CORS and a Future Geodetic Framework for Western Australia

July 2006
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Executive Summary

Introduction
The Department of Land Information (DLI) of Western Australia commissioned the technical study ‘CORS and a Future Geodetic Framework for Western Australia’ with the following Terms of Reference (TOR), in order to develop a future strategy for GPS CORS networks in Western Australia:

1. What CORS options are currently available and how good are they for Western Australia?

2. What are the uses of CORS technology beyond geodetic and survey control?

3. What is the required absolute and relative accuracy for a Western Australian CORS network now and in the future?

4. What is the likely impact of GPS modernisation, Galileo and GLONASS on CORS technology and how would this relate in a Western Australian context?

5. Should DLI wish to proceed with a trial CORS network in the Perth metropolitan area, how should that trial be designed to maximise benefit to DLI in future decision making?
Outcomes in relation to the TOR

TOR 1. What CORS options are currently available and how good are they for Western Australia?

General comments

- A number of CORS networks are currently operating in WA, providing different levels of service to different and often very specific markets and users. These include a small number of geodetic CORS, the AMSA, OMNISTAR and VERIPOS services, and a number of CORS run individually by mining, agricultural or other commercial concerns.

- Today, WA is covered by commercial real-time positioning service down to 10-20cm level. This level of service covers the majority of dynamic applications.

- Below the 10cm accuracy level, existing CORS systems, without upgrade, densification and refinement, are not capable of routinely providing geodetic and survey control accuracy requirements in any operationally practical way, nor over any significant area of Western Australia.

- Below the 10cm accuracy level, the positioning market is specialised and relatively small, being restricted mainly to surveyors, mining companies, agriculture and scientific applications. However, whilst the user base is specialised and small, the purpose of high accuracy applications is often in support of significant economic infrastructure and investment projects such as land development, construction (roads, harbours, bridges, pipelines etc), mine site (including safety) and mineral exploration type activities.

- Although few of the existing CORS could be classed as being of geodetic quality, many could easily be upgraded to a geodetic level if necessary. Many agencies would consider such upgrades if they were to provide a concrete legal link to the Geocentric Datum of Australia (GDA).
• The number of CORS networks and individual CORS within the State is set to steadily increase over the next two to five years.

• The study reviewed possible implementation models for establishing a geodetic CORS network system for the primary purposes of *geodetic datum definition and realisation*:
  
  o The *'top down model'*’, in which CORS networks are established and run by government and scientific agencies. Examples were provided from the United Kingdom and Ireland.

  o The *'bottom up model’* unifies all existing CORS networks in a region into a State or National network, under the umbrella of a single government organisation, a case study was provided from the United States.

*Geodetic CORS Networks*

• To practically implement a phased transition to direct definition and realisation of GDA94 and AHD71 throughout the populated areas of WA using GPS and AUSPOS would require around 25 optimally placed CORS network stations.

• In addition to routine surveying and geodetic operations, a 25 station state network would also be able to support:
  
  o an improved State height datum;
  
  o an independent State set of GDA-ITRF transformation parameters;
  
  o regionally computed IGS-style products, such as precise orbits and ionospheric models;
  
  o contribute to continental and global geodesy.

• High precision datum realisation directly through a State-wide CORS network is contingent not only on the installation of optimally placed CORS network stations, but also on technological advances in hardware (GPS modernisation, introduction of Galileo, regeneration of GLONASS, multi-satellite system reception geodetic receivers) and processing software (predominantly the AUSPOS system).
Given the timeline for relevant technological advances, the phased transition to direct high precision realisation of GDA94 and AHD71 through a State CORS network can be projected to be completed by 2015, assuming the projected GNSS modernisation program timeframes are realised, CORS network installation over a 2007 – 2010 period and a commitment to upgrading CORS receivers to multi-satellite system reception geodetic capability, as necessary. Therefore, notwithstanding the installation of a near-optimal State-wide CORS network, the practical realisation of both horizontal and vertical datums would continue to rely on ground marks in the short to medium term.

**Network RTK (NRTK)**

- Simulations indicate that with the current GPS constellation and existing technology, 100km NRTK is not a particularly feasible concept. However, with an inter-station spacing of 50km provision of reliable NRTK services are possible with GPS. The introduction of the Galileo satellite navigation system will greatly improve this situation, making NRTK with 100km inter-station spacing possible and greatly improving the reliability of 50km networks.

**AUSPOS**

- AUSPOS is an automated web-based GPS processing system delivering GDA (and ITRF) high quality datum realisation across the state. It is an important national asset which can already deliver.

- Although other automated web-based processing systems are available from other sources internationally, it is advantageous to the country, and consequently to Western Australia, to maintain its own system, both for legal and developmental reasons and to deliver GDA.

- In the short term, an improved CORS density in WA would improve AUSPOS solutions across the State, so long as data from any additional suitable stations were made available for AUSPOS processing.
In the longer term, to support a phased transition to direct high precision realisation of GDA94 and AHD71 through a State CORS network, AUSPOS requires re-development and state government organisations should support and assist Geoscience Australia (GA) in this process.
TOR 2. What are the uses of CORS technology beyond geodetic and survey control?

The following applications were identified as having potential State or National benefit and as being currently unsupported by the existing CORS infrastructure within Western Australia:

- Regional real time kinematic positioning services.

- Geohazard monitoring, including crustal monitoring, mean sea level monitoring, tidal loading determinations and atmospheric sounding.

- Post-processed kinematic surveying, particularly for airborne survey work.

- Regional IGS-style products such as precise orbits, atmospheric products and ITRF-GDA transformation parameters, which can be used to provide improved dynamic positioning solutions when supporting services such as OMNISTAR.

- Precision guidance systems, with application in agriculture and engineering, are currently supported in an ad hoc sense by the commercial sector. Availability of services is restricted in some areas of the State by commercial constraints.
**TOR 3. What is the required absolute and relative accuracy for a Western Australian CORS network now and in the future?**

This Study identified the accuracy requirements that a geodetic CORS Network system would need to achieve to be useful in horizontal and vertical coordinate realisation.

- **Geodetic applications**, such as datum maintenance and realisation, crustal monitoring, reference for survey control (support for AUSPOS), and tide gauge monitoring, have an absolute accuracy requirement of better than 1cm (95% confidence) in ITRF.

- **Survey applications**, such as transfer of survey control, cadastral surveys, engineering and deformation surveys, including post-processed dynamic applications such as airborne photogrammetry and laser scan surveys, require horizontal and vertical accuracy to 1-5cm (95% confidence), relative to GDA and AHD.

- **High precision dynamic applications**, such as cadastral pickup, road pick-up, machine guidance, high precision agricultural applications, wave-buoy monitoring, require 1-10cm (95% confidence) horizontal accuracy relative to GDA in real time.

- **Medium precision navigation applications** such as precision agriculture, high end vehicle tracking, asset mapping, require horizontal accuracy of 10cm – 1m relative to GDA in real time.

- **Standard navigation applications**, such as land, maritime or airborne navigation require horizontal accuracy in the order of 1 – 10m, usually relative to GDA, in real time. Note that for **liability critical** applications, medium and standard navigation applications may have much higher precision requirements.

- **All other navigation applications** requiring less than 10m accuracy real time can operate with standalone GPS.

Future accuracy requirements are more difficult to quantify. GA, based on collaboration at an international level and its own understanding of the requirements to meet future needs of its
National Geospatial Reference System has defined three levels of future geodetic CORS-based accuracy. These accuracies are about an order of magnitude more precise than current requirements. The GA-based future accuracy expectations are:

<table>
<thead>
<tr>
<th>Category</th>
<th>Accuracy Requirement</th>
<th>Application Examples</th>
</tr>
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</table>
| 1        | 1mm                  | Reference Frame Development  
|          |                      | National Datum (GDA, AHD, Gravity Field)  
|          |                      | Geodetic Science (Neo-tectonics, Sea Level Rise, Isostasy, etc.)  |
| 2        | 10mm at 1σ           | Mapping / SDI              
|          |                      | Precision Agriculture      
|          |                      | Mining / Construction, Engineering |
| 3        | 100mm at 5σ          | Liability Critical Services |
|          |                      | Safety of Life Applications |
TOR 4. What is the likely impact of GPS modernisation, Galileo and GLONASS on CORS technology and how would this relate in a Western Australian context?

**GPS modernisation**

- The current Block II GPS modernisation programme commenced in 2000 with selective availability being set to zero (i.e. switched off).

- Upgrade of 12 of the current generation satellites to carry the new civil L2C GPS code achieved. This improves the quality of geodetic static and Real Time Kinematic (RTK) coordinate precision solutions and improves RTK and Virtual Reference Station (VRS) systems over a longer range.

- The next generation of Block II GPS satellites (implementing 2006 – 2010+) will transmit an openly available third civilian frequency signal, known as L5, in addition to L2C. The availability of both L2C and L5 will significantly enhance RTK capabilities, especially in an urban environment.

- Beyond 2013, plans for Block III GPS could only be considered as indicative, with broad goals to increase signal strength (making indoor GPS more of a possibility), greater availability (i.e. more satellites), improved integrity and greater ‘survivability’ (i.e. less susceptibility to interference).

**Galileo**

- Currently in the development stage, with the first prototype satellite launched in December 2005. Satellites are designed to transmit up to 4 L-band frequencies, possibly with some only accessible on a ‘pay per view’ basis. Galileo will comprise a 30 satellite constellation with the full constellation planned to be operational by 2008 (although 2010 or even 2012 look more likely dates).

- With 30 satellites and potentially 4 L-band signals, Galileo may be seen as a direct competitor to GPS in the RTK market.
**GLONASS**

- By 1997 some 18 GLONASS satellites were operational and with dual GPS/GLONASS receivers and a combined total GPS/GLONASS constellation of over 47 satellites, improved RTK methods demonstrated the powerful potential of expanded GNSS systems over stand-alone GPS.

- Russian support for GLONASS has been variable up until recent times, and as a result the GLONASS system has lost much credibility within the GNSS user community. GLONASS potentially will rapidly be eclipsed by the superior technology offered by the Galileo and modernised GPS systems.

- GLONASS has not been considered in the simulation process. However, it is acknowledged that if an 18+ satellite GLONASS system were to be fully and reliably operational by 2010 or beyond, it could provide useful supplementation to GPS/Galileo.

**Combined GPS/Galileo**

- The future impact on CORS technology of the GPS modernisation program and the emergence of Galileo is likely to be greater if realised by the combined use of both systems. This will provide improved signal strength and reliability, translating to more rapid, reliable and accurate positioning solutions. In the Western Australian context there will be obvious advantages. The primary remaining issue is the accurate transformation of CORS derived positions into GDA94 and AHD71 coordinates.

In a Western Australian context, even if GPS/Galileo/GLONASS system improvements maintain their publicised timescales, there will be a natural lag of several years before users accept the new technology and go to the expense of trading in their existing for new hardware. Therefore the full impact of GPS modernisations, the introduction of Galileo and GLONASS regeneration will most likely be realised around 2015 rather than earlier.
**TOR 5. Potential DLI trial of a CORS network in the Perth metropolitan area to maximise benefit to DLI in future decision making?**

This Study identified a number of current proposals for various implementations of CORS networks in WA and indeed across Australia. Rather than proceed to establishing the infrastructure for a trial CORS network in the Perth metropolitan area, designed to maximise benefit to DLI in future decision making, unless of immediate priority, DLI could leverage off the infrastructure being proposed for CORS in WA and Australia.

In this context, a private Perth company is well advanced in its plans to initiate a 5 station CORS Network Real Time Kinematic (NRTK) geodetic quality system in the metropolitan area. DLI has been requested to provide assistance with the CORS network establishment. This assistance includes (i) providing specifications for all the sites and the data processing, (ii) providing the NRTK base station coordinate realisation, (iii) access to its Midland GPS site for data collection and (iv) ongoing network stability monitoring.

This NRTK geodetic quality system proposal within the metropolitan area, or one of the other potential CORS network initiatives, provides a firm basis for DLI trialling a CORS network in the Perth metropolitan area, at very low capital expenditure.
6. **Recommendations**

**Preamble**
This Study has found that a CORS-based system is a potentially powerful tool for future datum definition and realisation in Western Australia. Any future geodetic CORS network in WA (or Australia) would be capable of supporting the system of:

i) providing, realising and maintaining a modern integrated geodetic infrastructure system, both horizontally (GDA94) and vertically (AHD71), to meet the spatial infrastructure needs of the State;

ii) the legal traceability requirements as specified under the *National Measurement Act 1960*;

iii) high accuracy scientific applications such as sea level monitoring, atmospheric modelling and crustal monitoring.

The ability of such a network to successfully fulfil these roles would be dependent upon projected technological software and hardware developments coming online in the next 5 years.

The introduction of a WA CORS network would represent a policy of phased transition from datum definition and realisation through ground marks to a system of definition and realisation predominantly through the State CORS network. Given current technological limitations, for Western Australia this transition would be likely to take until 2015 and beyond.

Such a transition will be critical to maintain the State’s geodetic and navigational infrastructure, in the light of rapid technological developments, throughout the first half of the 21st century.

The following recommendations, drawn from the outcomes of this study, pertain to the role of DLI in datum definition and realisation and in the establishment of a CORS network in the state of Western Australia.
**Recommendation 1:** DLI to maintain its role of maintaining State standards for datum realisation, legal traceability and support for high accuracy scientific applications such as sea level monitoring, atmospheric modelling and crustal monitoring.

**Recommendation 2:** It would be beneficial to future State development and infrastructure to develop and install a State CORS network capable of high precision geodetic datum definition and realisation.

**Recommendation 3:** Given the size of Western Australia, the bottom up model for geodetic datum definition and realisation for CORS is financially attractive and facilitates cooperation with industry, rather than competition. Furthermore, since hardware upgrades are market driven, DLI would not be exposed to uncertainties caused by future technological development.

**Recommendation 4:** DLI to examine the legal framework for all CORS based positioning activities in WA.

**Recommendation 5:** DLI to lead definition and implementation of unified WA CORS network by initiating contact with CORS operators from all sectors across the State. DLI to clarify role and relationship with GA in any unified state CORS network.

**Recommendation 6:** An optimised network of around 25 geodetic CORS will be required to provide basic GPS coverage for high precision geodetic datum definition across the populated areas of the State.

Note that receiver upgrades at CORS sites would need to be undertaken after proven multi-satellite system reception geodetic receiver technology becomes available.

**Recommendation 7:** DLI to consider installation of a dense CORS network (i.e. 50-100km spacing) in the south-west of the State, for the support of the geodetic datum, the agricultural and resources sectors and geohazard applications.

**Recommendation 8:** Due to the increasing incompatibility between AHD and GPS derived orthometric heights, DLI must maintain a transformation surface across the State between
AHD and GPS derived orthometric heights. A State CORS network would provide the stable framework upon which this surface can be based and maintained.

**Recommendation 9:** DLI should develop a new ‘scientific’ height datum based purely on CORS GPS and the high precision gravimetric geoid in order to maintain a completely GPS compatible height datum for scientific applications and closely monitor the inconsistencies in the AHD.

**Recommendation 10:** There is an unfulfilled requirement for accurate ITRF-GDA transformation parameters for WA. DLI should use a CORS State network to compute State transformation parameters in conjunction with the GA national solution.

