Fringe 96

Application of SAR Interferometry to the Imaging and Measurement of Neotectonic Movement Applied to Mining and other Subsidence/Downwarp Modelling.

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Abstract

This collaborative project Between Doncaster College, RJB Mining(UK), GEC Marconi Research Centre, and Matra Marconi Space, will integrate Synthetic Aperture Radar (SAR) ERS1 and ERS2 satellite remotely sensed images and their derived interferograms(INSAR), differential interferograms(DiffINSAR) and associated Digital Elevation Models (DEM), with mining (and other types of), subsidence mathematical models. The subsidence models are used to determine the maximum mineral extraction, within the subsidence constraints imposed by conditions of permit, granted in the UK under the Town and Country Planning Act. The objective of the project is to use SAR derived elevation data to feed back to the subsidence model to improve subsidence prediction, mine productivity, conformity with regulatory consent and minimised environmental and economic impacts.

With many complex and inconsistent variables, the dynamics of mining subsidence are difficult to model. Reliability of modelling is extremely variable, reported actual to predicted subsidence in a range 48 - 773%. There is a general recognition of the inadequacy in both the empirical approach to subsidence modelling (SEH) and the more rationalist computer models. Remotely sensed data has the potential to improve subsidence modelling accuracy by significantly increasing the quantity of feed back data, compared to the quantity of data practicable by conventional land surveys. While land surveys conducted along road and canal bank lines produce a relatively small, highly accurate data base, diff DEMs have the potential to provide elevations at 1cm vertical resolution and 50m horizontal resolution. The significantly increased quantity of feed back data by INSAR should thus provide a more rational, statistically significant, scientific basis for the Mineral Surveyor to adjust the subsidence model.

The interferometric processor developed at MRC will be applied to demonstrate the monitoring of subsidence for two thoroughly validated and contrasting sites in the Czech Republic and the UK. The aims of the demonstration will be to assess the vertical accuracy and precision with which subsidence can be measured and to comment on whether the user specified horizontal location accuracy requirements are achieved. As an engineered movement, mining subsidence offers the best opportunity to develop the remote sensing techniques, further applicable to natural tectonic events, since the motions can be predicted spatially and temporally (albeit within the current range of error), are routinely land surveyed and are generally intensively geologically surveyed. The mining activity, being continuous, can provide a regular stream of dynamic statistical data for INSAR and Model validation, under near optimal controlled conditions, not possible under natural conditions.In the context of liability for economic and environmental impacts, and risk to major investment and production however, the technique has to be developed and demonstrated to a high level of dependability before it could be considered ready for application demonstration. Once validated, the extended INSAR techniques and improved subsidence modelling could be expected to contribute to wider opportunities and understanding in geological modelling generally, such as earthquake, landslip, heave, isostatic uplift and downwarp, volcanoes, glacial, fluvial and coastal geomorphology.

Introduction

The BONN Experiment [1] in 1992 by ESA/ESRIN, University of Stuttgart and Politechnico di Milano, demonstrated the capability of SAR differential interferometry to measure surface movement to centimetre resolution under experimental conditions using corner reflectors and transponders. The NAPEX Experiment [2] is currently extending this work on the area around Vesuvius, Naples, where surface relaxation of 3cm/annum is occurring. Due to the relative predictability and continuity of mining subsidence compared to natural tectonic movement and the availability of precision ground truth survey data, this proposal represents an unequalled opportunity to validate INSAR techniques and advance them a step towards operational application. The current development status of SAR Interferometry is discussed further.

Mining subsidence is typically limited by planning consent in the UK to 1 metre. The dynamics of subsidence involve vertical movement spreading beyond the worked panel at around 37 degrees from the vertical to a maximum depth nominally around 70% of the thickness of the worked panel. Surface strain results in regions of tension over the general area and compression creating a hump along the centre line. Variation in subsidence rate occurs due to inconsistency of geological formations, rock mechanical properties, and the overall uniqueness of each situation, e.g. depth of workings, mining technique, seam inclination, adjacent/subjacent working, face ends etc.

