National Elevation Data Framework

The Shared Digital Representation of Australia's Landform and Seabed

Science Case

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Note: This document is part of the input from which final documentation will be developed

Contents

Purpose

This document has been prepared for public discussion. It sets out the Science Case for the establishment of a National Elevation Data Framework. Those who wish to comment are invited to by:

1. Writing to Ian Batley, Executive Director, **ANZLIC -** the Spatial Information Council, GPO Box 337, Canberra, ACT 2601; email ian.batley@anzlic.org.au

or

2. Attending a National Workshop at the Shine Dome, Australian Academy of Science, Canberra on 18 March 2007.

Executive Summary

The purpose of the National Elevation Data Framework (NEDF) initiative is to develop a collaborative framework that can be used to increase the quality of elevation data and derived products such as digital elevation models (DEMs) describing Australia's landform and seabed. The aim is to optimise investment in existing and future data collections and provide access to a wide range of digital elevation data and derived products to those who need them.

The strategic imperative is how to optimise Australia's investment in elevation data and ensure this investment is directed at policy and operational needs at both national and local levels. Impetus for a national approach to collection of digital elevation data is coming from a range of sources. Most recently, the Council of Australian Governments (COAG) identified as a priority:

Develop a national digital elevation model (DEM) for the whole of Australia, with vulnerable regions being mapped using very high-resolution images. This would involve linked topographic and bathymetric information at a resolution relevant to decision-making.[1]

A primary operational need is to ensure that DEMs generated within the NEDF meet the needs of users, a significant user base being the science community. The purpose of this Science Case document is to outline the NEDF initiative and consider the science drivers for a National DEM. With the needs of science and other users in mind, DEM concepts are then overviewed, data acquisition technologies are presented in the context of commercial readiness, emerging technologies are touched upon and areas needing research attention are discussed.

This Science Case document is complementary to the NEDF Business Plan and it will inform the development of the NEDF Implementation Plan, which is to be prepared following the national workshop planned to be held in Canberra in March 2008.

Introduction

The need for digital models depicting the terrain surface is well recognized. Indeed, digital elevation models or DEMs are essential for a wide range of purposes in fields as varied as agriculture, intelligent transport, catchment management, environmental assessment, modelling the impact of rising sea level and for scientific and engineering purposes. DEMs could thus be said to comprise an essential data layer within the national spatial data infrastructure, but the reality is that Australia does not have a national DEM of sufficiency high resolution to fulfill the needs of many of the application areas highlighted above. As an initial illustration of this, consider that our national 9-second DEM (horizontal grid spacing of approximately 250m) has a vertical accuracy in the 10m range whereas assessments of potential coastal inundation associated with a tsunami or rising sea level requires elevation models with a vertical accuracy of better than 0.5m and a horizontal resolution of 1 second of arc (30m) or better.

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[1] COAG: *National Climate Change Adaptation Framework*, 2006.

Whereas Australia does not possess a high- or multi-resolution DEM covering the continental land mass and the near-shore seabed, there is nonetheless a considerable amount of DEM data available, both from private and public sources. Local area DEMs are being generated for a range of clients and applications, as are bathymetry surveys. Moreover, many states offer high resolution (sub metre vertical accuracy) DEM data for selected reasons, with there also being broad area and in some cases whole state coverage at medium (1-5m vertical accuracy) and low resolution (less than 5m vertical accuracy). Although much of this DEM data is within a common reference coordinate system, there are few commonalities related to coverage, quality, resolution and currency. Yet, there is an acknowledged need for a National DEM, the realization of which will be a complex, multi-year undertaking irrespective of the level of resources needed to bring such an initiative to fruition. As a first step, a conceptual framework needs to be developed. This in turn needs to go beyond purely technical issues of DEM generation to address issues such as standards and specifications, governance, shared investment in the collection of high-resolution elevation data and access policies. This paper discusses the scientific issues related to the development of a National Elevation Data Framework (NEDF) for a National DEM encompassing the continental land mass and the seabed out to the continental shelf. The focus of the paper is upon the science issues that need to be addressed in the formulation of a NEDF.

Background to NEDF Initiative

Prior to any discussion of the science drivers for a National DEM, it is useful to provide a background to the current NEDF initiative. ANZLIC – the Spatial Information Council, with the support of the Australian Greenhouse Office (AGO), Geoscience Australia (GA) and the Cooperative Research Centre for Spatial Information (CRCSI) is coordinating the development of a National Elevation Data Framework (NEDF). This initiative is at the request of the Australian Government following a decision by the Council of Australian Governments in April 2007 to identify as a high priority the development of a National DEM that links topography and seabed bathymetry. A Project Team comprising representatives of these organisations has been set up to guide the process leading to the following deliverables:

1. User Needs Analysis through direct contact with stakeholders around Australia.
2. Business Plan, setting out the intent and potential form of a NEDF, identifying key stakeholders and a preliminary review of existing usage of elevation data sets and products in Australia.
3. **Science Case to support the implementation of the project.**
4. Agreement on use of applicable data standards and access arrangements such as licensing.
5. Implementation Plan using the User Needs Analysis and feedback from stakeholders on issues such as governance arrangements, funding and standards.

Science Drivers

Irrespective of whether a DEM is understood to be a computer compatible model of the earth's topography or a digital cartographic representation of the topography and bathymetry, it is, in its basic form, a rectangular array of bare-earth elevations at regularly spaced intervals in two orthogonal directions, usually Eastings and Northings or latitude and longitude. There are relatively few unresolved science issues associated with DEMs when they are viewed in a purely geometric context. However, when the meaning of a DEM is taken to be more of a 'model', then a number of science drivers become relevant. At a fundamental level, these include the issues of geodetic datums and their dynamic characteristics, for while a DEM might be thought of a as a 3D shape in free space, many science questions apply when its absolute position, orientation and characteristics of deformation over time need to be known with respect to the earth's gravity field and to equipotential surfaces, best exemplified by mean sea level. Although mean sea level is, ideally, thought of as an equipotential surface, in practise it is not, due to the influence of currents and tides as well as distortions due to landforms (and possibly other factors). The Geoid is defined as an equipotential surface, but our geoid models are approximations limited by the available gravity measurements, and their accuracy.