**Recommendation 11:** Unless there are matters of urgency and priority, any potential trial of a CORS network in the Perth metropolitan area to maximise benefit to DLI in future decision making should be delayed until DLI can leverage off the infrastructure provided by other CORS initiatives in this State.
## List of acronyms

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFN</td>
<td>Australian Fiducial Network</td>
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<tr>
<td>AHD</td>
<td>Australian Height Datum</td>
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<td>AMSA</td>
<td>Australian Maritime Safety Authority</td>
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<tr>
<td>ARGN</td>
<td>Australian Regional GPS Network</td>
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<tr>
<td>AUSPOS</td>
<td>GA automated web-based positioning service</td>
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<tr>
<td>BoM</td>
<td>Bureau of Meteorology</td>
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<tr>
<td>CORS</td>
<td>Continuously Operating Reference Station</td>
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<tr>
<td>CSRS</td>
<td>Canadian Spatial Reference System</td>
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<tr>
<td>CSRS-PP</td>
<td>Canadian Spatial Reference System Precise Point Positioning service</td>
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<tr>
<td>DAFWA</td>
<td>Department of Agriculture and Food, Western Australia</td>
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<td>DGPS</td>
<td>Differential GPS</td>
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<td>DLI</td>
<td>Department of Land Information, Western Australia</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<td>GA</td>
<td>Geoscience Australia</td>
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<tr>
<td>GDA</td>
<td>Geocentric Datum of Australia</td>
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<tr>
<td>GNSS</td>
<td>Global Navigation Satellite Systems</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>GRAS</td>
<td>Ground-based Regional Augmentation System</td>
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<td>IERS</td>
<td>International Earth Rotation Service</td>
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<td>IGS</td>
<td>International GNSS Service</td>
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<tr>
<td>INSAR</td>
<td>Interferometric Synthetic Aperture Radar</td>
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<tr>
<td>ITRF</td>
<td>International Terrestrial Reference Frame</td>
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<tr>
<td>LBS</td>
<td>Location Based Service</td>
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<tr>
<td>NGS</td>
<td>National Geodetic Survey, USA</td>
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<tr>
<td>NOAA</td>
<td>National Oceanographic &amp; Atmospheric Administration, USA</td>
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<td>NRTK</td>
<td>Network Real Time Kinematic GPS</td>
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<td>NTC</td>
<td>National Tidal Centre, South Australia</td>
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<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
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<tr>
<td>OPUS</td>
<td>On-line Positioning User Service (USA system)</td>
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<tr>
<td>OSI</td>
<td>Ordnance Survey Ireland</td>
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<tr>
<td>OSUK</td>
<td>Ordnance Survey United Kingdom</td>
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<tr>
<td>OTL</td>
<td>Ocean Tide Loading</td>
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<tr>
<td>PDOP</td>
<td>Precise Dilution of Precision</td>
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<tr>
<td>PPP</td>
<td>Precise Point Positioning</td>
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<tr>
<td>PW</td>
<td>Precipitable Water</td>
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<tr>
<td>RINEX</td>
<td>Receiver Independent Exchange format – for exchange of GNSS data</td>
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<tr>
<td>RTCM</td>
<td>Radio Technical Commission for Marine Services</td>
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<tr>
<td>RTK</td>
<td>Real Time Kinematic</td>
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<tr>
<td>SEAFRAME</td>
<td>SEA-Level Fine Resolution Acoustic Measuring Equipment</td>
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<tr>
<td>SSM</td>
<td>Standard Survey Mark</td>
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<tr>
<td>SWSZ</td>
<td>South West Seismic Zone</td>
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<tr>
<td>VRS</td>
<td>Virtual Reference Station</td>
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<tr>
<td>WADGPS</td>
<td>Wide Area Differential GPS</td>
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1. Scope of this document
This document covers outcomes from the workplan detailed in the Proposed Technical Study document on ‘CORS and a Future Geodetic Framework for Western Australia’. The Proposed Technical Study was developed under the following Terms of Reference (TOR), in order to develop a future strategy for GPS CORS networks in Western Australia:

1. What CORS options are currently available and how good are they for Western Australia?

2. What are the uses of CORS technology beyond geodetic and survey control?

3. What is the required absolute and relative accuracy for a Western Australian CORS network now and in the future?

4. What is the likely impact of GPS modernisation, Galileo and GLONASS on CORS technology and how would this relate in a Western Australian context?

5. Should DLI wish to proceed with a trial CORS network in the Perth metropolitan area, how should that trial be designed to maximise benefit to DLI in future decision making?

The Scope is contained in Section 1 of this report. Section 1 also provides a definition of the terminology, particularly in terms of positioning applications and types of CORS network that will be used throughout the document.

Section 2.1 summarises the status of CORS facilities and services in Western Australia at the time of writing. Technical analyses associated with the evaluation these services (including the AUSPOS and OmniSTAR systems) are documented in the associated report “CORS and a Future Geodetic Framework for Western Australia – Technical Report”. Section 2.2 highlights likely future developments for CORS positioning services in Western Australia.

Section 3 discusses applications which are currently either unsupported or are only partially supported by existing positioning infrastructure in Western Australia, whilst section 4
discusses models for CORS networks in a West Australian context using examples from around the world. Section 4 includes a detailed discussion of models for height datums.

Section 5 discusses the options and issues related to the installation of a CORS network in Western Australia, including a summary of network simulations conducted as part of this study. The report concludes with a list of recommendations.

1.1 Definition of applications and types of positional accuracy in the context of this report

1.1.1 Geodetic applications, such as datum maintenance and realisation, crustal monitoring, reference for survey control (support for AUSPOS), water vapour estimation and tide gauge monitoring, have an absolute accuracy requirement of better than 1cm (95% confidence) in ITRF.

1.1.2 Survey applications, such as transfer of survey control, cadastral surveys, engineering and deformation surveys, including post-processed dynamic applications such as airborne photogrammetry and laser scan surveys, require horizontal accuracy to 1-5cm (95% confidence), relative to GDA.

1.1.3 High precision dynamic applications, such as cadastral pickup, road pick-up, machine guidance, high precision agricultural applications, wave-buoy monitoring, require 1-10cm (95% confidence) horizontal accuracy relative to GDA in real time.

1.1.4 Medium precision navigation applications such as precision agriculture, high end vehicle tracking, asset mapping, require horizontal accuracy of 10cm – 1m relative to GDA in real time.

1.1.5 Standard navigation applications, such as land, maritime or airborne navigation require horizontal accuracy in the order of 1 – 10m, usually relative to GDA, in real time. Note that for liability critical applications, medium and standard navigation applications may have much higher precision requirements.

1.1.6 All other navigation applications requiring less than 10m accuracy real time can operate with standalone GPS.
1.1.7 *Future accuracy requirements* are more difficult to quantify. GA, based on collaboration at an international level and its own understanding of the requirements to meet future needs of its National Geospatial Reference System has defined three levels of future geodetic CORS-based accuracy. These accuracies are about an order of magnitude more precise than current requirements. The GA-based future accuracy expectations are:

<table>
<thead>
<tr>
<th>Category</th>
<th>Accuracy Requirement</th>
<th>Application Examples</th>
</tr>
</thead>
</table>
| 1        | 1mm                  | Reference Frame Development  
National Datum (GDA, AHD, Gravity Field)  
Geodetic Science (Neo-tectonics, Sea Level Rise, Isostasy, etc.) |
| 2        | 10mm at 1σ           | Mapping / SDI  
Precision Agriculture  
Mining / Construction, Engineering |
| 3        | 100mm at 5σ          | Liability Critical Services  
Safety of Life Applications |

1.2 Definition of CORS and CORS networks

Continuously Operating Reference Stations (CORS) are defined as GPS (GNSS) receivers located permanently at sites having very accurately pre-determined coordinates. A CORS tracks GPS (GNSS) satellites continuously 24 hours a day. A CORS may be an individual receiver or may form part of a group of receivers strategically located across a region. Groups of CORS are referred to as CORS networks. Such networks may span areas of several tens of kilometres in dimension (for example the Singapore CORS network), or be regional, continental or even global in scale.

Components of CORS networks vary depending on the base application for which a network is designed. For example, a CORS network designed to provide real time positioning at the metre level of accuracy for emergency service vehicles generally has a different architecture to a CORS network to detect millimetres of crustal strain across an active geological fault.
1.3 Type of CORS network architecture

1.3.1 Geodetic CORS network

In this document, the term *geodetic* refers to CORS networks and their associated hardware which are designed to operate to the highest levels of positional accuracy on regional, continental and global scales. Examples of such networks are the International GNSS Service (IGS) global network, which underpins the International Terrestrial Reference Frame (ITRF) and through which precise orbital products are generated, and the Australian Regional GPS Network (ARGN), which is the foundation of the Geocentric Datum of Australian (GDA). Note however that ITRF and GDA are fundamentally different in character in that ITRF is a true three dimensional coordinate system whilst GDA represents a two dimensional horizontal datum. In Australia, height is represented separately by the Australian Height Datum (AHD). Vertical height datums are explored in detail in Section 4.5. Relating GPS (GNSS) 3D derived positions to the AHD is an important issue and explored in detail in Section 4.5.

The installation specifications for geodetic CORS receivers are the most stringent of all types of CORS network. Stations are usually situated on bedrock in carefully chosen multipath-free environments. Receivers are high precision dual frequency instruments using antennas which have strong multipath mitigation characteristics (usually choke-ring antennas) and whose geometric (phase centre) properties are well known. Traditionally, GPS data are collected at 30 second intervals, although a significant percentage of geodetic CORS stations now log at 1 second intervals.

Raw data are transmitted back to central archive for post-processing. Processing centres compute solutions using a number of geodetic data processing packages (eg Bernese, GAMIT, GIPSY) which apply the most detailed and recent modelling and estimation technique to produce solutions based on daily or weekly data sets. The raw data, usually in Receiver Independent Exchange (RINEX) format, are generally made available to external users, who may combine network data with their own data to produce post-processed position solutions. Alternatively, some organisations (eg Geoscience Australia, National Geodetic Survey (US), Natural Resources Canada) provide online data processing services which perform a similar function. Some of these services can also use their geodetic CORS network data to provide users with post-processed kinematic solutions.
The primary function of most government-owned geodetic CORS networks is to form a basis for geodetic datum realisation and definition. However, geodetic CORS networks also support a number of scientific applications, such as crustal motion monitoring, atmospheric sounding and earth observation. In Australia, the Australian Fiducial Network (AFN) contributes to the definition of the legal traceability of GPS positions.

Geodetic CORS networks can be upgraded to supply or contribute to DGPS, WADGPS, RTK or NRTK services by installing the appropriate hardware and firmware, processing software and communications software. Therefore, any receiver in a CORS geodetic network can be seen as potentially able to contribute to any of the aforementioned types of GPS service. Conversely, a receiver which constitutes part of a DGPS, WADGPS, RTK or NRTK service can be upgraded to become a constituent of a geodetic CORS network.

1.3.2 Differential (DGPS) CORS

Differential GPS is the simplest method of improving the accuracy of a hand-held GPS receiver in real-time. A reference receiver, situated at a known point, observes ranges (distances) to all available satellites. Because the coordinates of the receiver and the satellites are known, any error in the measured range (predominantly due to the atmosphere) can be estimated. It can be assumed that a similar error will affect nearby users. Therefore the reference station ‘broadcasts’ a series of ‘differential corrections’ representing the generated error estimates which can be applied by the user to substantially improve the accuracy of the position given by the user’s GPS receiver. Generally, the 10-15m horizontal precision of hand-held GPS units can be improved to a 1-5m level using DGPS techniques.

The provision of DGPS services is a well established industry and a number of organisations run individual DGPS CORS stations which transmit differential corrections, using (usually) VHF radio links, over regions of up to 1000km in radius. These corrections are broadcast in a format (RTCM) which has become the industry standard amongst navigation hardware. The main users of such corrections are in the field of land, maritime and air transport.

Since DGPS is based on the GPS code signal, DGPS CORS receivers tend to be cheap single frequency code receivers. Given the level of expected accuracy from a DGPS service, installation requirements for DGPS CORS are somewhat less stringent than for geodetic
CORS, with the main consideration for DGPS CORS service providers being convenience and security of hardware. ‘Geodetic’ CORS concerns, such as site stability, are not an issue although real time integrity is critical for any DGPS CORS service provider. Whilst individual DGPS CORS operate and transmit differential corrections independently of other CORS stations in the network, some architectures do transmit all data back to a master control site for purposes of integrity monitoring.

1.3.3 Wide Area Differential (WADGPS) CORS network

Similar to a DGPS CORS network, a WADGPS CORS network supplies differential corrections to a user to enable enhanced positioning in real time. A WADGPS Network consists of a regional network of CORS whose data are relayed back to a master control station, where a regional correction model is generated for GPS error sources, specifically ionosphere and satellite orbits. These corrections are transmitted to the user. The atmospheric model is transmitted as a function whose absolute value depends on the user’s approximate location, which can be derived from the user’s receiver point position solution. Satellite orbital corrections may also be applied. In the ‘Virtual Base Station’ approach, differential corrections from the different available reference stations are combined in a mathematical solution (an inverse-distance weighted least squares solution based on the approximate location of the user’s receiver) to generate RTCM corrections which ‘look’ as if they are generated from a nearby reference station.

WADGPS CORS receivers tend to be placed hundreds of kilometres apart. Although a user receiving WADGPS corrections requires only a single frequency code receiver, WADGPS CORS receivers are dual frequency, although not generally of geodetic CORS quality due to commercial limitations on their location (it is expensive as well as difficult to find and be able to establish permanent facilities at secure stable locations with good sky visibility). WADGPS communication to the user may be either VHF radio based or, more commonly, via communication satellite.

WADGPS CORS networks routinely deliver DGPS level positional accuracies to a user over regions of several thousand kilometres in extent. Modern systems can achieve sub-metre accuracy with an intrinsically high level of integrity. This level of service is widely used for
higher end navigation applications in the oil and gas industry, the agriculture sector and for augmenting air navigation systems.

1.3.4 Real Time Kinematic (RTK) CORS

Similar in concept to DGPS, RTK works by having a geodetic dual frequency carrier phase receiver situated at a known point and broadcasting RTK ‘corrections’ (in reality raw code and carrier phase data) to a roving user in the field. The users also require a geodetic dual frequency carrier phase receiver and hence the cost of an RTK system is substantially greater than that of a DGPS system. The range of RTK systems is limited by the quality of the terrestrial radio link between the reference station and the user, and the distance from the user to the base station. In WA, RTK is generally a local system (less than 10 km between the known and end user stations), is almost always established by the user and generally on an as required basis.

The major advantage of RTK is that it can provide a user with real time accuracy in the 1-2cm range (horizontal, 1σ), as shown in Figure 1. The results shown in Figure 1 for test surveys carried out on the Main Roads Western Australia RTK Test Network at Curtin University, indicate an accuracy of 17mm (easting), 15 mm (northing) and 46mm in the vertical directions (or 51mm 3 dimensionally) from 15 independent test surveys.

Note that the results represent cases where the roving antenna was within 5km of the base at all times. Beyond 5-10km RTK results can become significantly more variable. The main drawback of RTK as opposed to DGPS is a lack of robustness caused by the necessity to initialise the system which can take several minutes if satellite signal quality and numbers are sub-optimal. The system must also be reinitialised if lock is lost on all satellites.

RTK is popular in the survey industry although, as points observed through an RTK system simply represent radiations, some quality control and integrity issues exist. RTK is used widely for high precision maritime work (eg harbour approach), high precision agricultural applications, machine guidance, and mining applications such as stock pile estimation and set out. Because RTK systems are operating at the centimetre level, geodetic CORS stations (logging data at 1 second intervals) are ideal as RTK reference stations. Indeed, most geodetic
GPS receivers have the innate capacity to act as an RTK reference station. A number of geodetic CORS networks worldwide have been upgraded to provide RTK services close to CORS sites.

![Graph showing error distribution for RTK surveys](image)

**Figure 1** Results from the 15 independent RTK surveys conducted on Curtin University RTK benchmarking network

### 1.3.5 Network Real Time Kinematic (NRTK)

As with WADGPS, NRTK relies on a network of CORS receivers to provide users with regional error models which can be used to improve a user’s position. Whilst WADGPS and NRTK CORS network data communication architecture is very similar, the main difference is that NRTK has RTK-levels of accuracy but, in order to achieve centimetre level accuracy, a denser network of CORS is required than in a WADGPS network.

By necessity, NRTK CORS must be geodetic or very close to geodetic in quality and indeed, a number of geodetic CORS networks have been upgraded to provide NRTK services. CORS spacing can be in the order of 10km to approximately 100km although the higher the station density, the more reliability and integrity a system will display. Clearly, the main advantage of a NRTK CORS network is that a wider region of users can be reached than through individual RTK CORS stations of limited applicable range. As a rule of thumb, a RTK network requires...
about 30 CORS to give full coverage per 10,000 square kilometres; NRTK requires 5-10 CORS over a region of that size.

Two main NRTK architectures exist, Virtual Reference Station (VRS) and the Master-Auxiliary concept, as implemented in the Leica SPIDER software. Whilst conceptually very similar, the different architectures display some interesting differences, the most important of which is that a VRS network has a limited number of users, due to a requirement that the VRS network master control must be in two-way communication with each individual user. In theory, the Master-Auxiliary concept is not subject to this limitation. However, both architectures go some way to solving the ‘RTK radiation’ problem in terms of quality control through improved network integrity, although the amount of quality and integrity information actually supplied to the user can vary considerably.
2. CORS facilities and services in Western Australia – status as of October 2005

2.1. Existing CORS networks in Western Australia (as of October 2005)

2.1.1  Geodetic CORS network

2.1.1.1  Description, architecture
Currently, five geodetic CORS sites are operating in Western Australia: Yarragadee (Dongara), Karratha and Hillarys, operated by Geoscience Australia; New Norcia and Perth (Gnangara) operated by the European Space Agency (ESA) (Figure 2). An additional four sites, Darwin, Jabiru, Alice Springs and Ceduna, operated by Geoscience Australia (GA) as part of the Australian Regional GPS network (ARGN) (Figure 3), are sufficiently close to Western Australia to contribute to long range solutions. With the exception of Hillarys, all Western Australian CORS stations contribute to the International GNSS Service (IGS) global tracking network of geodetic CORS stations (Figure 4).

With the exception of Hillarys, where the GPS antenna is mounted on a galvanized pipe attached to a shed and jetty, each geodetic CORS in Western Australia operates dual frequency carrier phase geodetic GPS receivers with multipath minimising choke ring antennas situated on observing pillars which are periodically monitored by accurate local surveys to nearby deep-driven reference marks. Data from geodetic CORS stations in WA are relayed to, and archived by, Geoscience Australia (GA) in Canberra on an hourly basis. The data are also relayed to the IGS processing centres, including ESA.

