Land Subsidence Measurements at the Belridge Oil Fields from ERS InSAR Data

Marco van der Kooij

Atlantis Scientific Inc, 20 Colonade Rd, suite 110, Nepean, Ont, K2E 7M6, Canada

E-mail address: marco atlsci.com

http://www.atlsci.com

Abstract

Repeat-pass interferometry has a high potential for the measurement of land subsidence and absidence at oil and gas exploration and mining sites. At the Belridge and Lost Hills oil fields in California (U.S.A.) the subsidence rate is as high as 30-40 cm per year and is spatially and temporally variabel. This paper shows preliminary results of ERS differential interferograms and geocoded subsidence maps for this area. The phase coherence levels appear to be sufficient for accurate measurements even for time intervals up to 6 months between the interferometric acquisitions. Six subsidence maps for the time period between 1992 and 1996 were analysed and the subsidence rates were compared. It appears that the subsidence rates for 3 maps generated from data collected between November 1995 and April 1996 is consistent.

Keywords: SAR, interferometry, subsidence, oil

Introduction

The Belridge and Lost Hills Oil Fields are located approximately 100 km West of Bakersfield (U.S.A.). The size of the area is approximately 20 x 5 km. Oil production at this site has taken place for more than a decade and it is being extracted from a layer of diatomite sandstone. This rock is continuously compacting due to the reducing pressure caused by the extraction of oil. The compression and local collapse of the sandstone causes frequent oil well failures. The costs of replacements amounts to millions of dollars per year and can stop the oil production temporarily. The subsidence rates are related to the oil production rates and the characteristics of the reservoir. The dynamics and extent of the subsidence are poorly understood. In the Southern part of the Belridge oil field steam injection is used to attempt to reduce the subsidence. This attempt has been succesful in the sense that the subsidence has decreased. Well failures do still occur however. Conventional monument measurements are used to map the subsidence but these point measurements do not give a proper 2-dimensional overview and are expensive to collect. A remote sensing technique that could provide high accuracy maps of subsidence would be of great benefit to this problem.

In Repeat-Pass SAR Interferometry, two SAR datasets of the same area acquired from almost identical perspective are co-registered and combined into a so-called interferogram. The phase difference for each pixel of the interferogram is a measure for the local incidence and/or relative change in distance between scatterer and SAR antenna. From the phase information a digital elevation model (DEM) can be derived if no large scale deformation occurs between the recordings. DEM's with height accuracies below 10 m and horizontal resolutions in the order of the SAR image resolution can be achieved.

Large scale deformation in the range direction of the SAR sensor also contributes to the differential phase. These contributions can be retrieved by removing the contributions caused by the topography (the "elevation phase"). This requires the modeling of these contributions based on an input reference DEM and an accurate geometry of the interferometric acquisitions. This technique is known as differential InSAR (see e.g. Gabriel et. al. 1989). In the last five years it has received much attention as a provider of maps of large scale deformation with unprecedented accuracy (cm, mm level). The high resolution and two-dimensional coverage of large areas with this accuracy makes this technique almost incomparable to any other measurement technique. Important applications are the measurement of pre-, post- and co-seismic displacement fields caused by earthquakes (see e.g. the article by Massonet et. al, Nature, 1994) and the measurement of deformation prior to volcanic eruptions (e.g. Massonet et. al, Nature 1995).

A new application area that has received attention, is the potential monitoring of land subsidence and absidence at oil, gas and mining exploitation sites. This type of deformation is a worldwide phenomenon. The impact can be very significant: it can affect the ability to extract oil or gas and can also damage the infrastructure and affect the water management of large areas. An example of an area that is being investigated using spaceborne interferometric SAR data is a gas exploitation site in Groningen, The Netherlands (Van der Kooij et. al, 1995).

This paper describes first results of a study of the Belridge and Lost Hills oil fields using ERS interferometric SAR data. The area is covered by ERS-1 and ERS-2 since 1992. The large number of potential InSAR pairs (35 day repeat period and 1 day repeat period) allows a systematic investigation of the potential of (C-band) repeat-pass InSAR data for deformation measurements in this area. The following sections will describe the approach, the results and the analysis of the results.

