Advances in deformation measurments from spaceborne radar interferometry

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To better understand the characteristics and mechanics of hydrocarbon producing reservoirs there is a growing demand for accurate, repeated, and spatially continuous measurements of the earth's dynamic surface. Spaceborne Synthetic Aperture Radar (SAR) data is increasingly being used for radar interferometry (InSAR), a modern geodetic technique for measuring the topography and deformation of the earth.

This article provides an overview and results of the work done to date over North Omans Yibal hydrocarbon fields. The accuracy and error sources of InSAR measurements are looked at in more detail and an outlook is presented on the latest developments in this exciting new field.

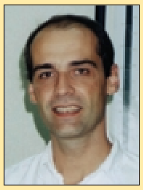

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Figure 1: SAR backscatter image of Yibal, Oman. ERS-1 C-band SAR.

Background

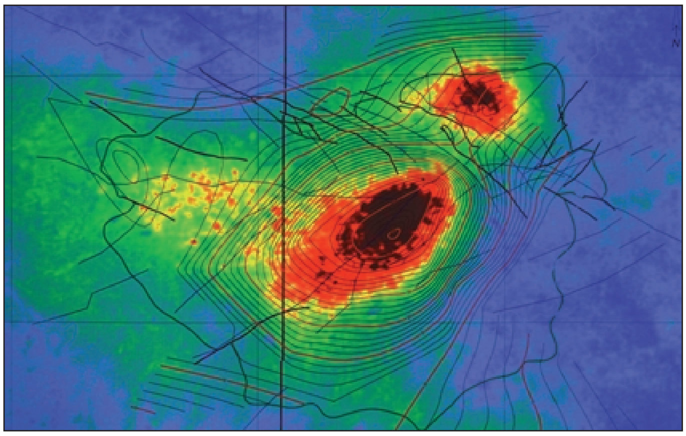
Synthetic Aperture Radar (SAR) systems measure both the magnitude and the phase of the transmitted electromagnetic signal that is back scattered from the earth's surface. The magnitude, or "brightness" of the surface, is what is usually associated with a remotely sensed image. *Figure 1* shows a typical backscatter image of Yibal. The phase represents a combination of the distance from the SAR antenna to the surface, and the surface scattering effect on the incident electromagnetic wave. The phase of a SAR image is uniformly randomly distributed and is of no practical value on its own.

If a second SAR data set is collected, then upon comparing the phase of the second image with the phase of the first, an interferogram can be formed. If the distance between the two orbital locations of the radar, called the baseline, is small then the surface scattering effects will be the same for the two images and thus are cancelled in the formation of the interferogram. Therefore the interferogram exhibits information related to the difference in distances from the surface to the two radar locations. Provided precise orbit parameters can be established and phase effects due to terrain are removed utilising an accurate Digital Elevation Model (DEM) the interferogram can be transformed into a deformation map yielding subsidence information between the two SAR acquisitions.

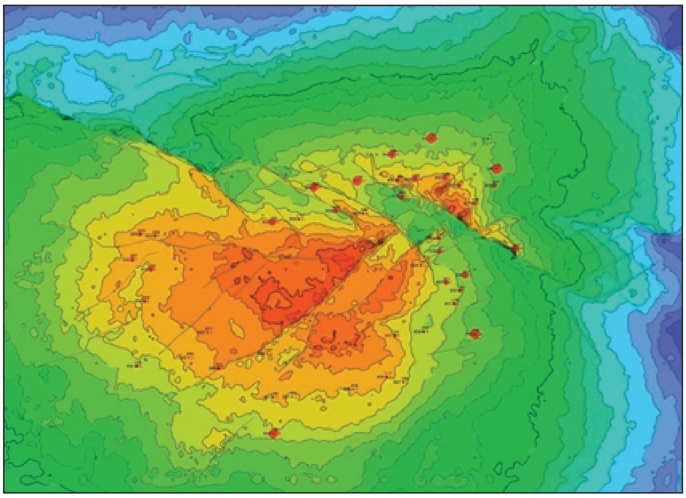
Yibal results

From the available SAR data in the period 1999-2000 several interferograms have been created of which the majority exhibit a similar phase pattern in the immediate vicinity of the Yibal hydrocarbon fields. The subsidence bowl can be identified with a spatial extent in the shape of a boomerang and two noticeable subsidence centres. The yearly maximum subsidence for this period is calculated from InSAR to be around 4 cm.