RJB Mining UK, as the end user partner in this proposal, is making available its land survey data and subsidence modelling, particularly for the Selby Coalfield. RJB will be collaborating with Doncaster College on land surveying, ground truth testing of differential DEMs, adjustment of DEMs and identification of anomalies, statistical analysis, satellite data interpretation and analysis, mining subsidence computer program modification and data feedback to subsidence modelling. Doncaster College through partnership with VSB University, Czech Republic, also has access to subsidence data and modelling for the Silesian Coalfield in North Moravia where 40 metre subsidence has been experienced in the recent past. This opportunity will further enable testing of experimental repeatability and the effects of different elevations, ground movement range and topography. The area is a focus of attention for environmental improvement/investment/monitoring, attracting both EC (EBRD) and US aid funding.

The dynamics of mining subsidence are difficult to model. The Subsidence Engineer's Handbook (SEH) [3] , revised by the National Coal Board in 1975, is still the standard reference text, applied largely by use of generalised graphs, usually empirically derived from observation, the results adjusted by local experience. Computer models are generally based on input parameters of seam thickness, depth of mining, amount and direction of seam gradient, adjusted in line with SEH, estimated on a system of annular zones in three dimensions. Reliability of modelling is extremely variable. C R Ferrari [4] of British Waterways (responsible for the security of undermined canal banks), has reported actual to predicted subsidence in a range 48 - 773%. It can be argued that the empirical nature of the models that form the basis of subsidence modelling is, on the one hand appropriate for the inconsistent conditions experienced. On the other hand the refinement of empirical models is dependent on quantity of data.

Currently Mineral Surveyors conduct line surveys of subsidence along roads and canal banks, this represents a very small proportion of the area of influence of the mine working. This small sample size will contribute to the wide variation in actual to predicted subsidence currently experienced. Remotely sensed data has the potential to improve subsidence modelling accuracy by significantly increasing the quantity of feed back data, compared to the quantity of data practicable by conventional land surveys. While land surveys conducted along road and canal bank lines produce a relatively small, highly accurate data base, SAR differential DEMs have the potential to survey the whole area providing elevations at 1cm vertical resolution, at 12.5m horizontal resolution. The significantly increased quantity of feed back data by SAR Interferometry should thus provide a more rational, statistically significant, scientific basis for the Mineral Surveyor to adjust the subsidence model.

By use of near real time images such as the Rapid Information Dissemination System (RAIDS) service being developed by MMS, it should be possible to monitor subsidence comprehensively at (currently) 35 day intervals , enabling rapid response to variance from modelled forecasts with clear economic and environmental benefits.

In order to exploit remote sensing data in monitoring subsidence and subsequently re-engineering mine workings, a clear program of technique development and demonstration is required. The remote sensing techniques are not proven, especially at the levels of confidence necessary when, environmental protection, major property damage liability, stability of railways, roads, canal banks and river and coastal flood protection are at risk, along with multi million pound mine investment and productivity.

Once the remote sensing techniques have been developed, it will be necessary to demonstrate application of these techniques through to the point of production of demonstration (calibrated) subsidence maps. The project will not end at this point. It is very important that the improved subsidence maps derived from remote sensing data are linked in to the appropriate subsidence model. The project will only be complete when the end user(s) are shown clear evidence that the subsidence model predictions are a clear and reliable improvement over those available without remote sensing data.

SAR Interferometry technique development

SAR interferometry is a relatively new technique for the generation of topographical height information. As such there are a number of issues which need to be explored in terms of image coherence and DEM calibration. There are two main factors which determine image coherence, firstly the perpendicular baseline separation of the image acquisitions (Bperp) and secondly changes in ground scattering characteristics between image acquisitions.

Coherence analysis

In order to extend the range of useful image pairs for INSAR, it is intended to experiment with generating elevation data from images of varying coherence. To establish to what extent useful elevation data can be extracted, less than optimum images will be filtered for the most coherent areas. In the extreme this may be limited to stable linear features such as roads, large buildings, hard surfaces etc.

As a routine process, filtering to remove the least coherent areas (caused by vegetation change, cultivation and variability in soil moisture etc) should improve the overall resolution and correlation with ground truth of the remainder of the image. Operational ranges of 'minimum useful coherence area' and 'maximum tolerable incoherence' should result, supported by correlation values with ground truth, to enable utilisation under the fullest possible image availability range. This is crucial for increasing the operational availability of INSAR imagery to commercial demand. The ability to specify a coherence coefficient for an image pair, (on a similar basis to specification of cloud cover on LANDSAT images) or pre filtered products to 'coherence values' and/or 'coherent area' specifications would advance the whole INSAR technique.

