Australian National Report to the International Association for Geodesy, 2007

INTRODUCTION

Research in Australia - related to or utilising geodesy - over the past four years is described in this document. The contributions below represent the work of university groups (Australian National University, Curtin University of Technology, RMIT University, The University of Melbourne, The University of New South Wales, The University of Tasmania), the Victorian Department of Sustainability and Environment, and Geoscience Australia. Other national institutes and universities conduct geodesy-related studies but have not contributed to this report. Activities over the 2003-2007 period have included the use of all space-geodetic techniques as well as terrestrial and airborne gravity. The report is structured along the framework of the IAG sub-commissions along with a comprehensive list of published works and reports.

In 2006, the Australian federal government awarded $15.8M over 4 years towards geospatial infrastructure, with the funding to be matched by around $20M co-investment from state and federal government departments and universities. The investment will fund new VLBI installations at Hobart and Yaragadee (co-located with the existing SLR installation) and a new site in the northern Northern Territory. Funding has been provided for operating costs for geodetic VLBI observations to be conducted every second day. A FG5 absolute gravimeter will be acquired in 2007, along with a relative gravimeter for observing the tidal deformation at key geodetic sites in Australia. A GNSS network of over 100 new sites - including co-location at all key tide gauge installations - will be installed over the next four years, providing a continuously operating reference system for Australia around the coastline and along all major transport routes. A 380-node linux cluster will be purchased to enable the scientific analysis of geodetic data and the inversion of other geophysical data sets. An additional 128-node linux cluster will be dedicated to the "software"correlation of VLBI data. The capability of the SLR system at Mt Stromlo will be upgraded to permit more successful ranging to satellites in higher orbits (such as GPS satellites). This represents a substantial investment in Australian geodetic infrastructure and will boost significantly the scientific data required to attain a mm-accurate reference system by 2020 as per the goals of GGOS.

National Geodesy

The maintenance of Australia's national datums (the Geocentric Datum of Australia 1994, and the Australian Height Datum 1971) is performed by the Intergovernmental Committee on Surveying and Mapping Geodesy Technical Sub-Committee, which is a committee consisting of representatives from each state government, and chaired by Geoscience Australia. This committee has a number of active work program items including:

a)Development of an XML exchange format for geodetic observations
b)Production of a national geodetic observations database
c)Unification of CORS networks for ITRF densification in Australia
d)Maintenance of the Standards and Practices for Control Surveys document
e)Quantification of positional uncertainty on existing control points

f)Height Modenisation (developing the relationship between AHD71 and national geoid models (collaboratively with Curtin University))
g)Repeat levelling connections between tide gauges in the Australian Baseline Sea Level Monitoring Array
h)Standards for Legal Traceability of Position for GPS Surveying
i)Monitoring options for new National Datums

This committee provides the operational interface between geodetic research groups and the public implementation of geodetic infrastructure.

1. REFERENCE FRAMES

1.2 Global reference frames

GPS

Geoscience Australia continued to operate the Australian Regional GPS Network (ARGN) during the 2003 to 2007 period, with new permanent GPS sites installed at Melbourne, Christmas Island, Burnie, Parkes and Sydney. Another site at Bundaberg in Queensland is currently under construction. The ARGN now consists of 21 stations in Australia and the Australian Antarctic Territory. The majority of the ARGN sites have been upgraded to contribute real time data in the RTIGS format to the International GNNS Service (IGS).

