Digital terrain modelling for exploration and mining

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Abstract

Models of ground surface elevation, slope, aspect, curvature, roughness, deformation, as well as other features are gathered together in the term Digital Terrain Model (DTM). DTMs can be generated from a wide range of technologies such as ground surveying, aerial and satellite imagery, including both active and passive sensors. Some elevation-derived parameters, such as roughness and slope can be measured directly using innovative active sensor technology and smart processing, rather than via traditional processing of elevation information. Such models are used as part of a visual interpretation process, and increasingly for computer-assisted analysis, including data correction and modelling applications. There is an ever-increasing demand for DTM information to be used in the mineral exploration and mining industry, and consistent pressure from industry to develop models of higher spatial resolution, higher accuracy, and better overall reliability, regardless of the world-wide location of interest.

This paper surveys the range of techniques available for DTM generation, including interpolation methods (contour or structure interpolation), optical or SAR stereo, and LIDAR, SAR interferometry and differential interferometry, and the economic placement of these various techniques in the local and regional context. The research issue of true-ground elevation models and slopes is also addressed, using LIDAR and SAR polarimetry as signpost technologies. Particular emphasis will be given to the strengths and limitations of new data sources that will, over the next few years, make the acquisition of elevation models of remote regions of the world inexpensive and relatively accurate.

Introduction

New Zealand is fortunate in that there is very good quality digital elevation model data available from Land Information New Zealand. These data are derived from aerial photography and full country coverage is available. For a very reasonable fee, one can purchase 20 m contour data and then create maps of elevation, slope, and aspect suitable for use down to 1:50 000 scale and, perhaps, 1:25 000. For higher resolution DEMs, aerial photographic surveys can be commissioned. However, many other countries have poor or non-existent contour information and topographic mapping. Furthermore, permission to fly aerial photographic surveys may be problematic. In these instances, space-based methodologies can be vital because they can provide medium-high resolution data over large areas at reasonable cost. Satellite data is also a most convenient and cost effective means of detecting deformation over wide areas. Applications include earth deformation caused by earthquakes, subsidence, swelling prior to volcanic eruptions, or terraforming. The various techniques for DEM/DTM generation, and their relative merits, are outlined below.

Contour interpolation and ground-based methods

Traditionally, DEMs are generated from the contours that have been derived from aircraft stereo imagery. Sophisticated mechanical devices called analytical plotters are used to align the images and allow an operator to view them in stereo while tracing along the contours. This methodology has produced large volumes of contour data around the world, much of which is now available in digital form for a reasonable cost.

The cost and availability of this data makes it a very attractive information source for the production of DEMs. In converting contour information to a DEM it is necessary to interpolate across the regions between contours. There are a wide variety of methods to achieve this and the accuracy and specific method chosen may depend to some extent on what additional information is available (e.g. spot heights, river network), and the eventual application of the DEM.

In its simplest form, interpolation can be performed based on the two closest contours. However, a smoother result can be achieved using splines, or similar methods, so that the fitted surface has no sharp transition at the contours. Additional information, such as break lines, is used in some interpolation algorithms to identify where smoothness should explicitly not be a constraint (Burrough & McDonnell, 1998). Another common constraint is to employ hydrology data to define areas where the second partial derivative should be zero. This enforces hydrological correctness so that water always flows in the correct direction over the fitted surface. A global drainage condition can also be imposed; this automatically removes spurious sinks where possible, and ensures a connected drainage network. For example, a modified thin plate spline interpolation algorithm that incorporates breaklines, spot heights, lake boundaries, sinks, and a total drainage constraint has been implemented as the Topogrid command in Arc/Info. This creates a grid or matrix of elevation values (Hutchinson 1988, 1989).

