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InSAR and Mathematical Modelling for Measuring Surface Deformation Due to Geothermal Water Extraction in New Zealand

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Abstract-This paper demonstrates the capability of differential interferometric synthetic aperture radar (DInSAR) for measuring the subsidence at Wairakei and Tauhara geothermal fields in New Zealand. Both conventional two-pass DInSAR and coherent targets were utilised. The potential of integration of DInSAR and mathematical modelling for geothermal subsidence monitoring and future subsidence prediction are also discussed.

***Keyword:* DInSAR, coherent targets monitoring, modelling, geothermal subsidence.**

I. INTRODUCTION

Geothermal energy is an important contributor to New Zealand's electricity supply. In 2000, eighteen percent of New Zealand's primary energy sources came from geothermal sources [1]. The extraction of underground geothermal fluid can lead to the changes of natural features, local ecosystems and subsidence of land. Extractions at Wairakei and Tauhara geothermal fields, located near Lake Taupo in North Island, have caused ground subsidence over 15m during the last 50 years [2]. Even though up to 60,000 t/day of geothermal water has been reinjected back to underground since 1996, there is still localised land subsidence of tens of millimetres per year. Traditional surveying techniques, such as precise levelling and GPS, have been used to monitor the subsidence. Subsidence is monitored at discrete locations (benchmarks) distributed throughout the field. Spatially information is calculated by contouring subsidence benchmarks.

In the past few yeas a new space remote sensing technology, radar interferometry using the synthetic aperture radar (SAR) imagery, has demonstrated its operational capability of monitoring the Earth's surface displacement due to natural hazards such as earthquakes and volcanic activities and man-made activities such as mining.

The objectives of this paper are to demonstrate the differential interferometric SAR (DInSAR) for the subsidence monitoring due to geothermal water extraction at Wairakei and Tauhara in New Zealand. It then discusses the potential of integration of DInSAR and mathematical modelling as the two complementary techniques.

II. DINSAR

This project started with the analysis using conventional two-pass DInSAR. The flow chart of DInSAR process is shown in Figure 1. Twenty three ERS-2 SAR data were acquired over this site from May 1996 to December 2003. Forty two interferometric pairs with perpendicular baseline less than 500m were selected amongst total 136 pairs formed from the combinations of the 23 acquisitions. Without the prior knowledge of the strength of conserved coherence for this area, these 42 pairs were tested. The results showed that the 3 pairs as listed in Table I had reasonable coherence level.

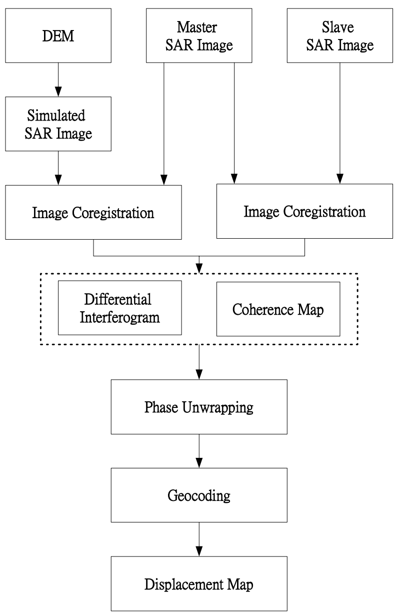

Figure 1. Two-pass DInSAR process flow chart.