Whereas the science of such phenomena as climate change and the resulting rises in sea level, tsunamis, broader scale tectonic motion and geomorphological and ecological change over time have little direct bearing upon the generation of DEM data in a geometric context, DEMs are nevertheless indispensable ingredients within scientific investigations into these and other global and local issues. Thus, it is imperative that in any endeavour aiming to establish a NEDF, the needs of the science community are adequately addressed. The science drivers for a National DEM are compelling, though they are often one step removed from the technological challenges facing the mechanics of generating broad area DEMs. However, the technologies of data acquisition for DEMs should not be viewed as being devoid of science issues, for they are not. What is imperative in any National DEM initiative is that the NEDF be designed such that science needs for the present and future are optimally accommodated, for a National DEM needs to serve many purposes beyond those related purely to the provision of elevation data within a national spatial data infrastructure.

If left to its own resources, the spatial information community will no doubt pursue an NEDF design that takes into account both the requirements arising from the User Needs Analysis referred to earlier, and long established mapping-based standards and specifications which pay due attention to the capabilities of current data acquisition technologies. In regard to the necessity for the proposed NEDF to meet broader national needs, the requirements of the science community must be taken into account and accommodated to the fullest extent possible. Without articulating in detail specific science needs, this document lays out a case that implicitly addresses these needs, with the only constraint being related to the limits of current and known emerging technologies.

User Needs

With its focus being upon technological and research issues, this Science Case document forms a complement to the User Needs Analysis, especially with regard to technical matters and key user requirements for a NEDF in terms of data sets and product specifications. These requirements are well summarised in the User Needs Analysis report and it is useful to recall the top five needs of private and public sector users of a national Digital Elevation Model (DEM), as determined across Australia from a series of recently held workshops:

- Develop and apply national standards for elevation data and access.
- Better ability to find and access elevation datasets, using a virtual data repository and a one-stop portal.
- Close the data gap along the coast between existing land and sea data sets.
- A common vertical datum for both land and sea elevation data.
- Leadership to develop a coordinated national elevation data acquisition program that is funded and involves all stakeholders and sectors.

A list of technical issues pertinent to the Science Case arise from these requirements. These include the need for:

- A high-resolution DEM of high vertical accuracy covering coastal and developed areas.
- A common vertical datum, potentially with an updated AHD specification fit for higher resolution data, along with better geoid and tide models.
- Standards in elevation data, modelling, metadata and temporal data.
- Use of metadata to describe all elevation data sets and products, and use of the Australian Spatial Data Directory and jurisdictional directories.
- Standards for error surfaces and modelling consistency, so derived surface products are defined consistently; bare earth or the canopy/building surfaces or a mix of both needed.
- Data management practices and capacity to handle large data volumes.
- A better description of DEM accuracy and sharper definitions of 'resolution'.
- Storage of both source and derived surface data.
- All data capture systems/platforms to capture relevant attribute data; this needs to be considered in choosing the right capture method.
- Flexibility to combine elevation data sources of varying accuracy, scale and lineage.

Although this document concentrates upon technologies and research challenges relevant to generation of digital surface models (DSMs) and DEMs to support the building of a NEDF, it must be emphasised that implementation of a National DEM constitutes a major engineering challenge rather than an initiative possessing significant scientific risk.

DEM Overview

A DEM is a digital cartographic representation of terrain elevation, void of vegetation and man-made features. It generally comprises uniformly spaced height values and can include both topographic and bathymetric data. The concept of a National DEM is relatively straightforward, namely the provision of bare-earth elevations within a grid of specified spacing, referenced to a vertical datum that is common to both the bare-earth elevations and bathymetric data. Realisation of a national DEM, however, is a more complex proposition for a number of reasons, which from a science standpoint include the data acquisition technologies involved, issues with the definition of a uniform vertical datum, the horizontal (grid spacings) and vertical resolutions involved, data quality and data formats. In building the science case for a national DEM, there is a need to address these and other issues, with an initial need to consider those issues impacting upon the establishment of a NEDF rather than upon project level concerns with DEM generation technologies and methodologies.

A term that is often used synonymously with DEM is DTM or Digital Terrain Model. However, DTM often implies the incorporation of additional elevation data within the otherwise gridded model. This can include the definition of breaklines that describe discontinuities in the terrain (e.g. creeks or ridge lines) and mass points for characterising significant topographic features. The discussion here will be restricted to a bare-earth DEM comprising solely gridded elevation data with the concept of a multi-resolution elevation model of consistent, nested grids being fully embraced.

Virtually all data acquisition technologies for DEM generation are based on remotely sensing the terrain and sea floor from above. As a consequence the surface modelled in the first instance is the 'reflective' surface that comprises buildings and vegetation as well as the bare earth. The DSM is a very useful elevation data set in its own right for it is employed for telecommunications planning, forest management, 3D simulation for disaster mitigation planning, air safety and city modelling with the now popular visually realistic fly-throughs. In the context of the provision of a national DEM using newly acquired data, a national DSM must in effect also be generated, with the former then being created through a post-processing of the latter. The accurate and comprehensive removal of 'above ground' features or 'artefacts' remains one the significant challenges in DEM generation, especially in urban and heavily vegetated areas. The development of improved models and algorithms for automatic artefact removal through more comprehensive feature extraction methods is currently an area of active research.

The main purpose of this paper is to lay out the science issues that must be taken into account when developing a NEDF. As mentioned in the introduction, the motivation for generating a national DEM is compelling, whether, it be in relation to coastal vulnerability assessment, natural resource management (especially water) or transportation and urban planning. The concentration here, however, is upon addressing the question of how a framework to accommodate multiple source, multiple resolution DEM data sets might be developed, such that a National DEM in 'product form' is brought to fruition technologically.

Why technologically, rather than scientifically? Simply because DEM generation is already an everyday process within the spatial information industry. There are a number of sensor types currently being employed to produce DSMs, and subsequently DEMs, with varying levels of horizontal resolution and vertical accuracy, and with differing levels of process automation and cost.