Approach

ESA-ESRIN's website was visited to find estimates of perpendicular baselines for the useful InSAR frames. From the large number potential InSAR pairs a selection was made using only those pairs that have small baselines (< approx. 200 m) and with time windows ranging from 1 - 10 repeat periods. In addition one ERS tandem pair was selected to generate a reference DEM to be used for differential interferometry. The elevation phase can be removed using this approach because the subsidence during the one day time interval is very small (approx. 1 mm or less). The advantage of using this approach over the three-pass approach (Gabriel et. al., 1989) is that we obtain real subsidence information over the time interval of the two passes that were used for differential interferometry instead of a complex combination of deformation during the three passes. This is very important considering the fact that the subsidence has an almost constant or slowly evolving deformation rate.

Atlantis' EarthView InSAR software has been used to process all the scenes. Full scene SLC products from Atlantis' APP (Advanced Precision Processor) were used. Very accurate orbit data from DUT (Delft University of Technology, the Netherlands) were incorporated during the processing. InSAR processing steps included automatic co-registration, "flat"-earth phase removal, spectral filtering, removal of elevation phase contributions using external (ERS tandem) DEM, interferogram enhancement, coherence map generation, phase unwrapping, height change map generation, terrain distortion removal and geocoding.

Results

Figure 1 shows the differential interferogram generated from ERS-1 data (ERS-2, November 5 1995 and ERS-1, December 9 1995). The perpendicular baseline for this example was 17 m. An ERS tandem mode pair was used to generate a reference DEM for correction of the elevation phase. The time difference between the passes of the differential interferogram was 34 days. We see two areas where subsidence occurred. The small area in the northern part of the image is the Lost Hills oil field, the long shaped area in the middle is the Belridge oil field. Some of the areas in the northern section are decorrelated. These areas are agricultural fields. Most of the other areas are sparsely vegetated scrublands.

Figure 1 *Differential interferogram created from ERS data (ERS-2, November 5 1995 and ERS-1, December 9 1995). The time difference between the passes is 34 days*

Figure 2 shows the differential interferogram generated from ERS data (ERS-1 February 17, 1996 and ERS-2, April 28, 1996). The perpendicular baseline for this example was 51 m. The ERS tandem mode pair was used to correct for the elevation phase. The time difference between the passes was 71 days. The same areas of subsidence show up again but now the number of subsidence fringes has increased approximately a factor 2.

Figure 2 Differential interferogram created from ERS-1 data (ERS-1 February 17, 1996 and ERS-2, April 28, 1996). The time difference between the passes is 71 days

Figure 3 shows the differential interferogram generated from ERS data (ERS-2 November 5, 1995 and ERS-1 February 17, 1996). The perpendicular baseline for this example was 227 m. The ERS tandem mode pair was used to correct for the elevation phase. The time difference between the passes was 104 days. The same areas of subsidence show up again but now the number of subsidence fringes has increased approximately by a factor 3. The fringes in the bottom left are due to remaining elevation phase effects.