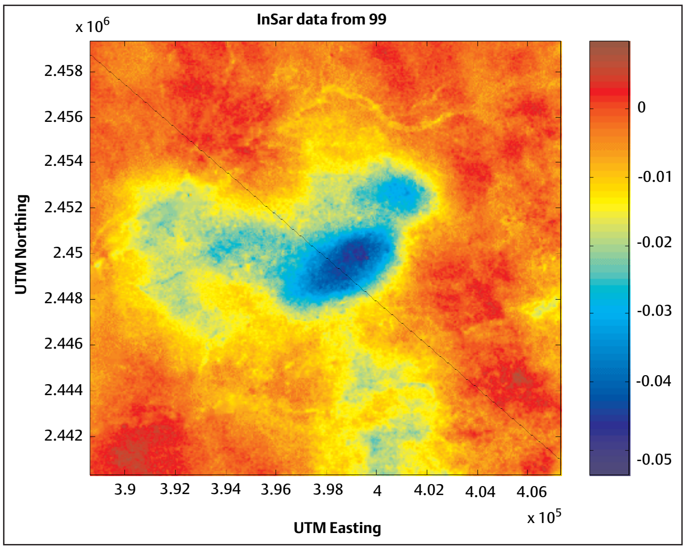
During the same period, accurate levellling has been performed by PDO's Geomatics Department. The detailed comparison between the two methods is shown in *Figures 2 through 6*. The InSAR results match



▲ *Figure 2: Deformation map derived from the differential interferogram. The image covers 30x20 km; colors reflect a boomerang-shaped subsidence signal up to 4 cm/yr. The overlay shows the interpolated leveling results.*



▲ *Figure 3: Contour map Top Natih stratigraphic layer.*



▲ *Figure 4: InSar subsidence data from 1999.*

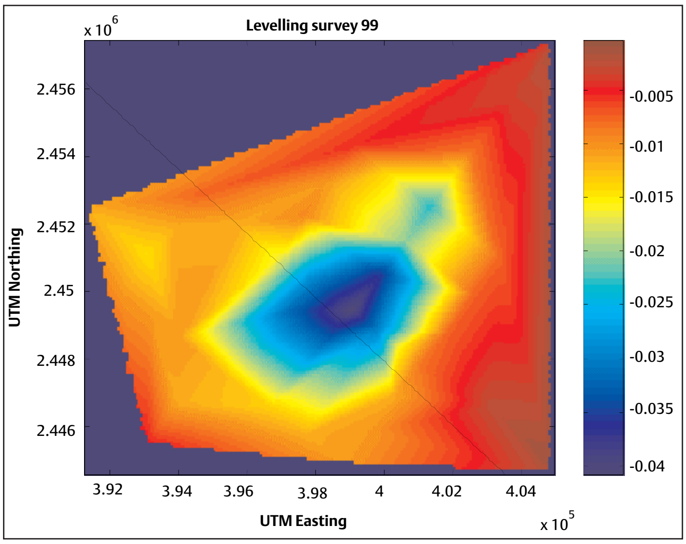
the conventional levelling data very closely and provide a much more detailed picture of the subsidence rates. It was also concluded that the extent of the subsided area was significantly larger than anticipated, resulting in an expansion of future levelling surveys.

The subsidence also compares very well with the subsurface Top Natih gas layer as shown in *Figure 3*, clearly indicating a very high correlation both in terms of shape and outline. Further studies also indicated a relation between the subsidence rates and the amount of Yibal gas production, both not being linear in time due to seasonal changes and varying demand.

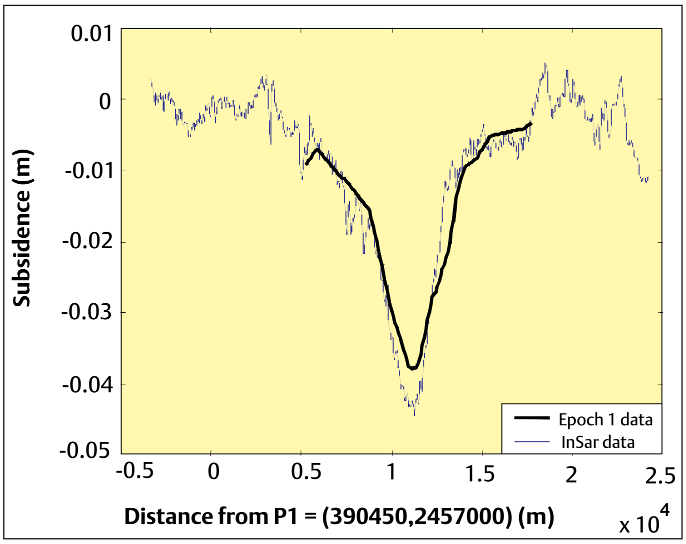
Accuracy and error sources

The accuracy of the InSAR results can be expressed in terms of the variances and covariances of the range observations for all resolution cells in the interferogram. Phase accuracies of a few millimetres are feasible, as long as the scattering characteristics of the earth's surface do not change significantly, as indicated by the degree of decorrelation. *Figure 7* shows the correlation image of the Yibal site for a period of 4 months. Dark areas, such as the wadis (stream beds) and seismic lines are decorrelated, whereas for most of the arid regions the temporal decorrelation is usually limited, even for time intervals of several years.