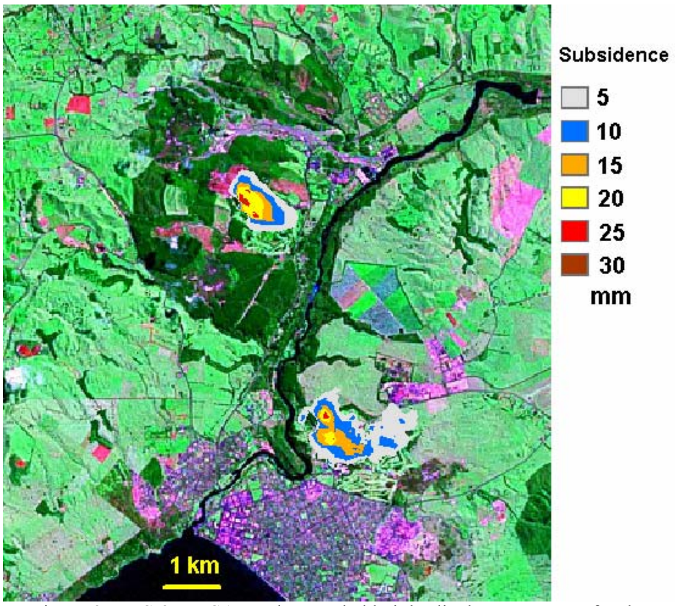

Figure 2. ERS-2 DInSAR colour coded height displacement map for the period of 1999/10/01 – 1999/12/10, overlaid on Landsat7 ETM image as the background. The Wairakei geothermal field is above the upper subsidence bowl and Tauhara is at the lower one

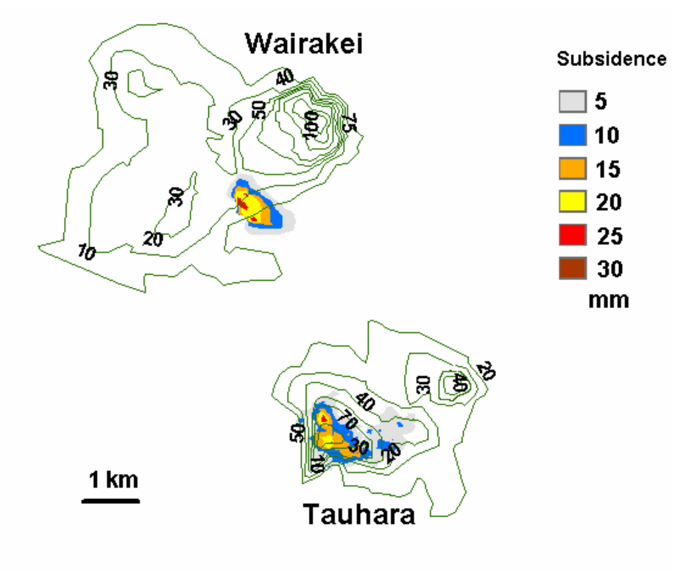

Figure 3. Subsidence rate contours from field survey coloured in dark green at the Wairakei-Tauhara system for the period 1997-2001 (mm/year) overlaid with colour coded DInSAR result for the period 1999/10/01 – 1999/12/10.

TABLE I.
ERS-2 INSAR PAIRS WITH REASONABLE COHERENCE.

Pair No.	Date of acquisition	Bperp (m)	Δ Days
1	1999/06/18	--	--
	1999/08/27	418	70
2	1999/07/23	--	--
	1999/08/27	-395	35
3	1999/10/01	--	--
	1999/12/10	-12	70

A 3 arc-second, approximately 90m resolution, Shuttle Radar Topography Mission (SRTM) DEM acquired in C-band was used to simulate the phase contribution of the topography during the DInSAR process. This 11 day space shuttle mission conducted in February 2000 used InSAR with signals in C (5.6cm) and X (3cm) bands of the microwave spectrum to create the first global DEM of the Earth, in the latitude band 60^{o}N to 57^{o}S. One of our research work for validation of DEMs showed the C-band SRTM DEM can has the RMS error of height less than 5m by comparing to the real-time kinematic GPS (RTK-GPS) field surveying data [3].

From the DInSAR results derived from the pairs in Table I, the subsidence fringes were not very evident in the differential interferograms and their background phases were inhomogeneous. Only the DInSAR result derived from pair 3 with a very short perpendicular baseline of -12m revealed some suspicious phase fringes which could be possibly due to the geothermal water extractions. The phase unwrapped height displacement is colour coded and overlaid on Landsat 7 ETM image as shown in Figure 2. The Landsat image gives the basic knowledge on the types of local land cover. It is represented in false-colour with bands visible green, near-infrared and mid-infrared displayed as blue, green and red respectively. Lake Taupo coloured black is located at the bottom of Figure 2. The buildings in the town are in pink and purple. A large portion of the image above the centre of the image is covered by forest. The DInSAR result suggested the maximum subsidence was about 3cm at both Wairakei (upper subsidence bowl) and Tauhara (lower subsidence bowl) geothermal fields.