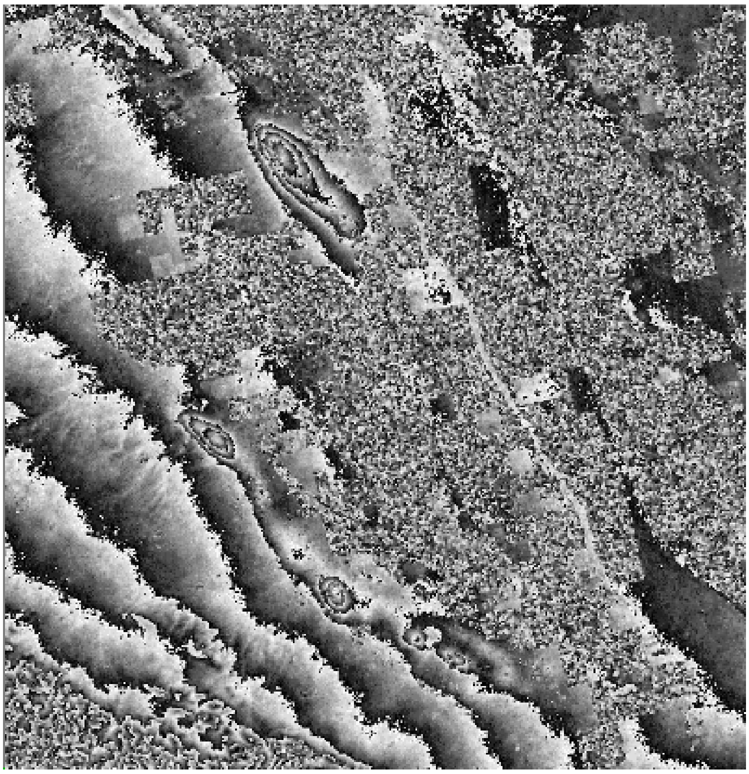

Figure 3 Differential interferogram created from ERS data (ERS-1 February 17, 1996 and ERS-2, April 28, 1996). The time difference between the passes is 104. days.

Figure 4 shows the differential interferogram generated from ERS-1 data (March 11, 1993 and September 11, 1993). The perpendicular baseline for this example was 6 m. The ERS tandem mode pair was used to correct for the elevation phase. The time difference between the passes was 175 days. The number of fringes has increased dramatically. Although the coherence is relatively low in many areas, it is still possible to quantitatively interpret the data in many areas.

Figure 4 Differential interferogram created from ERS-1 data for March 11, 1993 and September 11, 1993. The time difference between the passes is 175 days.

Analysis

The location of the subsidence areas as indicated by the interferograms corresponds with the location of oilwells in the area (personal communication, J. Berry, Shell Oil). The elevation phase corrections might not be perfect due to the small area that was processed and the small baseline of the reference ERS tandem DEM.

Height change maps were generated for all interferograms shown in the previous section including a pair generated from ERS-1 data (September 17, 1992 and November, 26, 1992). A deformation map generated from this pair is shown in Figure 5. A number of measurements have been performed for 15 indicated areas. This was done by comparing the measurements with the background levels (average value just west and east of the subsidence). The noise in the background is less than 5 mm rms. The largest source contributing to this noise is atmospheric effects. For a quantitative evaluation of atmospheric effects see Van der Kooij et. al. 1995.