Another very common interpolation technique is to represent the surface using a triangulated network (TIN) (Burrough and McDonnell, 1998). This was designed to avoid the redundancies of a matrix of elevation values. More topographically complex areas can be efficiently and accurately represented. The surface is broken up into small triangles of some defined granularity. The corners of the triangles will be on defined contours, and the height of points within each triangle is modelled as 2-D interpolation between the three corner points. This method is available in many commonly used commercial packages, including Arc/Info, and methods are available to convert between TINs and grids (matrices).

Terrain attributes cannot be derived from contours. Slope, aspect, line-of-sight visibility, horizon and profile maps, and surface area can all be calculated from TIN DEMs. A grid of elevation values is, however, more versatile in that a large variety of terrain attributes can be derived from them, e.g. slope, aspect, curvature (convexity and concavity), line-of-sight, watershed delineation, drainage network, wetness index, upstream area, slope position. Just as there are many interpolation methods, there are also a variety of methods that can be used to calculate terrain attributes. For example, Skidmore (1989) and Florinsky (1998) review the accuracy of various methods for calculating aspect and slope, which include fitting a multiple regression or a quadratic polynomial to a 3x3 window, a second order finite difference estimator (4 points), and a third-order finite difference estimator (8 points). Commercial GIS usually implement just one method.

Image disparity analysis (passive) methods

Optical

A satellite stereopair comprises two separate images acquired from two different positions in space. The different viewing geometry between the two scenes means that two points with slightly different elevations in the scene will have slightly different positions (known as a *disparity*) in the image itself. Provided one has access to a sufficiently detailed model of the imaging geometry, it is usually possible to derive the relative elevations of the points by measuring the disparity in the image position between two points (McNeill & Belliss 1996). Although it is theoretically possible to acquire two images at the same time from two different platforms, such as from two different aircraft or satellites, in general only one platform is used. This means that the second image of the stereo pair has to be acquired at a slightly different time than the first image.

In theory, the stereo pair could be acquired with any combination of viewing geometries, such as side-to-side viewing, forward-nadir viewing, or an arbitary combination of side- and forward-looking geometries; however in practice, either a forward-nadir or side-looking geometry is used. In the first, or along-track stereo, the two images will be captured along the flight line. This is the most common situation in conventional aircraft stereo, where frames are captured along a flight line and the viewing geometry results in effectively forward-aft or forward-nadir stereo viewing. Forward-nadir stereo has been successfully used in satellites, for example, the JERS-1 system.

In the second, or cross-track stereo, the stereo pair is acquired by capturing one image to the side of the flight line on one orbit track and a second image to the other side of a second orbit track. This is the most common form of stereo for satellite-based systems, such as SPOT. In this latter system, the separate flight lines are defined by the orbit of the satellite, and at any given point the satellite can view plus or minus 27 degrees either side of the nadir position.

The accuracy of passive stereo systems is principally determined by the accuracy with which one can estimate the disparity between corresponding positions in the stereo pair. In turn, this is broadly related to the ratio of the distance between the aircraft/satellite positions and the height above the terrain, known as the base-to-height ratio. Generally speaking, a base-to-height ratio above 0.1 is required for stereo, and values of between 0.6 and 1.1 are preferred. Although a higher base-to-height ratio is better, if the value is too high then it becomes difficult to estimate the disparity since the images of the stereo pair differ considerably. As a broad indication of error, a satellite digital viewing system with a base-to-height ratio of 1.0, will yield a DEM rms accuracy that is approximately one-half of the nadir spatial resolution. Table 1 lists some common present and planned satellite systems which would be suitable for stereo, with their nadir spatial resolution also indicated. The table is not an exhaustive list of such planned systems.

Along-track stereo and cross-track stereo have their respective advantages and disadvantages. As the images of the stereo pair must be acquired on different orbits, sometimes several days apart, cross-track stereo images sometimes suffer from changes in land cover, or sun angle, or some other environmental conditions. In a dynamic environment, such as New Zealand or the tropics, time intervals shorter than a week to ten days are preferred. The SPOT system has, at the time of writing, three satellites currently operating, roughly equally spaced around the same orbit. This means cross-track stereo is particularly easy to gather with, cloud-cover permitting, a few days between images. In general, along-track stereo is a preferred geometry, since these differences in time between images is minimised.