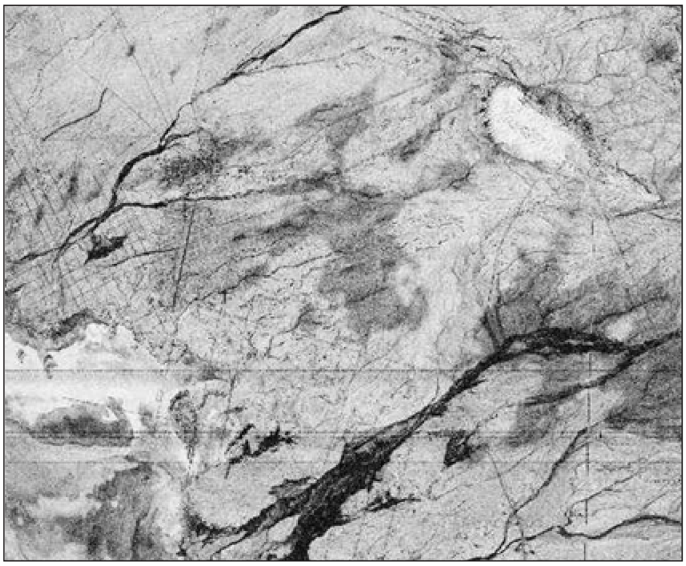
Nevertheless, the effective ranging accuracies are generally less accurate, due to spatial heterogeneities in the atmospheric refractivity, affecting the propagation velocity of the radar signals. Such heterogeneities, mainly induced by variations in the water vapour distribution, may decrease the accuracy of the range observations over the entire image considerably. Depending on the weather situation during the radar acquisitions, maximum water vapour induced delays of 3-80 mm have been observed. Evidently, several cms of atmospheric signal limit the detectability of a small subsidence signal considerably, enforcing longer observation intervals to enhance the subsidence signal relative to the atmospheric signal. Fortunately, atmospheric signal is very correlated spatially: it is a smoothly varying parameter. This results in an extended covariance function, which enables the quantification of the atmospheric error between any two points in



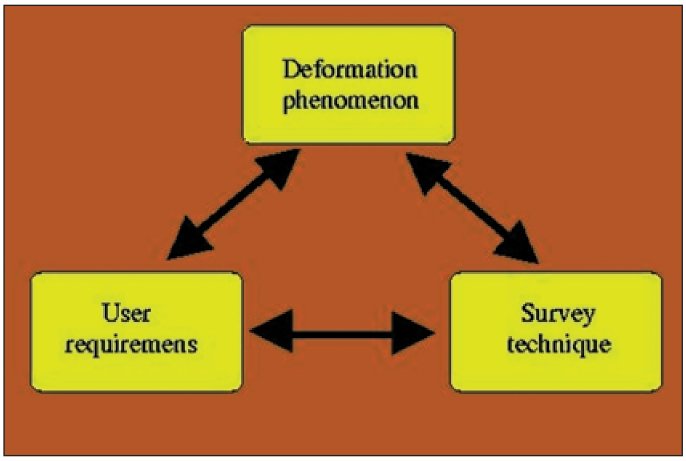
▲ *Figure 5: Yibal Epoch 1 levelling subsidence (1999). Interpolation using 45 measurements was done using MATLAB.*



▲ *Figure 6: Profile of subsidence along the lines shown in Figures 4 and 5.*



▲ *Figure 7: Correlation image for an interferogram between images acquired in May 1999 and September 1999. Bright areas are very correlated in time, whereas the wadis (stream beds) and surface disturbed by seismic lines appear dark (low correlation).*



▲ *Figure 8: Decisions for the application of a specific geodetic technique need to be evaluated against the user requirements and the characteristics of the deformation.*

the interferogram. Furthermore, the energy in the atmospheric signal exhibits a scaling behaviour: over spatial distances less than a few kilometres, it is usually nearly negligible, with increasing influence for longer distances.

Outlook

The feasibility of any geodetic technique for the observation of land subsidence needs to be evaluated on a case-by-case basis, in combination with the expected characteristics of the deformation phenomenon and the user requirements, see *Figure 8*. Advantages of InSAR are the possibilities of spatially near-continuous deformation mapping, high accuracies, frequent survey (monthly) updates, and cost-effectiveness. The frequent radar acquisitions result in a series (stack) of images, making time-series evaluations possible. Disadvantages are the dependency of stable surface scattering characteristics and currently the dependency on operational radar satellites and their acquisition preferences.

It is recommended that future work on refinement of the InSAR technique focus on definition of stakeholder requirements in terms of temporal coverage, spatial resolution of derived deformation maps, and quantitative estimation of variance and covariance parameters derived from InSAR measurements, in order to facilitate integration with other data and analyses.

Conclusions

InSAR provides a cost-effective subsidence-measuring tool (50% of conventional surveys) while acquiring continuous data over a large area.

InSAR has the ability to obtain historical deformation data by processing archived SAR.

Accurate, repeated and spatially continuous deformation information may shed light on subsurface depletion for shallow or high-pressure reservoirs. Clues may be provided on field wide drainage patterns and potential undrained areas, e.g. fault blocks or disconnected sand bodies.