	10-Nov-92	24-Sep-99	no
17-Jan-97	pair 14	30-Mar-93	25-Sep-99	no
21-Feb-97	pair 15	11-Apr-96	26-Sep-99	no
28-Mar-97	pair 16	30-Mar-93	30-Nov-93	**yes**
6-Jun-97	pair 17	19-Oct-95	28-Dec-95	no
11-Jul-97	pair 18	10-Nov-92	30-Mar-93	no
15-Aug-97	pair 21	6-Jun-97	13-Sep-02	**yes**
19-Sep-97	pair 22	30-Mar-93	11-Apr-96	no
31-Jul-98	pair 23	30-Nov-93	28-Dec-95	no
24-Sep-99	pair 24	10-Nov-92	29-Dec-95	no
21-Apr-00	pair 25	30-Mar-93	19-Oct-95	no
13-Sep-02	pair 27	21-Feb-97	13-Sep-02	no
	pair 28	17-Aug-93	14-Sep-02	**yes**
	pair 30	15-Aug-97	31-Jul-98	no
	pair 31	7-Nov-97	31-Jul-98	**yes**

to subdivision grading and building, the growth of crops, changes in lake levels such as Washoe Lake or the North Valley playas of Silver Lake and Swan Lake. Mountainous areas with dense forest will also create problems for data interpretation. Such changes in land surface activity can render interferogram data "incoherent" and this data is often omitted (whited-out) from the deformation grids. Therefore, we typically review theses deformation grids within the lands that have not undergone such land surface changes. This requires a good local knowledge and adequate recording of such activities.

Because this current report is limited to the ERS satellite data, the area of investigation only includes the most southern portion of Washoe County. Figure 1 shows the ERS data considered from west to east the Cold Springs to Spanish Springs valleys and south to Washoe Valley. Future reports (April 2007 and onward) will contain areas further north to and including Honey Lake Valley.

The deformation grids are presented as colored scale of changes (?) where warm colors represent deflation of the land surface and cool colors inflation of land surfaces. These changes are mapped in millimeters such that only variations greater than 10 millimeters (or 1 centimeter) where one inch equals 25 millimeters. Therefore changes noted in just a few millimeters are not worth noting. Also note that when viewing several deformation grids, the color scale is not consistent. This will be corrected in future reports. Major roads are plotted for reference and municipal wells are also represented as small black dots for correlation to deformation anomalies.

The focus of this investigation is of anomalies associated with very wet and very dry precipitation years as they relate to wellfields and ground water recharge areas. Consequently, there will be re-occurring anomalies over the same areas. Only brief and possible explanations of noted anomalies will be undertaken in these reports. Complete analysis of anomalies can be pursued if warranted.

Review of ERS 1 & 2 deformation grids

Figure 2. Pair 2 April 14, 1992 and November 11, 1993

This grid shows the interval between the 6th year of drought (April 1992), a fairly wet 3 months of winter (Dec92-Feb93) and the ensuing drought through November 1993. The grid shows little change in land surface between these 19 months. Two anomalies of deflation show up, but are not well defined due to incoherent data being removed. These are over the Silver Lake wellfield in west Lemmon Valley (~10mm) and the Steamboat Hills geothermal area in the S. Truckee Meadows (~10mm). Incoherent data was removed from the areas of Washoe Lake, Silver Lake and Swan Lake (both in Lemmon Valley) and probably reflect these playas regaining water from the past winter months. Incoherent data was also removed from the SE Truckee Meadows and NE Reno that probably reflects construction activities. The central Truckee Meadows trends towards inflation and might reflect recharge from the Truckee River and a reduction in pumping.

Figure 3. Pair 5 November 30, 1993 and October 19, 1995

This grid shows the interval between the near end of the 8-year drought (1987-1994) and a very wet winter and spring (Nov 94-Mar 95). As with the last grid incoherent data is missing at the Lemmon Valley playas, Washoe Lake, NE Reno and SE Truckee Meadows. The Steamboat geothermal area anomaly shows from 5 to 15mm of deflation (actually hypothesized as contraction of the rock reservoir). The other apparent anomaly is centered over the central Truckee Meadows wellfield where up to 10mm (<1/2inch) of deflation appears to have occurred. A similar pattern is shown in west Reno, but at a much less amount. This does correspond to a wellfield (Oppliger et al, 2005). Conversely, the UNR Agricultural Farm lands in east Reno trend towards inflation of land surface (>5mm), but is inconclusive.

Figure 4. Pair 10 April 14, 1992 and October 19, 1995

This deformation grid is similar in time frame from pair 5, but has a "beginning" end-point 19 months earlier. Therefore two very wet winters of 1994 and 1995 occurred between theses two end-points, encompassing 3½ years. The Steamboat geothermal reservoir shows as much as 4cm of deflation in this familiar pattern. A slight deflation (10mm) is noted in the west Reno wellfield and as much as 20mm of deflation in the central Reno wellfield. It is interesting to note that the two Lemmon Valley playas show an apparent deflation of 15-20mm. Given the time frame of two wet winters, one might expect the opposite. However, the anomalies of both plot beneath small wellfields where the Silver Lake playa is contained within the lower 1/3 of the anomaly. The Cold Springs and Swan Lake playas indicate little, if any change in land surface.