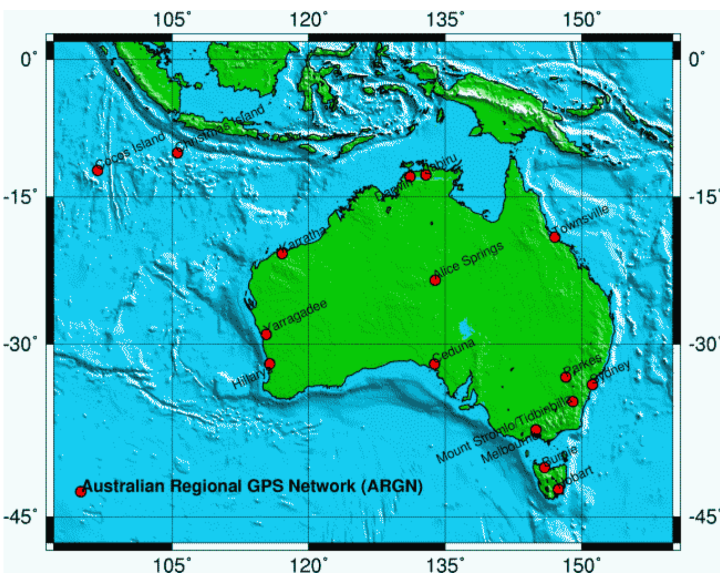

Figure 1. Australian Regional GPS network

SLR

Satellite Laser Ranging (SLR) at the Mount Stromlo (Canberra) and Yarragadee

(Western Australia) facilities have continued throughout the 2003-2007 period. The Australian systems were operated by Electro Optic Space Systems under contract to Geoscience Australia. The two SLR observatories contribute to the International Laser Ranging Service (ILRS). In 2007 Geoscience Australia became accredited as an associate analysis centre of the ILRS.

VLBI

The Geoscience Australia (GA) International VLBI Service (IVS) Analysis Center is located in Canberra. Currently the GA IVS Analysis Center contributes nutation offsets, three EOPs and their rates on regular basis for IVS-R1 and IVS-R4 networks and their predecessors (IRIS-A, NEOS-A). The EOP time series from 1983 to 2006 are available. Also the CRF catalogues using a global set of VLBI data since 1979 are regularly submitted.

The last global solution has been done using the new features of the OCCAM 6.2 software. VLBI data comprising 3415 daily sessions from 25-Nov-1979 till 07-Sep-2006 have been used to compute the global solution aus2006b. This includes, 638,913 observational delays from 1559 radio sources observed by 60 VLBI stations. Weighted root-mean-square of the solution is about 0.53 cm (about 16 picosec). The GA solution strategy used radio sources as close as possible to the ICRF. Coordinates of 212 defining sources were treated as global and imposed by the NNR constraints. 102 'other' sources were treated as local and their positions were estimated for each VLBI session. The rest of 1245 sources were treated as global without NNR constraints.

Studies have been undertaken to assess the effects of ground deformation (Titov and Tregoning, 2005) and source selection (Titov 2007) on the accuracy of VLBI parameter estimates.

Geodetic Activity at the Australian Radio-telescopes

During 2006 two Australian radio-telescopes (Hobart and Parkes) were involved in geodetic VLBI observations. The operations of the Hobart telescope for geodetic VLBI are supported through an Australian Research Council (ARC) grant awarded jointly to the University of Tasmania (UTAS) and GA. The Parkes 64-meter telescope participated in five geodetic VLBI sessions in 2006. Six sessions are planned for 2007. This program is promoted in cooperation with the Australian Telescope National Facility (ATNF).

New geodetic VLBI network

In November, 2006 the geospatial bid within the National Collaborative Research Infrastructure Strategy (NCRIS) capability "Structure and Evolution of the Australian Continent" has been approved. The VLBI part of this bid includes three new modern VLBI sites to be built in different parts of the Australian continent. The proposed design includes a small size dish (12 m) with high slewing rate (5 degrees/second) equipped with

Mark5B recorder. All sites will eventually be linked with the optic fibre to transmit the recorded data with high speed to the correlator facility which is being established.

Terrestrial Surveys at Collocated Observatories

Geoscience Australia performed routine precise terrestrial geodetic surveys at all collocated geodetic observatories in Australia including Yarragadee, Mount Stromlo, Hobart, and Parkes. Survey results have been supplied to the IERS. GA has been actively researching methods to improve the terrestrial connections (Dawson et al., 2007). GA in collaboration with University of Melbourne undertook photogrammetric observations of the Hobart VLBI dish on an attempt to quantify dish gravitational deformation. Geoscience Australia has also chaired the IERS working group on site survey and collocation since 2004.

1.3 Regional reference frames

The South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) is an Australian Government initiative, funded by the Australian Agency for International Development (AusAID), which is enabling South Pacific Island Countries to better manage their own environments and contribute to achieving sustainable development. A component of the SPSLCMP includes a CGPS site adjacent to precise tide gauges. Geoscience Australia has both operated and extended the South Pacific GPS network during the 2003 to 2007 period. The sites are located in the following countries: Samoa, Cook Islands, Tuvalu, Tonga, Nauru, PNG, Kiribati, Micronesia, Fiji,Vanuatu, Palau. The data from these GPS sites are available from Geoscience Australia for local and global scientific research and local applications. New sites in the Marshall and Solomon Islands, are in final planning.