Putting aside very important aspects such as cost, industry capacity and the business case for the moment, the Science Case boils down to 1) formulation of appropriate standards and specifications, which take due account of current and likely future technological innovations; 2) addressing research issues such as consideration of the vexing question of datum uniformity and consistency; 3) gaining an understanding of how the DEM data might be managed and disseminated to users; and 4) consideration of an implementation plan, from the technology point of view.

The Multi-Resolution Nested DEM Concept

Under ideal circumstances, Australia should possess a single high-resolution bare-earth DEM that also extends beyond the coastline. A 1/9th second (3m) post-spacing, 20cm vertical accuracy DEM is technologically feasible, using LIDAR for example, and represents the highest possible resolution available today for broad area application using operational technologies. Countries such as Switzerland and The Netherlands have high-resolution national elevation datasets already. A conservative cost for such a National DEM for Australia is $1.5 billion, and there are valid questions related to whether local industry could bring such a huge project to fruition in a reasonable time frame were it to be funded. Regardless, such a high-resolution DEM with national coverage is perhaps unwarranted, and the resources are clearly not currently at hand to achieve such a goal.

There are already single resolution 'National DEMs', notably the 9 second product from Geoscience Australia and so-called DTED Level 1 and 2 DEMS produced from space-borne radar interferometry, about which more will said later. These are lower resolution datasets, however, and they do not satisfy the higher terrain modeling accuracy necessary for critical analysis functions such as coastal vulnerability assessment, flood inundation mapping, assessment of the impact of rising sea levels and hydrological modelling for water resources management.

As a consequence of both the prohibitive costs associated with producing a National DEM of high-resolution and the questionable need for such an accurate terrain model over much of the Australian continent, it is necessary to consider a multi-resolution coverage as a practical and viable alternative. Moreover, as will be seen in the discussion of DEM generation technologies, there are really only three ranges of vertical resolution that are readily realizable with today's technology, these being 10-30cm, 50cm-2m and 5-15m. As can be anticipated, cost is directly proportional to resolution. Thus, the cost of implementing a NDEF is going to be largely a function of whether the DEM comprises either two or all three of these component vertical resolutions and the extent of the area to be covered by each. It should be kept in mind that in relation to 5-15m resolution DEMS, much of the needed coverage is already in place, and this is currently being complemented with a DEM generated from the SPOT 5 HRS satellite imaging system which will cover approximately 2 million km^2 at a resolution of 20m and a height accuracy of around 8-10m.

Associated with different vertical resolutions are distinct horizontal grid spacings, for example the 3-second, 1-second and 1/9th-second post spacings within the US National Elevation Dataset. In adopting multiple grid spacings, it is absolutely imperative that the nesting is consistent in terms of the reference datum, which from a practical standpoint would be either a geographic coordinate system (latitude, longitude) or projection coordinates on the Map Grid of Australia (MGA) reference system.

There are already many instances of multi-resolution DEMs in various jurisdictions within Australia, but thus far these have generally been considered as independent data sources, without consistent 'nesting', without full integration with appropriate resolution hierarchy for a given location and without consistency across resolution levels. Under a NDEF structure, there would be but a single point-of-truth elevation for any given location, irrespective of the resolution level of the DEM data being accessed. Moreover, there would be a smooth transition across resolution boundaries. These issues demand some applied research attention but they are not profound by any means. Instead, they are matters that need to be addressed within the overall data management system for the NDEF.

The idea of having a digital terrain model extend beyond the land, through the littoral zone, to link to near-shore bathymetry is very appealing, especially for studies of coastal vulnerability, from tsunamis for example. The term DEM is generic in meaning and can implicitly include undersea 'terrain'. The actual mechanism by which a land-based DEM can be propagated outwards to merge with bathymetric data is complex for three notable reasons, the impact of each of which basically varies as a function of location. The first is the fact that multiple datums are involved for the bathymetry data, the second concerns the considerable difficulty of DEM generation in the littoral and near shore zone, and the third is concerned with the relatively high expense of broad area bathymetric charting. Coupled with these issues is the rather intangible divergence of application priorities of users of on-shore and off-shore DEM data. For example, of primary concern to maritime interests is the datum formed by Lowest Astronomical Tide (LAT) since this yields minimum encountered water depth for vessels. Yet for a coastal dweller, the most crucial tidal datum is more likely to be a measure of maximum spring tide since this will indicate clearance height above water.

Returning to the issue of datums, the orthometric height reference for Australia, the Australian Height Datum (AHD) was established nearly 40 years ago. In order to tie the geodetic levelling data, which is by nature referenced to a geopotential surface, to mean sea level, the MSL values at 30 tide station locations around the country were held fixed. AHD thus corresponded well to MSL in 30 locations but the non-linear variations between the geoid (equipotential surface) and local MSL beyond the region of these 30 tide gauges has yet to be comprehensively modelled. This might well be of minor consequence for non-coastal regions, but the MSL-AusGeoid separation can amount to almost 1m in Northern Australia and is in many places in excess of 70cm. Compounding the difficulty in tying the bathymetric data to MSL and subsequently to AHD and AusGeoid is the fact that LAT for a particular chart, or portions thereof, might well have been determined with respect to local tide gauge information, independent of the MSL implicit in elevations with respect to AHD. Some such tide gauges, which currently number 100 or more around the Australian coastline, may well have leveling ties to AHD, but many do not. The issue of tying bathymetry datums into a DEM reference datum on a national basis is particularly vexing, at least at the resolution level of 10-30cm, which would correspond to the highest vertical accuracy level within the National DEM.

Adding to the problem of providing a single DEM that extends out to sea, beyond the littoral zone, is the very conspicuous absence of technologies capable of through-water terrain height determination in conditions of surf, turbid water and mangroves. Airborne laser bathymetry systems such as LADS and SHOALS can penetrate clear water to depths of 10s of metres but they rely on reflection of the laser beam from the sea bottom.