The subsidence rate contours based on field surveying data for the period 1997~2001 are shown in Figure 3. The maximum subsiding rates at the centre of the bowls are 125mm and 75mm per year at Wairakei and Tauhara respectively. Figure 3 shows the shape and location of the subsidence at Tauhara match the subsidence contours, but the result at Wairakei seemed to be biased by the decorrelation which is possibly due to the heavily vegetated land cover or atmospheric disturbance. The magnitude of the subsidence for most of the area at the centre of the subsidence bowl at Tauhara is 15mm over the period of 70 days. This is equivalent to the rate of 78mm a year if the linear subsidence rate is assumed. This is again very similar to the results of subsidence rate contours.

The DInSAR tests indicated that its capability for long-term and slow ground displacement is very limited, especially for the vegetated area. It led to the second stage of the DInSAR analysis by utilising the permanent scatterers.

III. PERMANENT SCATTERS INSAR

The number of useable interferometric pairs is limited due to temporal and spatial decorrelation and atmospheric disturbances. Some evolved DInSAR techniques, such as interferogram stacking, permanent scatterer InSAR (PS-InSAR), and coherent target monitoring (CTM), use multiple images (or multi-temporal interferograms) to increase the signal to noise ratio in the interferometric results. PS-InSAR and CTM both use large number of SAR images to identify the permanent scatterers or coherent targets, that are simply the point pixels having good phase stability throughout the input data, hence it is possible to measure the slow displacement over a long period of time.

The second stage of this project is to use CTM to estimate the temporal deformation profile for each of the detected coherent targets over this region. All 23 ERS-2 data were used and a single SAR image acquired near the centre of the period of 1996~2003 was selected as master scene to form the interferograms with the other images. This research is currently in progress and the preliminary analysis will be reported in the symposium.

IV. 2D and 3D Subsidence Modelling

The subsidence induced by geothermal water extraction is much more complicated than the subsidence due to the excavation of solid minerals. It involves changes in fluid dynamics, steam pressure, temperature and geological structure of the soils and rocks of the sub-layers. The Tauhara geothermal field is hydrologically connected to Wairakei so it is also referred as Wairakei-Tauhara geothermal system. Mathematical models of the geothermal reservoir have been used to predict the response of the shallow zone of the geothermal fields, such as the changes in surface heat and mass flows [4, 5].

In [2], a 2-D finite-element analysis subsidence model of the Wairakei-Tauhara system was studied. The model utilises underground pressure predictions from a reservoir model to determine ground subsidence. The model accommodates variable rock properties such as non-linear stress-strain behaviour. This model simulated the subsidence along a horizontal distance and matched to the historical survey data for calibration. This model also predicted that to 2050 the total subsidence (since 1950) will exceed 25m and 5m at Wairakei and Tauhara respectively.

Both DInSAR derived ground surface displacement maps and mathematical subsidence models of the geothermal fields need to be calibrated and validated using the ground truth data. DInSAR is able to reveal the subsidence during various time intervals which could be sometimes more frequent than the field survey. More importantly, the DInSAR results cover a great area and may discover any possible new subsidence zone. The DInSAR and mathematical modelling are complementary as the validated DInSAR results can be used to calibrate the model, hence the model can be used to predict the subsidence in the future.

V. Concluding Remarks

The subsidence at Wairakei-Tauhara geothermal system has been studied using DInSAR. One of the DInSAR results revealed the subsidence with the maximum magnitude of 25mm at Tauhara during 01 October – 10 December 1999. Assuming the subsidence rate is linear, the result agreed with the subsidence rate contours derived based on field surveys. The DInSAR result at Wairakei during the same period was biased due to the heavily vegetated land cover. Using CTM to estimate the temporal deformation profile for each of the detected coherent targets over this region is currently in progress. DInSAR and mathematical modelling are complementary and have the potential to reveal the past and present subsidence, furthermore for the prediction in the future.

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