Independent Review of Coal Seam Gas Activities in NSW

SUBSIDENCE MONITORING IN RELATION TO COAL SEAM GAS PRODUCTION

Prepared for the Office of the NSW Chief Scientist and Engineer
Final Report
November 4, 2013

Disclaimer

This report was report was prepared for, and on behalf of the NSW Office of the Chief Scientist and Engineer. The sole purpose of this report and the associated services performed by the CRCSI was to conduct a literature search and critical review on the current science and industry practice related to subsidence induced by Coal Seam Gas (CSG) production. The intent of such a paper is to inform and assist in developing policy and to assist with public understanding and to support policy development for specific elements of CSG operation and impact. The views, opinions and conclusions expressed by the authors in this publication are not necessarily those of the NSW Office of the Chief Scientist and Engineer. To the extent permitted by law, the Cooperative Research Centre for Spatial Information, excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this report (in part or in whole) and any information or material contained within it. The project team included employees of the Cooperative Research Centre for Spatial Information (CRCS), Geoscience Australia; an independent consultant and employees of SKM, a strategic consulting, engineering company. Prior to undertaking the work, all project members were required to declare and undertake that there were no matters concerning individuals or company interests, or activities which may call into question probity of individuals or the NSW Office of the Chief Scientist and Engineer, or give rise to any conflict with responsibilities as consultants. To manage any potential any potential conflicts of interest all sources of information for the report have been drawn from publically available documents, and been subjected to broader academic review by the CRCSI.

Contents

Executive Summary

The process of coal-seam gas (CSG) extraction involves removal of water from a coal seam to liberate methane and other gases that are tightly bound to the solid matrix of the coal. The water produced as a by-product during the extraction of CSG, often referred to as associated or co-produced water, is pumped to the surface through a production bore or well.

Ground subsidence associated with CSG extraction is caused by groundwater depressurisation of the coal seams and stress changes in adjacent or connected aquifers. The depressurisation results in a reduction in the "buoyancy" uplift water pressure, which in turn results in an increase in the effective stress. This net effect causes the matrix to compress, resulting in a reduction of total volume leading to associated subsidence. In other words, lowering of the pressure of water in voids (pores and fractures) in the coal seam and surrounding depressurised rock leads to compaction.

Currently the only publically available estimates of potential subsidence from CSG extraction in Australia relate to Queensland developments. Subsidence effects due to aquifer compaction have been predicted by proponents to be minor. Published estimates from CSG proponents of subsidence gradients across CSG extraction fields in south east Queensland range between 0.08-0.18m, with very small differential settlements. Surveying methods designed to monitor ground deformation associated with CSG extraction must therefore be able to measure to a high degree of vertical accuracy (1 – 2 cm) over very large areas (tens or hundreds of square kilometres) and for relatively long time frames of 10 or more years.

The most extensive subsidence-monitoring program in Australia is being carried out in Queensland, where four CSG companies have commissioned a regional satellite-based InSAR (Interferometric Synthetic Aperture Radar) study of historical and current earth surface movements. InSAR has previously been used in California to detect subsidence and rebound of as little as 25 mm associated with large-scale extraction and recharge of groundwater reserves for irrigation.

Knowledge gaps exist in the theoretical estimation of settlement because of uncertainty in the elastic modulus properties of the depressurised zone with coal measure sequences. Experience has shown that the theoretical estimates of total and differential settlement by various CSG proponents are very small.

Chapter 4 of this report includes a tabulated summary of satellite, surface and borehole techniques for monitoring surface deformation, including their accuracy, advantages, disadvantages, suitability for large areas and relative cost. Based on the need for extensive areal coverage and high vertical accuracy, the following techniques are considered most suitable:

Monitoring method. Synthetic Aperture Radar (SAR), supported by a ground Global Navigation Satellite Systems (GNSS) would enable the measurement of horizontal and vertical movement at discrete points to accuracies of 5mm and the measurement of vertical movements over broad areas (tens or hundreds of square kilometres) to accuracies in the order of 10mm at horizontal resolutions of 3m.

> **Stage 1** would be a baseline program of historical satellite data in areas of CSG activity over a time period of several years, assuming appropriate satellite data were available.

Stage 2 would be an on-going monitoring program throughout the life of the CSG production project and for a period of time after production has ceased.

Baseline monitoring. To monitor the effects of CSG production on surface deformation there is a need to measure the degree of subsidence and uplift that occurs over time due to natural processes such as seasonal rainfall and human activities such as groundwater extraction for urban water supply or agriculture. Initially a network of permanent survey marks (PSMs), surveyed using GNSS techniques, should be established to provide points of truth against which to check or calibrate InSAR data and to provide a known reference frame.   Regional monitoring could be achieved by completing an analysis of historical InSAR satellite data for a four-year period, e.g. 2007-2010 as is being done in Queensland. Investigations would need to be made to determine whether suitable InSAR data are available over proposed NSW CSG production areas. If not, an alternative option such as high-resolution SAR missions may need to be specifically tasked to acquired data. To ensure InSAR data are available for analysis it is essential to define potential CSG production areas and commission regular acquisition and analysis from a suitable supplier.

On-going monitoring. The initial baseline study should be followed up by on-going monitoring during CSG production and for several years after production has ceased. The GNSS network would need to be re-observed periodically (i.e. annually or more frequently) to calibrate and cross check against the InSAR data. The results from both the baseline and on-going monitoring would be presented as a series of average annual (baseline) and quarterly (on-going) deformation maps along with time series data for the period of the studies.

Glossary of Terms

ALOS	Advanced Land Observing Satellite, launched by the Japanese Aerospace Exploration Agency (JAXA) in January 2006.
AHD	Australian Height Datum. The datum used for the determination of elevation in Australia. The determination uses a national network of benchmarks and tide gauges and sets Mean Sea Level as zero elevation.
ALS	Airborne Laser Scanning. ALS includes a LiDAR system coupled with a survey grade GNSS receiver and an Inertial Measurement Unit (IMU).
Aquifer	A geological formation, group of formations, or bed that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.
Aquitard	A geological formation, group of formations or bed that retards but does not prevent the flow of water to or from adjacent aquifers. It does not readily yield water to wells or springs, but may serve as a storage unit for ground water.
AUSGeoid09	AUSGeoid09 is a 1' by 1' (approximately 1.8 km) grid of ellipsoid/geoid separation values produced by Geoscience Australia. It is used to convert heights between the ellipsoid (GDA94) and the Australian Height Datum (AHD). (See Brown *et al*, 2011)
Azimuth	The angle reckoned clockwise in a horizontal plane between the local meridian and that point.
BM	Benchmark, a term used to describe any item or feature used to mark a point as an elevation reference.
Bore / borehole	A hole sunk into the ground and completed for the extraction of water or other gas or liquid, or for observation of subsurface properties
Datum[1]	A datum is a reference from which measurements are made. A point, plane, or surface to which systems of measurement are referred or related to one another. Hence: 1. GEOCENTRIC DATUM A reference frame which has its origin as the Earth's centre of mass, which is directly related to the orbits of satellites. Positioning from these satellites is a critical element in modern surveying, mapping, geographic information systems, navigation, aviation, land and sea transport, emergency services, law enforcement and recreation. 2. GEODETIC DATUM The position of a reference spheroid as defined by the position of one selected station, usually near the centre of the survey area, known as the origin, and the azimuth from the origin to an adjoining station. 3. VERTICAL DATUM A reference surface to which elevations are referred, usually, but not always, mean sea level.
Ellipsoid	Mathematically-defined surface that approximates the geoid, the truer figure of the Earth. Sometimes referred to as a spheroid.
Extensometer	A stationary instrument set in a borehole that measures the compression within the borehole and hence gives a measure of subsidence over time at a single location.
Geoid[1]	The equipotential surface in the gravity field of the earth, which coincides, with the imaginary extension of mean sea level continuously through the continents. The direction of gravity (the plumbline) is perpendicular to the geoid at every point.

---

[1]Source: http://www.ga.gov.au/mapspecs/250k100k/appendix_l.html, Viewed 09 August, 2013.

GNSS	Global Navigation Satellite Systems. Collective description for all navigation satellite systems including GPS.
GPS	Global Positioning System. A constellation of US owned navigation satellites.
GRACE	The Gravity Recovery And Climate Experiment, a joint satellite mission of NASA and the German Aerospace Center, that has been making detailed measurements of Earth's gravity field since its launch in March 2002.
Groundwater[2]	Groundwater is the water located beneath the earth's surface in soil pore spaces and in the fractures of rock formations.
ICSM	Intergovernmental Committee on Surveying and Mapping.
InSAR	Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique using two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or elevation.
LiDAR	Light Detection and Ranging (LiDAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light.
MSL	Mean Sea Level. The mean level of the sea throughout a definite number of complete tidal cycles.
Orthometric	Orthometric height is, for practical purposes, "height above sea level". The current AHD datum is tied to MSL at thirty points around the Australian coast.
PSM	Permanent Survey Mark
Photogrammetry	The practice of determining the geometric properties of objects from photographic images.
Precise Levelling	A particularly accurate method of differential levelling that uses highly accurate levels and adopts a more rigorous observing procedure than general engineering levelling.
Radioactive Bullet Logging	A method to measure compaction and extension of a formation that involves shooting radioactive bullets into a formation at known depths and later surveying the bullets to monitor changes in depth.
RTK	Real Time Kinematic, used to describe a technique of GNSS surveying where observations are transmitted, in real time, from a stationary 'base' GNSS receiver to a roving 'Kinematic' GNSS receiver for immediate calculation of position.
Spheroid	Mathematically-defined surface that approximates the geoid, the truer figure of the Earth, sometimes referred to as an ellipsoid of revolution.
Subsidence	Usually refers to vertical displacement of a point, but the subsidence of the ground actually includes both vertical and horizontal displacements. Subsidence is usually expressed in units of millimetres (mm).
Tilt[3]	The change in slope of the ground as a result of differential subsidence, and is calculated as a change in subsidence between two points divided by the distance between those points. Tilt is therefore the first derivative of the subsidence profile. Tilt is usually expressed in units of millimetres per metre (mm/m). A tilt of 1mm/m is equivalent to a change in grade of 0.1%.

---

[2] Source: http://en.wikipedia.org/wiki/Groundwater, viewed August 9, 2013.
[3] Source: http://www.ukessays.com/essays/environmental-sciences/investigation-of-subsidence-in-the-hunter-region-environmental-sciences-essay.php, viewed August 9, 2013.

1. Introduction

1.1.   Objectives and context

The NSW Chief Scientist and Engineer was commissioned to undertake a review of coal seam gas (CSG) related activities in NSW. The Cooperative Research Centre for Spatial Information were requested to assist in the production of an information paper on subsidence monitoring, to inform and develop policy and to assist with public understanding.

The objective of this information paper is to provide a high-level review of the various methods used nationally and internationally to monitor land subsidence. The paper provides an analysis of the strengths and weaknesses of the various technologies and methods, particularly with respect to monitoring subsidence caused by CSG production. This information paper includes a brief review of measurement and recording of subsidence caused by CSG activities. It investigates the requirement and approach to developing baseline subsidence measurements to enable an understanding of ground motion caused by underlying natural and other manmade processes. This paper also attempts to identify uncertainties, unknowns or research gaps in relation to measuring and monitoring subsidence related to CSG activities.

1.2.   Scope of tasks

This report describes techniques that can be used to monitor subsidence over time.

The scope of tasks encompasses:

- Methods that can be used to measure and monitor subsidence, including land-based surveys, satellite and aerial monitoring and other techniques,
- The strengths and weaknesses of the various approaches, with international best practice,
- Baseline measurements,
- Examples of measurement of subsidence from CSG activities in Australia and overseas,
- Availability of on-line subsidence data in NSW regions with CSG activities and
- Knowledge gaps and uncertainties.

2. Overview of Subsidence Process

The process of CSG extraction involves the removal of groundwater from the coal seam to liberate methane and other gases that are tightly bound in the matrix of the coal that are of commercial CSG value. The groundwater is removed by a network of specifically designed CSG wells with their design largely dependent on the geological and hydrogeological conditions within each field. The groundwater targeted for extraction within the CSG field is confined to the coal measure rocks at typical depths of between the range of 300m to 1000m below the surface for most CSG fields in Australia.