SAR

Synthetic Aperture Radar (SAR) is a system that provides its own energy for illumination and is thus independent of sunlight. In addition, the microwave energy is able to penetrate clouds. Thus, SAR can be collected at any time, day or night. Space-based SAR stereo, or radargrammetry, is available now that there are space-based platforms that can vary their viewing geometry. SAR stereo pairs are gathered in a similar manner to those from optical sensors, although the geometry is somewhat different. There are a number of complicating issues with radargrammetry, including the variation of radar brightness with vegetation cover and average slope, and the changing disparity with average terrain slope.

The Canadian Radarsat-1 satellite is one example of a satellite that can provide SAR stereopairs. It is possible to collect these Radarsat stereopairs in a number of same-side and opposite-side configurations, and there are trade-offs to all these. In particular, the complicating effects of variations in SAR backscatter due to differing incidence angles is best mitigated by same-side image pairs; however, this does not give the best stereo radar results in all topographies. In a study of all the possible configurations, Toutin has determined the various tradeoffs involved in the selection of appropriate geometry, summarised in Table 2 (Toutin 1999). The accuracy of the resultant DEMs varies widely, depending on the precise geometry that is used, ranging from 14 m to 80 m at the 90% confidence level, depending upon the configurations and the relief.

SAR and optical stereo

It is also feasible to use combinations of optical and SAR data to generate stereopairs suitable for both planimetric and elevation features (Toutin, 2000). The advantage of this comparatively unusual approach is that optical and SAR data may be required for interpretation of the image and, if a DEM is not already available, combining the two datasets to form a DEM is an efficient use of resources.

Active methods

Interferometric SAR

SAR interferometry employs two SAR images acquired over the same area from positions spaced from tens of metres to hundreds of metres apart. Since SAR is a coherent form of illumination (like a laser), the images formed from SAR are spatially coherent over a short distance. By combining the phase from the two images in an appropriate manner, it is possible to derive an image which is related to the slant range between one of the image positions and the terrain, which, in turn, can be transformed into a DEM. In theory, the two SAR images could be captured from two different platforms flying in tandem, forming a true SAR interferometer, but it is more common to fly the platform a second time near the position where the first image was captured, in a configuration known as repeat-pass interferometry.

True SAR interferometer platforms are rare in space — in fact the only one flown was the short-term February 2000 flight of the Shuttle Radar Topography Mission (SRTM), described later in this section. True SAR interferometers are rather more common with aircraft, since repeat-pass interferometry is very difficult to achieve in the aircraft case, for a number of different reasons. Modern aircraft SAR interferometers can have metre or sub-metre resolution for swaths of several tens of kilometers, with the notable advantage that they can capture DEM data regardless of the weather conditions. A good example of the true SAR interferometer principle is the TOPSAR mode of the AIRSAR instrument, operated by the NASA Jet Propulsion Laboratory (JPL) on their research aircraft. TOPSAR uses two antennas, mounted on the left hand side of a DC-8. The TOPSAR system uses a fully automated processing system that generates a DEM without the use of tie points, although their use will

Satellite	Stereo	Launch	Nadir resolution
SPOT-1 through -4	Cross track	1986–	10 m
JERS-1	Along track	1992-1998	18 m
Ikonos	Along/cross track	1999–	1.0 m
EROS-A1	Along/cross track	2000 ?	1.8 m
QuickBird-1	Along track	2000 ?	1.0 m
QuickBird-2	Along track	2000 ?	1.0 m
OrbView-4	Along/cross track	2001 ?	1.0 m
OrbView-3	Along/cross track	2001 ?	1.0 m

Table 1.