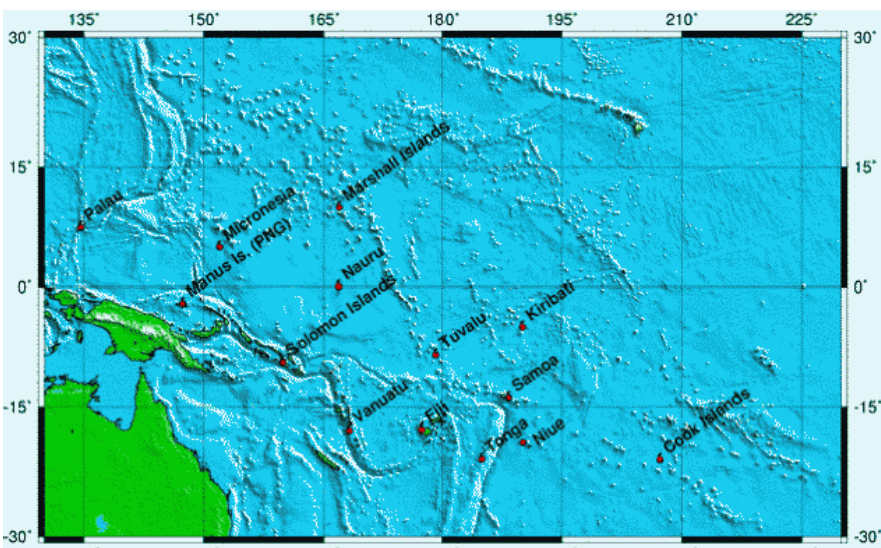

Figure 2. South Pacific Sea Level and Climate Monitoring Project GPS network

Geoscience Australia maintains an active Antarctic geodesy program within the Australian Antarctic Territory (ATT). In the 2004 to 2007 period GA installed remote autonomous GPS stations at Wilson's Bluff, the Grove Mountains and Bunger Hills in East Antarctica. GA has continued to refine the AAT terrestrial geodetic network with ongoing episodic GPS observations. GA has also routinely conducted the CGPS to tide gauge benchmark leveling connections at Mawson, Davis, Casey and Macquarie Island in support of the IGS GPS Tide Gauge Benchmark Monitoring - Pilot project (TIGA).

Geoscience Australia continued to contribute weekly regional RNAAC GPS solutions to IGS up to March 2006. Submissions ceased at that time because the only unique site not included in 3 or more IGS Global Analysis Centre solutions was the site AUST which is a US National Geospatial-Intelligence Agency (NGA) GPS monitor station. With the deployment of new GPS installations commencing as part of the AUSCOPE Project it is proposed to recommence RNAAC solutions to IGS some time in 2008.

Asia and Pacific Reference Frame

The work of the sub-commission on the Asia Pacific Reference Frame for this period has been carried out in conjunction with the Regional Geodesy Working Group of the Permanent Committee for GIS Infrastructure in the Asia and the Pacific region (PCGIAP). The role of this working group has been to coordinate regional cooperation in Geodesy amongst national agencies and to build a regional geodetic infrastructure. This group has the dual function to report on relevant activities to the UNRCC-AP and to the IAG sub-commission to the Asia Pacific Reference Frame. Members of this working group are nominees from national surveying and mapping organizations rather then being drawn from academic institutes.

The initial goal of the PCGIAP Geodesy Working Group was to establish a precise regional geodetic reference framework from Central Asia to the Pacific. A primary achievement of the working group has been to establish a single regional horizontal geodetic datum and provide linkages for individual country datums to this regional datum through densification of the International Terrestrial Reference Frame.

The 16th United Nations Regional Cartographic Conference for Asia and the Pacific (UNRCC-AP) held in Okinawa in July 2003, acknowledged the achievements of the PCGIAP Regional Geodesy Working Group and endorsed a resolution in relation to the ongoing activities of the Geodesy working group to:

- The enhancement of a regional geodetic infrastructure through annual cooperative campaigns, including ties to vertical datum origin points,
- Review the status of the regional geoid in relation to current and improved global gravity models available from satellite gravity, and the application of absolute gravity as a means of developing a regional gravity reference frame,
- Promote the application of new geodetic adjustment techniques and datum change transformation parameters for regional spatial data integration and for geo-

referencing cadastral and statistical information,

- Encourage the transfer of GPS technology to Pacific Island nations and other developing countries through regional and local geodesy workshop activities,
- Development of a catalogue of regional tide gauges for monitoring sea level changes and placement of GPS at key sites, and
- Review the status of geodetic networks in individual countries and upgrade the PCGIAP web site information.