Since extraction takes place at great depth, the groundwater is under pressure and the process of removal of groundwater from the coal measure rocks changes the overall pressure condition within the geological sequence. This pressure change is referred to as "depressurisation". The removal of groundwater which in-fills the pores and cracks (cleats) within the coal seams results in a reduction in the "buoyancy" and upward pressures in the coal measure rocks which was previously in equilibrium with the downward earth pressures from the weight of the overburden sequence of rock above and within the coal measures. Subsidence can thus occur due to the increase in vertical stress on the coal sequence rocks being depressurised.

Typical depressurisation in the CSG fields in Australia can be substantial. The hydrostatic pressure in the coal seams is required to be minimised to roughly 345kPa which correlates to a groundwater level 35m above the top of the coal seam as part of the depressurisation process (APLNG, undated, cited in Sydney Catchment Authority, 2012). Although depressurisation changes groundwater pressure within the coal measures the magnitudes of settlement in theory are small due to the very high elastic modulus properties (stiffness) of the coal measure rocks.

Currently the only publically available estimates of potential subsidence from CSG extraction in Australia relate to Queensland developments. Subsidence effects due to aquifer compaction have been predicted by proponents to be minor (Moran and Vink, 2010). Published estimates from CSG proponents of absolute subsidence across typical CSG fields in Australia are very small. These calculated settlements range between 0.08m to 0.18m within fields analysed for recent developments in S.E Queensland (QGC, 2012). Predicted compaction from these studies is similar to CSG studies in the western United States (Case, 2000). The resulting settlement (subsidence) gradients across CSG extraction fields are thus also inferred to be very small, and would generally not be expected to significantly impact on surface infrastructure. However potential impacts still need to be confirmed such as for transport infrastructure, streams, pipelines and irrigation lines and it is for this reason that subsidence monitoring is undertaken.

Current knowledge suggests subsidence induced by dewatering of coal seams is likely to be minor in comparison to long wall mining. However, small changes to surface topography could change overland flow patterns and in turn increase erosion (Moran and Vink, 2010).

The timeframe involved in pumping and associated depressurisation varies depending on the CSG field. Gas production typically becomes significant after a few months of pumping. The rate of depressurisation in the actual coal seam occurs over months to years. Furthermore the potential for depressurisation of the underlying and overlying units may take from years to tens of years. The overall process thus has implications on the time dependency of subsidence and the required period of monitoring.

3. Overview of subsidence monitoring techniques

The following section provides an overview of a range of monitoring techniques used internationally to measure and monitor surface deformation from subsurface mining and other causes.

Modelling of potential CSG subsidence in Australia indicates that the principle movement will be a change in height over a broad area caused by depressurisation of the coal seam, and any horizontal movement is likely to be negligible.

This paper describes a range of standard subsidence monitoring methods and approaches that provide a direct measure of surface deformation, as well as other technologies that measure observables that can be related, either directly or indirectly, to surface deformation. Some of the techniques discussed would require further research and development to confirm suitability for subsidence monitoring.

The techniques are broadly divided into three groups; surface techniques that involve measurement directly on the earth's surface, remote sensing techniques that involve measurement above the surface and borehole techniques that rely on measurements underneath the surface.

3.1.   Surface techniques

Land based survey techniques are typically used in combination with remote sensing or borehole techniques to provide points of truth against which to check or calibrate the observations and to provide a known reference frame (coordinate system or datum) for other datasets. Permanent Survey Marks (PSMs) are placed in positions where they are unlikely to be disturbed or damaged by processes other than those being monitored (e.g. damaged by a vehicle driving over it). The term Bench Mark (BM) is used to describe a PSM whose vertical position is known or monitored, but not its horizontal position, which is known to a lower level of accuracy. Once a network of PSMs has been established, surveyed and their positions determined they can be re-observed at a later date to determine the amount of movement, if any, that has occurred. Changes in position of PSMs provide a measure of movement at discrete locations across a study area.

PSMs are typically spaced at intervals across the study area, with higher density in areas of special significance. In some circumstances it can be an advantage to survey PSMs along an existing geophysical (seismic) section line, which allows evaluation of deformation against known geological structure data. For broad area deformation studies PSMs are often placed within road reserves or along existing tracks for ease of access. Some PSMs in the network should be located well outside the area subject to subsidence so that absolute positions, relative to a known datum, can be determined and maintained between surveys carried out at different times (epochs).

A number of land surface surveying techniques are available to accurately measure position and change in position over time. These include: precise levelling, high order traversing and Global Navigation Satellite Systems (GNSS) techniques.

In Australia the 'Standards and Practices for Control Surveys' are detailed in the Inter-governmental Committee on Surveying and Mapping (ICSM) publication of the same name, often referred to as 'SP1', sets out clear standards for accuracy for various control surveys. SP1 (ICSM, 2007) provides recommended survey and reduction practices for vertical and horizontal control surveys carried out using analogue or digital levels, electronic total stations (electronic theodolites

with built in electronic distance measurement) and survey grade Global Navigation Satellite System (GNSS) receivers. Within Australia, SP1 (ICSM, 2007) is the primary reference document used by surveyors to determine the most appropriate survey techniques and data reduction practices required to meet specified accuracy expectations for control surveys.

3.1.1. Precise Levelling

The height of PSMs can be most accurately determined by precise levelling. Precise levelling measures the differential elevation between sites and adopts a more rigorous observing procedure than general engineering levelling.

Using precise levelling techniques, accuracies in the order of 1mm over 1km can be achieved. Precise levelling is typically carried out using a digital level which electronically reads a bar-coded scale on the staff and includes data recording and reduction capabilities.

The procedure used for differential levelling is shown in Figure 1. The height difference between two points is measured, which enables the determination of the unknown height of one PSM from the known height of another. The diagram below illustrates the technique used to transfer a known height from point A to point B.

$$HI = Z_A + BS$$
$$Z_B = HI - FS$$
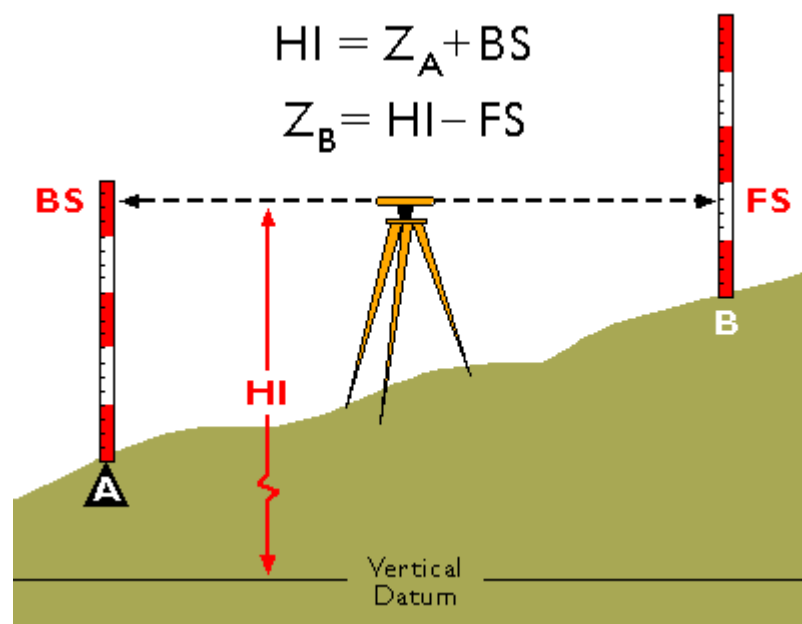
Figure 1: Differential levelling (Source: Wolf & Brinker cited in Pennsylvania State University 2013)

As described by the Pennsylvania State University (2013), a levelling instrument is positioned midway between a point at which the ground elevation is known (A) and a point whose elevation is to be determined (B). The height of the instrument above the datum elevation is HI. The surveyor first reads a backsight measurement (BS) off a levelling staff held over point A. The height of the instrument can be calculated as the sum of the known elevation at point A (ZA) and the backsight height (BS). The staff is then moved to point B. The surveyor rotates the telescope and then reads

a foresight (FS) off the staff at B. The elevation at B (ZB) can then be calculated as the difference between the height of the instrument (HI) and the foresight height (FS).

In precise levelling additional factors need to be considered including the curvature of the earth, which means that a line of sight that is horizontal at the instrument will become higher as distance increases. The line of sight from the instrument is also affected by refraction in the atmosphere which, due to the change of air pressure with elevation, causes the line of sight to bend downwards toward the earth. In precise levelling these errors can be eliminated or minimised by observing at certain times of the day, minimising sight distances, using equal forward and backsights and avoiding grazing rays close to the ground. The procedures required to achieve various orders of accuracy are clearly defined in SP1 (ICSM, 2007).

It should be noted that a properly set up level measures changes in height above the geoid (i.e. changes in height above mean sea level (MSL)) and not changes in height above the spheroid. Precise levelling therefore provides orthometric heights consistent with the Australian Height Datum (AHD), the standard height reference datum used in Australia.

Advantages

- Provides very precise height measurement at discrete points. Accuracies in the order of 1mm over 1km can be achieved.

Disadvantages

- Labour intensive, particularly over large areas or in steep terrain;
- Only provides heights at discrete points, interpolation required elsewhere.

3.1.2. Control Traverse

The vertical and horizontal coordinates of PSMs can be accurately determined by using a survey technique known as Traversing, which is used to establish survey control networks. Traversing can achieve accuracies in the order of 5-10mm over 1km. Traversing is typically carried out using Electronic Total Station instruments that enable multiple rounds of angles and distances to be observed and recorded without the need to manually point the instrument or record observations.

Traverse networks involve placing PSMs along a line or path of travel, and then measuring angles and distances between them to determine the location of the next PSM. As per Figure 2 below, positions are carried forward from the current traverse station (PSM) by measuring angles between the previous traverse station and following traverse station and by measuring the distances and vertical angles between adjacent traverse stations.
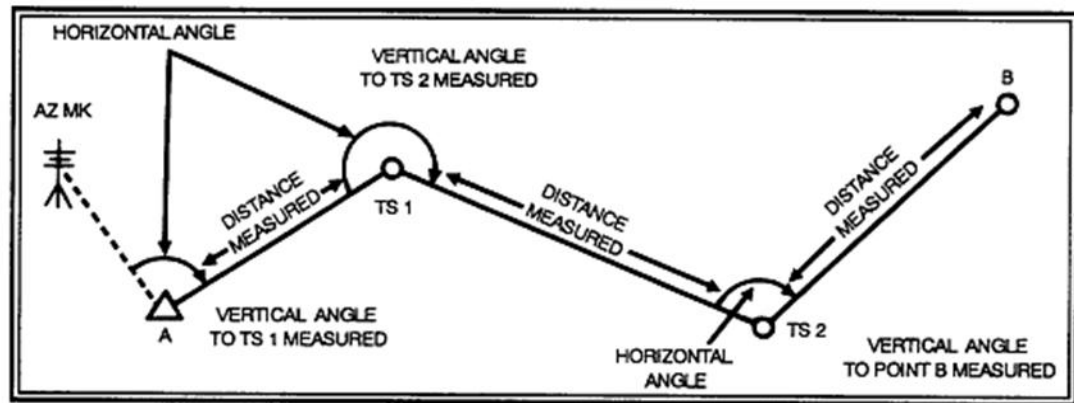
Figure 2: Principle measurements made in a Traverse (Source: Global Security, 2013)

Traverses start at a known point and require a known azimuth or direction to a second point. To avoid propagation errors, control traverses are closed against a known pair of PSMs to assure that observational errors are not carried forward. Closing the traverse enables quantification of any small errors in distances and angles that may accumulate throughout the traverse. If within allowable limits, the small errors are distributed throughout the traverse prior to reduction and calculation of positions for each of the traverse stations (PSMs).

It should be noted that a Total Station observes vertical angles from the zenith defined by a vertical plumb line. Therefore Traversing, as with Levelling, measures changes in height above the geoid and therefore provides orthometric heights consistent with the Australian Height Datum (AHD), the standard height reference datum used in Australia.

High-order traversing techniques include the use of 'constrained centring', observing reciprocal vertical angles and observing multiple distances and rounds of angles at each traverse station. As with Levelling, the procedures required for various accuracy expectations are clearly defined in SP1 (ICSM, 2007).

Advantages

- Provides very high quality horizontal and vertical measurement at discrete points. Can achieve accuracies in the order of 5-10mm over 1km

Disadvantages

- Labour intensive, particularly over very large areas
- Only provides position or change of position at discrete points, interpolation required elsewhere

3.1.3. GNSS techniques

GNSS is a generic term that refers to all global navigation satellite systems. The most widely known constellation of navigation satellites is the Global Positioning System (GPS), which refers specifically to the US navigation satellite system.