Terrain relief	Flat 0-10° slopes	Rolling 10-30° slopes	Steep 30-50° slopes
Radiometric disparities	small	medium	large
Geometric disparities	large	medium	small
Compromises	Opposite-side with steep viewing angles	Opposite-side with steep or shallow viewing angles or same-side with large intersection angles	Same side with small intersection angle and steep or shallow viewing angles

Table 2. Characteristics of SAR radargrammetry.

improve results. RMS errors are around 1-2 m in flat terrain and 3 m in moderate terrain. The NASA JPL PACRIM-1 mission in 1996 included New Zealand and acquired TOPSAR data of several areas, including White Island, Wanganui, Wairarapa, and part of the Southern Alps. The more recent August 2000 PACRIM-2 Mission collected TOPSAR swaths over White Island, Ruapehu and Ohakune, Rotorua, North Otago, and part of the Southern Alps. A PACRIM-3 mission is planned for early 2003.

Satellite repeat-pass interferometers exploit the fact that satellite orbits repeat their paths almost exactly after a fixed number of days, known as the repeat period. The repeat period depends on the characteristics of the satellite orbit, and is essentially fixed. For best results, repeat pass interferometry requires the repeat period to be as short as possible, since an increasing time interval between images degrades coherence, and therefore the DEM quality. In some cases, this degradation can render interferometry impossible.

The quality of DEMs from repeat-pass interferometry depends to a large degree on the geometry of the specific satellite being used, the nature of the local terrain, and the type of vegetation on the ground surface (McNeill and North, 2000). To take a specific example, tandem-mode repeat pass interferometry using the European Space Agency's ERS-1 and ERS-2 satellites to capture images one day apart in time, can generate good DEMs of a 100x100 km area at 25 m spatial intervals, with altimetric accuracies on the order of plus-or-minus 20 m at the 90% confidence interval. Arguably, these DEMs are useful at the 1:100 000 and perhaps the 1:50 000 scale, and are suitable for general purpose mapping.

In general, increasing the time interval between the images of a repeat-pass interferometric pair will degrade the resolution, and lush vegetation will also make the processing more difficult. Also high ground slopes pose difficulties for steep-viewing satellites such as ERS-1 and ERS-2. Most successful applications of DEM generation from repeat-pass SAR interferometry have been in dry, less vegetated environments, generally with tandem-mode data. As a rule, lush vegetation environments with dynamic growth pose difficulties for interferometry, and in these environments a longer SAR wavelength is preferable. It is generally true to say that interferometry is quite difficult in the New Zealand environment.

X-SAR/SRTM Mission

The Shuttle Radar Topography Mission, involving a consortium of agencies in the USA, Germany, and Italy, flew in February 2000 with a fixed baseline single-pass spaceborne interferometric SAR. It aimed to produce a topographic map of the earth's land surface between 60 degrees North and 56 degrees South latitude using C-and X-band interferometric SARs, covering some 80% of Earth's land mass during the 11-day Shuttle mission. Processing from this mission is, at the time of writing, not complete, but is expected to be released some time during the 2002 calendar year. The products to be generated will be DEMs with 30 m spatial sampling and better than 16 m absolute vertical height accuracy at the 90% confidence level. Unfortunately, this high-accuracy product will not be available outside the USA, and the only product expected to be available world-wide will be degraded to a spatial resolution of 100 m.

In New Zealand, Landcare Research was a principal investigator for the X-band interferometer on the SRTM mission. Two test sites, on Banks Peninsula and the Macraes mine site in Otago, had radar reflectors installed on site during the Shuttle mission and were precisely surveyed. Information from these corner reflectors is being used, at the time of writing to calibrate the DEMs from the X-band instrument from the German Space Agency (DLR). The precise DEMs will be used to investigate the characteristics of the DEMs and to understand how their accuracy changes with the changing vegetation over various parts of New Zealand.