DEM Acquisition Technologies

As mentioned, any new DSM/DEM data acquisition programs that are to be undertaken within the foreseeable future for the purpose of building a National DEM are going to involve one of a finite number of sensor technologies. The purpose of the following discussion is to overview the current techniques for DEM generation, primarily to illustrate their capabilities and associated costs (in board terms). The technologies to be considered are photogrammetry; airborne light detection and ranging (LIDAR), also termed airborne laser scanning; interferometric synthetic aperture radar (IFSAR) and bathymetric sonar. In the case of photogrammetry and IFSAR, the sensor platforms can be either airborne or spaceborne. Also, airborne laser scanning can be used for shallow water bathymetry as well as topographic surface modelling. All technologies generate, in the first instance, DSMs though both LIDAR and multi-band IFSAR have the potential of penetrating vegetation to provide bare-earth elevations.

Photogrammetry

As a tool for topographic mapping, photogrammetry has a long history. Traditionally elevation data was extracted from stereo aerial photography in the form of contours. Then, with the advent of analytical photogrammetric processes some 30 years ago, automated DSM generation through image matching technology became feasible. From that time until the present day, levels of process automation have been enhanced, to the point where, today, the generation of a DSM from digital aerial or satellite imagery is a fully automatic batch process, with the resulting DSM often being employed to support orthoimage generation.

Broad area DEM generation via photogrammetry is presently not the preferred approach, except in special circumstances such as very high accuracy DEMs of better than 10cm vertical resolution or the extraction of DSMs for high resolution 3D city modelling. The latter is exemplified by Microsoft’s current program to create high definition, photorealistic city models of the world’s 400 largest cities. This initiative, which is well underway, employs the Vexcel Ultracam X digital camera flown in a block configuration of 80% forward overlap and 60% side overlap at an imaging scale that yields a 15cm ground sample distance (GSD). DSM and subsequently DEMs to around 30cm vertical and 2-3m horizontal resolution can be generated with a high degree of automation through such a process.

Whereas the program being undertaken by Microsoft for its own proprietary purposes uses a digital frame camera, an alternative sensor configuration is a line scanning camera such as the Leica ADS40, which is employed by both the NSW Lands Department and the Department of Defence. Once again, DSMs can be generated with a high level of automation to a vertical resolution of as high as 10cm. Whereas the subsequent removal of above-ground features to produce a DEM can be automated to some extent, a considerable amount of skilled operator intervention is generally also required, the editing work being carried out in a visual 3D environment, which is a particularly beneficial attribute of the photogrammetric technique. Nevertheless, the cost of the DSM-to-DEM conversion can be very significant, and can exceed the total cost of producing the DSM from digital stereo imagery.

High resolution satellite imaging systems have gained popularity for DSM generation at vertical resolutions within the range of about 1m to 10m. For example, the recently launched World View 1 satellite has a 50cm GSD, which will support DSM extraction to around 1-1.5m vertical accuracy; and the dedicated DEM generation program of SPOT Image, namely the SPOT 5 HRS system, yields DEMs with a nominally 8m or so height accuracy and 20-30m horizontal resolution. All satellite imaging systems used for 3D terrain modelling use line scanner technology, with the 2.5m resolution ALOS PRISM satellite having a 3-line scanner geometry similar to that in the ADS40 aerial camera.

While aerial photogrammetry remains a flexible and accurate means of topographic mapping, it tends not to be a preferred technology for stand-alone DEM generation over large project areas where terrain models with vertical accuracies in the 10cm to 1m range are required. The technologies of LIDAR and IFSAR are presently more popular alternatives.

LIDAR

Airborne laser scanning or LIDAR has evolved over the last decade into the clear 'technology of choice' for the generation of high-resolution DEMs, as characterised by vertical accuracies of 10-30cm and horizontal post spacings of 1-3m. The advantages of LIDAR centre upon its relatively high-accuracy of 10-15cm in height and around 1/2000th of the flying height in the horizontal, and upon the very high mass point density of around 1 point/m^2. This high point density greatly assists artefact removal in the DSM-to-DEM conversion. Moreover, LIDAR has high productivity of around 300 km^2 of coverage per hour, and it can be operated 'locally', day or night. In practise, data acquisition is generally confined to daylight hours since most LIDAR units nowadays come with dedicated digital cameras (usually medium format), the resulting imagery being used both to assist in the artefact removal process and for orthoimage production.

One of the most significant attributes of LIDAR is multi-pulse sensing, where the first returned pulse indicates the highest point encountered and the last the lowest point. There may also be mid pulses. As a consequence, LIDAR has the ability to 'see through' all but thick vegetation. Whereas it might not be certain from where in the canopy the first pulse was reflected, it can be safely assumed that a good number of the last returns will be from bare earth. This greatly simplifies the DSM-to-DEM conversion process in vegetated areas. The advantages of LIDAR over high-resolution photogrammetry in urban and city environments are less pronounced since the reflections of surfaces such as the sides of buildings can complicate shape definition and obscure breaklines. A further shortcoming of LIDAR units designed for terrain modelling is that the typically 1m or so laser wavelengths employed do not support water penetration. There are, however, airborne laser systems specifically designed for shallow water bathymetry, the Australian developed LADs system being a prime example. LADS will be discussed in a later section.

As with the photogrammetric DSM-to-DEM conversion, considerable manual post processing of the filtered and thinned out LIDAR DEM is required to 'clean' the bare-earth representation. The cost of the manual post-processing stage has been reduced over recent years as software systems have become more sophisticated. Although the manual intervention may account for 90% of the post-processing budget, it is now down to something in the order of 20%-30% of the overall project budget. One approach to reducing manual post-processing times for LIDAR is lidargrammetry which essentially entails the generation of fictitious images formed from laser intensity data. These are then viewable in stereo, thus bringing the attributes of stereo photogrammetry to LIDAR post-processing. At this stage, however, lidargrammetry could be said to be still under development and there has yet to be wide commercial uptake of the technique, which in practise closely follows a photogrammetry workflow.

In many respects LIDAR data is similar to image acquisition from aerial photography: flights are carried out in strips, with a nominal side overlap of around 30%, depending upon terrain. 'Accuracy' is again a function of flying height, but in the case of LIDAR the heighting accuracy (i.e. ranging accuracy) remains reasonably constant whereas the ground sampling density varies. In general, LIDAR is less expensive than standard photogrammetry, with the cost advantages becoming more pronounced as project areas become larger.