All activities during this period 2003 -2006 were guided by a work plan through to the 17th UNRCCC-AP which was held in United Nations Regional Office in Bangkok in September 2006. However unexpected tectonic events have had a significant impact on Geodesy in this period with Indonesian earthquakes and devastating tsunami aftermaths of the December 2004 events, requiring more detailed attention to reference frameworks related to these events.

There were a number of recent face-to-face meetings held to maintain contact between working group members and to assist progress on projects. These included the following:

- An informal meeting of the working group was held during the 10th PCGIAP meeting in Bangalore, India in January 2004
- A regional Geodesy workshop was held in Chengdu, China in September 2004 in conjunction with IAG commission 2
- A special Tsunami workshop was hosted by Indonesia in Bali in May 2005
- A regional Geodesy workshop was hosted by Geoscience Australia immediately before the IAG General Assembly in Cairns Australia in August 2005
- An associated meeting on regional gravity was hosted by Mongolia in Ulan Baatar in June 2006

A full report of the 11th PCGIAP meeting in Bali is available on the PCGIAP web site http://www.gsi.go.jp/PCGIAP/bali/bali_rep.htm and presentations for the Cairns meeting are available on CD from.

At the 13th PCGIAP meeting in Seoul, republic of Korea, June 2007, PCGIAP approved a resolution for WG1 to hold the next Regional Geodesy Workshop in conjunction with the 14th PCGIAP meeting at a location and date to be chosen during 2008. Some member countries have proposed to produce a combined GPS solution in terms of ITRF2005 covering all annual campaigns from 1997 to 2007 for presentation of results at this workshop.

Annual, week-long GPS regional campaigns were observed in 2004, 2005 and 2006. Geoff Luton from Geoscience Australia continued to be the coordinator for annual GPS observation campaigns for ten years in a row. Participation in the campaigns typically included:

2003- 30 countries & 124 sites
2004- 25 countries & 91 sites
2005- 23 countries & 79 sites

2006 - 24 countries & 67 sites
2007 - Campaign to be held late September/early October with Australia continuing to coordinate measurement campaign

Data from these campaigns is collated and available to countries requesting the observational data. Combined solutions have been compiled by Geoscience Australia and submitted for use in ITRF determinations.(through geoff.Luton@ga.gov.au). Near concurrent regional geodetic VLBI projects, have been arranged each year with the Asia Pacific Space Geodynamics group. They have had the following campaigns recently:

APSG-18	12 SEPTEMBER	2006
APSG-19	10 OCTOBER	2006
APSG-20	11 SEPTEMBER	2007
APSG-21	10 OCTOBER	2007

Whilst the GPS campaigns have been undertaken for ten years, it is apparent that with the increase in continuous stations it is no longer essential to hold campaigns on specific dates to disseminate the precise global coordinates for infrastructure points through the region. Some agencies such, as Geoscience Australia (GA) now compute regular weekly solutions. Observation campaigns can be observed at the individual country's convenience as GA offers to include such campaigns in their weekly regional solutions. Changes to technology now enable observations made at any time throughout the year to be included in regular regional computations, which in turn are forwarded to Global geodesy bodies for inclusion in the densification of the International Terrestrial Frame.

Height systems and vertical datums have been considered in general through a proposed "rigorous" orthometric height system (Tenzer et al. 2005, Santos et al. 2006). In the Australian context, it was confirmed that the Australian Height Datum (AHD) uses a modified form of the normal-orthometric height system (Featherstone and Kuhn 2006). A simulated mountain gravity field was used to 'benchmark' existing height systems (Dennis and Featherstone 2003).

The (mainly north-south) distortions in the AHD have been addressed, despite the Australian Government's desire to retain the AHD for the "foreseeable future" (Featherstone 2004, 2006). This will necessitate "fitting" the next generation of gravimetric quasigeoid to GPS-levelling data (Fotopoulos et al. 2003, Featherstone and Sproule 2006, Soltanpour et al. 2006). An indication of the surface to be used to fit the gravimetric geoid model to the AHD at GPS-levelling points is shown in Figure 3. Work at Curtin University is currently underway to extend Geoscience Australia's earlier work on the AHD by running readjustments that are free of constraints to mean sea level (MSL) at multiple tide gauges, including "rigorous" orthometric corrections and other data.