Differential interferometry

In interferometry, outlined in section 3.1, two images are used to infer height from the coherent change (known as the spatial phase) between two SAR images. If some small movement occurs during the period between the two images, then the coherent signal consists of a component of change due to the topography and a second component due to movement (deformation). These components can be separated, either by gathering a third image coherent with the other two, or by making reference to a very precise DEM. The result, after suitable processing, is a map of surface elevation change or deformation. This is known as differential interferometry. Simple interferometry is quite sensitive to the geometry of the SAR positions, and to the vegetation as well. Differential interferometry is extremely sensitive to these factors, and is very difficult to achieve, except in the most favourable of circumstances. These favourable circumstances include little or no vegetation, little temporal change between the scenes, and suitable imaging geometry. Even so, when the conditions are suitable, changes in elevation at the centimetric-scale, or less, can be measured.

Differential interferometry can be used to detect small-scale movement of the earth towards or away from the sensor, where ground conditions are suitable. This technique was made famous by the 1992 Landers Earthquake in California, when the measurement of the phase shift in interferograms taken before and after the earthquake was used to measure the movement on the faultline (Massonnet et al. 1993). In this study, researchers were able to detect seven millimetres of motion on a fault located 100 km from where the quake had struck. The methodology has been used in New Zealand to investigate the Arthurs Pass Earthquake in June 1994 (North et al. 2000). The technique can also be used to detect and estimate changes in the surface topography to sub-centimetric accuracies. For example, using over seventy C-band SAR images of Paris, scientists at Eurimage have produced maps showing the relative subsidence, due to urban loading and the excavations for The Metro, in the area. IGNS in Lower Hutt are currently researching the use of multiple pass ERS-2 data for deformation assessment in the Taupo Volcanic Zone. Many volcanic eruptions are preceded by surface deformation, so it may also be possible to use this technique for prediction and disaster prevention. It is used for measuring subsidence over old mine sites, cities built on unstable land, or in active geothermal and hydrothermal areas. Other promising applications areas are crustal motion from solid earth tides or tidal loading.

LIDAR

Laser scanning provides a high density DEM by firing active coherent optical laser pulses from a platform (aircraft, helicopter or satellite) to the ground and timing their return. The returning laser pulses may, of course, be returned from the vegetation canopy (if any), vegetation understorey, or from the ground surface. By looking closely at the distribution of laser pulses and inferring which came from the top of the vegetation and which came from the true ground, it is possible to estimate the true height of the vegetation layer, and thus, by inference, the true ground height. This process does require that the vegetation is sufficiently sparse to allow a reasonable proportion of the laser pulses to penetrate to the ground and return to the aircraft, and this can be problematic in some dense forest regions.

Most commonly installed in an aircraft, this technique is potentially capable of generating DEMs with an accuracy at the 1–10 cm level, with swaths on the order of 500–1000 metres. There is no current airborne lidar service in New Zealand but an Australian company (AAM Surveys, see *http://www.aamsurveys.com.au*) can, and has, undertaken contract flying in this country, most recently in early 2000.

True ground digital elevation models

Frequently, exploration geologists are interested in the true ground layer beneath the vegetation, perhaps to search for geological features that are expressed on the terrain surface, or for site surveys. Aside from direct ground surveying, there are relatively few techniques to infer true ground height (true ground DEM) from an aircraft or satellite platform.

Stereo interpretation

The most obvious technique for producing a true ground DEM is to estimate the height of trees in the vegetation layer and compensate for this layer by a constant offset from a DEM calculated at the top of the vegetation layer. This process assumes that the ground DEM closely follows the canopy DEM, which may not necessarily be the case in complex vegetated environments.

LIDAR

As noted in section 3.4 above, LIDAR may reflect off trees and through gaps in the canopy and be reflected back from the ground, and are thus recording both ground and non-ground points. There are two ways in which this scattering behaviour can be used to infer a true ground DEM. First, if only the first returned laser pulse is provided by the LIDAR system, then sudden apparent jumps in the DEM can be interpreted as canopy-ground gaps. Careful processing of the dataset can thus yield an estimate of the true ground DEM, provided there are sufficient gaps in the vegetation to give an adequate canopy-ground separation. Second, if the vertical, or height, distribution of laser pulses is returned by the LIDAR, then it is usually possible to estimate the vegetation height from the distribution measurement. LIDAR systems that return the vertical distribution of returned laser pulses are neither common nor cheap, and none are operating in Australasia, to the authors' knowledge.