GNSS 'survey' receivers differ significantly from commercially available 'navigation' receivers. Navigation receivers (the type used for bushwalking, boating or in car navigation) rely on signals broadcast from GNSS satellites to calculate position to an absolute accuracy in the order of 5 to 10m. Encrypted satellite signals can be interpreted by military 'navigation' receivers to determine more accurate position fixes, but even these do not approach the accuracy expectations required for control surveys.

GNSS 'survey' receivers measure the difference in phase between one or more of the carrier waves transmitted by navigation satellites to derive very accurate three dimensional baselines or vectors between pairs of GNSS 'survey' receivers. Using these carrier wave measurements baselines between 'survey' receivers can be measured to accuracies in the order of 1 part per million (or 1mm over 1km).
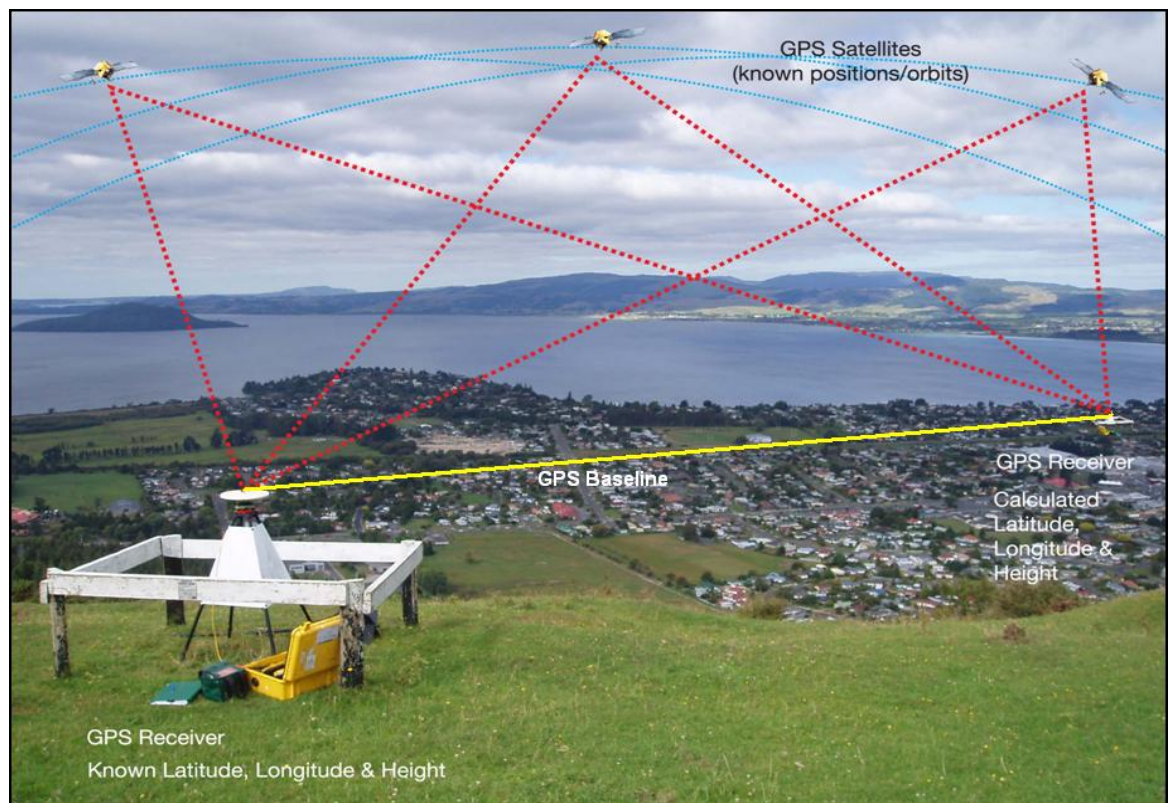

Figure 3: A pair of GPS 'Survey' receivers recording carrier phase measurements used to derive an accurate 'baseline' between the receivers (Source: ICSM, 2013)

A GNSS baseline is determined by using two survey grade GNSS receivers, one at each end of the line to be measured (Figure 3). They collect data from the same GNSS satellites at the same time. The duration of these simultaneous observations may vary with the length of the line and the accuracy required. The difference in position between the two points is calculated by comparing the data from both receivers. Many of the uncertainties of GNSS positioning, including satellite and receiver clock errors, signal delays caused by the atmosphere and uncertainties in satellite positions are cancelled out or minimised because they are common to observations at each end of the baseline (ICSM, 2013).

GNSS satellites orbit with an altitude of around 20,000 km, so the ends of the baseline can be a long way apart and still observe the same satellites. This means that baselines can be measured between points that are hundreds or thousands of km apart, without the need for inter-visibility between the points.

GNSS uses a geocentric reference frame as the basis for measurement and calculation. This reference frame measures heights differently to the Levelling and Traversing techniques discussed above. The reference frame used by GNSS consists of an ellipsoid (or spheroid), which models the size and shape of the earth. For GNSS the centre of the ellipsoid is coincident with the centre of mass of the earth, the point around which satellites orbit.
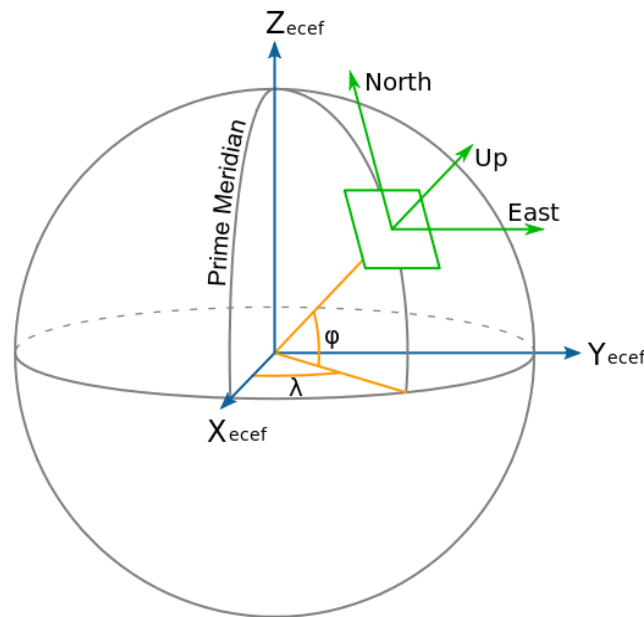
Figure 4: Reference system used in GNSS Surveying (Source: Wikipedia, 2010)

As per Figure 4 above, coordinates in this reference system can be expressed in Cartesian coordinates (X,Y,Z), geographical coordinates (latitude and longitude) or in a user defined map projection (E,N). GNSS baselines are typically described in terms of ΔX, ΔY and ΔZ.

In the case of geographic coordinates or map projection coordinates, heights are expressed as a height above or below the ellipsoid. Ellipsoid heights (heights above the ellipsoid) are not the same as orthometric heights (heights above the geoid or MSL which are determined by levelling or traversing). The difference between an ellipsoidal height and a MSL height (referred to as N) can be large (up to 100m) and irregular due to the varying density of the earth (Figure 5).
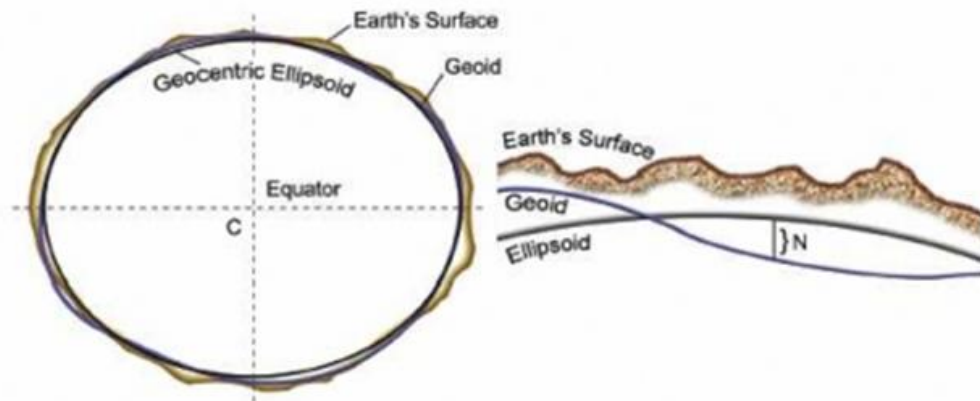
Figure 5: Relationship of the earth's surface, the geoid, and a geocentric ellipsoid. The height difference (N) between the geoid and the geocentric ellipsoid is the geoid separation (Source: Committee on Floodplain Mapping Technologies, National Research Council, 2007)

A model of the separation between the ellipsoid and the geoid is required to convert ellipsoid heights into geoid heights and vice versa. An ellipsoid/geoid separation model for Australia has been developed by Geoscience Australia (Brown *et al.*, 2011). This model, known as AUSGeoid09 is suitable for most control surveys. In some cases a more precise ellipsoid/geoid separation model may need to be developed. If heights in terms of AHD are required, all GNSS surveys will require direct connection to PSMs with known heights in terms AHD.

3.1.3.1.   GNSS network (Static network)

A single baseline from a known position is enough to give the position at the other end of the baseline, however additional GNSS baselines to other points are often measured to give a check on the results and an estimate of the uncertainty of the calculated position. A network of GNSS baselines provides the most accurate method of establishing and monitoring an array of PSMs across a broad area. A GNSS network can achieve accuracies of 1-3mm over areas of hundreds or thousands of square km.

An array of PSMs can be accurately positioned by measuring a network of GNSS baselines between them (Figure 6). A network of GNSS baselines can be adjusted using the method of 'least squares', which minimises the sum of the squares of all the small differences or errors in the baselines across the network. A network adjustment also provides statistics that describe how well the network of GNSS baselines fit together and how well they fit the known PSMs, as well as providing valuable information on the reliability, in terms of error ellipses, of the newly calculated coordinates of previously unknown PSMs.
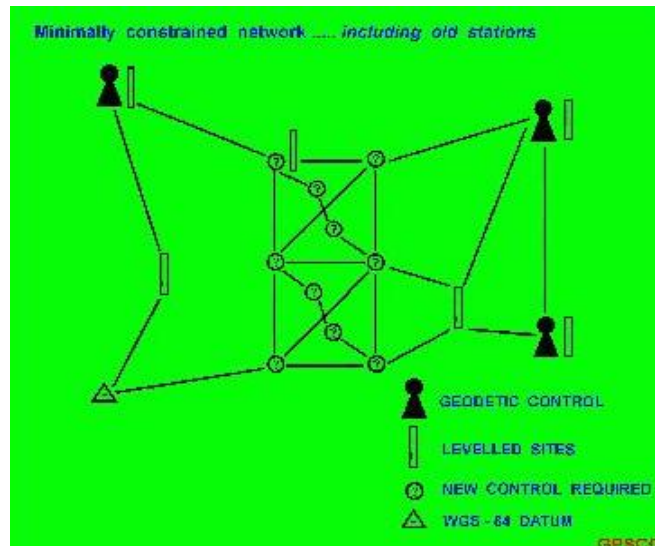
Figure 6: Typical GNSS survey control network (Source: UNSW School of Surveying and Geospatial Engineering, 2013)

As with other control survey techniques, the procedures required to be adopted in carrying out GNSS network surveys varies depending on the accuracy required. The PSM spacing, number of satellite carrier wave frequencies used, the observation time for each baseline, the number of repeat setups at each PSM and the differencing techniques used to calculate the baselines are all factors that determine the class of the survey and they are clearly defined in SP1 (ICSM, 2007).

Advantages

- Provides high accuracy horizontal and vertical measurement at discrete points. Baselines between 'survey' receivers can be measured to accuracies in the order of 1 part per million (or 1mm over 1km);
- More cost effective than levelling or traversing over large areas.

Disadvantages

- Only provides position at discrete points, interpolation required elsewhere.