Figure 5. Pair 16 March 30, 1993 and November 30, 1993

This pair is interesting in that it encompasses an 8 month period of spring, summer and fall. This period falls within the later part of the drought and should reflect wellfield pumping effects. The two Lemmon Valley areas again show deflation anomalies where the Silver Lake wellfield (west LV) indicates 10-20mm of change and the Lemmon Valley wellfield (east LV) 5-10mm of land elevation change. It is probable that the effect is due to municipal pumping. In Spanish Springs a 10-20mm deflation is shown centered over the Spanish Springs wellfield active during this time frame. It is interesting to note that a slight inflation is indicated between these two playas and may reflect fault structure acting as an impermeable barrier to ground water flow.

The central Truckee Meadows wellfield shows an inflation of land surface of 15-20mm. Widmer (2005) noted that this anomaly was due to minimal municipal pumping and the lag effects of ground water recharge from late spring snowmelt. The south Truckee Meadows wellfield north of the Mt. Rose Highway indicate a 10mm deflation centered over three production wells. And a 10mm deflation anomaly is seen over western Washoe Lake.

Figure 6. Pair 21 June 6, 1997 and September 13, 2002

This deformation grid spans five years that begin with two above average wet winters (and three wet winters past) and then three increasingly dry years. The Lemmon Valley area shows a general inflation of land surfaces with the playa area anomalies inflating 10-20mm. Little change is noted in other areas except the Steamboat geothermal anomaly (as much as 8cm of deflation), the central Truckee Meadows wellfield (5-10mm deflation) and the wellfield north of the Mt. Rose Highway (5-10mm deflation). Washoe Lake data is incoherent and was omitted.

Figure 7. Pair 28 August 17, 1993 and September 13, 2002

This deformation grid has the endpoints that reflect the near ending of the 8-year drought and the middle of a 5-year drought, but with 5 very wet winters in between. While this particular figure is “colorful” little change in land surface is noted over this nine-year time frame. In fact, the only anomaly shown of note is over the Steamboat geothermal and wellfield north of the Mt. Rose Highway that indicates a 5-10mm deflation.

Figure 8. Pair 31 January 17, 1997 and July 31, 1998

This grid is similar to Figure 7 (Pair 28) in that little change is noted and that much of the area of interest is affected by incoherent data. The time frame encompasses an 18-month time frame where precipitation was well above normal. Of note is that the beginning scene was taken a couple of weeks after the New Year's flood of 97. A poorly defined anomaly is seen over the central Truckee Meadows wellfield (5-10mm of deflation) and the Steamboat geothermal area (2-15mm deflation).

Discussion and Summary

Re-occurring anomalies consistently show up in the areas of municipal wellfields. Most have indicated a lowering of the land surface on the order of 10-20mm over different time periods. These deformation grids show both a deflation of land surfaces and inflation. This demonstrates the dynamic nature of the land surface as it apparently relates to aquifer "elasticity". The cumulative effects from these deflations are shown to be insignificant within this time period as shown in Figure 7 where a nine-year span shows little "long-term" deformation over the largest wellfield in the central Truckee Meadows.

It should be noted that the last two deformation grids span several years and resulted in areas with much incoherent data. This is probably due to major changes in these land surfaces such as grading in subdivision construction and water levels in the playas.

The most significant anomaly is centered over the Steamboat Springs geothermal reservoir that has been developed for power generation. The anomaly is hypothesized to be the result of the cooling of the rock reservoir and consequent cooling of the host rock. This cooling will result in contraction of the rock and therefore the apparent deflation. In this particular anomaly, the deflation is not necessarily just in the vertical dimension, but most likely in the horizontal direction as well (Oppliger, personal communication).

References

Amelung, F., Galloway, D.L., Bell, J., Zebker, H.A., and Laczniak, R.J., Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation, *Geology*, *27*, 483-486p., 1999.

Oppliger, G., Widmer, M., Goudy, C. and Huntington, J., 2005. The relation between satellite based radar differential interferometry ground deformations and groundwater production and level data in the Truckee Meadows. Consultant report prepared for the Washoe County Regional Water Planning Commission, Reno, Nevada. 35p.

Widmer, Michael., 2005. The use of DInSAR for aquifer pumping analysis. Technical memorandum to Jeanne Ruefer dated May 5, 2005 on file with the Washoe County Department of Water Resources, Reno, Nevada. 8p.

Zebker, H., Rosen, P., Goldstein, R., Gabriel, A., and Werner, C. 1994. On the derivation of coseismic displacement fields using differential radar interferometry: The Landers earthquake. Journal of Geophysical Research, Solid Earth. Vol. 99, no. 10, pp19617-19634.