Data processing is undertaken by GA using the Bernese GPS Processing Software version 4.2. Daily solutions are computed using standard geodetic processing strategies, which includes site coordinate estimate and estimation of tropospheric zenith delay parameters at 2 hourly intervals. Seven daily solutions are combined at the normal equation level to obtain a weekly coordinate solution and associated quality statistics. A regularly updated analysis report can be
found on the GA website, including ITRF-GDA transformation parameters\(^1\). The transformation model is a 14 parameter time-dependent model.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{european的空间位置.png}
\caption{European Space Agency CORS worldwide locations \hspace{1cm} \texttt{http://nng.esoc.esa.de/gps/gps_net.html}}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{argn.png}
\caption{Australian Regional GPS Network (ARGN) \hspace{1cm} \texttt{http://www.ga.gov.au/geodesy/argn/}}
\end{figure}

In addition to performing daily and weekly geodetic solutions, GA also uses the raw GPS data archive from the ARGN to offer a 24 hour online web-based GPS processing service, AUSPOS. Within Australia, this service allows users to directly derive GDA coordinates from their own GPS data. The service also accesses the IGS data archive to allow users in any location worldwide to compute solutions from their own data.

Since its inception in November 2000, AUSPOS has proved to be a successful and widely used service and has gone some way to being adopted as an ‘industry standard’ in Australia. A number of similar services are available worldwide, most notably AUTO_GIPSY (JPL), CSRS_PP (Canadian Spatial Reference System) and SOPAC (Scripps Permanent Orbit and Array Centre). These services are available to users in Western Australia and they are evaluated in the accompanying technical document. Notably, AUTO_GIPSY and CRSR_PP are point positioning services which rely on IGS models and products to compute solutions, rather than forming baselines. Therefore, for these systems, dense regional networks are not an issue, although a course regional network of stations is necessary to ensure IGS products are adequately covering a region. Because DLI has direct access and input to AUSPOS through GA, this report will assume that AUSPOS will continue to be the primary online service provider for the State for high precision applications. The future development of AUSPOS will be important to the development of State geodetic infrastructure and will be discussed subsequently.
2.1.1.2 Accuracy

a) Bernese Geodetic Solutions

Figure 5 shows a time series of recent IGS solutions derived by Geoscience Australia for New Norcia and Karratha, showing that the coordinates of the geodetic CORS sites in Western Australia are known relative ITRF2000 to about 7mm rms in the horizontal and 10mm rms in the vertical. These uncertainties are standard for sites in the IGS network and represent the ‘best’ that can be achieved in a global network.

![Time series for Karratha](image1)
![Time series for New Norcia](image2)

Figure 5  Geoscience Australia Time series for Karratha and New Norcia geodetic CORS

b) AUSPOS

The quoted AUSPOS accuracy from GA is:

“Typically, a good quality geodetic receiver and antenna, with 24 hours of data using the IGS final orbit product, should give results to better than 10mm horizontally and 10-20mm in the vertical.”

Furthermore, GA state that 2 hours of data generally give coordinates to better than 20mm horizontally and 50mm in the vertical, although the recommended occupation time is a minimum of 6 hours with IGS Final Precise Orbits. IGS Final Precise Orbits are not available.

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until two weeks after the observations, hence solutions requested beforehand will not reflect the best achievable accuracy.

As part of this study, AUSPOS has been independently benchmarked against other web-based geodetic positioning services for a number of global stations. Furthermore, AUSPOS has been evaluated for a number of sites in Western Australia. The full analysis from the AUSPOS evaluation is presented in the accompanying technical document, the main conclusions being:

− The accuracy of AUSPOS (and other web-based position services) refer to observations that are undertaken with dual frequency geodetic quality receivers and using the IGS Final Precise Orbits;
− the accuracy of AUSPOS quoted by GA is realistic for Western Australia for 24 hour data sets and for observing sites within about 300km of ARGN stations;
− 6 hour data spans for observation sites in Western Australia provide results at the level quoted by GA so long as observing sites are within about 300km of ARGN stations;
− for sites further than about 300km from CORS stations, results are more variable, suggesting long baseline models in AUSPOS could be improved;
− AUSPOS solutions are at the same level of quality as other web-based position services.

2.1.1.3 Supported applications

The primary function of existing geodetic ARGN CORS in Australia (Figure 3 above) is to define GDA. This definition also includes the definition of legal traceability for position and definition of transformation parameters between GDA and ITRF. Furthermore, whilst the ARGN cannot be used to directly define the Australian Height Datum in its current form, the ellipsoidal heights generated do form a reliable high quality link between AHD and AUSGEOID.

From a geodetic point of view, GDA is currently realised in WA through a hierarchical network of ground points including the Australian National Network, the Statefix network and local networks such as the Metrofix network which covers the Perth metropolitan region. These hierarchical networks are strongly interconnected and represented by traditional ‘marks in the ground’.
Since the introduction of the AUSPOS service, it has been possible for a user to realise GDA coordinates directly through the Australian geodetic CORS network by simply submitting GPS data to this online service. Theoretically, provided a user meets all the conditions to achieve cm level accuracy, the existence of such services may be seen to remove the requirement for interim networks of ground points. This issue will be revisited in section 5 of this report.

Navigation service providers usually link their CORS sites to GDA via AUSPOS, hence passing on GDA coordinates to their users. It is important to realise that in 2005 GDA is not simply being realised through a series of marks on the ground maintained by DLI, but is being realised continuously in a dynamic sense by CORS service providers supplying GDA-compatible corrections to their users. See the accompanying technical document for analysis of existing capabilities of AUSPOS and associated online services. Note however that the OmniSTAR system works with ITRF coordinates which are then transformed by users in Australia to GDA using GA transformation parameters.

Through the contribution of geodetic CORS data to the IGS, the existing CORS sites in Western Australia indirectly contribute to the production of IGS products. Most widely used of these products are the precise orbit and satellite clock products which offer substantial improvements on the GPS broadcast ephemeris. The availability of such products is of exceptional value to the positioning community. Other IGS products, such as the atmospheric models, are, to date, less widely used, mainly because the turnaround time in production is insufficient for the real time applications for which they would be of most use.

The existing geodetic CORS network in WA also supports scientific ‘geohazard applications’ and atmospheric studies. These applications will be discussed in more detail subsequently.

2.1.1.4 Weaknesses/other issues

a) Geodetic Solutions

The distribution of geodetic CORS in Western Australia is sparse and uneven. Unlike Precise Point Positioning (PPP) services such as AUTO_GIPSY and CSRS, AUSPOS demonstrates a clear baseline length dependence in terms of accuracy delivery. Using current technology and algorithms, the maximum baseline length for AUSPOS processing to achieve 1-2cm GDA
realisation anywhere in the state should be 300km. Clearly this CORS station spacing criteria is met in some parts of the state, but not in others.

The precision of the GA 14 parameter transformation model relating GDA and ITRF in WA is dependent on the number of CORS stations contributing to the solution. From this point of view, the existing network is certainly suboptimal and ITRF-GDA transformation parameters could be improved in WA by densification of the CORS network.

Whilst the requirement for datum realisation at the 1-3cm level can be theoretically met without the need for ground control points, even a 300km geodetic CORS station spacing would still require a minimum of 6 hours of station occupation for a user defined GDA control point. Clearly, such an occupation time is, in many cases, impractical (the proposed DLI User Survey will provide an independent operational perspective on this point).

Height remains a problem in a ‘world without ground marks’ scenario as all GPS height definition is substantially worse than in the horizontal. Advances in GPS processing models still have been unable to resolve all height issues, although AUSPOS models (AUSPOS runs Microcosm software) are well known to be not as up to date as they might.

Scientific applications requiring geodetic CORS have somewhat different demands to that of datum definition/realisation. Applications such as sea level monitoring and crustal monitoring depend on spatial density of stations, whereas, in principle, geodetic datum realisation requires a relatively sparse network of stations. Similarly, atmospheric sampling is extremely dependent on site spacing. It is obvious that the current network of CORS stations in Western Australia is insufficient to service any of these scientific applications on a regional basis. Note however, it is adequate on a continental basis for, for example plate motion measurement, due to the overall stability of the Australian continent.

**b) AUSPOS**

The main weakness of the AUSPOS system as it stands may be summarised as:

1. the necessity for the observation of long data sessions in order to obtain 1-2cm accuracy in the horizontal.
2. solutions show a baseline length dependence when baselines of greater than about 300km are included in the solution, representing deficiencies in the Microcosm
processing models applied (eg ocean tide loading models, lack of the latest mapping functions).

3. the solution is composed of 3 baselines formed relative to the nearest CORS. The accuracy of the solution in ITRF is highly dependent on the quality of the ITRF coordinates of the 3 CORS stations used in the solution. Furthermore, poor data quality, for any reason, at one of the selected CORS and/or at the observer’s site will have a detrimental impact on the AUSPOS coordinate solutions.

4. the two week delay in obtaining full accuracy through use of the IGS Final Precise Orbits.

At the time of writing, upgrades to AUSPOS are being implemented at GA (see p34).

2.1.2 Australian Maritime Safety Authority (AMSA) Differential GPS Network – A Free to Air Service

2.1.2.1 Description, architecture
The existing AMSA GPS network has been operational since December 2002 (AMSA originally declared its system operational in February 1998). It comprises 4 stations in Western Australia: Albany, Fremantle, Exmouth and Karratha (Figure 6).

![Figure 6 AMSA DGPS network](http://www.amsa.gov.au/Shipping_Safety/Navigation_Safety/Differential_Global_Positioning_System/Coverage_Map/)
AMSA offers a standard differential service to maritime users. Two independent single frequency GPS receivers are located at each site, generating differential range corrections which are broadcast in the LF/MF band (285 – 325kHz). Stations have built-in integrity monitoring and station status is reported to users through coastal navigational (AUSCOAST) warnings. Stations automatically flag satellites operating outside specification and include ‘unhealthy’ warnings in the broadcast RTCM corrections (AMSA follows the DGPS transmission standards as recommended by the International Association of Lighthouse Authorities) within a few seconds of a problem being detected at a satellite. Maximum system latency is 3 seconds.

2.1.2.2 Accuracy
Quoted accuracy for the AMSA network is < 10 metres (95% confidence) with typical maritime users achieving 2-4 metres. As with any standard DGPS service, position accuracy degrades with distance from the reference station.

AMSA reference stations must meet legal traceability requirements and they are currently coordinated into GDA/ITRF through the ARGN. Stations in Western Australia are quoted as having an absolute WGS84 accuracy of 10cm in the horizontal (http://www.amsa.gov.au/).

2.1.2.3 Supported applications
The primary function of the AMSA network is to support navigational aids such at Electronic Chart Display and Information Systems (ECDIS) and the Automatic Ship Identification System (AIS). AMSA complies with a number of international standards, such as RTCM (Radio Technical Commission for Maritime Services), IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) and ITU (International Telecommunications Union), to ensure that equipment on international vessels is capable of receiving and using the system’s DGPS signals.

2.1.2.4 Additional comments
Many large port authorities (e.g. Fremantle) have their own RTK capability for inshore surveys, berthing applications/under keel clearance.
Legal traceability is clearly an issue for AMSA. As an organisation, AMSA would benefit from incorporating their stations into a state/national CORS infrastructure, hence giving a continuous legally traceable link to GDA.

AMSA GPS reference stations are not of geodetic quality.

2.1.3 OmniSTAR network – a Commercial System

2.1.3.1 Description, architecture
Fugro OmniSTAR operate a worldwide network of GPS reference stations with over 70 reference stations and 3 network control centres globally. Four reference stations (Perth, Kalgoorlie, Karratha and Broome) are located in Western Australia, as is one master control centre (Perth) (Figure 7). The reference station in Darwin can also contribute to coordinate solutions in Western Australia.

![Figure 7 OmniSTAR reference stations in the West Australian region](image)

OmniSTAR offer different levels of service in Western Australia, including the same type of standard DGPS service offered by AMSA, employing VHF systems for short ranges and low
frequency transmitters for medium ranges. However, the strength of OmniSTAR is in its WADGPS capability, which involves transmitting differential corrections via the Optus geostationary communication satellite.

2.1.3.2 Accuracy
OmniSTAR offers two levels of WADGPS service: VBS (Virtual Base Station) and HP (High Performance). The VBS service is quoted as providing sub-metre accuracies at the 95% confidence level, whilst the HP service claims decimetre level of accuracy.

Independent tests on the OmniSTAR service in Western Australia, conducted as part of this study and described in section 4 of the associated technical report, confirm the quoted accuracy level of the HP service, although degradation in accuracy was detected for the station most distant from the OmniSTAR reference stations. This could be a distant-dependent issue or simply a problem with data quality at the local station. However, it may be concluded that OmniSTAR can offer reliable positioning at the 10-20cm level in the horizontal across the State.

2.1.3.3 Supported applications
OmniSTAR operates in the agriculture (precision farming, crop dusting), survey (mining and land), and exploration (land, offshore and aerial) sectors. Its 10-20cm real time horizontal coverage from the HP service represents the benchmark for high precision statewide real time services.

2.1.3.4 Additional comments
The existence of the OmniSTAR service offers a real-time decimetre-level service across the state of Western Australia. Independent tests have backed up the company’s accuracy claims. The service is robust and reliable with high levels of integrity.

With the introduction of the HP service, there is now a requirement for OmniSTAR reference receivers to be of geodetic quality i.e. dual frequency and adhering to IGS installation standards.
As with all service providers, integration of the OmniSTAR network into a legally traceable framework through a statewide geodetic CORS network would be advantageous both in terms of aiding GDA realisation and strengthening the legal basis for the system.

OmniSTAR currently works in ITRF and thus relies on a coordinate transformation to supply GDA coordinates. Transformation parameters and other products derived from regional and global CORS networks will become increasingly important as the OmniSTAR service develops further.

2.1.4 Veripos – a Commercial System

2.1.4.1 Description, architecture
Veripos is a subsidiary of Subsea 7, a leading sub sea engineering and construction contractor. It supplies standard DGPS services via VHF and satellite communications links. In Western Australia, this service is delivered through reference stations (single frequency receivers) situated at Perth, Exmouth, Dampier, Broome and Darwin (Figure 8). Raw observations from each station are sent to a regional master control station, where integrity checks are performed and differential corrections generated and uploaded. Typical data latency is quoted as 2 seconds, with a 5 second average age of correction and predicted availability 99.997% (http://www.veripos.com). These figures are typical of DGPS systems such as the AMSA and the OmniSTAR DGPS service.
2.1.4.2 Accuracy
Quoted accuracies are 1-3m (2DRMS) up to 1000km from a reference station; <5m (2DRMS) up to 2000km from a reference station.

Reference station coordinates are derived in ITRF2000 using post-processed dual frequency carrier phase in GIPSY-OASIS II processing software. Reference station coordinates are claimed to be at the cm level.

2.1.4.3 Supported Applications
The Veripos system is aimed exclusively at the offshore oil and gas industry.

2.1.4.4 Additional Comments
The Veripos system is similar in functionality to the AMSA system, with the exception that differential corrections are delivered primarily through communication satellite rather than VHF radio link, giving the system longer range.

2.1.5 Individual CORS facilities in Western Australia
A large number of CORS are operated across the State by individual entities who have usually installed reference stations to satisfy their own needs. It is somewhat difficult to quantify the exact number and location of these installations. The main areas of operation are land transport, agriculture, the mining industry and surveying.

2.1.5.1 CORS in the mining industry
The majority of open cut mine sites in the State now use RTK GPS for surveying and therefore run their own CORS.. Figure 9 shows the location of mines in Western Australia and it can be assumed that the majority of locations have CORS capability in some form or another.
RTK systems are also becoming more widely used on mine sites for high precision machine control whilst some mines now have their own separate DGPS systems (or subscribe to OmniSTAR) to support truck fleet management and hazard and collision avoidance.

2.1.5.2 Agriculture

Agriculture is a major growth area for positioning services with the majority of agricultural operations in the State now utilising some form of satellite based positioning. Installation of CORS stations for agricultural applications has been, to date, on a strictly ad hoc basis. A number of companies such as Agsystems, Precision Farming Australia, Rinex, Satloc and Trimble Precision Agriculture specialise in supplying positioning solutions to the industry, whilst the OmniSTAR XP product will specifically target the agriculture sector.

As with the mining industry, it is difficult to quantify the number and type of CORS stations installed for agricultural purposes. Cost and economics are a much more significant driving force in agriculture than the mining industry. It may be generalised that DGPS CORS are widely operating in agricultural regions whilst a number of farms are running their own RTK
systems. From a government point of view, the Department of Agriculture and Food Western Australia (DAFWA) has run three differential stations in post-processed mode, located in Albany, Narrogin and Moora (Figure 10). These stations are for DAFWA uses only, however, and are not currently being maintained.

![Figure 10 Agriculture Western Australia DGPS stations (post-processing only)](image)

**2.2 Known future upgrades/system developments**

**2.2.1 Geodetic CORS upgrades**

*a) NASA installation in Kalgoorlie (expected late 2006)*

NASA has a policy of supporting installation of CORS at locations where they can significantly benefit global and regional geodetic CORS networks. In 2005, negotiations began between NASA and DLI with regard to installing such a CORS in Kalgoorlie. This installation is likely to take place in 2006 with the station possibly becoming an integral part of the ARGN and IGS networks.
b) Australian Baseline Sea Level Monitoring Project (expected late 2006/ early 2007)

The National Tidal Centre (NTC) provides the management and operational support for the Australian Baseline Sea Level Monitoring Project. The project is designed to monitor sea level around the coastline of Australia and to identify long period sea level changes. NTC maintains an array of SEAFRAME (SEA-Level Fine Resolution Acoustic Measuring Equipment) stations which measure sea level very accurately, and record meteorological parameters. The array consists of fourteen standard stations and two supplementary stations (Lorne and Stony Point) (Figure 11), which are owned by port operators.