3.1.3.2. Real Time Kinematic (RTK)

RTK surveying is similar to the GNSS baseline method, except that while one GNSS survey receiver remains stationary on a known PSM (Base Station), the other moves or roves between points and only needs to be stationary at each point for a few seconds. Coordinates derived from single RTK measurements are typically accurate to around +/-20mm.
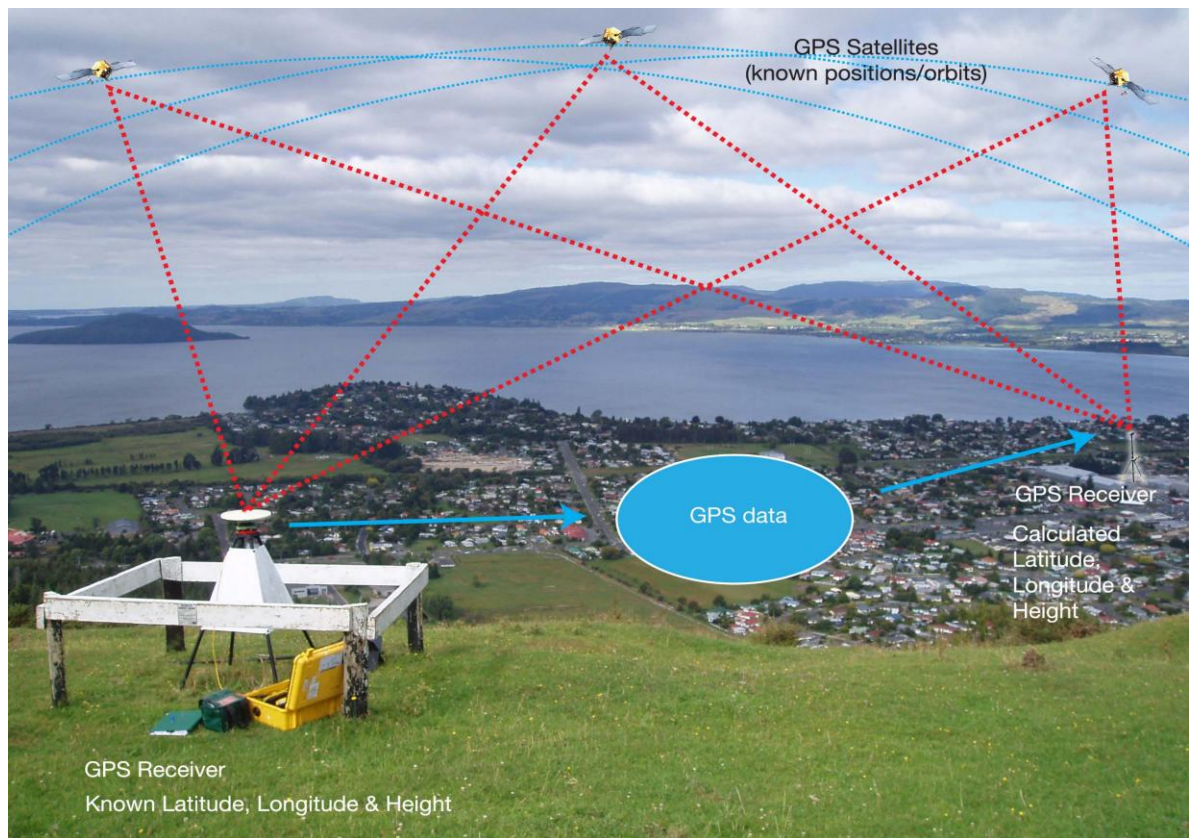
Figure 7: Example of a Real-Time Kinematic GNSS survey. A GPS 'survey' receiver at the Base Station transmits phase measurements in real time to the Rover 'survey' receiver to enable determination of the baseline and the calculation of the Rover's position (ICSM, 2013)

Phase measurement data collected by the Base Station receiver is transmitted via radio or mobile phone to the roving receiver where it is used to calculate the GNSS baseline between the Base Station and the Rover, whose position is computed and stored within a few seconds (Figure 7).

The accuracy of RTK techniques relies on the roving receiver maintaining a continuous lock on the GNSS satellite signals. If the roving receiver loses lock on the satellite signals for any reason (for example, by passing under trees) then the roving receiver will need to regain reception of the satellite signals and re-initialise at a known point.

Although RTK techniques can give similar baseline accuracy to the static baseline method, this method is generally limited to a distance of around 20 km. Unlike the static GNSS baseline network approach discussed above, which requires multiple baseline measurements to each PSM, the RTK approach uses only a single baseline to determine a PSM's position. In control surveys it is essential that multiple occupations of the unknown points be carried out using different Base Stations on each visit to verify the results. These and other RTK procedures for various classes of control survey are defined in SP1 (ICSM, 2007).
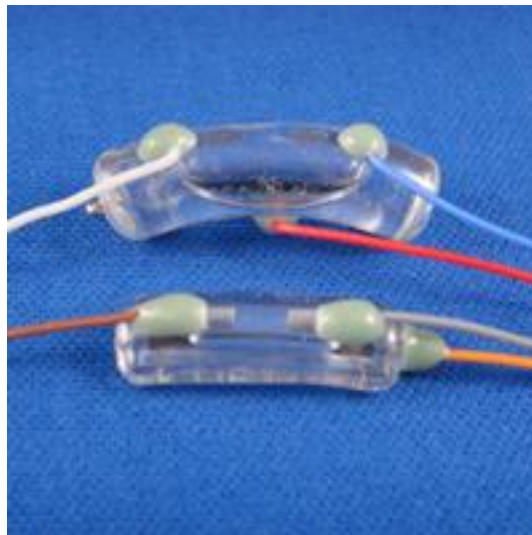
Advantages

- Provides high accuracy horizontal and vertical measurement at discrete points. Coordinates derived from single RTK measurements are typically accurate to around +/-20mm;

- Can be more cost effective than a GNSS network survey in clear areas within broadcast range of a base station.

Disadvantages

- Limited to approximately 20km from base station;

- Less accurate than GNSS baseline network survey;

- Only provides position at discrete points, interpolation required elsewhere;

- Impractical in some areas if roving receiver cannot maintain lock (e.g. due to heavy vegetation or tall buildings).

3.1.4. Tiltmeters

Tiltmeters are instruments that measure tilt, or change in angle from the horizontal. They are typically used to monitor ground motion caused by volcanoes, landslip or other movement or used in structures subject to loading or settlement. Early tiltmeters measured the deviation of a plumb line. Modern tiltmeters use an electrolytic tilt sensor which consists of a spirit bubble with electrodes that measure the position of the bubble within an electrolytic solution (see Figure 8). In conjunction with an appropriate recording device, tiltmeters can provide continuous monitoring at discrete points. Modern tiltmeters are very sensitive and can measure tilts to better than 1" of arc (1/3600 of a degree) which equates to less than 5mm over a distance of 1km (Spectron Glass and Electronics Incorporated 2013)

Figure 8: Modern electronic tiltmeters (Source: Spectron Glass and Electronics Incorporated, 2013)

Advantages

▪ Provide near-continuous tilt measurements at discrete points. Can measure tilts to better than 1" of arc (1/3600 of a degree) which equates to less than 5mm over a distance of 1km.

Disadvantages

▪ Provides change in tilt measurement only, does not provide a change in position.

3.1.5. Microgravity Survey

Gravity varies with the distance from the Earth's centre of mass and with changes in subsurface density. The distance of a point from the Earth's centre of mass can be directly related to its elevation, therefore microgravity measurements can be used to monitor changes in height (due to subsidence) and changes in surface density (due to fluid extraction). Gravity can be measured to an accuracy that equates to changes in height of around 1 to 2cm.

Undertaking a microgravity survey involves the collection of sensitive gravity measurements on the ground surface at discrete points. Changes in gravity are referred to as gravity anomalies and are normally interpreted to reveal subsurface variations in density (Telford *et al.*, and Seigel *et al.*, cited in Benson, *et al.*, 2003).

Microgravity surveys have been used for decades in oil and mineral exploration. Advances in microgravity equipment have improved the accuracy and efficiency of obtaining microgravity data and have extended the application of the method to geotechnical and environmental site characterisations (Kaufmann and Doll, cited in Benson *et al.*, 2003).

The United States Geological Survey (USGS) Arizona Water Science Centre has used microgravity for groundwater monitoring, as aquifer storage increases after heavy rain and decreases with groundwater pumping and natural discharge. Repeat microgravity measurements over time showing increases in gravity indicate an increase in groundwater storage due to the extra mass in the subsurface, whereas decreasing gravity over time indicates a decrease in storage. Gravity studies between 1999 and 2002 in the Tucson Valley in Arizona show the largest decrease in gravity in areas where local groundwater providers extract ground water and increase where water is actively recharged (O'Rear, 2011).

Microgravity surveys may be able to be used to monitor the effects of CSG production on the environment. Given that microgravity readings are linked to both height and ground water storage volumes and that reduction in ground water storage volumes is directly related to surface subsidence, it follows that gravity surveys may provide an alternative method to monitor subsidence and groundwater extraction.

The microgravity method could potentially be used to monitor CSG activities but would probably require further scientific investigation and detailed modelling to separate the effects of subsidence and water extraction.

Advantages

- Relatively easy to measure;

- Gravity can be measured to an accuracy that equates to changes in height of around 1 to 2cm.

Disadvantages

- Does not measure deformation directly;

- Responds to both subsidence and water extraction;

- Only provides measurements at discrete points, interpolation required elsewhere.

3.2. Remote sensing techniques

Remote sensing involves the acquisition of information using sensors mounted on a satellite or aircraft platform. Unlike ground surveys that are limited to monitoring specific locations that rely on interpolation of surface change in areas away from the monitoring points, remote sensing techniques can measure surface movement for specific locations and over broad areas.

Repeat surveys allow for the monitoring of changes in relative or absolute subsidence over time. Most remote sensing techniques rely to some extent on ground survey data to provide control or calibration of the data.

### 3.2.1. Interferometric Synthetic Aperture Radar (InSAR)

Interferometric synthetic aperture radar, abbreviated InSAR, is a satellite-based remote sensing technique that uses radar signals to measure changes in land surface elevation over time (Figure 9). InSAR has been demonstrated as a cost-effective solution to measuring land surface deformation on a regional scale with a high degree of spatial detail and resolution. In ideal measurement conditions InSAR can measure ground surface subsidence or uplift at the sub-centimetre level. The technique has been successfully demonstrated in Australia and internationally for monitoring: subsidence from underground long wall mining (Chang *et al.*, 2007a, 2007b); earthquake studies with a measurement capability of better than 3 mm (Cummins *et al*. 2008), and aquifer response to groundwater pumping (Amelung *et al.*, 2008).

Interferometry measures small differences in phase between the transmitted radar signal and the reflected radiation from the Earth's surface. The phase of the outgoing wave is compared to the phase of the return signal, which depends on the distance to the ground. This is observable as a phase difference or phase shift in the returning wave. Although the total distance to the satellite (i.e., the number of whole wavelengths) is not known to the same level of precision, the extra fraction of a wavelength can be measured extremely accurately (Figure 10) by calculating the relative distance changes between pixels over the imaged areas. By adopting reference pixels outside the area of deformation, or alternatively by using GPS for control, highly precise relative measurements of subsidence can be determined.
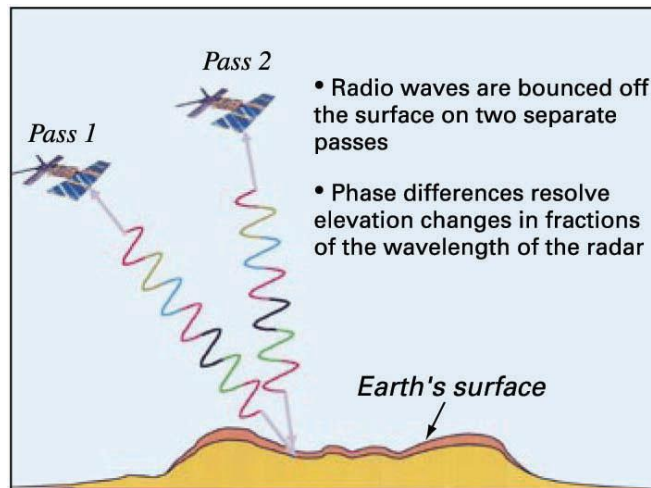
Figure 9: Diagram showing how radar interferometry detects subsidence of the Earth's surface. Both the distance between the satellite positions and the amount of subsidence (red layer) are exaggerated for clarity (Source: Helz, 2005)
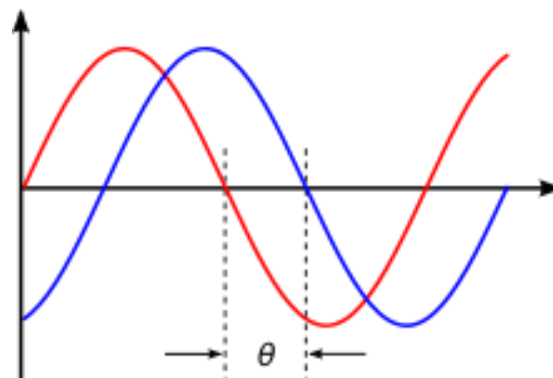

Figure 10: Basic principle of phase measurement (Source: Wikipedia, 2009)

Because conventional SAR satellites repeat the same ground tracks over time, interferometry can compare two images of the same area taken from the same position at different times. Slight differences in the path of the satellite, and changes in atmospheric conditions between each pass can be modelled and corrected. If the initial height of the topography is known, the total number of wavelengths can be calculated, and the deformation signal can be extracted. The difference in phase between images is displayed in an image known as an interferogram. Due to the cyclic nature of phase, the interferogram shows repeating fringes representing a multiple of wavelengths (Figure 11).