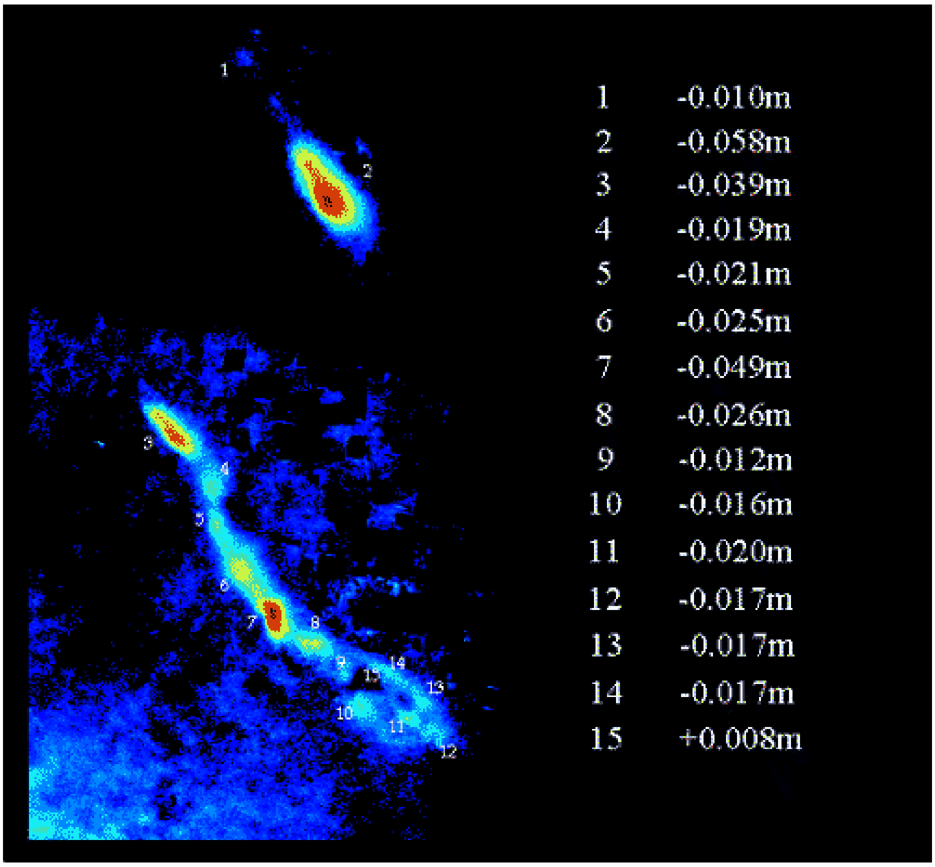

Figure 5 Height change map generated from ERS-1 data (September 17, 1992 and November, 26, 1992). A number of measurements have been performed for 15 indicated areas

To check the consistency of the height change maps for 1995 and 1996, the deformation rates for three height change maps were calculated. The rates were calculated as a height change per 35 days and plotted in figure 6. Along the horizontal axis the November 1995 - February 1996 datapoints are plotted. Along the vertical axis the November 1995 - December 1995 and the February 1996 - April 1996 are plotted. A perfect consistency of the deformation rates would give a perfect straight line across the plot. As can be seen, the deviations from the straight line are very small (less than 5 mm).

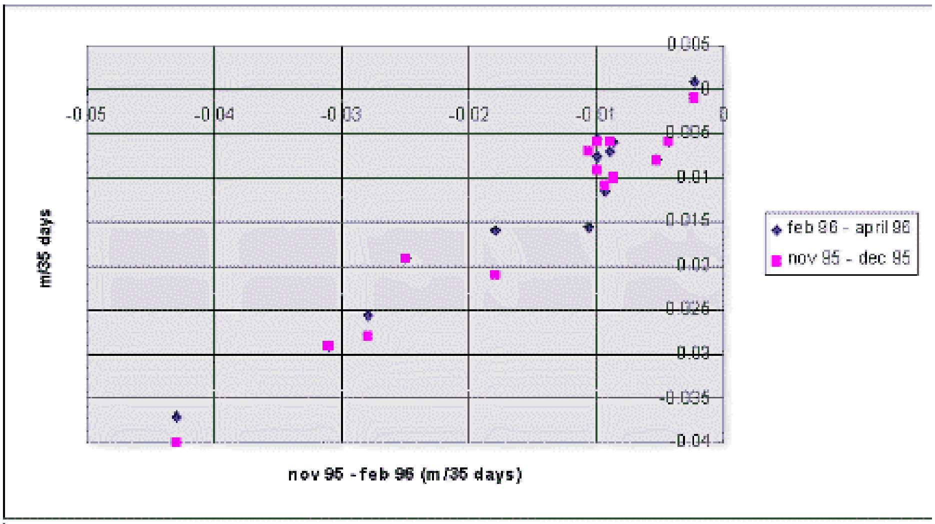

Figure 6 Consistency of the deformation rate. The deformation rates for three height change maps were calculated. The rates were calculated as a height change per 35 days. Along the horizontal axis the November 1995 - February 1996 datapoints are plotted. Along the vertical axis the November 1995 - December 1995 and the February 1996 - April 1996 data points are plotted.

Conclusions

Good quality interferograms have been created for an area where land subsidence due to oil exploitation is a very serious issue. The consistency of the height change rates in 1995 and 1996 and height change rms calculated in "background" areas suggest that very accurate monitoring of height change is possible in the Belridge and Lost Hills Oil Fields. Further analysis and comparison with in-situ monument measurements will reveal more details of the spatial distribution and origin of the subsidence that can be measured as well as the accuracy.

Acknowledgments

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