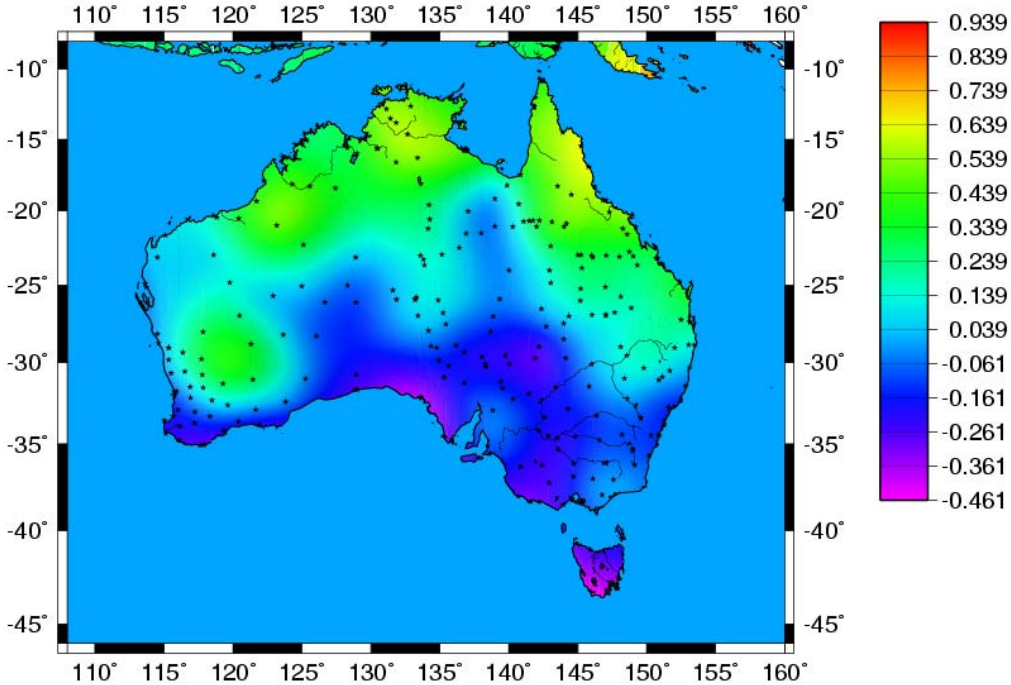

Figure 3: Differences (in metres) between a gravimetric quasigeoid model and the AHD at GPS sites

Existing datum transformations to the GDA94 were investigated in Western Australia by Kinneen and Featherstone (2004), showing that they perform within their claimed precision.

2. GRAVITY FIELD

2.1 Gravity and gravity networks

In cooperation with Geoscience Australia and the Research School of Earth Sciences at the Australian National University, the University of Kyoto, Japan, used their FG5 instrument #210 for repeat measurements of absolute gravity at Mount Stromlo and Tidbinbilla during March and April 2004. This followed use of the FG5 instrument in Antarctica for a number of successful measurements by the Japanese. The measurements at Mount Stromlo provided a repeat calibration on the Superconducting Gravimeter #SG-CT031. An absolute gravity measurement campaign was carried out by Micro-g Solutions for Geoscience Australia during May and June 2005 using FG5 instrument #111. Repeat measurements were made at 8 sites across Australia. Another repeat absolute gravity observation was carried out in February 1999 at Mount Stromlo and Tidbinbilla, using FG5 #206 of the Université Louis Pasteur in Strasbourg, with support from Geoscience Australia and the Research School of Earth Sciences at the Australian National University. Operation of the superconducting gravimeter at Mt Stomlo was affected by the destruction of the building by a bushfire in January 2003, although the equipment was unaffected. Once power was restored, observations recommenced.

As part of the NCRIS funding, it is proposed to purchase an FG5 gravimeter and one or more precision absolute gravimeters (Superconducting gravimeter or earth tide meters).

The regional gravity coverage of Australia has been significantly enhanced in recent years mostly by Government funded surveys to promote mineral exploration. More than 100,000 stations have been added to the National Gravity Database, maintained by Geoscience Australia, in the last five years bringing the total continent-wide coverage to over 1.4 million gravity stations. The majority of these new stations were acquired on regular grids that varied from 4km to less than 1 km spacing, with the most common spacings being 4 km, 2.5 km and 2 km (Richardson etal, 2007).