The basic observables of the SAR technique are the backscatter amplitude (or intensity), the signal travel time and coherent phase. The backscatter amplitude image obtained from SAR observations in many ways appears much like conventional optical imagery. The amplitude is a function of the

surface properties, including roughness, slope, and reflectivity. The travel time is a function of the sensor-to-target range and the phase of the return signal is a function of the surface properties and the sensor-to-target range (Elachi, 1988). Interferometric Synthetic Aperture Radar (InSAR) is an imaging technique which exploits the coherent radar signals in SAR data so as to make precise measurements of the geometry of the imaged surface and its change with time.

In general, the coherent (phase) component of an InSAR image contains information regarding: the change of the range from the sensor to the target between images, which can include surface deformation, earth curvature and surface topography effects; atmospheric effects; and observation noise resulting from, for example, changes in the surface scattering behaviour between acquisitions.
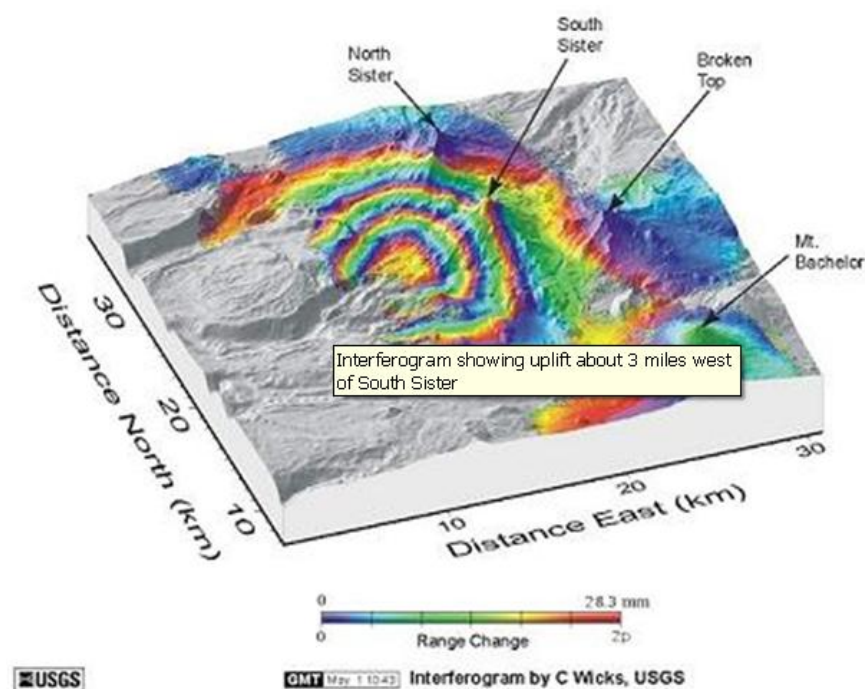
Figure 11: Interferogram showing repeated fringes caused by an uplift of the Earth's surface (Source: USGS, 2013)

InSAR has been widely used for the construction of digital elevation models (e.g. Madsen *et al.*, 1993) and the detection of small deformations of the Earth's surface since the first observations of the co-seismic deformation associated with the 1992 Landers, California, earthquake (Massonnet *et al.*, 1993). Geophysical applications to measure surface deformation using satellite-based InSAR observations have become increasingly common. InSAR research has focused on surface deformation due to natural processes, such as earthquakes (e.g., Simons *et al.*, 2002; Massonnet *et al.*, 1996), volcanoes (e.g., Amelung and Day, 2002; Dzurisin, 2003; Lanari *et al.*, 2002; Massonnet and Feigl, 1998; Pritchard and Simons, 2002, 2004); landslides (e.g., Catani *et al.*, 2005); and glacier motion (e.g., Pritchard *et al.*, 2005; Bamber *et al.*, 2000); together with

anthropogenic processes, such as subsidence caused by groundwater extraction (e.g., Bawden *et al.*, 2001; Hoffmann *et al.*, 2001) and mining activity (e.g., Raucoules *et al.*, 2003).

Limitations of the InSAR technique associated with decorrelation and un-modelled atmospheric signal can be in part mitigated by temporal analysis techniques where many SAR acquisitions are combined in a single analysis. There are many published temporal analysis techniques including simple image stacking, persistent scatterers InSAR, and the Small BAseline Subset (SBAS) techniques.

High resolution InSAR satellites need to be specifically tasked to acquire data over an area of interest. Other InSAR satellites, like the now inoperable ALOS satellite, have generated an archive of data over broad areas. Access to archived InSAR data provides the opportunity to map deformation over areas of interest for a period time prior to CSG production, thus providing the opportunity to assess deformation caused by natural and manmade causes other than CSG production. More detailed on-going monitoring can then be carried through the acquisition and analysis of high resolution InSAR data specifically tasked to cover the area of interest.

Advantages

- Provide broad area measurement at horizontal resolutions of 2m to 100m depending on the sensor system used;
- Provide the opportunity to model ground deformation over a period prior to CSG production;
- Under favourable conditions, accuracies of 5mm to 10mm are possible in the line of sight of the radar;
- Cost effective for measuring subsidence on a regional scale (Galloway 2000);
- Can acquire InSAR data through clouds in the sky.

Disadvantages

- Accuracy is dependent on vegetation, topography, the sensor, image processing methods and the atmospheric conditions when the measurements were acquired (Amelung *et al.*, 2006);
- More effective for determining subsidence in urban than rural areas;
- Measures change in height between epochs, needs ground control to determine absolute heights.

3.2.2. Stereo photogrammetry

Photogrammetry is the practice of determining the geometric properties of objects from photographic images. Photogrammetry is a passive form of remote sensing and relies on the ambient visible or infrared light reflected from the surface. Unlike InSAR, aerial photography relies on a clear view of the ground and cannot be acquired through cloud.

Satellite imagery would not provide the resolution or accuracy required for the measurement of the relatively small levels of deformation expected from CSG production. Photogrammetric techniques using high resolution, large scale photography enables absolute accuracies in the order of +/- 50mm to be achieved for points on clear, well defined features.

Vertical aerial imagery is typically acquired by a series of overlapping perspective centred images or an image strip using a push-broom sensor which acquires multiple view angles in a single pass. Both provide stereo coverage but with differing effects on the perspective of the imagery (Figure 12).

Digital photography has now almost completely replaced film photography. The terms 'digital' and 'softcopy' photogrammetry are interchangeable and refer to any photogrammetric operation involving the use of a digital raster photographic image data rather than hardcopy film based photographs.

Stereo photogrammetry involves calculating the three-dimensional coordinates of an object visible in overlapping images (referred to as a stereo model). In stereo photogrammetry common points are identified on each of the overlapping images forming the stereo model. Lines of sight (or rays) can be constructed from the camera locations to each object. It is the intersection of these rays (triangulation) that determines the three-dimensional location of the objects. Perspective centre imagery enables more accurate measurement than push-broom imagery.
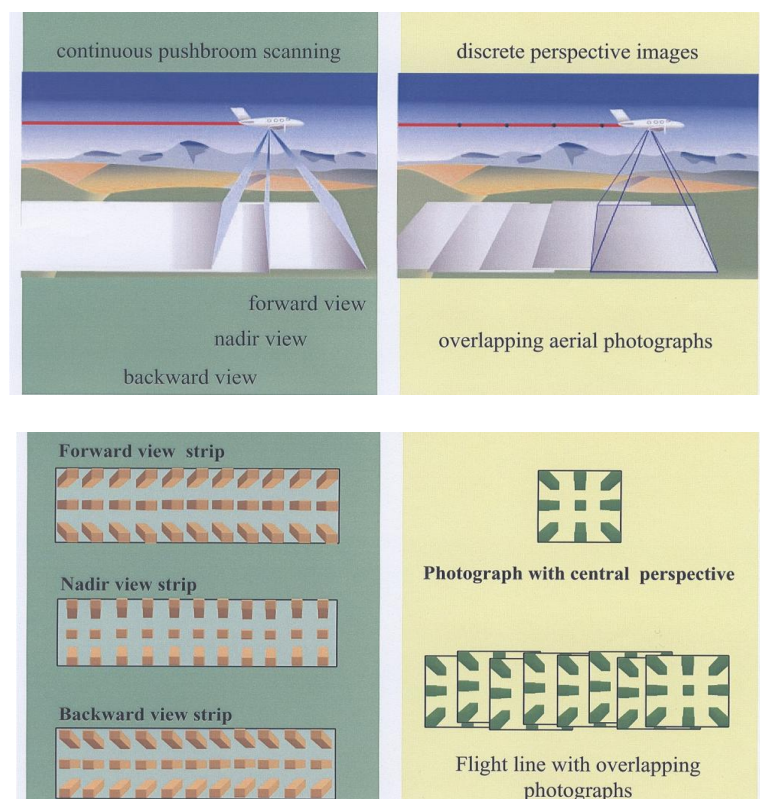
Figure 12: Difference between perspective centre and push-broom sensors (Source: Leica, 2008)

The term 'inner orientation' defines the geometric parameters of the camera itself. This consists of the image coordinate reference system (in pixels), the focal length of the lens and also includes the radial distortions of the lens. The term 'exterior orientation' of a camera defines the images location in space and its view orientation. The exterior orientation can be determined using surveyed

ground coordinates of features visible in the imagery, known as Ground Control Points (GCPs). Once the 'interior' and 'exterior' orientations are known for both images, forming a stereo model, the positions of all other features in the model can be determined and measured in real world coordinates.

Various methods have been devised to eliminate or reduce the requirement for GCPs in every model. These include using common image tie points to determine the relative orientation of multiple models within a block of images. A process called aero-triangulation uses this approach to significantly reduce the number of GCPs required. The use of inertial measurement systems on board the aircraft reduces the requirement for ground control still further.

The accuracy of photogrammetry is determined by the resolution and focal length of the camera system, the flying height and methods used. High resolution photography acquired at low level provides the highest accuracy but the trade-off is cost because the lower the photography is flown the more frames are required to cover a given area.

Advantages

- Provides broad area measurement;
- Using low level photography vertical accuracies in the order of 50mm are possible.

Disadvantages

- High accuracy photogrammetry is not cost effective over very large areas.

3.2.3. Airborne LiDAR

Light Detection and Ranging (LiDAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light. The term airborne LiDAR involves using a LiDAR system in a moving aircraft and is often referred to as Airborne Laser Scanning (ALS). ALS has become a technology of choice for the acquisition of digital terrain or surface data over broad areas. LiDAR surveys can achieve a vertical accuracy of around 10 to 15cm following Australian LiDAR Acquisition Standards published by ICSM (2011).

ALS incorporates a LiDAR system with a survey grade GNSS receiver and an Inertial Measurement Unit (IMU), which determines the absolute position and orientation of the sensor, and a computer to control the system and store data. The laser scanner uses an oscillating mirror or rotating prism, so that the light pulses sweep across a swath of landscape below the aircraft (Figure 13). Large areas are surveyed with a series of overlapping parallel flight lines. The laser pulses used are eye safe and flights can be carried out day or night, as long as the skies are clear.

LiDAR systems can measure over 100,000 pulses every second and have the capability of measuring multiple points per square metre on the ground (typically between 1 and 40). The laser footprint varies from around 10cm up to 1m. The footprint size and the number of points measured per square metre are a function of the LiDAR system used, the flying height and speed of the aircraft.