Vertical stability of the gauges is surveyed by State organisations, the data being archived by Geoscience Australia. To date, only one of the three SEAFRAME sites in Western Australia, (Hillarys), is monitored using CORS GPS. Plans exist to install geodetic CORS at the two other SEAFRAME stations at Broome (likely installation date 2006) and Esperance (likely installation date 2007 - though subject to funding).
c) GA National Collaborative Research Infrastructure Strategy (expected 2007/08, subject to funding approval)

Geoscience Australia is leading a bid for funding from the National Collaborative Research Infrastructure Strategy (NCRIS) for a significant upgrade of the Fundamental Australian Geodetic Infrastructure\(^3\). Expressions of interest closed in February 06 and successful bids will be announced in September 2006. Approximately 100 CORS stations have been proposed nationally. For Western Australia, the bid includes between 10 and 30 new CORS GPS sites, the locations of which are yet to be determined. Funding is, however, subject to government approval.

d) AUSPOS upgrade (2006 onwards)

GA has moved from Microcosm to Bernese V5.0 as its primary GPS processing software. This software allows a number of advanced modelling options that are not currently available in Microcosm. GA has commenced a project to port AUSPOS from the Microcosm engine to the new Bernese engine.

GA has also expressed an intention to further develop AUSPOS by incorporating regional non-IGS CORS into the solution where appropriate, i.e. sites that meet suitable quality compliance criteria. Such a move would likely improve coordinate accuracies and reduce occupation times whilst leaving the primary function of the AUSPOS service unchanged.

A number of further extensions to the existing AUSPOS service have been suggested, including

- Long range Kinematic positioning
- Regional Orbit improvement for Precise Point Positioning applications
- Single frequency processing using Regional ionospheric models
- Application of high rate real time RINEX data to drive down occupation times and solution delivery times

Such suggestions have a sizeable research component, however, and represent features likely to be implemented only in the medium to long term.

\(^3\) [http://auscope.org.au/](http://auscope.org.au/)
2.2.2 Ground-based Regional Augmentation System (GRAS)

A Ground-based Regional Augmentation System (GRAS) is essentially a WADGPS CORS network designed for the aviation industry (Figure 12). To this end, a GRAS incorporates a higher level of integrity than a standard WADGPS system.

An Australian GRAS is currently being developed by Airservices Australia, the Australian government's air navigation service provider. Airservices Australia has contracted Honeywell's Defence & Space Electronic Systems business in Minneapolis; and GPS at Systems Ltd in Melbourne to assist in implementing the new system, which should be operational by 2008.

GRAS reference stations will have dual frequency receivers logging at a high observation rate, installed to near geodetic CORS specifications. Specific requirements have been released by Airservices Australia in relation to GRAS CORS siting, the most pertinent to this document being:

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4 Airservices Australia: http://www.airservicesaustralia.com/
1. Sites must be close to an Airservices Australia maintenance centre.
2. Sites must have low RF noise environment to ensure good GPS reception.
3. At least another two stations must be situated within 600 nautical miles (1100km) (ensuring integrity against site failure).
4. Such that the entire area, where service provision is required, is surrounded by the stations installed.
5. Sites must have easy access to both power (if possible mains and backup/standby/emergency power), and communications (both Telstra land line and Airservices Australia satellite communication.)
6. Each CORS site to run a receiver and a backup receiver contiguously for integrity purposes.

![Figure 13 Proposed GRAS stations in Western Australia](image)

At present, likely sites for GRAS CORS are Perth, Carnarvon and Derby (Figure 13).

### 2.2.3 Industry CORS initiatives
AAMHatch have developed and tested a long range airborne GPS system which relies on post-processing data logged from a regional CORS network. This joint project with Curtin University is supported by the Australian Research Council.

It may be anticipated that more RTK base stations will be installed, predominantly by the surveying and agriculture sectors, as the market demands. Within the duration of this project, one privately run NRTK service has been declared operational in the Perth Metropolitan region. This network and its possible impact is simulated in section 5 of this report.

2.3 Summary/Discussion in relation to positioning status in WA as of today.
A number of CORS networks are currently operating in WA, providing different levels of service to different and often very specific markets and users. The number of CORS networks and individual CORS is set to steadily increase over the next two to five years.

Although few of the existing CORS could be classed as being of geodetic quality, many could easily be upgraded to a geodetic level if necessary. Many agencies would consider such upgrades if they were to provide a concrete legal link to GDA.

WA is covered by commercial real-time positioning service down to 10-20cm level. This level of service covers the majority of dynamic applications highlighted in section 1.1. Below the 10cm level, the positioning market is relatively small, being restricted mainly to surveyors, mining companies and scientific applications. Although major interest in high precision positioning is emerging from the agricultural sector, it may be some time before cm level positioning can be proven to be cost-beneficial to farming operations. Even then, the agricultural market for, say, NRTK, is relatively small.

AUSPOS is an important national asset which can already deliver high quality datum realisation across the state. Although other automated web-based processing systems are available from other sources internationally, it is advantageous to the country, and consequently to Western Australia, to maintain its own system, both for legal and developmental reasons and to deliver GDA. It is likely in the future that GA will tailor

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AUSPOS to meet the specific needs of users in Australia in order to improve solutions at local and regional levels.

In the short term, an improved CORS density in WA would improve AUSPOS solutions across the State, so long as data from any additional suitable stations were made available for AUSPOS processing. In the longer term, AUSPOS requires some re-development and State government organisations can support and assist GA in this process with the aim of deriving the benefit of more accurate solutions.
3. Unsupported additional CORS applications in WA as of October 2005

This section highlights CORS applications in WA which are currently unsupported by existing CORS infrastructure. They are therefore applications which could become available if appropriate densified CORS networks were available across the State.

3.1 Limited coverage for development of regional IGS-style products

Future high accuracy rapid positioning will depend on the timely availability of accurate satellite orbits and clocks, earth rotation parameters and atmospheric parameters. Automated services such as AUSPOS and CSRS are dependent on such products, which are computed by the IGS with various degrees of latency (Figure 14)\(^6\). As latency decreases, these products will become increasingly important for real time applications.

With the exception of Hillarys, the existing operating geodetic CORS in Western Australia feed data into the IGS product solution. Additional CORS in WA could also be expected to feed into IGS, hence strengthening data availability for the region. However, due to the computational load, it is unlikely (though not impossible) that all stations from a WA geodetic CORS network would feed into IGS. Therefore, regional products such as regionally generated orbits and atmospheric products could become part of the fundamental positioning infrastructure by being available to support AUSPOS and other high precision activities. The responsibility for generating regional IGS-style products would likely be taken by GA (see section 4.3) rather than any State government organisation.

\(^6\) http://igscb.jpl.nasa.gov/components/prods.html
<table>
<thead>
<tr>
<th>IGS Product Table (GPS Broadcast values included for comparison)</th>
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<tbody>
<tr>
<td><strong>GPS Satellite Ephemerides</strong></td>
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<tr>
<td><strong>Satellite &amp; Station Checks</strong></td>
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<tr>
<td><strong>Broadcast</strong></td>
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<tr>
<td>Sat clocks</td>
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<tr>
<td><strong>Ultra-Rapid (predicted half)</strong></td>
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<td>orbit</td>
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<td>Sat clocks</td>
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<td><strong>Ultra-Rapid (observed half)</strong></td>
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<td><strong>Final</strong></td>
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<tr>
<td>orbit</td>
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<tr>
<td>Sat &amp; SLR clocks</td>
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</table>

Note 1: IGS accuracy limits, except for predicted orbit, based on comparisons with independent laser ranging results. The precision is better.
Note 2: The accuracy of all clocks is expressed relative to the IGS timecode, which is linearly aligned to GPS time in one-second segments.

<table>
<thead>
<tr>
<th>GLONSASS Satellite Ephemerides</th>
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<tr>
<td><strong>Geocentric Coordinates of IGS Tracking Stations</strong></td>
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<td><strong>(-150 sites)</strong></td>
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<td><strong>Final positions</strong></td>
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<td><strong>Final velocities</strong></td>
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<th>Polar Motion (PM)</th>
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<td><strong>Polar Motion Rates (PM rates)</strong></td>
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<td><strong>Choke of day (COD)</strong></td>
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<td><strong>Ultra-Rapid (predicted half)</strong></td>
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<td>PM</td>
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<td>PM rate</td>
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<td>LOD</td>
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<tr>
<td><strong>Ultra-Rapid (observed half)</strong></td>
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<td>PM</td>
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<td>LOD</td>
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Note: The XXI uses VLBI results from IERS Bulletin A to calibrate long-term LOD bases.

<table>
<thead>
<tr>
<th>Atmospheric Parameters</th>
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<tr>
<td><strong>Final tropospheric zenith path delay</strong></td>
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<tr>
<td>4 mm</td>
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<tr>
<td><strong>Ultra-Rapid tropospheric zenith path delay</strong></td>
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<tr>
<td>6 mm</td>
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<tr>
<td><strong>Final Ionospheric TEC grid</strong></td>
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<td>2-8 TECU</td>
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<tr>
<td><strong>Rapid Ionospheric TEC grid</strong></td>
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<tr>
<td>2-9 TECU</td>
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</table>

**Figure 14  IGS Product Table**
3.2 Support for post processed precise kinematic applications

As discussed in section 2.2.3, a perceived requirement for post-processed high precision kinematic capability in the State, mainly for airborne survey work, has led to some recent industry-funded development work.

Kinematic processing is currently available in WA from web-based post-processing services. Lack of independent quality control on these services means they are little used in the State although test results computed as part of this project (section 3 of the associated technical document) indicates that post-processed kinematic solutions can be as good as 5cm in the horizontal and 10cm in the vertical.

Whilst the addition of a long range kinematic option to AUSPOS has been suggested (see section 2.2.1d), it would appear more likely that some form of joint collaboration between industry and government will deliver such a service in the future.

3.3 Lack of NRTK coverage

No NRTK coverage is currently available anywhere in Western Australia. Although, the most likely short-term market for RTK users in the Perth Metropolitan region is finite, with most potential users coming from the survey sector, it is likely that at least one, and possibly more, NRTK systems will be operating in the region by early 2007. Problems with the commercial viability of existing NRTK systems are acknowledged in a recent paper published by Leica7.

A bigger driver for NRTK is coming from the agricultural sector. For example, one resolution from the 3rd National Controlled Traffic Farming Conference in Gatton, Queensland, July 2005 was "that networks of 2cm GPS base stations be established in all cropping districts". A number of agricultural applications are beginning to require RTK/NRTK accuracies. These applications include guidance and automatic steering, precise fertiliser and seed placement, controlled traffic, bore coordination, clearing assessment etc. There is also a developing requirement in the agricultural sector for support from CORS networks for applications involving reliable and consistent positioning to national standards such as Genetically

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7 J. van Cranenbroek, Vincent Lui* and Ryan Keenan (2005). Making Profitable GNSS RTK Infrastructure, Leica Geosystems, Heinrich-Wild-Strasse, Heerbrugg, 9435, Switzerland
Modified plot trial management, fire ant management and canker virus. These applications require positioning that can support legal processes and actions.

Commercially, the main issue with providing NRTK services for the agriculture sector is the low density of users per region. The maximum NRTK CORS spacing of current off the shelf systems is the order of 70-100km, which would require many tens of stations to cover the entire Western Australian agricultural region. Whilst it is likely to be more economical for farmers in local area to combine resources to install NRTK on a limited scale, rather than purchase individual RTK systems, before any such systems are installed a solid economic benefit will have to be clearly demonstrable to the farming community. In Western Australia at least, the adoption of NRTK for agriculture, should, in the short-medium term, be market driven.

3.4 Geodetic CORS networks to support for geohazard monitoring and research

3.4.1 Crustal monitoring for seismic deformation
In the last decade, a number of countries in seismically active regions have established CORS GPS networks to provide estimates of horizontal co- and post-seismic deformation of points on the Earth’s surface. For example, the Japanese CORS network comprises some 1200 GPS receivers, spaced roughly at 20km from one another. The Southern California Integrated GPS Network (SCIGN) network near Los Angeles comprises some 100 receivers. This network is being extended over the entire western USA to form what will be called the Plate Boundary Observatory (PBO) with several hundred GPS receivers spaced at roughly 50km. The horizontal motion caused by the seismicity in these areas is of the order of a few centimetres per year, which is relatively easy to detect using CORS. This is not the case in Western Australia which, although being widely regarded as forming part of a geologically stable continent, also hosts a reasonable amount of intraplate seismic activity (Figure 15), predominantly in the South West Seismic Zone (SWSZ).

A number of geodetic monitoring surveys have been undertaken in the SWSZ, the most recent being a 48 point network observed by episodic GPS in 2002 and repeated in 2004. Unfortunately, due to the inherent noise in episodic GPS solutions and the relatively small crustal motion, the episodic, campaign-based approach to GPS-geodetic monitoring of the
SWSZ is unlikely to be able to detect the likely small amounts of surface motion in the near future.

Based on international best practice in geodetic monitoring, from a scientific perspective CORS network should be established across the SWSZ. However, this has to be tempered against the small amount of likely deformation. However, if there is a large earthquake in the SWSZ that produces surface rupture, there will be a need to quantify this, so there is the need to have the appropriate geodetic infrastructure in place. This will add to understanding of the causes of the seismicity, and hence improved risk mapping and emergency management planning.

A SWSZ CORS network would be located based on the parallel considerations of the best available tectonic models of the region and contemporary (last 30 years) of earthquake records. One main issue is that CORS provide only localised point samples of regional crustal motion. Even if CORS were installed at each of the 48 points in Figure 15 there is no guarantee motion could be detected. A more realistic approach would be to use a combination of limited CORS networks in geologically targeted areas (to provide high precision ground control) and the spatial resolution of differential interferometric synthetic aperture radar (DInSAR), which can detect small amounts of vertical motion over large areas.

The SWSZ is located in the heart of the Western Australian wheat-belt region. As such, any CORS infrastructure used to continuously monitor the SWSZ has a potential spin-off in precision agriculture. In this case, CORS stations installed for geodetic monitoring of the SWSZ could also be used to as an NRTK network for precision agriculture.
Figure 15  Seismic activity in south western Western Australia and the 48-point geodetic monitoring network established in 2002.

3.4.2 Mean sea level monitoring
The Australian Baseline Sea Level Monitoring Project was discussed previously in section 2.2.1b. CORS stations are important for monitoring vertical crustal motion at tide gauges, without knowledge of which it is impossible to identify whether sea level is rising or the land upon which the tide gauge is situated is sinking. In spite of the proposed installation of CORS at the Esperance and Broome tide gauges (2.2.1b), it would be beneficial, from a scientific perspective, to monitor more tide gauge sites. Notwithstanding cost, logic would dictate that all ten tide gauges in Western Australia which were used in 1971 to define AHD in the State (Figure 16) be monitored by CORS.
CORS located at these sites would also aid validation of the national geoid model, AUSGEOID, and provide information about local sea surface topography.

### 3.4.3 Tidal loading determination

**a) Ocean Tide Loading**

The oceans move periodically due to the gravitational attractions of the Moon and Sun, and in turn the solid Earth responds periodically due to the change in the mass distribution of the water of the oceans. This is the *ocean tide loading (OTL) displacement*, and its vertical range can be more than 10cm over the course of about 6 hours in some parts of the world, such as North West Australia. OTL displacement, if incorrectly mitigated, can propagate directly as an error source into GPS coordinate solutions (Figure 17). Hence, for high precision geodetic GPS height solutions, it is critical to ensure that OTL can be mitigated sufficiently for every station in a CORS network.
Modelling OTL displacement requires OTL parameters, computed per site by convolving a model of the ocean tides throughout the world with a model of the Earth’s rheology using Green’s loading functions. However, OTL models differ significantly around the Australian coast (Figure 18) and OTL model errors propagate into the final coordinate (particularly height) solution.

b) Atmospheric Pressure Loading

The need to correct GPS measurements for ground displacements due to atmospheric pressure loading (APL) has long been recognised (and included in the International Earth Rotation Service (IERS) Standards and Conventions), with largest peak-to-peak height displacements of around 15 mm possible over timescales of 1-2 weeks (Figure 19). Importantly, however, almost all geodetic GPS analyses do not currently apply corrections to the GPS measurements for atmospheric pressure loading effects. Invariably, the presence of APL leads to a degradation of geodetic CORS solution, predominantly in the height component.

![Atmospheric pressure loading displacement amplitudes (mm) at the (a) S1 and (b) S2 tidal periods](image)

Figure 19  Atmospheric pressure loading displacement amplitudes (mm) at the (a) S1 and (b) S2 tidal periods

The impact of APL in the GPS error budget is an area of active research.