When compared to airborne IFSAR as a technology for DEM generation, LIDAR displays advantages that go beyond its inherently higher accuracy. For a start, LIDAR is a near nadir sensing system, with its field of view extending only about 20^0 each side of the vertical. This allows penetration into urban canyons and enhanced prospects for penetration through vegetation. As will be discussed in the next section, IFSAR is side-looking, which can leave shadowing and data voids in the oblique ranging data, thus complicating somewhat DEM acquisition over urban areas. Over small areas LIDAR displays cost advantages over airborne IFSAR, but when it comes to very large area coverage IFSAR is more cost competitive. A complicating factor in any IFSAR versus LIDAR cost comparison in Australia at the present time is that neither of the world's two prominent commercial providers of airborne IFSAR surveys base a sensor unit locally. Thus, the highly specialised aircraft carrying the IFSAR platform would need to be ferried in from overseas, likely from North America.

There are many variables influencing the cost of DEM generation by LIDAR. These include the size and shape of the project area, its proximity to the aircraft base, the extent of vegetation and artefacts that will require filtering in the DSM-to-DEM processing and the terrain relief. It is no easy matter to provide representative cost estimates, though it can be said that prices have dropped markedly over recent years. An indicative cost for producing a DEM from LIDAR over a large, several thousand square kilometre area, in Australia, is from \$A100-250 per km^2.

IFSAR

Synthetic Aperture Radar (SAR) has been employed for a few decades as an imaging technology in remote sensing. Through an augmentation of a conventional airborne or spaceborne SAR system with a second receiving antenna, spatially separated from the first, it has been possible to utilise the principles of interferometry to extend SAR from a 2D imaging system to a 3D topographic modelling technology. The resulting Interferometric Synthetic Aperture Radar (IFSAR) system determines the relative heights of imaged ground points as a function of the phase difference of the coherently combined signals received at the two antennas. The first commercial IFSAR system for DEM generation, the Intermap STAR 3i system, appeared in the mid 1990s and global focus was brought onto the capabilities of IFSAR to produce DEMs with the successful completion of the Shuttle Radar Topography Mission (SRTM) in 2000.

SRTM employed two IFSAR units, one C-band and one X-band. Over the period of 11 days some 119 million km^2 or 80% of the earth's surface was imaged. The radar data recorded covered the land mass between latitudes of 60^0 N and 56^0 S. Two DEM products were generated, one each at so-called DTED levels 1 and 2. The level 1 SRTM DEM has a post spacing (grid interval) of 3 seconds (approx 90m) and an absolute vertical accuracy of 16m; the relative height accuracy is closer to 10m. The DTED 2 DEM has the same vertical accuracy, but a denser post spacing of 1 second (30m). Australia is covered by both DEM products, the first being freely available, whereas the DTED2 dataset currently has restricted distribution.

In the context of a national DEM, the SRTM DTED1 DEM is of moderate interest as a consistent lower resolution elevation model, though it is more strictly a DSM rather than a bare-earth DEM. Work is currently underway within CSIRO to generate bare-earth DEM data from the SRTM 3-second DSM. The current DTED2 coverage, which is maintained by the Department of Defence, is of better resolution and quality than the DTED1 and it could be argued that this already constitutes a National DEM, albeit one with restricted access that is only of relatively low resolution. Tests have indicted that, overall, the DTED2 DEM of Australia has a relative RMS height accuracy of about 8m. This accuracy level is well below what is required in Australia's coastal regions and inland catchment areas, but would likely prove useful as a consistent DEM product for much of the continent. Efforts are currently underway to remove access restrictions on the SRTM DTED2 DEM, though there is no indication at this time whether this initiative will prove successful. The same DEM product is publicly accessible in the U.S. and in some other countries.

At the present time there are basically two commercial providers of airborne IFSAR DEMs, both being US-based. One is Intermap Technologies, who operate a number of X-band sensors, and the other is Fugro EDI whose GeoSAR system employs X- and P-band sensors. In broad terms, both commercial providers offer similar radar imaging and DEM generation services, though the GeoSAR system has the potential of more automatic DSM-to-DEM conversion due to the vegetation penetration capabilities of P-band radar. Beyond the heavily build-up areas of major cities and very rough mountainous areas, the Australia terrain can be characterized as being ideal for DEM generation via airborne radar. Both the Intermap STAR-4 and GeoSAR systems can produce DSMs to 1m vertical accuracy, and better, with a post spacing of 5m. Moreover, use of stereo radar imagery as a complement to the process allows a semi-automated DSM-to-DEM conversion. With the GeoSAR system, the bare-earth DEM generation is greatly assisted by provision of a P-band DEM.

Airborne IFSAR can record data at a very rapid rate, namely around 100-200 km^2 per minute, which is some 10-20 times the area acquisition rate of LIDAR (the IFSAR swath width is generally 8-20km). Moreover, data collection in not impeded by clouds. Over the past two or three years, there has been a considerable upsurge in 1m-accurate DEM generation via IFSAR, with national DEMs being commercially available through Intermap's Nextmap product line. The first Nextmap DEM was of the United Kingdom and coverage now extends to most countries in Western Europe, much of North America and to Indonesia and the Philippines. Under a cooperative agreement between Papua New Guinea and Australia, the Department of Defence is currently constructing a national radar DEM for PNG, the source data having already been collected with both the STAR-4 and GeoSAR systems.

As a tool for providing DEM data within the NDEF, airborne IFSAR holds a lot of promise, but it is likely only to be cost effective at the present time for large area coverage. Based on project areas of 500,000 km^2 or larger, an indicative cost for airborne IFSAR DEMs of 1m vertical resolution and 5-30m horizontal resolution is \$A60 per km^2.

A second source of radar DEMs is single-pass spaceborne IFSAR. Under the Tandem X program of Germany's DLR and the Infoterra company, the current TerraSAR-X satellite will be joined in space by a second X-band SAR unit. With the orbits of the two satellites being tightly controlled, single-pass IFSAR operation will be possible as will vegetation removal using new techniques for polarmetric radar interferometry. The intended elevation model product from Tandem X is a global DTED3 DEM of 12m post spacing and 2m vertical accuracy. Such a system would be an attractive candidate for generating sizable DEM segments of the NDEF if it were available today. Current expectations are that Tandem-X will not be producing DEM data commercially until 2012 or 2013, even if the second satellite is successfully launched in late 2009.