Individual LiDAR distance measurements are very accurate however ALS is limited by the system's ability to determine the absolute position and orientation of the sensor at the time each pulse is emitted (Figure 14). As a result, although the relative accuracy of sequential LiDAR point measurements is in the order of a few millimetres the absolute accuracy is limited to around 10 to 15cm. Horizontal accuracy is typically three times the vertical accuracy (i.e. 30-45cm).
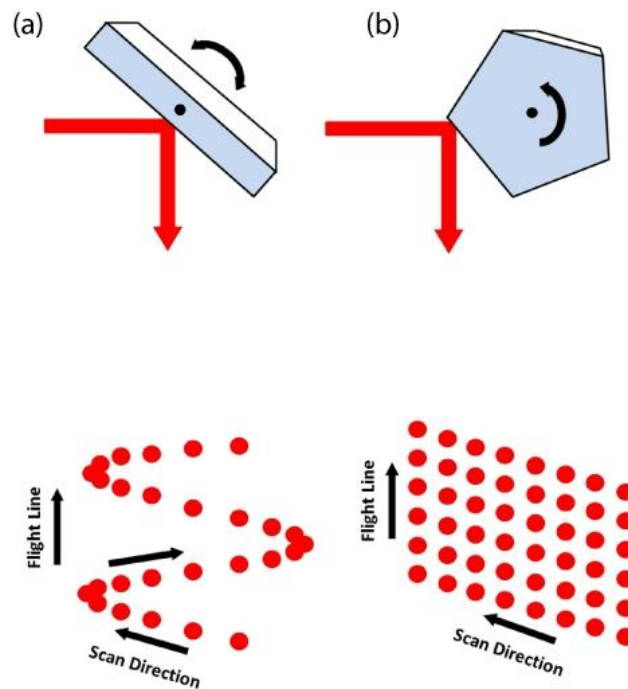

Figure 13: Typical LiDAR systems (a) Oscillating scanning mirror, (b) rotating polygon scanning mirror (Source: IOP Science, 2013)
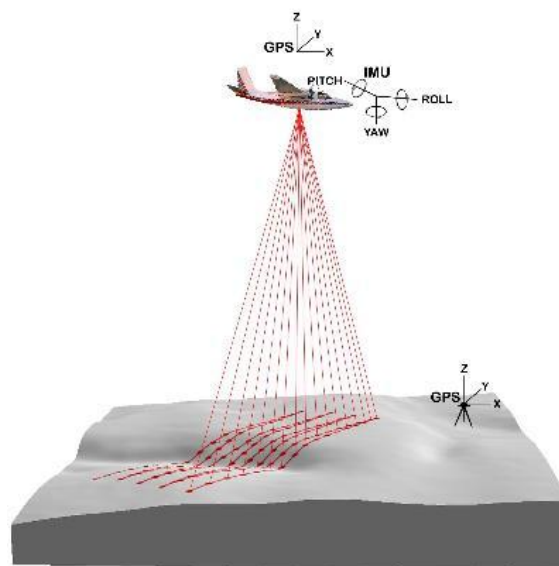
Figure 14: LiDAR is limited by the need to accurately measure the position and orientation of the LiDAR system at the time of measurement (Source: GIS Development, 2013)

When modelling the terrain it is important to filter or classify point cloud data collected by ALS into 'ground' and 'non-ground' returns. ICSM have developed a standard LiDAR point cloud classification coding system that defines specific codes for specific feature types (eg, ground, buildings, low, medium and high vegetation, etc.). They have also developed a system that defines how well the classification process has been carried out (ICSM, 2011).

For many applications the quality of the point classification or filtering process is just as important as the fundamental horizontal and vertical accuracy of LiDAR data itself. For example, poorly filtered or classified LiDAR point cloud data can lead to a large number of 'non-ground' points in a ground elevation model that purports to represent the ground. Figure 15 below shows a LiDAR derived ground surface model clearly showing the effects of ground subsidence caused by long wall mining.
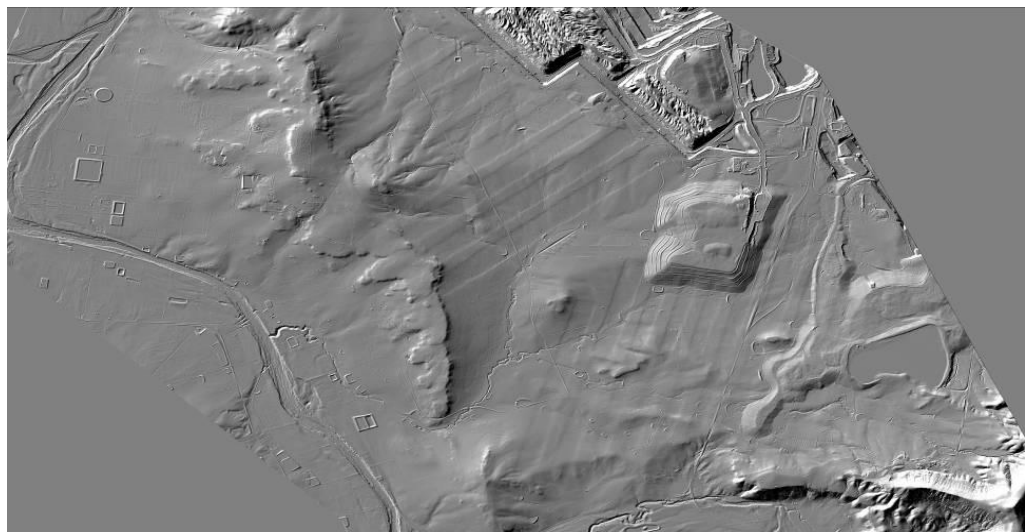
Figure 15: LiDAR derived ground surface model clearly showing the surface deformation effects from long wall mining (Source: Terranean Mapping Technologies, 2008)

Like any airborne survey, the first square kilometre is expensive, owing to the mobilisation costs of the aircraft, equipment, and personnel. However, the cost drops significantly as the area increases. The technology is commercially available through a number of contractors in Australia and world-wide (University of Washington 2006).

Advantages

- Provides broad area measurement with absolute vertical accuracy of 10-15cm;
- Very cost effective over large areas.

Disadvantages

- Vertical accuracy of 10cm may not be high enough to monitor predicted subsidence from CSG production;
- Significantly affected by ground cover which can vary between surveys.

3.2.4. Gravity Recovery and Climate Change Experiment (GRACE)

The GRACE satellite system maps the earth's gravity field by making accurate measurements of the distance between the two satellites using GPS and a microwave ranging system. GRACE has been used to map the Earth's gravity field with unprecedented accuracy, yielding crucial information about the distribution and flow of mass within the Earth and its surroundings and improving the understanding about the Earth's natural systems (NASA 2013).

Gravity changes as a response to the changes in mass of water on or beneath the surface. Satellite mapping of gravity using GRACE, along with measurements on the ground, could help us understand more about the effects of water movement caused by CSG production and could be linked to land subsidence. The use of gravity data collected from GRACE, together with ground data associated with CSG activities could be the subject of further scientific investigation to determine if GRACE gravity data can be used to monitor the effects of CSG production on the environment.

Advantages

■ Can detect changes in the Earth's gravity over time over large areas.

Disadvantages

■ Changes in the Earth's gravity can be caused by both subsidence and water withdrawal;
■ Does not measure deformation directly;
■ May not have a direct, observable link to deformation.

3.3. Borehole techniques

There are a number of monitoring techniques which measure the compression or expansion of material through which a borehole has been drilled. These systems measure the change in distance over time from the bottom to the top of the borehole or from a number of locations within the borehole.

3.3.1. Extensometer

A borehole extensometer measures the changes in longitudinal displacement over time along the length of a borehole. Borehole extensometers typically consist of a vertical borehole lined with a tube around 10cm in diameter. A wire or thin rod, anchored at the base of the borehole, passes through the tube to the surface. Changes in surface height relative to the base of the borehole can be measured as a change in the length of the wire or rod. These changes are typically recorded by a measuring device on the surface. Extensometers have been used to measure the deformation between bottom of a borehole and surface with a vertical accuracy of 3mm (Reed and Yuill, 2009).

Extensometers allow the detailed measurement of subsidence at a specific location. With a suitable recording device the measurements can be continuous throughout the period of instrumentation.

Multiple extensometers are required to monitor the cumulative impacts from multiple pumping bores over a broad area.

Advantages

- Subsidence measurements can be made at a specific location to an accuracy of around 3mm;
- Extensometers can measure continuously throughout the period of instrumentation.

Disadvantages

- Multiple extensometers are required to measure subsidence over broad areas;
- Extensometers only measure deformation between the bottom and the top of the borehole.

3.3.2. Radioactive bullet logging

Radioactive bullet logging involves shooting radioactive bullets into the walls of boreholes. Each bullet contains a long lived, but low strength, radioactive source. The relative depths of the radioactive bullets are later measured using a gamma ray probe which is lowered down the borehole.

Measurement error is in the order of 1cm over 100m. Logging time of around one hour for each 20 m of borehole is required for measurements (Poland *et al.*, 1984).

Advantages

- Subsidence measurements can be achieved for a point source of subsidence, such as near a pumping bore to an accuracy of around 1cm over 100m;.
- Can measure differential compression throughout the borehole

Disadvantages

- Logging can be time consuming
- Accuracy limitations may not detect predicted levels of subsidence from CSG production

3.3.3. Casing-collar logging

Similar to radioactive bullet logging but uses magnetic collars anchored to the geological strata within the borehole. The positions of the collars are later resurveyed by a magnetic detector passed down the borehole, and any change in position is used to measure compaction or expansion.

Advantages

- Subsidence measurements can be achieved for a point source of subsidence, such as near a pumping bore.

- Can measure differential compression throughout the borehole

Disadvantages

- Logging can be time consuming
- Accuracy limitations my not detect predicted levels of subsidence from CSG production.

4. Comparative analysis of monitoring options

A comparative analysis of the various deformation monitoring options discussed in the previous section has been carried out with particular consideration to their suitability to monitoring the levels of subsidence likely to be associated with CSG production.

Current published estimates of potential subsidence gradients across Australian CSG extraction fields range from 0.08-0.18m (QGC, 2012). While this is significantly less than subsidence induced by long wall mining (Sydney Catchment Authority, 2012), CSG fields may cover the entire aerial extent of an underground coal seam and hence may extend over hundreds (or thousands) of square kilometres. The subsidence from CSG production maybe small enough to fall within the natural variability of landscape processes, but local effects may arise if depressurisation of aquifers causes some dewatering of unconsolidated alluvial deposits at the surface.

Techniques suitable for monitoring deformation from CSG therefore must be capable of measuring small changes in height, in the order 1-2cm, over very large areas (hundreds to thousands of square kilometres) and over relatively long time frames of 10 or more years.

The assessment approach includes, for each option, a review of:

- the measurement observable (e.g. change in height, position, tilt, gravity, etc),
- the accuracy of the measurement observable,
- the advantage and disadvantages of the technique and
- a relative comparison of the
    - accuracy,
    - suitability for monitoring large areas,
    - relative cost and
    - overall suitability for monitoring deformation from CSG production.