The Australian Fundamental Gravity Network (AFGN) consists of over 900 gravity stations at over 280 locations throughout Australia and provides a common basis for all gravity surveys conducted within Australia. Over the last five years Geoscience Australia has conducted a program aimed at providing a more consistent and accurate network for gravity surveys. This has involved the measurement of absolute gravity at 63 existing AFGN stations using an A10 portable absolute gravimeter to determine the accuracy and precision of the current Australian gravity datum, Isogal84. These portable absolute measurements have been augmented by more precise absolute measurements conducted with FG5 instruments during geodetic campaigns that are reported elsewhere in this report. These absolute measurements have shown that the Isogal84 datum is 78 microgals higher than the absolute measurements and that the accuracy of the stations in the AFGN is approximately 30 microgals (Tracey, 2006).

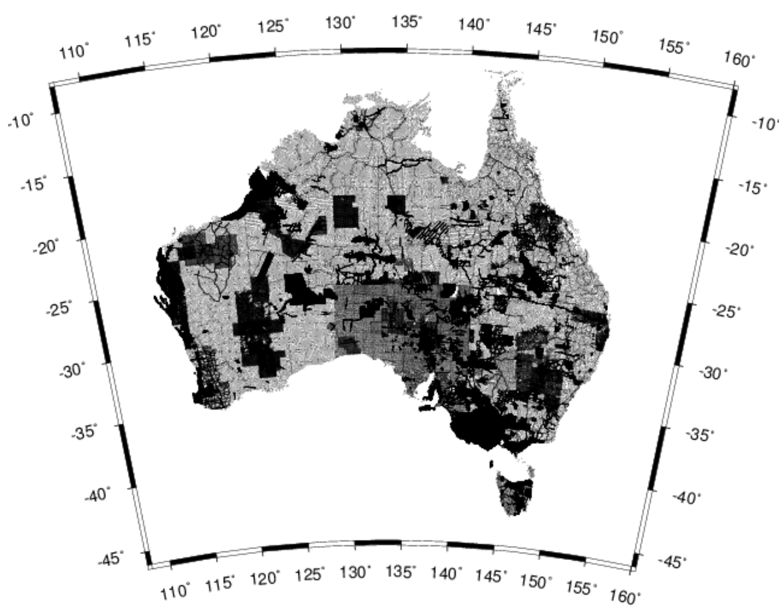

Figure 4 Coverage of Australian land gravity observations. The dense areas have been observed recently using GPS controlled gravity surveys for resource exploration

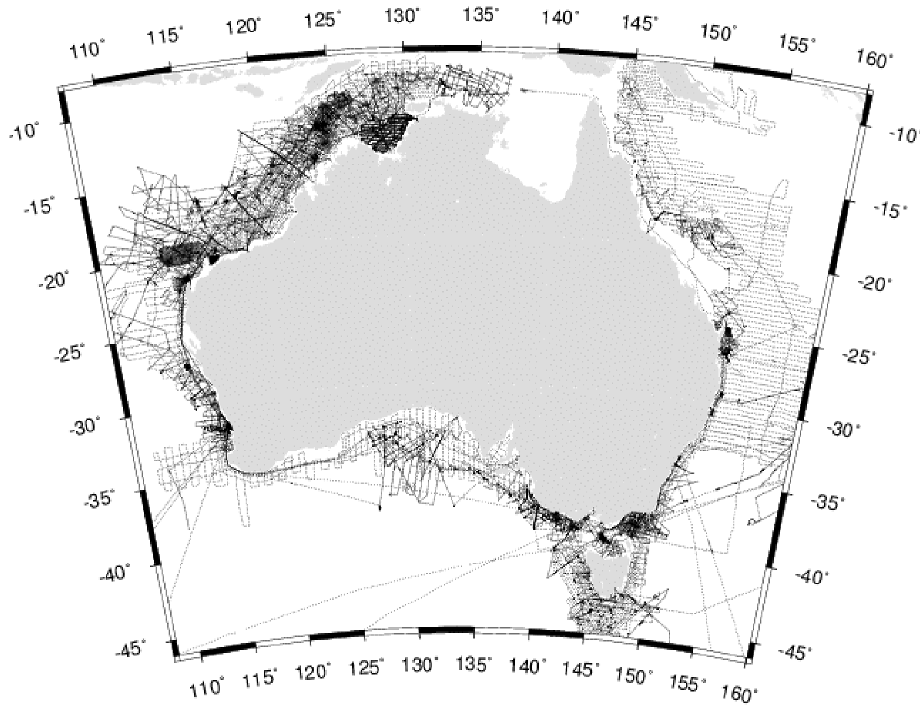

Figure 5. Coverage of Australian marine gravity observations. Most of these observations have not been crossover adjusted