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c) Impact of tidal loading in Western Australia

Weaknesses in modelling both tidal loading and atmospheric loading contribute to a degraded geodetic coordinate solution for Western Australia. Errors in loading models degrade the definition of GDA in the State. The resultant weaknesses in height impact on AHD definition, validation and resolution of geoid models and the detectable resolution of sea level change. From a scientific point of view, in Western Australia, a higher density of geodetic CORS stations than present, particularly in coastal areas, is desirable to test and improve tidal models. Whilst such improvements remain in the research domain, it will be difficult to substantially impact on current achievable height accuracies with CORS networks without the support and infrastructure offered by a densified State CORS network.

3.5 Monitoring vertical crustal displacements due to groundwater movement

In certain geological situations, widespread groundwater withdrawal can result in long-term ground subsidence. Furthermore, seasonal groundwater variations can result in seasonal ground displacement, such as those observed by Bawden et al (2002)\textsuperscript{10} in the Santa Ana basin in Los Angeles. Such ground signals have been observed in California using both INSAR and the dense network of CORS GPS receivers (Watson et al, 2002)\textsuperscript{11}. Groundwater related displacement can mask smaller tectonic signals and must be taken into account when interpreting GPS CORS time series.

Little is known of the impact of groundwater variation on vertical crustal displacement in Western Australia and, in particular, the Perth Metropolitan region. A densified State CORS network could provide a framework on which to base studies on the geodetic impact of groundwater variation (for example, deformation of the AHD). However, such studies would require integration of INSAR observations and geodetic monitoring of the AHD into the framework offered by a CORS network over a period of several years and would require a significant investment on behalf of the State and/or Federal government.


3.6 Atmospheric Sounding

GPS signals are retarded by the Earth’s neutral atmosphere (‘troposphere’) on propagating from satellites to receivers. Tropospheric delays may be mapped to the zenith and estimated at CORS sites from the GPS data. Estimates of atmospheric water vapour benefit weather forecasting and research into atmospheric storm systems, the hydrologic cycle, atmospheric chemistry and global climate change.

Traditional precipitable water (PW) sensors include ground and satellite based water vapour radiometers, radiosondes, ground-based humidity sensors and research aircraft. GPS can be considered a complementary sensor, providing economical, continuous estimates of PW in all weather at a spatial resolution governed solely by the number of receivers. The potential impact on quantitative precipitation forecasting by assimilating GPS estimated PW into numerical weather prediction (NWP) models, has been demonstrated in Australia by Penna et al (2005)\textsuperscript{12}.

It is generally accepted that a high-resolution network of geodetic CORS will allow diagnosis of three-dimensional water vapour applicable to mesoscale weather prediction. For example, networks with station spacing as little as 40km are providing meteorological information in parts of Europe (eg Finland, UK, Switzerland). To be effective for meteorological forecasting in a practical sense in Australia, GPS estimated PW estimates must be available to the Bureau of Meteorology (BoM) in near-real time and at a spatial resolution that densifies the existing radiosonde network (Figure 20).

\textsuperscript{12} Glowacki TJ, N Penna and W Bourke (2006). Validation of GPS based estimates of integrated water vapour for the Australian region and identification of diurnal variability, \textit{Australian Meteorological Magazine} (accepted).
Given the size of the State, optimal CORS spacing for meteorological applications in Western Australia is problematic. BoM are currently researching the potential impact of GPS on their operation and have not, to date, expressed a firm commitment to installing or supporting CORS in Australia. However, given the sparsity of radiosonde sites in Western Australia, any future densification of the WA geodetic CORS network would likely be of interest to BoM in the long term, although extraction of PW products from the national geodetic CORS networks in near real time would require a significant investment to upgrade GPS data processing facilities in Australia, either at GA or elsewhere.
4. Geodetic datum maintenance and realisation

4.1 Existing State geodetic network in Western Australia
The existing State geodetic network is realised through some 29,000 permanent ground marks (SSMs) which represent successive network densifications traceable back to ARGN. Issues regarding the maintenance of the geodetic ground network and its relationship to the Spatial Cadastral Data Base have been highlighted elsewhere. This report considers models by which CORS networks can be used for datum realisation and to enhance geodetic infrastructure in the State of Western Australia.

4.2 Datum realisation through other CORS services and service providers
Currently, GDA coordinates can be derived in Western Australia without the necessity of occupying any of the State’s geodetic ground marks. The horizontal datum can be realised at a 0.1m – 5m level through any of the service providers described in section 2 (provided their CORS are coordinated into GDA), or at the 1-2cm level, through the AUSPOS service. Recall, however, that AUSPOS requires a minimum 6 hours occupation time at a point and has been demonstrated to provide better results with 24 hour observation session lengths and baseline lengths of less than 300km. Further, use of the IGS Final Precise Orbits is recommended for highest accuracy and this implies a two week latency between observations and results.

NRTK CORS networks can deliver horizontal datum realisation at the 1-2cm level in real time. Furthermore, a densified State CORS network would lead to reduced AUSPOS processing times, as would an AUSPOS processing software upgrade. Therefore, it is foreseeable that a future State CORS network could reduce the requirement for substantial numbers of permanent ground marks in the State. If and when this scenario is realised, the need for future maintenance of the existing SSM infrastructure could be reduced.

Two alternative models for datum realisation through CORS networks are presented in this section.

4.3 Models for Geodetic Datum realisation through regional CORS networks

4.3.1 Top down model
The first geodetic CORS networks were installed in the late 1980s and early 1990s by government and scientific agencies. Primarily, the role of these CORS has been to aid ITRF definition. It is unsurprising, therefore, that regional CORS network densification has historically been driven ‘from the top’ by government organisations wishing to define their own geocentric datums. A typical example is Australia, where the ARGN was installed in the early 1990s to form the basis for moving the non-geocentric AGD to the geocentric GDA and thus align the national geodetic datum with ITRF and WGS84. Such moves were designed to facilitate the national adoption of GPS as a primary positioning facility and similar datum redefinition has been applied, through CORS, by many nations worldwide.

Early CORS networks were installed without regard to other potential applications of the network. For example, regional CORS networks designed for crustal deformation monitoring were not designed to supply DGPS corrections or, when the technology became available, WADGPS services.

This approach to CORS networks is defined as the ‘top down model’ (Figure 21). In this model, CORS networks are installed to support national and state level infrastructure (including legal traceability in Australia) and scientific applications. Note that the terms ‘national’ and ‘state’ are somewhat interchangeable. Since the State of Western Australia is bigger than many nations, what might be classed as a State sub-network in Western Australia (for example a CORS network across the Perth Metropolitan region) would be classed as a national network in other parts of the world.

In the top down model, national or state CORS networks realise the geodetic datum by supplying data to users for post-processing. Post-processing may be undertaken by user-driven software or, as in the case of Australia, a government-supplied online processing service. These networks also feed data into the IGS global network and hence contribute to the generation of quality IGS products for the region.

With the development of real-time network solutions, it has become clear that geodetic CORS networks can be upgraded to perform dual functions, such as supplying RTK and
DGPS corrections to local users and delivering WADGPS and NRTK services. The addition of such services to geodetic CORS networks can appear attractive to the organisations running the network from a financial point of view, as additional services can offer a source of revenue which, in principle, can provide a geodetic CORS network with a ‘business case’.

Figure 21  Top down model for geodetic datum realisation through State CORS networks

Three downsides exist to the ‘commercial geodetic CORS’ model. First, a government-owned CORS network offering positioning services can form direct competition to commercial concerns. Second, whilst commercialising a geodetic CORS network may be an attractive proposition for a government organisation, provision of a service does not guarantee the presence of a profitable market, particularly as the CORS locations may not be optimal for other applications. Finally, guaranteeing integrity and reliability for any service supplied by government can add significant expense to running a network. In some cases, this expense can be greater than the additional income generated from users buying access to the service.

To illustrate the top down CORS model, examples are given from the United Kingdom and the Republic of Ireland.
a) United Kingdom (Ordnance Survey)

The Ordnance Survey UK (OSUK) runs about 30 CORS, installed to ensure most locations within the country are within 100km of the nearest station (Figure 22). The network configuration is such that major urban areas are served by several CORS. OSUK also supports some 900 precisely positioned ground marks (known as passive stations), situated such that any survey on the UK mainland should have several ground control points within a 25-30km radius. CORS data are available for download and users require their own GPS data post-processing software for computing the coordinates of their points in the national coordinate system. Quoted achievable accuracy is 1 cm in the horizontal (using dual-frequency GPS survey equipment and observation periods up to 1 hour) with 5cm horizontal accuracy quoted as ‘routine’\(^\text{14}\). Vertical accuracy is usually 2-3 times worse.

![Figure 22 UK Ordnance Survey Active GPS network](www.ordnancesurvey.co.uk/)

The OSUK system represents a no-frills CORS based geodetic datum realisation system. The national geodetic datum is defined ‘from the top’ by government and it is left to users to connect to the network by occupying passive control sites or processing data themselves downloaded from the CORS sites. With the exception of data archiving, no additional services are supported (although OSUK have recently suggested that they may, in the future, offer a DGPS service in conjunction with industry partners), this setup representing the

\(^{14}\text{www.ordnancesurvey.co.uk/}\)
simplest (and cheapest) method for implementing a CORS geodetic network. Station spacing is sufficiently dense to upgrade the network to NRTK if necessary.

The OSUK CORS network is instructive for Western Australia because it covers a similar sized region to the Perth Metropolitan Region and the South West Land Division. The combination of ‘passive’ control points and a 100km CORS spacing represents a cost-effective solution to datum realisation at the 1cm level whilst reducing the necessary GPS observation period to less than 1 hour. This OSUK configuration also represents the state of today’s technology. With similar technology, any datum realisation through CORS in WA would require a similar network of passive and CORS sites in order to reliably reach the 1cm level.

b) Republic of Ireland (Ordnance Survey Ireland)

Ordnance Survey Ireland (OSI) have adopted a similar dual network of passive control points and CORS to OSUK. The network comprises 16 CORS and 211 passive stations (Figure 23).

![Figure 23 Irish Passive and Active CORS networks. Active CORS network also supports a long range RTK service](http://www.osi.ie/gps/index.asp)
The point of interest regarding the OSI CORS configuration, however, is that the OSI network offers a commercial NRTK service in addition to supplying data to users for post-processing. The OSI CORS installation was designed to cover the dual functionality of datum realisation and NRTK service provision. The NRTK capability was supplied as an off-the-shelf solution by Leica and delivers 3cm in the horizontal and 7cm in the vertical real time\(^{15}\). Data communication is via mobile phone and the service is supplied on a subscription basis.

The OSI model of providing NRTK on top of the geodetic CORS functionality is a logical progression for usage of CORS networks. However, this type of top down approach supplies a service irrespective of whether or not there is any demand for that service. The actual business case is rather nebulous in the absence of market research. The provision of a NRTK service across a nation or state can be seen by the organisation offering the service as either a non-profit making venture for the public and national good or as a commercial operation. In the case of OSI, the VRS NRTK system initially installed could support up to 170 users simultaneously. It may therefore be inferred (though official Figures are not available), that the number of subscribers to the OSI NRTK RTK is somewhat less than 170, a number which is unlikely to make the service viable from a commercial point of view. The population of Western Australia is about half that of the Republic of Ireland and the current NRTK market here is, in all likelihood, equally finite.

\(^{15}\) www.osi.ie/
4.3.2 Bottom up model

The examples of top down models from OSUK and OSI indicate that whilst geodetic CORS networks installed by national and state government agencies provide critical and cost-effective infrastructure for datum realisation, it is difficult to justify provision of additional services from the commercial point of view alone. One major disadvantage of the top down model is services are being provided on the expectation that demand will appear in the future. This is particularly true for NRTK services which, at present, have a finite user base across the country, whilst DGPS and WADGPS services supplied by geodetic CORS networks implicitly must compete within the real-world market.

There is an argument that a government organisation should use any CORS network to offer DGPS, WADGPS, RTK and NRTK services as part of its role in developing national or state positioning infrastructure i.e. that such services should be provided for the national and state benefit, particularly in regions where market forces are unlikely to result in development of such infrastructure. The ‘public good’ argument must be offset against the long term cost and commitment to operating a CORS network on such a basis. The extra expense in providing real time services is primarily due to the necessity of guaranteeing reliability and integrity to users, including the costs associated with maintaining reliable communication links.

The ‘bottom up’ model (Figure 24) for state or national CORS network infrastructure acknowledges that by 2005 many different organisations in a state or nation have CORS networks operating for various applications. As can be seen from section 2 of this report, this is very much the case in Western Australia. The bottom up model unifies all existing CORS networks into a State or National network, under the umbrella of a single government organisation, for the primary purpose of geodetic datum realisation. Individual organisations are encouraged to upgrade their CORS sites to geodetic level and supply their raw GPS data in a timely fashion to the overseeing government organisation. In return, the sites are monitored in daily and weekly static solutions, the sites are integrated into the geodetic datum as fundamental reference points and a direct legal link may be provided for the site to the national geodetic framework. Data from sites can also feed into regional and IGS global network solutions.
Figure 24 Bottom up model for datum realisation through State CORS Networks

One important aspect of this model is that individual CORS networks continue to supply their own specialised services, which are often tailored to specific markets. The unified network does not compete with these services but concentrates on making the data available to users for datum realisation in a post-processed sense, and for using the data for scientific and geodetic applications.

In the bottom up model, the role of the state or national government organisation is defined explicitly as custodian of the geodetic datum, supporter of high precision scientific applications and ‘guarantor’ of legal traceability and provider of system integrity monitoring. Datum realisation is supplied by commercial service providers, although users may also realise the datum directly using freely supplied data from the unified network or, in some cases (including Australia), utilising online post-processed positioning services.

This model has the advantage that the state/national government organisation plays predominantly a coordination role rather than going to the expense of installing and maintaining its own CORS network. However, to support state/national objectives,
government may need to upgrade existing CORS infrastructure AND establish additional CORS sites where deficiencies in coverage are perceived.

The unified network model avoids duplicating and competing systems, alternatively providing a complementary system that serves a range of individual commercial positioning services as well as the needs of government. One obvious disadvantage of the model is that many disparate organisations must be persuaded to ‘buy in’ to the whole unified network concept.

The bottom up model is illustrated using the example of the United States. The National Geodetic Survey (NGS), an office of NOAA's (National Oceanographic and Atmospheric Administration) National Ocean Service, coordinates two CORS: the National CORS network (Figure 26) and the Cooperative CORS network (Figure 25). Both CORS systems represent a multi-purpose cooperative endeavour involving many government, academic, commercial and private organisations (Figure 27).

The National and Cooperative networks comprise numerous sub networks operated by more than 155 of these organisations. Collectively, these networks include more than 1000 sites. Each National CORS site runs a geodetic receiver. For a site to join the NGS CORS network, the operating agency must agree that the data from the site and the site coordinates will be freely available for NGS to distribute to the public. In return NGS computes daily coordinate solutions for the station. Station data are available for user post-processing (usually within 1 hour of collection) or, more generally, through an internet-based post-processing service, OPUS (On-line Positioning User Service) as a means to provide GPS users with easier access to the National Spatial Reference System (NSRS). OPUS is an AUSPOS-style service requiring a minimum of 2 hours data with a recommended data span of 4 hours. Baselines are formed by combining user data with data from the three nearest CORS.

The main difference between the National and Cooperative CORS networks is that the user downloads the data from NGS with the National network and the user downloads the data from a participating organisation with the Cooperative network. OPUS users may select to use data from the Cooperative network if data from closer and better quality sites than offered by the National network are available.
Figure 25 US Cooperative CORS Network
(http://www.ngs.noaa.gov/CORS/)

Figure 26 US National CORS Network
(http://www.ngs.noaa.gov/CORS/)
For inclusion in the National network, a station must significantly enhance the network’s functionality in terms of coverage, data quality, reliability and latency. NGS CORS selection criteria are given in Appendix 2. Although the networks of some participating organisations, such as the U.S. Coast Guard and U.S. Army Corps of Engineers provide real time services, significantly, NGS has no plans to become directly involved in broadcasting corrections or developing real-time positioning systems.

The cooperative network concept has proved to be very successful in the United States, with the networks growing at a rate of about 10 sites per month. NGS has positioned itself as coordinator and archive of the National CORS network in support of activities including remote sensing, weather forecasting, satellite tracking, geophysics, and time transfer. By coordinating and supporting the Cooperative network, NGS has effectively increased its own capacity for delivery of datum realisation in a cost-effective manner by incorporating existing GPS infrastructure into the datum realisation process.
4.4 CORS network models and Geoscience Australia

Geoscience Australia’s ARGN network (see section 2.1.1.1) represents a typical first order CORS network in the top down mode. It represents fundamental geodetic infrastructure for the definition of GDA. GA has proposed a 3 stage development process to enhance its existing geodetic positioning operation (Figure 28).

GA has recognised that a number of State or jurisdictional CORS networks have been, or soon will be, established in Australia. These include GPSnet, SYDNet (New South Wales), SUNPOS (Queensland) and some private networks (eg OmniSTAR). All these systems provide access to GDA in one form or another. Recognising that ARGN densification is desirable from both a datum definition and scientific perspective, in phase 1 of this development initiative, GA has expressed an intention to negotiate data exchange agreements with network providers which would allow GA to have access to data from these networks, thus achieving densification through utilisation of existing infrastructure (a bottom up approach).