4.1. Surface measurement techniques

Monitoring technique	Measurement Observable	Measurement Accuracy	Advantages	Disadvantages	Accuracy Achievable	Suitability for Large Areas	Relative cost	Overall suitability	Comments
Precise Levelling	Measures the height difference between two PSMs. Enables the height of PSMs to be determined	Height differences of 1mm can be determined over distances of 1000m	▪ Provides very precise height measurement at discrete points	▪ Very tedious and time consuming over long distances or over steep terrain ▪ Only provides height at discrete points, interpolation required elsewhere.	Very High	Low	High	Medium-Low	Not as efficient as GNSS network
Control Traverse	Measures the distances and angles between PSMs Enables the position and height of PSMs to be determined	Position and height differences of 5-10mm can be determined over distances of 1000m	▪ Provides high quality horizontal and vertical measurement at discrete points	▪ Labour intensive, particularly over very large areas. ▪ Only provides height & position at discrete points, interpolation required elsewhere	High	Medium	Medium	Medium	Not as efficient as GNSS network
GNSS Baseline Network	Measures GNSS baselines or vectors between PSMs. Network of baselines adjusted by least squares Enables the position and height of PSMs to be accurately determined	Individual baselines can be measured to an accuracy of 1 parts per million. Height and positions of PSMs within the network can be determined to better than 10mm over very large distances	▪ Provides high accuracy horizontal and vertical measurement at discrete points ▪ More cost effective than levelling or traversing over large areas	▪ Only provides height & position at discrete points, interpolation required elsewhere	High	High	Low	**High**	Most efficient methodology to establish and monitor control over large areas. Use in combination with InSAR.
Real-time Kinematic	Measures GNSS baselines or vectors between PSMs. Enables the position and height of PSMs to be accurately determined	Individual baselines can be measured to an accuracy of 1 or 2 part per million. Height and positions of PSMs within the network can be determined to around 20mm	▪ Provides high accuracy horizontal and vertical measurement at discrete points ▪ More cost effective than or levelling traversing over large areas	▪ Limited to around 20km from base station ▪ Only provides height & position at discrete points, interpolation required elsewhere	Medium-High	Medium-Low	Low	Medium	Not the best approach over very large areas
Tiltmeter	Measure change in tilt at discrete locations	Changes in tilt can be measured to 1" of arc (equivalent to 5mm over 1000m)	▪ Provide near continuous tilt logging at discrete points	▪ Only measures tilt ▪ Only provides measurement at discrete points, interpolation required elsewhere	Medium	Medium	Medium	Medium	Tilts caused by CSG production unlikely to be significant
Microgravity	Absolute or differential microgravity measurement at discrete locations	Accuracy of raw gravity measurement is very high (~10microgal). Sensitive to changes in elevation as well as sub surface density in repeated surveys. Resolution of elevation is around 1cm.	▪ Relatively easy to measure	▪ Sensitive to both changes in elevation due to subsidence plus changes in subsurface density due to water extraction ▪ Only provides measurement at discrete points, interpolation required elsewhere	Medium	High	Medium	Low-medium	Has been used in oil production in North America to track water incursion into oil reservoirs.

4.2. Remote sensing techniques

Monitoring technique	Measurement Observable	Accuracy	Advantages	Disadvantages	Accuracy Achievable	Suitability for Large Areas	Relative Cost	Overall Suitability	Comments
InSAR	Measures a grid of pixels over a large area. Pixel ground sample distances can be between 10m and 100m depending on the satellite used. Pixel values represent the change in height between measurements	Changes in height in the order of 5-10mm are measureable over very large areas	▪ Provides broad area measurement ▪ Archival InSAR data provides the opportunity to model ground deformation over a period prior to CSG production ▪ Under favourable conditions, accuracies of 5mm to 10mm is possible in the line of sight of the radar ▪ Cost effective for measuring subsidence on a regional scale ▪ Can acquire InSAR data through cloud ▪ Most effective in urban areas	▪ Accuracy is dependent on the sensor, image processing methods and the atmospheric conditions when the measurements were acquired ▪ More effective for determining subsidence in urban than rural areas. ▪ Measures change in height between epochs, needs ground control to determine absolute heights ▪ Can be effected by change in ground cover between observations	High	High	Low	**High**	Best to measure small changes in elevation of large areas. Greatest efficacy in urban environments, so early warning indicators should be feasible.
Photogrammetry	Measures a grid of pixels or predefined points over a large area. Any ground sample distance can be used. Observation values represent the position and height of the ground	Accuracies of 50mm can be achieved on clear ground	▪ Provides measurement over a broad area	▪ High accuracy photogrammetry not cost effective over very large areas ▪ Highest accuracy achievable at limit of modelled subsidence range expected from CSG production	Low	Medium	High	Low	Accuracy limitation and cost make this option unsuitable for very large areas
Airborne Laser Scanning (ALS)	Measures random ground points over a large area. Density of points can vary from 1 to 40 points per square metre. Observation values represent the position and height of the ground.	Accuracies of 100mm can be achieved on clear ground	▪ Provides measurement over a broad area	▪ Highest accuracy achievable beyond the limit of modelled subsidence range expected from CSG production	Low	High	Low	Low	Accuracy limitation make this option unsuitable for very large areas
Satellite GRACE	Experimental pair of satellites that continue to develop a detailed gravity model of the Earth. GRACE can detect changes in the Earth's gravity model caused by the movement of ground water.	The Earth's gravity models being produced by GRACE are orders magnitude better that earlier gravity models. How these new gravity models can be used to interpret changes in ground water or other subsurface density and how these changes effect surface subsidence is yet to be determined	▪ Can detect changes in the Earth's gravity over time	▪ Changes in the Earth's gravity model can have many causes unrelated to CSG production ▪ Does not measure deformation directly ▪ May not have a direct link to deformation	Low	Medium	Low	Low	May be of interest as a research project but unlikely to provide useful information related to measuring and monitoring deformation

4.3. Borehole techniques

Monitoring technique	Measurement Observable	Accuracy	Advantages	Disadvantages	Accuracy Achievable	Suitability for Large Areas	Relative Cost	Overall Suitability	Comments
Extensometer	Direct measurement of deformation by monitoring the difference in height from the bottom of a borehole to the surface.	1-3mm over the depth of the borehole.	▪ Extensometers can continually measure and log subsidence	▪ Expensive to install ▪ Only measure deformation between the bottom and the top of the borehole ▪ Only provides measurement at discrete points, interpolation required elsewhere	High	Low-Medium	High	Low-Medium	May be useful in helping develop a greater understanding of how to model CSG subsidence
Radioactive Bullet logging	Indirect measurement of column deformation by monitoring the difference in height from the surface to radioactive bullets fired into the formation at known depths.	Around 1cm over 100m	▪ Can measure differential subsidence throughout the length of the borehole	▪ Expensive to install ▪ Only provides measurement at discrete points, interpolation	Medium	Low	High	Low	May have some relevance in helping develop a greater understanding of how to model CSG subsidence
Casing collar logging	Indirect measurement of column deformation by monitoring the difference in height from the surface to magnetic casing collars in the borehole	Around 30mm between collars	▪ Can measure differential subsidence throughout the length of the borehole	▪ Expensive to install ▪ Only provides measurement at discrete points, interpolation required elsewhere	Low	Low	High	Low	Limited accuracy

5. Review of CSG monitoring activities

5.1.   National CSG Monitoring Activities

Due to only the recent emergence of the industry, there are no long baseline studies, however, there are currently four CSG proponents in Queensland collaborating to commission a regional InSAR study of historical and current earth surface movements, to provide certainty for regulatory and public concerns (Dawson *et al.*, 2011).

The Queensland Government has recently installed a bore line in the Condamine Alluvium that will be used to monitor subsidence on a transect across the alluvium on an on-going basis (Moran and Vink 2010).

The Federal Government, through Geoscience Australia has started to establish the Australian Geophysical Observing Network (AGON). AGON infrastructure will include a network of radar corner reflectors (clearly visible in InSAR images) and a geodetic network for monitoring ground deformation in Australia (Dawson *et al.*, 2011).

The geodetic network of PSMs will be coordinated and monitored using a GNSS network. The radar corner cube reflectors placed in the Surat Basin in Queensland will be linked into the GNSS network to provide a direct link between InSAR measurements and the GNSS network. This combination of precise remote sensing and targeted ground measurements represent the current best practice to determine the impacts of CSG extraction on land subsidence (Dawson *et al.*, 2011).

Limited numerical modelling of the potential maximum subsidence across CSG fields suggests that the settlement rates may be within the range of natural variations in surface material changes caused by natural fluctuations in groundwater. However a limitation of the theoretical estimation of settlement is the lack of information on actual storativity and specific yield characteristics and variability across coal basins. With only recent development of significant CSG activities in Australia, there is currently little measured data to evaluate evidence of subsidence and hence the actual consequences of CSG extraction on surface impacts such as stream flows or impacts on surface infrastructure. This is currently the major knowledge gap.

Primary subsidence issues remain associated with shallow groundwater extraction in largely unconsolidated and clay-rich sediments. There may be a concern in Australia in areas where shallow coal seam targets immediately underlie the alluvial systems, such as the Condamine Alluvium in Queensland and the Namoi valley in northern NSW. In this situation, propagation of dewatering effects may lead to partial dewatering of these surface alluvial aquifers potentially causing additional settlement at the surface. Ross and Jeffery (1991) reported a maximum subsidence of 210mm from 1981 to 1990 near Wee Waa in the Lower Namoi Valley due to groundwater extraction for irrigation purposes.

Although there is a long history of development of empirical equations applicable for underground coal mining operations that allow forward predictions of potential settlement effects, there is as yet insufficient empirical information in the CSG industry to develop similar relationships. A coordinated, combined research effort is required to gather such information.

5.2. International CSG Monitoring Activities

While InSAR has been used internationally to effectively measure and assess the magnitude of human-induced subsidence, a search of the literature found the most relevant published examples of its use are limited to the United States. GNSS and InSAR have been used to detect and measure subsidence in the Coachella Valley, California, between 1996 and 1998. The study outcomes showed that InSAR can produced detailed data over large areas and that it is particularly useful in detecting vertical land-surface changes outside the extents of the GNSS network. The detailed spatial resolution of InSAR data also enabled the generation of maps which complemented the coarse spatial resolution of the GNSS network (Amelung *et al.*, 2005).

A follow-on investigation for this same region from 1998-2000 highlighted that InSAR was more useful for determining land-surface changes in urban areas than were the GNSS measurements, and that the GNSS measurements were more useful for determining changes in agricultural areas. Several locations had both GNSS and InSAR measurements and these agreed reasonably well. The study also showed the localised character of the deformation was typical of the type of subsidence characteristically caused by localised pumping; however, the subsidence may also be related to tectonic activity in the valley (Amelung *et al.*, 2005).

InSAR was also used to map regional-scale subsidence caused by aquifer-system compaction in the Antelope Valley, California. In the period from 1993 to 1995 a correlation between the regions of maximum subsidence and declining water levels was observed. In another area within the same valley, approximately 25 mm of additional subsidence was measured, even though groundwater levels had been recovering since 1990, indicating a delay in the effects of groundwater pumping induced subsidence due to the presence of thick aquitards (Galloway *et al.*, 2000).

In another InSAR study in the south western Santa Clara Valley, surface uplift of up to about 25 mm was measured over a period of five years. The uplift was attributed to groundwater recovery following a reduction of groundwater pumping and increased recharge (Galloway *et al.*, 2000).

6. Recommended subsidence monitoring program

6.1.   General

From an evaluation of the options available for monitoring subsidence over large areas, synthetic aperture radar (SAR) technology, supported by a GNSS network, is identified as the most cost effective technique to quantify potential deformation of the land surface due to CSG production activities. These techniques will enable the measurement of horizontal and vertical movement at discrete points to accuracies of 5mm and the measurement of vertical movements over broad areas to accuracies in the order of 10mm at horizontal resolutions as high as 3m.

Stage 1 would be a baseline program to study historical and current surface movement.

Stage 2 would be an on-going monitoring program throughout the life of the CSG production project and for a period of time after production has ceased.

6.2.   Baseline monitoring

To properly monitor the effects of CSG production on surface deformation there is a need to understand subsidence and uplift that occurs over time due to natural processes such as seasonal rainfall and human activities such as groundwater extraction for urban water supply or agriculture.

Initially a network of PSMs, surveyed using GNSS techniques, should be established to provide points of truth against which to check or calibrate InSAR data and to provide a known reference frame.

Broad area monitoring could be achieved by completing an analysis of historical InSAR satellite data for an eight-year period 1992-2000 using the European Remote Sensing (ERS) Satellite archive data (ERS1 and ERS2) held by Geoscience Australia, or alternatively a four-year period (January 2007 – January 2010) using Advanced Land Observing Satellite (ALOS) data. In a similar study in Queensland, ALOS, launched by the Japanese Aerospace Exploration Agency (JAXA) in January 2006, was selected. One of the sensors on board ALOS contained a phase array type L-band synthetic aperture radar (PALSAR) which provided images at a horizontal resolution of 30m with a maximum interferometric revisit time of 46 days. ALOS became inoperable in April 2011, but while it was active it operated in background acquisition mode, collecting data over large areas.

Investigations will need to be made with JAXA to determine if suitable data from this mission are available over proposed NSW CSG production areas. If no archival ALOS data is available a study will be required to identify an alternative option. High-resolution SAR missions currently available do not operate in background acquisition mode and will need to be specifically tasked to acquire data. To ensure InSAR data is available for analysis it is essential to define CSG study areas and commission regular acquisition and analysis from a suitable supplier.

6.3.   On-going monitoring

The initial baseline study would need to be followed up by an on-going program to monitor deformation as CSG production progresses and possibly for some years after production has ceased.

The GNSS network would need to re-observed periodically to determine which PSMs are moving and by how much and to check against the InSAR results.