Sproule et al. (2006) used a digital elevation model and interpolated nearby gravity data to identify gross errors in the Australian land gravity database. This showed that the short-wavelength quality of the database is good, with only 0.2% outliers being detected.

2.2 Spatial and temporal gravity field and geoid modelling

A long-term project, endorsed through the IAG special study group 3.177, was finally completed to yield two synthetic [simulated] gravity field models. CurtinSEGM (Kuhn and Featherstone 2003b, 2005) is a global model based on forward modelling (e.g. Kuhn and Featherstone 2003a, Kuhn and Seitz 2005). The second, called AusSEGM (Baran et al. 2004, 2006), is over Australia only. These models are for the validation of geoid computation theories methods and computer software. AusSEGM is freely available as electronic supplementary material with Baran et al. (2006).

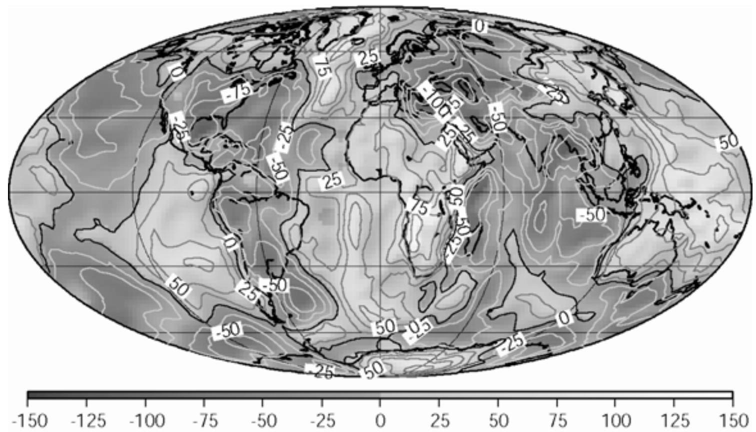

Figure 6: Geoid heights from CurtinSEGM (units in metres)

Forward gravity modelling (Kuhn and Featherstone 2003a, Kuhn and Seitz 2005) was applied to regional and global data sets for gravity field recovery (Kuhn and Featherstone 2005, Tsoulis and Kuhn (2006). The optimal spatial resolution of crustal mass distributions for forward modelling has been discussed by Kuhn and Featherstone (2003a), while Kuhn and Seitz (2005) compare the solution of Newton's integral in the space and frequency domains. Tsoulis and Kuhn (2006) provide a review on recent developments in forward gravity modelling and its application for synthetic Earth gravity modelling and gravity recovery.

2.3 Dedicated satellite gravity mapping missions

Various experiments have been run with geopotential models derived from the Gravity Recovery and Climate Experiment (GRACE), showing some potential errors in the Australian land gravity anomalies (Featherstone 2003d,e, 2005).

2.4 Regional geoid determination

Work has continued on refining the Australian gravimetric quasigeoid model as a replacement of AUSGeoid98 (e.g., Featherstone et al., 2005, 2007). Various aspects have been considered, including deterministic kernel modifications (Featherstone 2003a,f; Vanícek et al. 2003, Featherstone et al. 2004b, Sjöberg and Featherstone 2005), computation of ellipsoidal corrections (Claessens 2006), consideration of topographic mass-density data (Kuhn 2003), the use of gravity disturbances (Kirby 2003), and the geoid to quasigeoid separation (Tenzer et al. 2006). The new model is expected in late 2007.

New solutions to ellipsoidal geodetic boundary-value problems were derived, which are of use in the analytical computation of global gravity field models (Claessens and Featherstone 2005) and in geoid modelling (Claessens 2006). These solutions are based on new relations among spherical harmonics (Claessens 2005). Holmes (2003) gives a detailed analysis of ultra-high degree spherical harmonic synthesis.

Work at Curtin University is looking at the introduction of non-stationary covariance functions and anisotropy into least-squares collocation (LSC), which borrows from spatial statistics and Kriging. This is motivated by clear non-stationarity and anisotropy in Australian gravity anomalies.