Under this model, GA would process submitted 3rd party data through the standard regional processing solutions routinely undertaken at GA and provide the network operators with quality controlled time series results for the sites. The benefit to data suppliers would be independent validation of site stability and site data and, potentially, direct network validation in terms of legal traceability.

Figure 28  GA 3 stage development initiative for future Australian geodetic infrastructure
In phase 2 of the development initiative, GA wishes to commit to second generation development of the AUSPOS post-processing service. This includes a change of processing engine, minor updates to processing models and introduction of additional CORS sites. The net result will be to enhance the accuracy and reliability of the AUSPOS service in Australia and additionally, reduce the recommended user occupation time to below 6 hours.

In the final phase of this initiative, targeted research and development into updating GA data processing capabilities is proposed. This could include generation of regional IGS-style orbital and atmospheric products, provision of a CSRS-style kinematic post-processing service for AUSPOS and dedicated research into reducing AUSPOS processing times. This phase is somewhat undefined as yet and the direction of the future development of GA processing and AUSPOS is still open to debate.
4.5 CORS, vertical height datums and the AHD

4.5.1 Background
Traditionally, vertical geodetic datums have been established independent of horizontal geodetic datums, forming what is commonly called a “two plus one” datum definition. This is the case with the Australian Height Datum (AHD), which was established in 1971, compared to the former Australian Geodetic Datum (AGD, 1966 – 2000) and GDA (2000 ->).

With the introduction of a CORS infrastructure, there is an “in-principle” temptation to abandon the AHD. However, such an approach could be problematic in practice. It is a well established fact that the system of benchmarks and SSMs that realise AHD are used at the local level on a daily basis for a significant number of users, particularly in the engineering construction and utility services disciplines. The wide spectrum of frequent users of AHD strongly supports the ongoing provision of a system of spirit levelled ground marks. Currently, a move to a sophisticated technology-driven replacement solution is not expected to be supported by the community of users in respect of realising the AHD.

The weakest links in the accuracy of the AHD are its well-known distortions, the accuracy of the geoid model and the fact that the AHD is a height system using a truncated (thus less accurate) form of the normal-orthometric height system. The datum is defined point-wise via class C spirit levelling observations to 30 tide gauges on the mainland.

4.5.2 USA approach
First, it is instructive to look at the USA. From Mayer (2005, pers. comm.):

“NGS is responsible for the creation and maintenance of the United States geodetic reference framework. In order to address unmet spatial infrastructure issues, NGS has embarked on a height modernization program whose …most desirable outcome is a unified national positioning system, comprised of consistent, accurate, and timely horizontal, vertical, and gravity control networks,
joined and maintained by GPS and administered by the National Geodetic Survey.\textsuperscript{16,17}

As a result of this program, NGS has altered the way it maintains the national spatial reference system. In the past, NGS created monuments, such as brass disks, and surveyed these monuments to assign them horizontal and/or vertical coordinates in the form of geodetic latitude and longitude and orthometric height. NGS no longer does this and has shifted that responsibility to the private sector under NGS supervision. Instead of building new benchmarks, NGS has implemented a nation-wide network of continuously operating global positioning system (GPS) reference stations known as the CORS (Continuously Operating Reference System) with the intent that the CORS shall provide survey control in the future.

Although GPS excels at providing horizontal coordinates, it cannot directly measure an orthometric height; GPS can only directly provide ellipsoid heights. However, surveyors and engineers seldom need ellipsoid heights so NGS has created highly sophisticated, physics-based, mathematical software models of the Earth's gravity field that are used in conjunction with ellipsoid heights to infer orthometric heights\textsuperscript{18,19}. Thus, in the future, vertical control at the Federal level will not depend on gravity-corrected differential levelling. Instead, published heights will be the result of GPS-measured ellipsoid heights converted into orthometric heights via geoid models.

When GPS is used to measure the orthometric height of some point of interest, say a control marker, the accuracy of the height assigned to the marker depends on the intrinsic accuracy of GPS for measuring ellipsoid heights and the accuracy of the geoid model at the marker. GPS can be expected to measure ellipsoid

\textsuperscript{16} National Geodetic Survey. 1998. National Height Modernization Study Report to Congress.


heights at the 2 cm level precision or better. …..the national, overall precision of the current, best geoid model (GEOID03) [is] … 2.4 cm (1-sigma)."

The statement regarding the accuracy of the geoid model is over optimistic, because GEOID03 was fitted to GPS on North American Vertical Datum (NAVD) benchmarks (Roman et al., 2004) with little regard for the error budget of the GPS or [Helmert] orthometric height data. This will be discussed later in the Australian context.

4.5.3 CORS and the vertical

A CORS network will allow the user to determine ellipsoidal heights of the stations occupied. For these to become physically meaningful, e.g., to manage fluid flow, they must be converted to a height system related to the Earth’s gravity field. This is achieved using a quasigeoid model. This introduces three issues regarding the accuracy of the resulting normal-orthometric heights: 1, the accuracy of the ellipsoidal heights, 2, the accuracy of the quasigeoid model, and 3, the accuracy of the AHD.

The use of a CORS network will change the way in which the quasigeoid model is used. Previously, differential GPS over a baseline from an existing AHD benchmark would apply the geoid height difference to the GPS-derived ellipsoidal height difference to yield an AHD height difference. In this way, common geoid errors would cancel, giving a more precise result. However, with a CORS network, the quasigeoid will be used in an absolute sense, so will not benefit from the cancellation of geoid errors.

4.5.3.1 CORS ellipsoidal heights

GPS is intrinsically weaker in the height determination than the horizontal. Crude estimates are 2-5 times worse. As such, this raises an immediate challenge when trying to define a vertical datum for CORS observations. However, this has to be balanced against the accuracy of the existing vertical datum.

4.5.3.2 Quasigeoid heights

The accuracy of a quasigeoid model is notoriously difficult to estimate. The mathematics used in its computation prevent rigorous error propagation, and the accuracy of the input data is poorly understood, but is known to vary from place to place. This explains why no firm
error estimates are provided with geoid models. A very crude error estimate of the AUSGeoid98 model, in an absolute sense, is about 20-30 cm RMS.

4.5.3.3 AHD heights
The AHD is well known to contain regional distortions and a dominant north-south slope of ~1.5m. As such, the heights derived from GPS and a geoid model, in the absolute sense, do not agree with published AHD heights, and the differences reach a metre or more. As such, CORS and a geoid model will not deliver AHD heights at any respectable level of accuracy.

This raises the question of the future of the AHD. ICSM has decreed that the AHD will be kept for the foreseeable future. As such, a warped version of AUSGeoid06 will be produced, whereby it is fitted to GPS-AHD data. However, this is still unlikely to challenge geodetic levelling over short distances. As such, there is still a need to maintain the AHD, unless the option of defining the vertical datum by GPS and a geoid model is adopted, which is being considered in, e.g., Canada and New Zealand and used in the USA.

4.5.4 AUSGeoid06
AUSGeoid06 will be released mid to late 2006 and will include significantly improved datasets from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. The model will also be fit to AHD benchmarks using least-squares collocation. This is necessary to deliver more accurate AHD heights in an absolute sense. However, it clouds the issue, leading users to believe that there are fewer problems in the AHD. While it may be difficult for DLI to abandon the AHD or create a new AHD in WA (which is not recommended), the new quasigeoid model will be an improvement on AUSGeoid98.

In terms of a CORS network, the warped AUSGeoid06 will provide a more direct transformation (in an absolute sense) to the AHD, but this will not be perfect and 5-10 cm RMS errors will remain. As such, spirit levelling, especially over short distances will be preferable.

4.5.5 Height Datum and a way forward for WA
The AHD remains an issue for the State, being fundamentally incompatible with orthometric heights derived from ever improving GPS ellipsoidal heights and gravimetric geoid height. ‘Warping’ GPS+geoid heights to fit AHD essentially hides the problem from users and will
require constant maintenance as each new generation of GPS or geoid yields improved heights that expose more deficiencies in the AHD.

In terms of the height error budget, the ‘warping’ technique adds an extra error source since it relies on a network of GPS points which may be of variable quality. Definition and maintenance of such a surface is best realised through a CORS network and until WA has a CORS network, height definition throughout the State using GPS will be sub-optimal.

Acknowledging the current political expediency of maintaining the existing AHD, it is recommended that the State define a new ‘scientific’ height datum based purely on CORS GPS and high precision gravimetric geoid, whilst maintaining and supporting the AHD in its current form. In this way, DLI can closely monitor differences between AHD and the GPS+geoid ‘scientific’ datum and maintain a completely GPS-compatible height datum for scientific applications.
5. A CORS network for Western Australia

5.1 Western Australia – where are we now?
As can be seen from section 2 of this report, a number of CORS networks already exist or will exist in the near future in Western Australia. Furthermore, a large number of single CORS are operating in the agricultural, mining, and to a lesser extent, surveying sectors. The majority of these stations are not of geodetic quality.

State-wide positioning services are available from the commercial sector at the 10-20cm level real-time. AUSPOS can deliver better than 2cm in the horizontal given 6 hours of data or more using precise orbits and where the user-ARGN station separation is less than 300km. Users requiring better levels of accuracy or solutions over shorter time periods must currently rely on their own reference stations and utilise the current physical geodetic network of ground marks.

5.2 Likely future developments and timetable of GNSS upgrades.

5.2.1 GLONASS
The Russian GLONASS system came online in the early 1990s and by 1997 some 18 satellites were operational. The addition of up to 24 GLONASS satellites to the existing GPS constellation, resulting in a total constellation of over 48 satellites became an attractive proposition for GPS users. A number of GPS manufacturers, notably Ashtech and later Javad Systems released GPS/GLONASS combined RTK systems which did indeed demonstrate the powerful potential of expanded GNSS systems over stand-alone GPS. The benefit was particularly demonstrable in areas of previously poor sky visibility.

Unfortunately, the economic situation in Russia led to a moratorium on new and replacement satellite launches in the late 1990s. When the possibility of securing funding support from Europe evaporated in the light of the Galileo programme, the Russians reiterated their support for the GLONASS programme, pinning their hopes on slashing costs by redesigning the new GLONASS-K satellites to have a 10-12 year lifetime. In spite of plans to bring the constellation up to 18 satellites by the end of 2005, three launches at the end of December 2005, will bring the current constellation up to only 15 operation satellites, with a number of satellites reaching the end of their operational lifespan (see table below).
The GLONASS system has lost much credibility within the GNSS user community and operators of combined GPS/GLONASS RTK systems are becoming increasingly rare. Few companies are prepared to pay additional dollars for GLONASS capability which is, at best, marginal. In spite of a commitment by President Putin\(^\text{20}\) in January 2006 to ensure 18 operational satellites in orbit by 2008, GLONASS will rapidly be eclipsed by the superior technology offered by the Galileo and modernised GPS systems. Even the entry of India into a joint strategic partnership with Russia\(^\text{21}\) in late 2005 is unlikely to provide GLONASS with the impetus to challenge the GPS/Galileo hegemony.

GLONASS Constellation Status
(March 10, 2006)

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GLONASS Status 10.03.06
(http://www.glonass-center.ru/nagu.txt)

For these reasons, in this study, GLONASS has not been considered in the simulation process. However, it is acknowledged that if an 18+ satellite GLONASS system were to be fully and reliably operational by 2010 or beyond, it could provide useful supplementation to GPS/Galileo.

5.2.2 GPS

The GPS modernisation programme, initiated by the switching off of selective availability in May 2000, is now in full swing, although some political uncertainty still surrounds the funding of the programme. Two main aspects of the GPS modernisation programme will

\(^{20}\) http://www.gpsdaily.com/reports/Putin_And_Ivanov_Discuss_Future_Of_GLONASS_System.html

impact on the quality and reliability of future GPS positioning. These relate to the availability of improved and additional signals to the end user.

Up to 12 of the current generation of GPS Block IIR (replenishment) satellites, currently in storage, are to be upgraded to Block IIR-M satellite (modernised replenishment) models which will carry a new civil L2 GPS code, known as L2C. The first receiver tests with the Block II R-M were reported in 2004 using the Trimble R7 RTK system whilst the first Block IIR-M satellite was launched in 2005. All 12 Block IIR-M satellites should be in commission by 2007 although at that stage less than half the complete constellation will be transmitting L2C.

The L2C signal will make L2 tracking simpler and more reliable, thus reducing noise on the L2 carrier phase observable (which is currently noisier than the L1 carrier phase observable). This will reduce the likelihood of L2 signal loss of lock and the impact of ionospheric scintillations in the atmosphere. Incidents of loss of lock due to receiver dynamics will also be reduced; with existing receivers this is a significant problem. Any improvement in the quality of the L2 phase signal will improve the speed and reliability at which ambiguities can be resolved which will result in improved reliability in RTK solutions. Lower signal-to-noise ratios on L2 will also improve coordinate precision, particularly for longer range RTK and VRS.

The next generation of GPS satellites will be the Block IIF constellation. The first launch is scheduled to take place in 2006. These satellites will transmit a signal openly available to users at 1176.45Mhz (known as L5), in addition to L2C. The availability of the third civilian frequency will significantly enhance RTK capabilities. Not only will the addition of extra signals improve the speed at which ambiguities can be resolved, but improved tracking capabilities (due to the superior quality of L2C and L5 over L1 and L2) will greatly assist multipath mitigation. It is likely that future RTK systems running in urban environments will be able to operate at an order of magnitude better than current systems, simply due to the multipath mitigation techniques that will be enabled by the presence of the third frequency. GPS IIF is scheduled to be in place by 2010.

Beyond 2010, GPS III is currently in the design phase. Plans are somewhat fluid, with broad goals such as increased signal strength (making indoor GPS more of a possibility), greater
availability (i.e. more satellites), improved integrity and greater ‘survivability’ (i.e. less susceptibility to interference) high on the agenda. However, it is rather early to predict what will come to pass at this stage.

5.2.3 Galileo

In spite of GPS Block IIR-M and GPS Block IIF modifications, sky visibility and satellite geometry will remain the restricting factors on RTK GPS over the next decade. Experiences with the integrated GPS/GLONASS system clearly demonstrated the potential for improved positioning in restricted visibility situations and the possibility of a combined GPS/GALILEO system will open up a whole new vista for user of satellite positioning.

Galileo is a European initiative, to be designed and run by the European Space Agency (ESA). It is currently in the development stage, with the first prototype satellite launched in December 2005. Being a civilian system, Galileo signals (satellites are being designed to transmit up to 4 L-band carriers) will be freely available, although some may be only accessible on a ‘pay per view’ basis. Galileo will comprise a 30 satellite constellation orbiting at 23 600km, controlled by two Control Centres in Europe. The development phase is scheduled to be completed by 2005, following which a programme of satellite launches will take place, resulting in the full constellation planned to be operational by 2008 (although 2010 or even 2012 look to be a more likely dates.

With 30 satellites and potentially 4 L-band signals, Galileo may be seen as a direct competitor to GPS in the RTK market. However, utilising the combined 58 satellite constellation (28 GPS satellites are in orbit today) for RTK positioning would practically eliminate geometry related problems in all but the most restricted environments.

5.2.4 Summary

The lead in time for GPS modernisation and Galileo means that these developments are unlikely to impact on DLI survey requirements over the next 4 years. Whilst GPS Block IIR-M satellites will gradually be introduced, with Galileo satellites becoming available at a faster rate after 2006, it is unlikely that direct benefits will be visible to users prior to 2010. It is unlikely that existing users will be keen to invest in an untried system. As a result, market penetration of the new (and more expensive) receivers which will be able access the new signals is likely to be slow in this interim period. Certainly, by 2008, RTK may well be
capable of meeting much improved specifications in terms of accuracy and reliability and around that time a complete reappraisal of the capabilities and validation procedures for RTK positioning will undoubtedly be appropriate by all organisations involved in the positioning sector.

5.3 Benefits of expanding the existing geodetic CORS network for Western Australia

From a geodetic perspective, expanding the existing geodetic CORS network would:

- improve the realisation of GDA;
- provide improved height infrastructure in Western Australia;
- assist in definition of legal traceability to GDA across the State;
- contribute to an improved AUSPOS service for the State;
- assist in tidal modelling and hence improve height datum resolution;
- provide an improved data set for AUSGEOID validation and improvement;
- aid mean sea level studies;
- aid seismic geohazard monitoring;
- provide an improved atmospheric sounding data set across the State;
- contribute to improved regional orbital and atmospheric models;
- possibly contribute to improved IGS Products

5.4 The role of DLI in definition of State geodetic infrastructure

Historically, national datum definition has been the role of GA, with State survey organisations performing the function of realising the datum in their respective States through ground control marks. GPS has changed this situation. Today in Western Australia, suitably equipped and skilled users can realise GDA coordinates through GPS service providers or AUSPOS without ever having to access a DLI ground mark. For the skilled user, when this capability can be realised in a more realistic observational timeframe with less latency in the solution and can be achieved over the whole State, then as GNSS techniques improve still further reliance on the ground mark network should become increasingly less important over the next decade.