Bperp to resolution relationship

The physical separation of repeat orbits has to be within a perpendicular baseline (Bperp) orbit separation tolerance to satisfy interferometric geometry. Bperp up to 600m is the limit for INSAR but precision deteriorates beyond 300m. There is ambiguity over the relationship between Bperp and INSAR resolution and application. With the volume of data available for the UK and Czech test areas, it is intended to derive a relationship between Bperp and DEM/Differential DEM resolution, in order to establish repeatable Bperp values for optimum, median and minimum useful resolution of surface change/elevation, under various surface/topographical conditions.

SAR subsidence demonstration.

The interferometric processor developed at MRC will be applied to demonstrate the monitoring of subsidence for two thoroughly validated and contrasting sites in the Czech Republic and the UK. The aims of the demonstration will be to assess the vertical accuracy and precision with which subsidence can be measured and to comment on whether the user specified horizontal location accuracy requirements are achieved.

Consideration will be given as to how the accuracy of results varies as a function of type of terrain, weather conditions and vegetation conditions. On the basis of this, comments will be made on the circumstances under which the application will be viable, given a relationship between coherence and differential DEM precision and accuracy.

Advancement of Subsidence Engineering Science

There is a general recognition of the inadequacy in both the empirical approach to subsidence modelling (e.g. SEH) and the more rationalist computer models. There a high expectation that this new opportunity in remote sensing, should enhance the understanding of the dynamics of subsidence, the neotectonic imaging and modelling techniques then also being applicable to other geological processes.

As an engineered movement, mining subsidence offers the best opportunity to develop the remote sensing techniques, further applicable to natural tectonic events, since the motions can be predicted spatially and temporally (albeit within the current range of error), are routinely land surveyed and are generally intensively geologically surveyed. The mining activity, being continuous, can provide a regular stream of dynamic statistical data for INSAR and Model validation, under near optimum controlled conditions, not possible with unpredictable natural events.

In the context of liability for economic and environmental impacts, and risk to major investment and production however, the technique has to be developed and demonstrated to a high level of dependability before it could be considered ready for application demonstration.

1. It is at this stage hypothesised, that the increased statistical significance of INSAR DEM feedback will improve the reliability and precision of the SEH modelling methodology.

2. Computer models are deemed by Mineral Surveyors to oversimplify subsidence dynamics, but clearly are the appropriate tool for dynamic modelling generally. Incorporation of INSAR DEM data could provide well researched, statistically significant model adjustment, for specific typical geological structures, or localised field conditions, but subject to rigorous validation testing. A general technique for generation of geological model adjustment could be developed, given opportunity for sufficient trials of repeatability.

3. Hybrid modelling combining SEH, Computer Model and INSAR derived factors could be expected to draw on the strengths of each subsidence modelling technique.

4. The scale of data collection theoretically possible through INSAR, in 3 Dimensions and multi temporally by satellite repeat cycle, should enable 3D animation of tectonic movement and multivariate spatial/geostatistical analysis. There is a prospect of thus identifying dynamics and explanations of motions, not previously apparent or adequately scientifically explained, thereby improving the science and understanding of subsidence. Once validated, the extended INSAR techniques and improved subsidence modelling could be expected to contribute to wider opportunities and understanding in geological modelling generally, such as earthquake, landslip, heave, isostatic uplift and downwarp, volcanoes, glacial, fluvial and coastal geomorphology.

Progress to Date

Research funding from the British National Space Centre started in July 1996.

Preliminary results indicate that mining subsidence can be detected by INSAR but that availability of INSAR data is less than optimum.

The ERS Tandem Mission has produced fewer opportunities for INSAR pairs at 1 day repeat under ideal ground conditions of minimum vegetation than expected, due to the Tandem Mission only spanning one winter. There were also gaps in availability of INSAR pairs for the UK test site during the Mission.

There is thus the challenge of producing interferograms and DEMs from sparse data after filtering for coherent areas from longer repeat cycle INSAR pairs. This challenge is considered to be important because commercial application of the technique depends on being able to produce useful results with available data, which is not neccesarily of optimum specification.

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