SAR polarimetry

Using the differing landcover penetrability of the different wavelengths of radar, and by using polarimetric characteristics plus the wavelengths to infer where scattering took place, it is possible to derive sufficient information to produce some information about the true ground DEM. In arid environments, this can be used to qualitatively infer the presence of sub-surface structures. The accuracy of this assessment of a sub-surface structure will depend upon the denseness and structure of the cover involved, along with the sensor geometry. Recently, using AIRSAR data in Western Australia, a number of previously unrecognised synclinar structures in the basement, and a paleochannel in the regolith, have been used to better target new exploratory drill sites (Tapley, 1995).

A current experimental technique for estimating vegetation height, and one rapidly gathering much favour, uses a specialised form of radar termed polarimetric-interferometric synthetic aperture radar, or PolInSAR. The technique combines two quite separate effects unique to radar imaging of the vegetated environment. First, in SAR interferometry, as outlined in section 3.1, the interferometry signal is sensitive to the position of the parts of the vegetation in the forest layer. SAR polarimetry, which illuminates the forest layer with radar energy of different orientations (horizontal, vertical, etc) is sensitive to the orientation of the various parts of the forest layer. It makes sense to suggest, and it turns out to the true in practise, that SAR interferometry using a polarisation signal will be sensitive to both the positions and orientations of the various parts of the vegetation layer. Although the formal description of PolInSAR is mathematical in nature, essentially the components of the forest layer, including the canopy, branches, trunk and understorey, can be described, including their effective heights. By this manner, the total height of the vegetation layer can be estimated, and the true ground DEM calculated from the standard DEM.

Discussion

There is often a trade-off between costs and accuracy/spatial resolution with the various ways of obtaining digital elevation models. Table 3 summarises the characteristics of the most common data sources. Within New Zealand, many current requirements for DEMs can be met by aerial photography or contour data; however, as the user community becomes more discerning, the need for true ground DEMs is likely to increase and some of the the techniques outlined above will become more relevant.

Source	Description	Availability	Coverage	DEM accuracy	Cost
Conventional aerial photos	Black and white aerial photographs	On demand, flying weather permitting	All NZ; sometimes limited in overseas countries	Centimetric	Expensive
Contours	Data based upon previous aerial photo surveys	On demand	All NZ; limited elsewhere in the world	Roughly half the countour interval	Very reasonable
SPOT stereopairs	Panchromatic data with a spatial resolution of 10m	Some available; can be ordered	World wide	+/- 10m at 90% confidence level, for 1:1 B:H ratio	Moderate
ERS -1/ERS-2 interferometry	C-band SAR Tandem mode interferometry	Data of most of the world acquired 1997/98.	World wide	Best case scenario of height error of 5m; 10m rms typical	Moderate
Radarsat-1 stereopairs	C-band SAR with a variety of beam modes and look angles	Ordered on demand.	World wide	Best case scenario (ideal viewing geometries, moderate relief) of 11m	Medium
SRTM	C-band and X-band SAR	Will be available, but perhaps at reduced resolutions, by 2002	C-band — full coverage between +/- 57 deg lat X-band — 50% coverage between +/-57 deg lat	C-band – 30m horiz, 10m vert X-band – 20m horiz, 5m vert	Low
AIRSAR TOPSAR	L-and C-band cross-track interferometry	Opportunity to obtain data for selected sites.	Selected NZ sites available; some world-wide sites	1-2m in flat areas; 3m in moderate relief areas	Expensive, but custom product
LIDAR	Scanning laser on aircraft platform	Can be commissioned and mobilised from Australia	A few NZ sites available; more common in Australia	As good as 0.15m in low relief areas	Expensive

Table 3. Summary of characteristics of selected digital elevation model sources.

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