In cognisance of this, DLI is reviewing its role in how it might in the future realise for and deliver to users the GDA and AHD across the State. This entails a review of (i) need for the current reliance on and maintenance of ground marks in the geodetic network; (ii) how a
technology-driven solution might impact this; and (iii) what implementation arrangements and transition timeframes would be required to change to a new system whilst supporting the current level of service.

A fundamental role of DLI is to maintain the realisation and delivery of GDA and AHD within Western Australia to a standard that meets the State’s and community needs and expectations. Implicitly, realisation of the datum within the State represents the basic legal representation of spatial infrastructure. Therefore, there is a strong argument that all government agencies and all private service providers in the State should have their CORS networks tightly integrated into GDA, and these networks should be continuously monitored in a national context. The current and future role of DLI is the custodial authority for position and height, and provision of the legal traceability of the geodetic system. The current methodology is provided through the system of ground marks, and the future may be through CORS networks. Such a role would cross all applications, from navigational positioning at the 1-5m level to the highest level positioning requirements monitoring the integrity of the core stations that define GDA in Western Australia.

Within such a datum realisation role, it is logical to assume DLI may wish to install and run its own CORS network to provide the State geodetic infrastructure, with the additional benefit if being able to support scientific applications across the State. However, experience from other countries and within Australia suggests that providing anything other than geodetic services will be difficult to justify from a purely commercial perspective.

5.5 Model for a unified State CORS network

In Western Australia, a number of different organisations are operating CORS networks under different auspices. A large number of individual operators, particularly mine sites and local survey companies, run their own individual CORS. Several major players have plans for installing additional CORS in the near future. Given the existing CORS infrastructure, this situation provides an opportunity for DLI to assume the lead in a 'bottom up' approach to building CORS (geodetic) infrastructure in the State, without committing to the expense and risk of developing its own network. However, some CORS densification in WA is desirable on the part of DLI as market forces are unlikely to result in certain remote regions becoming accessible to CORS technology.
Such a strategy would require DLI to liaise with existing CORS service providers to upgrade existing sites to geodetic network specification, with capacity to log and archive raw GPS data and communicate the data back to a central archive (eg DLI or GA) on a hourly/24 hourly basis, thus unifying all disparate networks across the state under the auspices of a core geodetic network realising GDA. This assumes that GA processing can be extended to carry extra Western Australian stations in their weekly/daily solutions. However, similar to NGS, it is recommended that DLI do not commit to providing any form of real time positioning service for Western Australia in the near future. A fundamental tenet of the bottom up strategy is that market demand should drive the provision of positioning services, rather than vice-versa.

DLI should be prepared to install and run CORS at locations deemed important to maintain integrity of the unified network where market forces are unlikely to result in adequate CORS coverage. However, the general strategy would be to rely predominantly on the infrastructure of other organisations, that geodetic data is available to all users, and concentrate on guaranteeing that CORS sites supplying data to the network are installed to adequate standards and specifications, similar to the NGS requirements in Appendix 2.

In the unified model, DLI would also take the lead in defining and maintaining the legal traceability requirements for positioning through CORS in Western Australia. DLI should be an important ‘link’ in the chain of traceability leading from users to CORS networks to ARGN to nationally defined standard. However, this important link does not, as yet, formally exist in this State.

The unified CORS network strategy relies on the continued development and enhancement of the AUSPOS service and the cooperation of GA in the archiving and inclusion of data in their regional solutions. Clearly, the relationship between DLI and GA is critical and DLI would have to work closely with GA and support and encourage further developments of AUSPOS and the ARGN.

5.6 Case studies
A number of simulated case studies are presented, representing potential designs for Western Australian CORS networks. Two types of CORS networks have been simulated –‘geodetic’ networks which nominally cover the entire state and would be used to support datum
definiton within the State and supply data to an enhanced AUSPOS service; and NRTK whose primary function is to deliver real time high precision positioning services.

Network quality analysis has been realised through GNSS simulation software which was originally written by Sandra Verhagen\(^\text{22}\) at Delft University of Technology in the Netherlands and has been adapted for this project by Dr Guorong Hu of Curtin University of Technology. Network quality has been assessed using a series of statistically simulated design parameters. These design parameters, briefly described below, are defined mathematically in section 5 of the accompanying technical document:

**Number of CORS stations within specified range**

For specific locations across the State, the number of CORS within a set threshold (eg 300km) is computed for different network configurations. Results from the AUSPOS tests cited in the accompanying technical document indicate superior AUSPOS performance if baselines for all CORS stations contributing data to a solution are less than 300km.

**Network Determinant**

The internal precision of derived coordinates for individual stations in a network is usually represented by a three dimensional error ellipsoid at, say, 95% confidence. Station error ellipsoids are derived from the network covariance matrix. The Network Determinant is a design parameter which, through the covariance matrix, reduces all individual error ellipses to a single numerical estimate representative of the internal precision of the network as a whole. A large Network Determinant represents a strong internal precision.

**Network Condition Numbers**

When we estimate coordinates in a least squares network adjustment, the probability of the least squares equation system giving an optimal answer depends on how well conditioned the equation system is. An ill-conditioned network is essentially unstable, in which case introduction of small errors can cause solution coordinates to vary significantly. The sensitivity of the network to error is represented by the Condition

\(^{22}\) S. Verhagen (2002), *Visualization of GNSS-related design parameters; Manual for the Matlab user interface VISUAL.* (not published, distributed with the software)
Number. The larger the condition number, the more ill-conditioned a system is, implying that the solution might be inaccurate.

**Network Internal Reliability**

Network Internal Reliability can be understood as the ability of the network to detect and resist gross errors in the observations. Reliability of a network depends on the geometry of the network, the accuracy of the observations and the total number of observations available.

**Ambiguity Success Rate**

The ambiguity success rate is the probability of successful ambiguity resolution under ‘normal’ conditions (i.e. with no significant systematic biases present) at any location in a NRTK network. Ambiguity success rates presented in the subsequent case studies represent single epoch network RTK solutions. It should be noted that a) multiple epoch solutions will give improved success rates and b) a success rate of less than 100% does not indicate a network is unusable at that point but simply likely to operate sub-optimally relative to locations which can achieve a 100% success rate. Conversely, simulations do not include any ‘real world’ factors such as restricted sky visibility and the presence of multipath or interference. Therefore, a practical user sense, success rate simulations may be considered over-optimistic.

**5.7 Geodetic CORS network case studies**

**5.7.1 Case study: existing State CORS network**

Figure 29 shows the existing geodetic CORS in Western Australia. According to Eckl et al (2001)\(^2\) the dependence of coordinate accuracy on the baseline length is insignificant when (a) using the final GPS orbits from the International GPS Service (IGS) after fixing integer ambiguities; (b) baseline length within 26-300km; (c) fixing ambiguities where possible; and (d) the observing session is within 4-24h. Under these conditions, the accuracy of the baseline solution in the north, east and up components (S\(_n\), S\(_e\), S\(_u\)) was found to be a function of the length of observation session (T) only:

\[ S_n = \frac{k_n}{T^{0.5}}; \quad S_e = \frac{k_e}{T^{0.5}}; \quad S_u = \frac{k_u}{T^{0.5}} \]

where \((S_n, S_e, S_u)\) are expressed in mm, \(T\) is expressed in hours (H) and:

\[ k_n = 9.5 \pm 2.1 \text{ mm h}^{0.5}; \quad k_e = 9.9 \pm 3.1 \text{ mm h}^{0.5}; \quad k_u = 36.5 \pm 9.1 \text{ mm h}^{0.5}. \]

These figures were empirically derived by Eckl et al (2001). On this basis, 300km baseline length is defined as the maximum threshold distance for the purpose of the geodetic datum control transfer. A GPS receiver set up within 300km of a CORS station and whose data are observed adhering to the above conditions, should be able to realise a relative baseline solution with accuracy as represented by the functions described above. Numerical examples for different observation times are shown in table 5.1 below.

<table>
<thead>
<tr>
<th>Observation time (T) (hours)</th>
<th>(S_n) (mm)</th>
<th>(S_e) (mm)</th>
<th>(S_u) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.8</td>
<td>5.0</td>
<td>18.2</td>
</tr>
<tr>
<td>6</td>
<td>3.8</td>
<td>4.0</td>
<td>14.9</td>
</tr>
<tr>
<td>8</td>
<td>3.6</td>
<td>5.5</td>
<td>12.9</td>
</tr>
<tr>
<td>12</td>
<td>2.7</td>
<td>2.9</td>
<td>10.5</td>
</tr>
<tr>
<td>24</td>
<td>1.9</td>
<td>2.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*Table 5.1 Predicted baseline accuracies for baseline lengths up to 300km for varying observations spans (after Eckl et al, 2001).*

In Figure 29, circles of radius 300km are represented, centred on the current available CORS. Sites inside these circles meet the Eckl criteria and, given greater than 4 hour observation spans, can be expected to achieve baseline solutions commensurate with the accuracies given in table 5.1. It is clear from Figure 29, therefore, that on a single baseline basis, much of the populated part of the State is covered by existing CORS stations.

However, single baseline GPS is insufficient for providing a verifiable level of quality control for datum densification. To perform a network adjustment and hence compute error statistics for points derived from the State CORS network, a minimum of 3 baselines are required. Using the threshold described above, to meet the requirements of table 5.1 an unknown point whose coordinates are to be determined to a geodetic level through the State CORS network
should be within 300km of at least 3 CORS stations. This criteria fits in well with the results from the AUPOS service presented in as part of this study. AUSPOS uses the nearest 3 CORS to the point whose coordinates are to be determined, and has demonstrated improved results and reliability if all CORS used in the solution are less than 300km from the unknown point. It may therefore be stated that a desirable design criteria for a State Geodetic CORS network would be for all areas to be within 300km of at least 3 CORS.

Figure 29 The existing geodetic CORS stations in Western Australia (as of October 2005)
Figure 30 illustrates the region in Western Australia that meets the ‘3 CORS within 300km’ criteria. Clearly, the Metropolitan region and its environs are covered but much of the State (in reality 86% of the surface area) does not meet this criteria. It may therefore be concluded that densification of the State geodetic control network is desirable from the point of view of optimizing single baseline processing, for first order datum densification using GPS, and for optimizing the service available to AUSPOS users across the State.

5.7.2 Case study: unified State CORS network

Figure 31 presents a ‘unified’ state CORS network in Western Australia, including the stations from the Australian Regional GPS Network (ARGN), IGS stations (section 2.1.1), AMSA stations (section 2.1.2), Fugro OmniSTAR stations (section 2.1.3) and DAFWA stations (section 2.1.5.2). Compared with the previous case, Figure 31 shows that baseline
coverage can be expanded to cover most of the south-west region of the State with this configuration, with sparser coverage around the populated regions in the north.

Figure 31: Unified CORS network in Western Australia

Figure 32 shows that the unified CORS network improves the coverage for regions where at least three CORS stations are within a radius of 300km to around 20% of the surface area of the State. However, this level of coverage is still limited and suggests that more densification is necessary if regions outside the greater metropolitan area and the south-west are to be covered.
5.7.3 Case study: enhanced unified State CORS network

Figure 33 presents a situation in which 10 sites from the ‘unified’ CORS network has been enhanced by the installation of an additional 10 CORS in an optimal configuration as determined by maximising the Network Determinant. These stations could be new stations or geodetic upgrades of independently operating stations, such as described in section 2.1.5.1 and Figure 9. Clearly, these additional 10 stations enable baseline coverage across most of the populated regions of the State.
Figure 33 Enhanced unified geodetic CORS network in Western Australia with an additional 10 stations placed in optimal configuration
Figure 34 shows that, in this case, the addition of 10 new stations to the unified CORS network improves the coverage for regions where at least three CORS stations are within a radius of 300km to around 50% of the surface area of the State, with the majority of population centres, mining and agricultural regions and areas of high economic value being fully covered.

Whereas Figures 33 and 34 show the optimal configuration for a network comprising 10 new stations in addition to the 11 (existing) station unified network shown in 5.7.2, Figure 35 shows the Network Determinant for an enhanced optimal unified network. Figure 35 demonstrates how the network determinant can be used as a tool to compare any proposed network configuration for any number of stations against the optimal network configuration for the same number of stations.
Figure 35 Network Determinant as a function of number of stations, based on the case of adding up to 10 new CORS stations to the unified CORS network in WA.

Figure 36 shows the Network Condition Number for the enhanced optimal unified network, based on the number in the stations in the network. For all the network configurations presented in the previous sections, the condition number lies between 4 and 7. Generally speaking, this fact indicates that these GPS CORS networks are well conditioned. The condition number for the STATEFIX network, which may be considered as the benchmark network for Western Australia, was approximately 4.8. Therefore, the optimality of the networks shown in these case studies is on a par with that of the STATEFIX network. As with Figure 35, Figure 36 can be used as a benchmark against which proposed network configurations can be tested.

Figure 36 Network Condition Number as a function of number of stations, based on the case of adding up to 10 new CORS stations to the unified CORS network in WA.
Logistically, it will be difficult to install CORS at the optimal locations across the State. Therefore, it is recommended that any future proposed network be first tested using these tools to assess the proposed configuration against the optimal configuration.

5.7.4 Enhanced geodetic products

Input of data from, for example, an additional 16 CORS stations from WA would improve the precision of ITRF-GDA transformation parameters by up to a factor of 4 (precision is proportional to the square root of the total number of stations included in the least squares solution for the transformation parameters). Given the size of WA, there is a strong argument, from a scientific point of view at least, for DLI to maintain a set of State ITRF-GDA transformation parameters, concurrent to the national parameters defined by GDA but ‘uncontaminated’ by observations from the east, which, due to variations in intra-plate motion, might not accurately represent tectonic motion in WA.

Similarly, inclusion of additional CORS stations in precise orbit computations can improve the precision of precise satellite ephemerides. Figure 37 shows the ground track of GPS satellite PRN 1 whilst Figure 38 shows the percentage improvement in Position Dilution of Precision (PDOP) for computation of the coordinate of the satellite if all AFN stations and 16 additional CORS stations from WA are added into the global orbital solution. The red line in both plots indicates the time when the satellite is visible over WA. The orbital simulations are described in more detail in section 7 of the accompanying technical document.

It can be seen from Figure 38 that the geometrical improvement in the precision of the orbit of GPS PRN01 can be as much as 25%. It may therefore be concluded that a WA CORS network could contribute to an improvement in precision of regional precise orbits.
5.7.5 Geodetic network case studies: conclusion

Even if a ‘unified’ geodetic CORS network was established using all existing government and service providers’ CORS, this would not be sufficient to supply the entire State with geodetic datum services through GPS. An enhanced unified network could fulfil the majority of the State’s needs. It has been shown that an additional 10 CORS stations across the State could meet the 300km range threshold in most populated regions. Furthermore, an enhanced unified network could improve the precision of ITRF-GDA transformation parameters across the state by up to a factor of 4 if included in GA solutions, improve satellite orbit precision by as much as 25% if included in regional precise orbit solutions, and be used as the basis for a State scientific height datum.
5.8 NRTK case studies

5.8.1 Suitability of the Geodetic network for NRTK

In the first case study we consider the ambiguity success rate for a Network RTK system for the case of the enhanced unified geodetic network outlined in section 5.7.3. The limiting factor for network RTK is station spacing and it can be clearly seen from Figure 39 that with a station spacing of several hundred kilometres, ambiguity resolution is only possible relatively close to CORS locations. In effect, the network is capable of supplying single baseline RTK, with the station spacing too large to provide NRTK services.

![Figure 39 Ambiguity success rate for GPS-only system for the enhanced unified network presented in section 5.7.3](image)

It is evident that, for a region the size of Western Australia, the requisite spacing of a geodetic control CORS network is incompatible with the supply of NRTK services. Whilst a geodetic CORS network could, in theory, be used to provide a framework for installation of NRTK services, substantial CORS densification is required to reliably deliver those services. A case study for a more localised NRTK for the Perth Metropolitan region is presented in sections 5.7.2 – 5.7.3 below.
In relation to Figure 39, it may be added that Galileo and modernised GPS, once operative, will both improve the reliability of ambiguity resolution and extend the operational range of NRTK (see sections 5.8.3 and 5.8.4). However, simulations indicate that, even with Galileo, the station spacing required for a geodetic CORS network of Western Australia will be too wide to supply reliable NRTK coverage across the State. However, the number of stations required for densification will be reduced over time and hence there is a strong argument that establishing a geodetic CORS network in the near future could provide a foundation for future modernised GPS/Galileo NRTK services across the State.

5.8.2 Case study: Perth Metro NRTK – 5 station network

We first examine the properties of a theoretical NRTK configuration comprising 5 CORS at an inter-station distance of 60-70km, broadly designed to cover the Perth Metropolitan region. The network ranges from Two Rocks in the north to Mandurah in the south and as far east as Gidgegannup (Figure 40).

Figure 40 Five station NRTK configuration for Perth Metropolitan region

Figures 41 and 42 show the simulated ambiguity success rates for this network for both GPS and GPS augmented with Galileo. Note that none of the simulations presented in this section include modified GPS, first, so as to emphasise the direct impact of Galileo and, second, because the third GPS frequency is not scheduled to be fully available until several years after Galileo reaches full operational status (approximately 2015), its impact on this DLI study will be less immediate than Galileo. However, it is acknowledged that beyond 2015
GPS modernisation will substantially contribute to improvements in accuracy and reliability of NRTK.