In Queensland the CSG proponents jointly selected the Radarsat-2 satellite operated by the Canadian Space Agency. As with the JAXA satellite the Radarsat mission will conclude at some point in the future and another satellite selection process need to be undertaken to ensure continuous data acquisition.

In Queensland the rate and timing of satellite acquisition follows the guidance provided by the data acquisition and processing specialists (Altamira Information) and may vary between suppliers.

The results from both the baseline and on-going monitoring would be presented as a series of average annual (baseline) and quarterly (on-going) deformation maps along with time series data for the period of the studies.

7. References

Amelung, F., Day, S. 2002, InSAR observations of the 1995 Fogo, Cape Verde, eruption: implications for the effects of collapse events upon island volcanoes. *Geophys. Res.* Lett. 29, 120000–120001.

Amelung, F., Ikehara, M. E. & Sneed, M. 2005, USGS, California, viewed 03 July 2013, <http://pubs.usgs.gov/wri/wri014193/>.

Amelung, F., Dixon, T. H., Dokka, R., Ferretti, A., Kim, S. W., Novali, F., Rocca, F., Sella, G., Wdowinski, S. & Whitman, D. 2006, 'Supplementary Information for Space Geodesy: Subsidence and flooding in New Orleans: Analytical Techniques and Measurement Uncertainty', *Nature* 441, 587-588.

Amelung, F., Bell, J.W., Bianchi, M., Ferretti, A., & Novali, F. 2008, Permanent scatterer InSAR reveals seasonal and long term aquifer-system response to groundwater pumping, *Water Resources Research*, 44: 2. W02407.

Bamber, J., Hardy, R., and Joughin, I. 2000, An analysis of balance velocities over the Greenland ice sheet and comparison with synthetic aperture radar interferometry, *J. Glaciol.*, 46, 67–74.

Bawden, G. W., W. Thatcher, R. S. Stein, C. Wicks, K. Hudnut, and G. Peltzer. 2001, Tectonic contraction across Los Angeles after removal of groundwater pumping effects, *Nature*, 412, 812–815.

Brinker, R. C. & Wolf, P. R. 1994, *Elementary surveying, 9th ed.*, HarperCollins College Publisher, New York.

Brown, N. J. , Featherstone, W. E. , Hu, G. and Johnston, G. M. 2011, 'AUSGeoid09: a more direct and more accurate model for converting ellipsoidal heights to AHD heights', *Journal of Spatial Science*, 56: 1, 27-37.

Case, J.C. (2000) Subsidence potential related to water withdrawal in the Powder River Basin. *Wyoming Geo-Notes,* 68:19-20.

Catani, F., Casagli, N., Ermini, L., Righini, G. & Menduni, G. 2005, Landslide hazard and risk mapping at catchment scale in the Arno River Basin. *Landslides*, 2: 4, 329-343.

Chang, M. H. C., Ge, L. & Ng, A. 2007a, Longwall Mining Subsidence Special Project. NSW Department of Environment and Climate Change, viewed 4 July 2013, <http://www.planning.nsw.gov.au/planningsystem/pdf/southerncoalfieldinquiry_decc_attachment_5.pdf>.

Chang, M. H. C., Ge, L. & Rizos, C. 2007b, Mine Subsidence Monitoring Using Multi-source Satellite SAR Images. *Photogrammetric Engineering and Remote Sensing*, 73: 3, 259-266.

Committee on Floodplain Mapping Technologies, Natural Research Council. 2007, Elevation Data for Floodplain Mapping, *The National Academies Press*, Washington, D. C.

Cummins, P., Dawson, J., Leonard, M., & Tregoning, P. 2008, Shallow intraplate earthquakes in Western Australia observed by Interferometric Synthetic Aperture Radar, *J. Geophys. Res.*, 113, B11408, doi:10.1029/2008JB005807.

Dawson, J., Garthwaite, M. C., Hislop, A., Nancarrow, S., Thankappan, M., & Williams, M. L. 2011, Corner Reflectors for the Australian Geophysical Observing System and Support for Calibration of Satellite-Borne Synthetic Aperture Radars, the Committee on Earth Observation Satellites Working Group on Calibration and Validation Synthetic Aperture Radar Subgroup.

Dzurisin, D. 2003, A comprehensive approach to monitoring volcano deformation as a window on the eruption cycle. *Reviews of Geophysics*, 41: doi: 10.1029/2001RG000107. issn: 8755-1209.

Elachi, C., 1988, Space radar remote sensing: applications and techniques. *IEEE*, New York.

Galloway, D. 2000, USGS, California, viewed 03 July 2013, <http://pubs.usgs.gov/fs/fs-051-00/>

GIS Development, India, viewed 03 July 2013, <http://www.gisdevelopment.net/application/urban/products/mi08_223.htm>.

GlobalSecurity 2013, viewed 03 July 2013, <http://www.globalsecurity.org/military/library/policy/army/fm/6-2/Ch5.htm>.

Helz, R. L. 2005, USGS, Virginia, viewed 03 July 2013, <http://volcanoes.usgs.gov/activity/methods/insar/public_files/InSAR_Fact_Sheet/2005-3025.pdf>.

Hoffmann, J., Zebker, H.A., Galloway, D.L. & Amelung, F. 2001, Seasonal subsidence and rebound in Las Vegas Valley, Nevada, observed by synthetic aperture radar interferometry, *Water Resour. Res.*, **37,** 1551–1566.

ICSM. 2007, 'Standards and Practices for Control Surveys (SP1)', ICSM Publication No.1, viewed 9 July 2013, <http://www.icsm.gov.au/publications/sp1/sp1v1-7.pdf>.

ICSM. 2011, Digital Elevation Guidelines and Specifications, viewed 9 July 2013, <http://www.icsm.gov.au/elevation/index.html>.

ICSM. 2013, Fundamentals of Mapping, viewed 03 July 2013, <http://www.icsm.gov.au/mapping/surveying4.html>.

IOP Science, 2013, viewed 12 August 2013, <http://ej.iop.org/images/0034-4885/76/8/086801/Full/rpp437052f02_online.jpg>.

Kaufmann, R. D. & Doll, W. E. 1998, Gravity meter comparison and circular error, Journal of Environmental and Engineering Geophysics, in Benson , R. C., Kaufmann, R. D., Yuhr, L. & Hopkins, R. 2003, Locating and Characterizing Abandoned Mines using Microgravity, Technos, Inc., Lexington, Kentucky, viewed 03 July 2013, <https://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/ktwkshp/ky0316.cfm>.

Lanari, R., De Natale, G., Berardino, P., Sansosti, E., Ricciardi, G.P., Borgstrom, S., Capuano, P., Pingue, F. & Troise, C. 2002, Evidence for a peculiar style of ground deformation inferred at Vesuvius volcano. *Geophysical Research Letters*, 29: doi: 10.1029/2001GL014571. issn: 0094-8276.

Leica. 2008, sourced from Leica ADS40 promotional brochure.

Madsen, S.N., Zebker, H.A., and Martin, J.A. 1993, Topographic mapping using radar interferometry: Processing techniques, IEEE Trans. *Geosci. Remote Sensing*, 31, 246-256.

Massonnet, D. Rossi, M., Carmona, C., Adragna, F., Peltzer, G.,Feigl, K. and Rabaute, T. 1993, The displacement field of the Landers earthquake mapped by radar interferometry. *Nature*, 364, 138-142.

Massonnet, D., Feigl, K., Rossi, M., and Adragna, F. 1996, Radar interferometry mapping of deformation in the year after the Landers earthquake. *Nature*, 369, 227-230.

Massonnet, D., and Feigl, K. 1998, Radar interferometry and its application to changes in the Earth's surface, *Rev. Geophys.*, 36: 4, 441–500,doi:10.1029/ 97RG03139.

Moran, C. and Vink, S. 2010, Assessment of impacts of the proposed Coal Seam Gas operations on surface and groundwater systems in the Murray-Darling Basin, Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University of Queensland.

NASA 2013, viewed 03 July 2013, <http://science1.nasa.gov/missions/grace/>.
O'Rear, R. 2011, Microgravity Measurement for Groundwater Analysis, USGS, (Online Video), viewed 09 August 2013, <http://gallery.usgs.gov/videos/380>.

Pennsylvania State University, Nature of Geographic Information, viewed 03 July 2013, <https://www.e-education.psu.edu/natureofgeoinfo/book/export/html/1620>.

Poland, J. F., Yamamoto, S. & Working Group. 1984, 'Field measurement of deformation', in Poland, J. F. (ed.), Guidebook to studies of land subsidence due to ground-water withdrawal, UNESCO, Michigan.

Pritchard, M. E. and Simons, M. 2002, A satellite geodetic survey of large-scale deformation of volcanic centres in the central Andes. *Nature*, 418, 167-171.

Pritchard, M. E. and Simons, M. 2004, An InSAR-based survey of volcanic deformation in the southern Andes. *Geophys . Res. Lett.* 31, doi:10.1029/2004GL020545.

Pritchard, H., Murray, T., Luckman, A., Strozzi, T., and Barr, S. 2005, Glacier surge dynamics of Sortebræ, East Greenland, from synthetic aperture radar feature tracking, *J. Geophys. Res.*, 110, F03005, doi:10.1029/2004JF000233.

QGC, 2012; Approval Conditions 49 to 52 Stage 2; Water Monitoring and Management Plan. Second Revision 23 April 2012 Submission, viewed 02 October 2013, <http://www.qgc.com.au/media/233102/10.0_-_ground_motion_monitoring_and_management_plan.pdf>

Raucoules, D., Maisons, C., Carnec, C., Le Mouelic, S., King, C., and Hosford, S. 2003. Monitoring of slow ground deformation by ERS radar interferometry on the Vauert salt mine (France) Comparison with ground-based measurement. *Remote Sensing of Environment*, 88, 468-478.

Reed, D. J. and Yuill, B. 2009, 'Understanding Subsidence in Coastal Louisiana', Pontchartrain Institute for Environmental Sciences University of New Orleans, LA.

Ross, J. and Jeffery, L. 1991, Ground subsidence and bore collapse associated with groundwater withdrawals – Namoi Valley NSW, Technical Services Division: hydrogeology unit. Department of Water Resources.

Seigel, H. O. 1995, High precision gravity survey guide, in Benson , R. C., Kaufmann, R. D., Yuhr, L. & Hopkins, R. 2003, Locating and Characterizing Abandoned Mines using Microgravity, Technos, Inc., Lexington, Kentucky, viewed 03 July 2013, <https://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/ktwkshp/ky0316.cfm>.

Simons, M., Fialko, Y. and Rivera, L. 2002, Coseismic deformation from the 1999 Mw 7.1 Hector Mine, California, earthquake as inferred from InSAR and GPS observations, *Bull. seism. Soc. Am.*, 92, 1390–1402, doi:10.1785/0120000933.

Spectron Glass and Electronics Incorporated 2013, viewed 23 September 2013, <https://www.spectronsensors.com/tilt-sensors.php>.

Sydney Catchment Authority 2012, Literature Review – Coal Seam Gas Impacts on Water Resources (Draft Revision 4), viewed 16 October 2012, <http://www.sca.nsw.gov.au/__data/assets/pdf_file/0019/39223/CSG-Impacts-on-Water-Resources-Draft-Revision-4.pdf>.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A. 1976, Applied Geophysics, in Benson , R. C., Kaufmann, R. D., Yuhr, L. & Hopkins, R. 2003, Locating and Characterizing Abandoned Mines using Microgravity, Technos, Inc., Lexington, Kentucky, viewed 03 July 2013, <https://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/ktwkshp/ky0316.cfm>.

Terranean Mapping Technologies 2008, sourced from Trackstar LiDAR & Large Scale Photogrammetry Error Analysis Presentation.

University of Washington 2006, Lidar Overview, viewed 03 July 3013, <http://forsys.cfr.washington.edu/JFSP06/lidar_technology.htm>.

UNSW School of Surveying and Geospatial Engineering 2013, viewed 12 August 2013, <http://www.gmat.unsw.edu.au/snap/gps/gps_survey/chap5/fig69.jpg>

USGS 2013, viewed 03 July 2013, <http://volcanoes.usgs.gov/activity/methods/insar//>.

Wikipedia 2009, viewed 03 July 2013, <http://en.wikipedia.org/wiki/File:Phase_shift.svg>.

Wikipedia 2010, viewed 03 July 2013, <http://commons.wikimedia.org/wiki/File:ECEF_ENU_Longitude_Latitude_relationships.svg>