The PALSAR IFSAR sensor on the ALOS satellite can yield 15m post-spacing DEM data, to a vertical accuracy of around 5m, but not necessarily for all terrain. Thus, in the context of a potential data acquisition system for a national DEM, spaceborne IFSAR should be seen as a complementary technology to alternative techniques rather than as a primary DEM data source, at least until the Tandem-X system is fully operational in five years or so.

Bathymetric DEM Acquisition

Two current technologies present themselves here: airborne lidar bathymetry (ALB) and sonar. Taking ALB first, this is an attractive, cost-effective and accurate alternative to shipborne sonar recording in conditions of relatively clear water where the depth is less than 50m or so. From the point of view of maritime charting ALB is a complement rather than competitor to sonar, since it may have insufficient resolution to pick up all sea-floor hazards. From a DEM generation perspective, however, ALB offers an attractive stand-alone technology for near-shore DEMs (subject to water clarity) and shoreline mapping. There are a number of operating ALB systems, one of the first and most well-known being the Australian developed Laser Airborne Depth Sounder (LADS), now operated by Tenix Defence Systems. The data acquisition rate of LADS is some 20 times that of vessel-based sonar surveys, and the depth/height accuracy can be as high as 30cm or so in favourable conditions. The cost of ALB is significantly higher than LIDAR, an indicative cost being of the order of \$500/km^2. From every perspective, the cost is much more attractive than sonar alternatives. It is noteworthy in the context of the NDEF that ALB can simultaneously gather 3D topographic and near-shore bathymetric data, which is a unique attribute.

Sonar is a well-known acoustics based technique which is most commonly seen in marine echo sounders. In the context of the NDEF initiative, virtually all deeper water bathymetric data which might be integrated into a national DEM will have been gathered by sonar survey systems, and most commonly nowadays multi beam sonar. Sonar systems, and indeed the acoustic technology variations employed for bathymetric surveying will not be further considered in this paper, the emphasis of which is upon building a NDEF for, overwhelmingly, Australia's topography and also for its littoral zones and near shore subsea terrain, where feasible.

Emerging Technologies

Current DEM data acquisition technologies are based on either stereo image triangulation or ranging. This situation is likely to continue into the foreseeable future, with there being no fundamentally new technologies on the horizon. Nevertheless, the capabilities of current technologies are unlikely to remain static. We are witnessing the deployment of earth observation satellites with higher spatial resolution and the emergence of digital aerial imaging systems that provide higher image resolution, a higher redundancy in coverage (eg 90% forward overlap) and consequently more accurate DSMs, along with more automated and comprehensive DSM-to-DEM conversion.

A correspondingly encouraging situation is being witnessed with the ranging systems. Whereas the ranging accuracy of Lidar does not really need to improve, we are seeing the generation of systems with significantly higher pulse rates, which translates to higher horizontal resolution. This in turn allows flights of higher altitude that provide data over a larger swath width. In the IFSAR area the potential of the TerraSar Tandem X system exemplifies the emerging capabilities of satellite-borne systems for high-resolution broad-area DEMs, and in airborne SAR the utilisation of L-band and P-band systems will provide an ever improving capability of recovering DEMs of vegetated and forested areas. In short, it can anticipated that for the next decade at least, 'emerging' technologies will in fact constitute continued refinement of existing DSM/DEM data acquisition systems, complemented by enhancements in data processing. Improvements in the algorithms for data filtering and 3D feature extraction should also be anticipated, such that automated DSM-to-DEM conversion will become more robust and reliable, with less requirement for manual editing.

In regard to emerging survey techniques that can potentially collect bathymetry in turbid water, Airborne Electro-Magnetic Bathymetry (AEMB) is a technology that in spite of being researched for more than 20 years is nevertheless still in its infancy. The Marine Operations Division of the Defence Science and Technology Organisation (DSTO), in collaboration with the Australian Navy, is currently developing an AEMB system. At its present stage of development, this system has shown that it can operate successfully in turbid water and can collect depth data down to about 50-60 metres with a vertical accuracy of about ±0.5 – 1.0 m. However, the horizontal resolution of the system is currently limited, with the "footprint" of the depth measurement being approximately equal to the flying height of the aircraft. This renders the technology inapplicable for high-resolution bathymetric surveying in the near shore zone. Work is underway to improve the performance of the AEMB system, but a matching of the resolution of Bathymetric LIDAR is not likely to be achieved in the foreseeable future. Airborne electromagnetic systems are usually flown at heights of only some tens of metres above the terrain in order to get sufficient signal from the subsurface. This leads to only a small footprint and limits coverage.

Commercial Readiness of Technology

In terms of readiness for large-scale DEM generation, as envisaged under the NDEF, all the technologies described above are currently employed by commercial service providers for this very task. Indeed, the commercial systems in use represent the state-of-art in sensor technology for DEM production, and it is not feasible to set specifications and requirements which are not consistent with the capabilities of current LIDAR, IFSAR and photogrammetry systems. There are currently no imminent technological breakthroughs that would fundamentally alter the three basic sensor-dictated quality categories for DEMs. These are 1) a vertical accuracy of 10-30cm, which requires LIDAR or photogrammetry; 2) 50cm-2m vertical resolution which is achievable with airborne IFSAR, photogrammetric processing of 1m resolution satellite imagery and digital aerial photography (and Tandem-X in the future); and 3) 5-10m vertical resolution which is produced by medium resolution imaging satellites such as SPOT5 HRS and ALOS PRISM and some spaceborne repeat-pass IFSAR systems.