It is interesting to note that the geometry of the network shown in Figure 40 causes the ambiguity success rate to be less than 100% for regions around two of the CORS sites, Mandurah and Two Rocks. NRTK ambiguity success rates tend to be weakest near extremities of the network, particularly around CORS which are ‘out on a limb’. For GPS only, the success rate drops off rapidly in regions outside the confines of the network. Including Galileo does not significantly improve the 100% success rate region (Figure 41) but does have a large impact on the 90% success rate region (Figure 42). In the network illustrated, incorporation of Galileo will greatly extend the size of the serviceable region (at a 90% level).

![Figure 41  100% NRTK Ambiguity Success Rate](left figure GPS-only; right figure GPS + Galileo)
Galileo also substantially increases the internal reliability of the network, as illustrated in Figure 43, which shows the regions with a redundancy greater than 20 for both GPS and GPS + Galileo solutions. Clearly, the internal reliability of the GPS-only network is somewhat limited. This value represents the likelihood of the network being able to detect internal errors, which impacts on the speed of ambiguity resolution and the speed at which incorrect ambiguity solutions can be detected and corrected. The extra observations available from Galileo will greatly increase available redundancy and hence improve reliability.
5.8.3 Case study: Greater Perth Metropolitan region NRTK – 100km network

This and the subsequent case study consider situations whereby existing CORS stations, which might form part of a State Geodetic Network, are densified to provide NRTK with 100km and 50 km inter-station spacing respectively. In both cases, it is assumed that CORS stations at Perth (Gnangara) and New Norcia are upgraded to NRTK capability and the DAFWA GPS station at Narrogin (section 2.1.5.2) is brought online as a NRTK CORS. In this case, an additional 7 CORS stations are assumed to be situated around the greater Perth Metropolitan region to provide NRTK at 100km spacing (Figure 44).

Figure 45 shows the simulated ambiguity success rate for the 100km network for GPS and GPS + Galileo configurations. It is evident from Figure 45 that 100km station spacing performs poorly for ambiguity resolution, even at a 90% level and that Galileo will make a significant difference to the allowable NRTK inter-station spacing. As Figure 46 shows, Galileo will also allow more robust solutions with a 100km inter-station spacing.
Figure 44  Simulated NRTK configuration for greater Perth Metropolitan region, 100km inter-station distance

Figure 45  90% NRTK Ambiguity Success Rate for 100km inter-station distance (left figure GPS-only; right figure GPS + Galileo)
5.8.4 Case study: Greater Perth Metropolitan region NRTK – 50km network
This case illustrates the densification of the network highlighted in section 5.8.2 from a 100km inter-station distance to a 50km inter-station distance, achieved by adding an additional six stations into the network, that is, 13 new stations in total (Figure 47).
Figure 47  Simulated NRTK configuration for greater Perth Metropolitan region, 50km inter-station distance

Figure 48  90% NRTK Ambiguity Success Rate for 50km inter-station distance
(left figure GPS-only; right figure GPS + Galileo)
Figure 48 shows the simulated ambiguity success rate for both GPS and GPS + Galileo configurations, whilst Figure 49 shows the network redundancy for both configurations. It is
notable that the success rate is at the 100% level within a range of about 50km of any CORS site for the GPS only network. In comparison with the network configuration with 100km inter-station distance (Figures 45 and 46), the superiority of the 50km network for GPS only NRTK is very clear. The improvement when adding in Galileo to the 50km network is marked, though not as significant as for the 100km network. Galileo generally increases the reliability but makes little impact on the 100% ambiguity success rate region.

A 50km CORS network across the greater Perth Metropolitan region could also be used to provide data for redundant post-processed static and kinematic solutions. Figure 50 shows the region within which three or more CORS would be within 50km for this network configuration. Furthermore, such a station density would provide good data coverage for inclusion in meteorological mesoscale models and for providing a framework for geodetic crustal monitoring (the same could be said for the 100km network).

5.9 Summary and Conclusions

5.9.1 Geodetic CORS networks
To practically implement a direct realisation of GDA and AHD in all of WA through a GPS/AUSPOS system implementation, installation of an optimally placed CORS network of about 25 stations would be required. Many of these stations could be site upgrades of CORS already being run by other organisations. However, it is unlikely that a ‘unified’ network approach would be able to offer full coverage to all populated areas across the State. Here, ‘full’ coverage is defined as ensuring any location in the populated part of State is within 300km of at least 3 CORS. Even if a unified strategy was to be successfully adopted, it is anticipated that something in the order of 10 additional CORS will be required to cover regions which are unlikely to become supported by commercial interests.

A 25 station state network would be able to support regionally computed IGS-style products, such as precise orbits and ionospheric models, and would support global and continental geodesy. It could also support an independent State set of GDA-ITRF transformation parameters and improved national transformation parameters for the State. Whilst astute positioning of new CORS, for example at tide gauges or in the South-West seismic zone would support some scientific applications (including a scientific State height datum and
possible meteorological applications), the wide spacing between stations would limit the use for the network to some extent. However, the network would provide an extremely valuable framework for future applications. The importance of such infrastructure to the State cannot be overvalued. For example, a recent study for Natural Resources Canada\textsuperscript{24} which conservatively estimated that Canadian national geodetic infrastructure added from $60 billion to $90 billion to Canadian GVA (Gross Value Added), i.e. 6\% - 9\% of the Canadian total GDP.

Notwithstanding the installation of a near-optimal State-wide CORS network, the practical realisation of both horizontal and vertical datums would continue to rely on ground marks in the short to medium term. The adoption of the technology by the spatial information industry will result in a natural reduction in the usage of physical ground marks over time. This would assist DLI in a phased approach to a reduction in resources committed to ground mark maintenance. One viable option for DLI in the context of a new State CORS network is, in the first instance, to thin the maintenance of the existing ground point network down to a core set of passive GPS stations designed to ensure, for example, 20 – 50km station spacing for users. This approach has been used successfully in the UK (section 4.3.1(a)) and also Canada.

5.9.2 NRTK
Simulations indicate that with the current GPS constellation and existing technology, 100km NRTK is not a particularly feasible concept. However, with an inter-station spacing of 50km provision of reliable RTK services are possible with GPS. The introduction of Galileo will greatly improve this situation, making NRTK with 100km inter-station spacing possible and greatly improving the reliability of 50km networks.

The concept of local NRTK, as in the example shown in section 5.8.2 with 5 CORS across the Perth Metropolitan region, has limited value from the point of view of geodetic datum definition. The main operational issue for such a network is the size of the region which can be reliably covered with a limited number of stations. However, such networks will become substantially more robust with the inclusion of Galileo.

\textsuperscript{24}Natural Resources Canada (2004), National Geodetic Infrastructure Requirements Study NRCan 03-0628, Final Report.
For the NRTK simulated in section 5.8.2, perhaps the driving question is economic: how many users would wish to subscribe to a network with this level of spatial coverage? Clearly, this question also applies also to the 50km and 100km networks simulated in sections 5.8.3 and 5.8.4, although note that all networks simulated are given purely as examples and do not represent any recommendation on the part of this report. With NRTK, financial considerations are as important as scientific considerations.

Installation of a 50km NRTK may be a viable consideration in the south-west, where such a network could support the agricultural (and possibly part of the mining) sector and double up for geohazard monitoring of the South-West Seismic zone and densification of the number of GPS monitored tide gauges for sea level monitoring. Whilst it is not recommended that DLI move into the NRTK market, based on Figure 15, a network of 15-30 CORS at 50-70km spacing should be able to provide suitable coverage for these scientific applications in the south-west of the State. It is recommended DLI consider installing a scientific CORS network in the south-west, possibly in partnership with industry concerns who may wish to develop the market for NRTK in the region.
6. Summary, actions and recommendations

CORS networks are already present in WA and are being used for datum realisation outside the auspices of DLI. The State control point network will become increasingly anachronistic as space-based positioning systems continue to develop. DLI must decide whether as an organisation it wishes to retain control of basic state geodetic infrastructure or relinquish that control in the long term to a combination of private concerns and GA. Therefore, recommendation 1 may be defined as:

**Recommendation 1:** DLI to maintain its role of maintaining State standards for datum realisation, legal traceability and support for high accuracy scientific applications such as sea level monitoring, atmospheric modelling and crustal monitoring.

In relation to the number of ‘navigation’ users in Western Australia realising GDA through WADGPS/GPS service providers, the number of users performing high accuracy datum realisation through ground control points is relatively small and promises to decline as satellite-based services improve. As shown by examples from the UK, Ireland and United States, CORS are effectively the new SSMs. As mentioned previously, it is now possible to compute GDA coordinates in WA to 2cm *without the use of the DLI ground control network.* The future role of the SSM network in Western Australia will not be defined by DLI but rather by the market. For example, it is now possible for surveyors to reliably AUSPOS their data rather than connect to DLI ground control points. Therefore, the question is not about whether or not DLI should maintain or phase out the ground control network, but rather how will DLI be positioned once most users are realising GDA coordinates through other systems. Three options are open to DLI:

1. No action, with DLI continuing to maintain the ground control network for the foreseeable future or until it becomes redundant.
2. DLI could impose datum definition on the State through installing its own CORS network (the top down model).
3. DLI could attempt to coordinate existing CORS infrastructure into a unified CORS network (the bottom up model).
It must be stressed that any installation of CORS infrastructure should not result in the immediate discontinuation of the State ground mark infrastructure but a phased approach to the gradual reduction in the number of maintained and operational ground marks.

These options, therefore, lead to recommendation 2:

**Recommendation 2:** It would be beneficial to future State development and infrastructure to develop and install a State CORS network capable of high precision geodetic datum definition and realisation.

Models for developing CORS networks on a regional basis were discussed at length in section 5 of this document and drawing on this discussion it is possible to formulate recommendation 3:

**Recommendation 3:** Given the size of Western Australia, the bottom up model for geodetic datum definition and realisation for CORS is financially attractive and facilitates cooperation with industry, rather than competition. Furthermore, since hardware upgrades are market driven, DLI would not be exposed to uncertainties caused by future technological development.

As custodian of the legal aspect of positioning in the State, and recognising the important future role CORS networks are likely to play in the State, it will be important for DLI define a legal framework for CORS based positioning. Such a framework should encompass all CORS service providers. As a prelude to defining such a framework, this report therefore recommends:

**Recommendation 4:** DLI to examine the legal framework for all CORS based positioning activities in WA.

As a corollary to recommendations 3 and 4, the recommended model for a DLI State CORS network and DLI’s relationship with external CORS service provides, recommendation 5 states:
Recommendation 5: DLI to lead definition and implementation of unified WA CORS network by initiating contact with CORS operators from all sectors across the State. DLI to clarify role and relationship with GA in any unified state CORS network.

Recommendations 6 and 7 relate to technical details of network design for future CORS networks in Western Australia:

Recommendation 6: An optimised network of around 25 geodetic CORS will be required to provide basic GPS coverage for high precision geodetic datum definition across the populated areas of the State.

Note that receiver upgrades at CORS sites would need to be undertaken after proven multi-satellite system reception geodetic receiver technology becomes available.

Recommendation 7: DLI to consider installation of a dense CORS network (i.e. 50-100km spacing) in the south-west of the State, for the support of the geodetic datum, the agricultural and resources sectors and geohazard applications.

Recommendations 8, 9 and 10 relate to technical issues related to maintenance of the AHD and GDA-ITRF transformation parameters across the State:

Recommendation 8: Due to the increasing incompatibility between AHD and GPS derived orthometric heights, DLI must maintain a transformation surface across the State between AHD and GPS derived orthometric heights. A State CORS network would provide the stable framework upon which this surface can be based and maintained.

Recommendation 9: DLI should develop a new ‘scientific’ height datum based purely on CORS GPS and the high precision gravimetric geoid in order to maintain a completely GPS compatible height datum for scientific applications and closely monitor the inconsistencies in the AHD.

Recommendation 10: There is an unfulfilled requirement for accurate ITRF-GDA transformation parameters for WA. DLI should use a CORS State network to compute State transformation parameters in conjunction with the GA national solution.
Finally, recommendation 11 relates directly to item 5 in the initial terms of reference (TOR 5):

*Recommendation 11:* Unless there are matters of urgency and priority, any potential trial of a CORS network in the Perth metropolitan area to maximise benefit to DLI in future decision making should be delayed until DLI can leverage off the infrastructure provided by other CORS initiatives in this State.
Appendix 1

NGS CORS SELECTION CRITERIA

I. REFERENCE STATION PROVIDER
   A. Required:
      1. Provider must provide the information required to complete an NGS site log.
      2. Provider must agree to notify NGS:
         a. Prior to planned down times.
         b. Of expected outages.
         c. Of changes of equipment, firmware, or antenna locations and dates of implementation.
      3. Provider must anticipate continuous long-term operation (many years).

II. SITE
   Required:
   1. Stable site (minimal local horizontal and vertical movement). Sites which are specifically intended for subsidence or deformation monitoring should be identified as such on the site information form.
   2. Stable antenna mount (less than 1-cm short-term variability).
   3. Stable power with 5 minute battery backup.
   4. Minimum electromagnetic interference.
   5. Relatively clear horizon with any obstructions higher than 10 degrees located as far away from the reference antenna as possible and located to the north of the reference antenna.
   6. The agency or firm responsible for the CORS facility which is to become part of the NGS CORS network will provide NGS:
      a. Schematic of the antenna support monument/structure
      b. Site obstruction survey
      c. Site sketch
      d. Representative photographs of the facility, including monument, antenna, receiver and related equipment, potential obstructions, and overall facility.
   7. CORS provider will submit three consecutive continuous 24-hour data sets to NGS to test for site suitability and multipath conditions.

A. Desired:
   1. Stable power with battery backup for at least 30 minutes.
   2. On site contact during working hours.
   3. Antenna tower height less than 10 meters.

B. Preferred:
   1. Stable power with battery backup for at least 6 hours.
   2. Provider owns land and facilities.
   3. Adequate security for equipment.
   4. Survey marker(s) (reference marks) near antenna.
   5. Receiver and communications hub located inside a building providing protection from weather and elements.
   6. Antenna located in a minimal multipath environment.

III. EQUIPMENT
Required:
1. Receiver
   0. Must be at least dual frequency (L1 and L2).
   1. Must be able to track at least 8 satellites above 10 degrees.
   2. Must have automatic switching between operating modes to retain full wavelength L2 when AS is on.
   3. Must be capable of sampling at 30-second interval.
   4. Must provide:
      1. L1 C/A-code pseudorange or P-code pseudorange.
      2. L1 full wavelength carrier phase.
      3. L2 full wavelength carrier phase.
      4. Pseudorange accurate to better than 0.5 meter RMS.

2. Antenna
   0. Must be at least dual frequency.
   1. NGS phase center variability model available.
   2. Capable of maintaining 1-cm stability.

A. Desired:
   1. Multiple independent antenna and receiver setup.
   2. Choke ring antenna with radome.

B. Preferred:
   1. Provider owns equipment.
   2. Receiver
      0. Able to track all satellites in view above 7 degrees.
      1. Can provide:
         0. L1 and L2 pseudorange accurate to better than 0.25 meter RMS.
         1. L2 P-code pseudorange.
         2. L1 and L2 Doppler.

IV. COMMUNICATIONS
   Required:
   1. Provider will establish and maintain on-site Internet, X.25 protocol or other connections which may be negotiated with and supported by NGS.
   2. Provider will be responsible for equipment maintenance.

V. DATA HANDLING
   Required:
   1. Data will be freely available for distribution.
   2. Data must be converted to RINEX 2 format using NGS-approved software.
   3. CORS will be operated 24 hrs/day, 365/366 days/year except during scheduled maintenance periods.
   4. Data will be recorded on a 30-second or shorter interval.
   5. Data will be stored on-line on site or at a central data facility for 7 days.

A. Desired:
   1. Data will be backed up using CD ROM media (ISO 9660, mode 1, Yellow Book compliant) with CDs retained.

B. Preferred:
   1. Data will be stored on-line on site or at a central data facility for 14 days.
2. Data will be backed up using tape media with a 14-day recycle period.
3. Data compression by public domain software or in self-extracting format.

VI. COORDINATE SYSTEM CONNECTION
   Required:
   1. NGS must be able to determine an NAD 83 position for the site that is accurate to 2 cm in the horizontal dimension and 4 cm in the vertical dimension with 95% confidence.
   2. Reference marks at the CORS site (if any) must be connected to:
      0. The NGS CORS antenna reference point at the 5-millimeter level of accuracy.
      1. NAVD 88 orthometric height at the 2-centimeter level of accuracy in the conterminous United States and as deemed appropriate by NGS elsewhere.

VII. ANCILLARY ISSUES
   Desired:
   1. Meteorological data sampled and logged every 10 minutes.
   2. Meteorological data in RINEX format.
      0. Temperature (+/- 1 degree centigrade accuracy).
      1. Barometric Pressure (+/- 0.1 millibar accuracy).
      2. Relative Humidity (+/- 1 percent accuracy).
      3. Sensors at same height (+/- 0.1 meter) as reference antenna.

VIII. FUNDING
   Required:

Sponsoring agency will pay for on-site equipment and communications connection costs and for future maintenance.