DSM-to-DEM Conversion

The generation of a bare-earth DEM from a DSM involves a number of processes beyond the obvious initial filtering to remove all above-ground features. These include:

i) Possible conversion of height datum, either to change to a new datum (e.g. AUSGEOID to AHD) or to account for local distortion in the datum such that the resulting DEM better reflects local mean sea level conditions, for example.

ii) Map projection or other horizontal coordinate transformation.

iii) Resampling. DSMs will generally be produced in the form of a Triangular Irregular Network (TIN) since the mass points forming the DSM will not, in the first instance, be uniformly spaced. DEMs are generally raster formatted to a grid, which will possess one or more uniform spacings. A common grid spacing structure is that of the National Elevation Dataset of the US, which comprises grid spacings of 3 seconds of arc (approximately 90m), 1 second (approximately 30m) and 1/9 second (approximately 3m). The 3″ and 1″point spacings in latitude and longitude are also used in the definitions of the US military's Digital Terrain Elevation Data (DTED) products. The resampling or gridding of a TIN to a raster DEM is essentially an interpolative surface fitting process.

iv) Overlapping DEMs need also to be mosaicked so that there is continuity and consistency between the adjacent elevation models. This process may in circumstances require coordinate transformations.

v) Edge matching and sliver filling are further necessary processes in the production of large-area DEMs, which are generally tiled. Thus, the data at the tile edges needs to match, and gaps arising in the DSM acquisition, which is usually carried out in strips, need to be filled via surface interpolation.

vi) Finally, it is necessary to generate the metadata files associated with the DEM.

Returning briefly to the initial artefact removal and filtering process, the success of automated processes is a function of point density and height resolution in the cloud of mass points. Popular approaches include morphological filtering, autoregressive processes and least-squares interpolation.

The production process stages for the National Elevation Dataset produced by the US Geological Survey is illustrated in Figure 1. It is important to keep in mind that all current DEM generation technologies involve a significant DSM-to-DEM conversion process. The characteristics of both the underlying terrain and the particular sensor technology will dictate the degree of complexity of the process. Issues include, for example, the fact that photogrammetry techniques beneficially support artefact removal in a visual 3D environment, whereas removal of above ground features in LIDAR DSMs is greatly aided by both the very high density and vertical resolution of the mass points and the provision of multiple returns (ranges) which allow penetration of the vegetation layer. Also, IFSAR DSMs can be accompanied by intensity images that support stereo visual interpretation to aid in the DSM-to-DEM conversion.

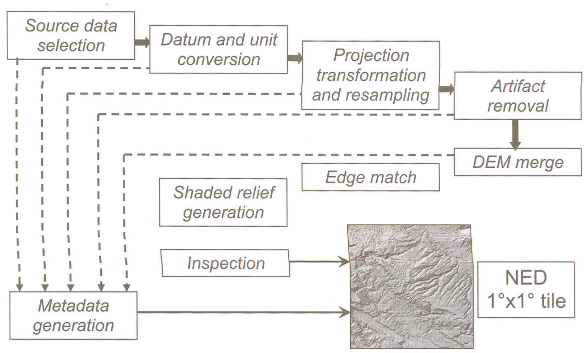

Figure 1. Production processes for the National Elevation Dataset.

NEDF Configuration and Costs

The concept of a multi-resolution nested National DEM raises the immediate question of what areas of the continent need to be covered at which of the three fundamental vertical resolutions there are on offer: 10-30cm vertical accuracy (3-5m post spacing) from LIDAR; 1-2m or so (5-10m post spacing) from airborne and eventually spaceborne IFSAR; and 5m or less (20-30m post spacing) from existing sources or from satellite imaging systems such as SPOT5 HRS and ALOS PRISM. In most respects it can be assumed that all bathymetric data to be incorporated into an NEDF will be from either ship-borne sonar or, in near shore areas of shallow water, from laser bathymetry.

The prioritization of resolutions within an NEDF will be a function of particular user needs. For example, it is widely acknowledged that LIDAR DEM coverage around the coast is warranted for coastal vulnerability assessment and modelling. Yet such studies would logically need to address topography at elevations of, say, 20m or less, thus removing the need for much of the coastline topography to be modelled to such high resolution. Conversely, while large areas in sparsely populated inland regions may warrant DEM coverage to only 10m or so vertical resolution, inland river basins such as the Murray Darling require high resolution ‘hydrologically enforced’ DEMs to support water resource management.

A detailed breakdown of the Australian continent by resolution requirements for a National DEM is beyond the scope of this science case document, though it is useful to consider some of the rough-order-of-magnitude costs that need to be taken into account in planning such a national dataset. The following dot points are offered to provide at least some insight into broad-area DEM acquisition costs. For this exercise, the assumption has been made that an initial, largely automated DSM-to-DEM conversion has also been accomplished:

- Let us first assume that, of Australia's approximately 35,000km coastline, about 25% would need comprehensive near shore bathymetry, which for argument's sake needs to extend to 1km from shore. The cost of acquiring this data by bathymetric LIDAR, where feasible to do so, would conservatively be at rate of approximately \$500 per km^2 or around \$5 million. Ship borne sonar costs are generally at least 10 times higher.
- For coastal topography, let us assume that all areas that are connected to the coast by land at of 20m elevation or less should be surveyed by LIDAR. A rough cost of producing a high-resolution DEM for this 230,000km^2 area is \$40 million. As it happens, this land area is that classed as Major Cities and Inner Regional Australia by the Australian Bureau of Statistics' Remoteness Categorisation. A mitigating factor here in relation to cost is that much of Australia's east and south-east coastline has recently been or is currently being surveyed with LIDAR and the resulting DEM data could readily be integrated into the NEDF.
- There has been a good deal of recent attention paid to the need for a comprehensive DEM of the Murray Darling Basin to aid in water resources management and auditing. The cost of producing a LIDAR DEM for the Basin, which covers about 14% of Australia's land mass, would amount to \$150 million. Scaling back vertical accuracy requirements from 20-30cm to 1m would allow airborne IFSAR to be employed, which would reduce the cost to \$50 million.
- A further speculative scenario is that 10% of the continent would warrant DEM coverage at the 1m vertical resolution. The cost of producing a DEM via airborne IFSAR to meet this specification via airborne IFSAR would amount to around \$45 million. As it happens, Outer Regional Australia, as categorised by the Bureau of Statistics, happens to constitute just over 10% of Australia's land mass.
- Under whatever resolution breakdown is formulated for the NDEF, it is probable that, notwithstanding requirements for better elevation modelling of inland river catchments, some 80% of the Australian continent will warrant DEM coverage at 5-10m vertical resolution. The costs involved in generating such DEM coverage are very difficult to estimate, especially given that much of the required data is already available, from multiple sources. The extent of new acquisitions using SPOT 5 HRS or ALOS PRISM, for example, are difficult to estimate in the absence of a comprehensive quality audit of existing DEMs. If the SRTM DTED2 DEM maintained by the Department of Defence is made available for the NEDF, then there is a reasonable prospect that little new DEM data will need to be produced. On the cost front, an estimate for producing the national low-resolution coverage would then likely run to \$millions rather than \$tens of millions.

From the scenarios above, one can infer that the final NEDF will comprise data from all three vertical resolution levels. Adoption of the areas of high-resolution coverage by LIDAR, medium resolution data from airborne IFSAR and low-resolution coverage from existing sources and the SPOT 5 and ALOS satellite systems hypothesised above yields an overall broad cost estimate for generating a National DEM of around $100 million. This figure could be reduced by 40% or so should the 1-2m resolution layer be dispensed with, and it would grow significantly if the shoreline mapping and shallow water bathymetry components were to be expanded. Regardless of whether a two-resolution or three-resolution NEDF is to be adopted, it is likely that a budget of between $50 million and $100 million will be required to produce a National DEM that will both meet the strongly expressed needs of users and fulfil all its currently envisaged requirements. It is reassuring to note that such a project could readily be accommodated by the local spatial information industry; all the technologies and experience are in place to handle such a multi-year undertaking.

Outstanding Research Issues

Although it has been stated that the creation of a National DEM is technologically quite feasible at the present time, this should not imply that further research and development into a number of aspects related to generating and managing a NEDF is not needed. Sample issues that require research are the following:

Artefact Removal

Within the DSM-to-DEM conversion process, there remain unresolved issues which preclude the practical realisation of fully automatic artefact removal. Indeed it is widely acknowledged that the editing process involved in the conversion currently accounts for up to 90% of the total cost of post-processing. As surface height data density and resolution grows, so the level of success of automatic artefact removal improves, but more robust feature extraction and filtering techniques are still warranted. A good illustration of this problem is in the filtering of DSMs produced from high-resolution satellite imagery. Consider, for example, a DSM generated by comprehensive point feature and edge matching within a stereo image pair covering a nominal scene size of 120km^2. Following an initial filtering to remove obvious data 'spikes', the resulting DSM will display a height accuracy (RMS 1-sigma) of around 2m. A 3-sigma tolerance is thus about 6m and so it is not at all feasible using this DSM data alone to automatically remove the majority of above ground features encountered in the urban Australian landscape. Single-story houses and other than tall trees cannot be removed, thus resulting in a positive height bias in the final DEM. This situation becomes worse as resolution drops and the positive height bias could be anticipated to be more pronounced for imaging systems such as SPOT 5 HRS and ALOS PRISM.

One promising avenue for better artefact removal is through a merging of sensor data. Integrated LIDAR and imaging systems, for example, offer the prospect of improved feature extraction to complement the very dense mass point clouds from LIDAR, leading to more robust filtering of above ground artefacts, more efficient (rapid) processing and significant cost savings. Further research into data fusion from different sensors for DSM-to-DEM conversion is warranted.

Height Datums

A second science question that arises in the DSM-to-DEM conversion process is that of conversion of the data to an appropriate height datum. This matter has been touched upon elsewhere in this paper, but the basic problem is again worthy of illustration. Consider the case of a LIDAR generated DEM of a coastal region in North Queensland. The DEM datum is initially set to the WGS84 ellipsoid as a consequence of the absolute positioning of the LIDAR sensor being via kinematic GPS. A height conversion from ellipsoidal to orthometric is then carried out using geoid height information from AusGeoid. However, what is ultimately required in the context of analysing coastal vulnerability and sea-level rise is the height with respect to mean sea level.

A further transformation is then required between AusGeoid and the AHD. However, there can be discrepancies in actual ‘local’ MSL and AHD amounting to 70cm or more as a consequence of sea-surface topography. What then should be adopted as the DEM datum? Should it be AHD or true MSL? Moreover how might bathymetric data be merged with the land based DEM, given that the MSL-related LAT datum for the bathymetry will have been determined independently of AHD, even though the offset between the two may be known within the local area. One need only imagine the extrapolation of this local example to a national dataset to appreciate the significant complexities involved in tying ellipsoidal height-based DEM data into an orthometric height datum that accounts in some way for the need to link to ‘true’ MSL and bathymetric datums. In the context of formulating specifications for the NEDF, resolution of the datum issue requires research attention.

Integration of Bathymetry

In spite of the very worthwhile aspiration of achieving a NDEF that incorporates bathymetric data in near-shore areas, it may well be practical from an implementation point of view to concentrate initially on topographic coverage, after which the incorporation of bathymetry could be considered as a second stage operation. The focus would be upon carrying out the bathymetry integration into the NEDF in accordance with the priority of need for coastal vulnerability assessment, balanced against the realization that technology solutions for near-shore bathymetry are by no means universal. Further research into this area is needed.

A further four research issues related to the bathymetry component that warrant attention are 1) a DEM requirements study, 2) the development of a data sharing model, 3) harmonisation of vertical datums for bathymetry and 4) an assessment and evaluation of data collection strategies.

NEDF Data Management

Within the broad umbrella of data management issues pertaining to the proposed NEDF there are a number of problems that need further research. These relate in broad terms to data structure, management and dissemination. Technical issues such as tiling, on-the-fly conversion to different DEM resolutions, generation of appropriate quality indicators, supported data formats, and datum conversions where required. The design of an appropriate web-based access portal requires investigation as it will need to support rapid access during times of emergency (tactical) use and at other times for more routine planning and management purposes.

Watching Brief

An on-going process of review of advancements in DSM/DEM generation technologies should be implemented to ensure Australia is routinely provisioned with the most up-to-date advice on all important aspects regarding the production and maintenance of a National DEM. The 3D modelling of our continental land and seabed terrain, along with the utilization of DEMs, is an evolving area that has promise for a number of branches of science.

Prepared in October 07 and revised in February 08 by:

Prof Clive Fraser, Research Director, Cooperative Research Centre for Spatial Information, on behalf of the Technical Steering Committee for the National Elevation Data Framework for Australia, who are advising ANZLIC – The Spatial Information Council.