The definition of the gravity anomaly has been revisited (Vanícek et al. 2004, Hackney and Featherstone 2003), and experiments run to determine the best gridding and interpolation methods (Goos et al. 2003, Zhang and Featherstone 2003).

There has been close collaboration between Australia and New Zealand on their quasigeoid model and the specific issues of 13 different vertical datums in use there (Amos and Featherstone 2003a,b,c, 2004, 2005, Amos et al. 2005a,b).

3. GEODYNAMICS AND EARTH ROTATION

3.1 Earth tides

The inter-comparison of different geodetic analyses requires a homogenous approach to modeling all geophysical signals, including the Earth tide. As part of a long term study involving the absolute calibration of the satellite altimeters in Bass Strait (see 4.1), the Earth tide model within the GAMIT GPS processing software was augmented to reflect the IERS 2003 conventions. Watson et al (2006) investigated the impact of the model change, comparing coordinate time series and tropospheric delay estimates computed using IERS 1992 and IERS 2003 solid Earth tide models. This work is part of a body of work in the recent literature that has refined our collective understanding of systematic error sources, particularly high frequency mis-modeling of periodic signals and their propagation to the low frequency end of the spectrum. Penna and Stewart (2003) showed that tidal effects alias as long-period features in GPS height time-series, the propagation method of which was derived in Stewart et al. (2005). These developments are clearly required in order to achieve the results required for high accuracy applications such as monitoring the global water cycle and absolute sea level change.

3.2 Crustal deformation

A number of studies focused on the analysis of GPS, seismic and remote sensing data, around a dense network of stations situated close to the tip of an active propagating rift on the Amery Ice Shelf, East Antarctica (Fricker et al., 2005; Bassis et al., 2005) as well as a comparison of terrestrial survey data and GPS measurements over a 30+ year period on the Amery Ice Shelf (King et al., 2007). These studies contributed to an understanding of the dynamics of ice shelf processes. Investigations were also carried out into high-precision techniques for GPS processing on moving ice shelves (King et al. 2003; Nguyen et al, 2005). Balance flux velocity results were derived for the Lambert Glacier Basin, East Antarctica, using satellite and model results and compared to GPS-computed surface velocities (Testut et al., 2003). Glacial isostatic adjustment observations in East Antarctica continued, with the augmentation of the network in 2007 by a new site in Enderby Land near the location of a mass increase detected from GRACE (e.g. Chen et al., 2006).

Geoscience Australia in collaboration with the Research School of Earth Sciences (RSES) ANU, Western Australia Department of Land Administration, New Zealand Institute of Geological and Nuclear Sciences, Curtin University of Technology and the University of Western Australia has observed two campaign GPS networks of 50 Stations each, in the South West Seismic Zone (SWSZ), located in Western Australia, and the South Australian Seismic Zone (SASZ), located in the Flinders Ranges. These observations will contribute to the natural hazard assessment. A geological model has been constructed for the Southwest Seismic Zone in Western Australia (Dentith and Featherstone 2003). The episodic GPS measurement programme that was initiated to attempt to detect surface motion associated with the seismicity (Featherstone et al. 2004) has not yet observed any real deformation in the zone.

Wavelet techniques (e.g., Kirby 2005) have been used to determine the effective elastic thickness of the lithosphere (Swain and Kirby 2003a,b). This has been applied globally (Kirby and Swain 2004), in Australia (Kirby and Swain 2006, Swain and Kirby 2006) and South America (Tassara et al. 2007).

Tectonic studies in Papua New Guinea involved the assimilation of GPS data, seismic tomography and aftershock locations to understand plate configurations (Tregoning and Gorbatov, 2004; Tregoning et al. 2005). An upper bound was placed on intra-continental deformation of the Australian Plate from GPS data (Tregoning, 2003). Modelling of atmospheric pressure loading deformation and aliasing of such loading into scale factor errors was investigated (Tregoning and van Dam, 2005a, 2005b).

In the period 2004 -2007, the Department of Geomatics at the University of Melbourne has been involved in a crustal monitoring project using GPS along part of the Gippsland coast in eastern Victoria. The project has been carried out for the Victorian Department of Primary Industries and the Department of Sustainability in cooperation with AAMHatch Pty Ltd. Over the four years of the project, four deformation surveys have been carried out, connecting the local subsidence monitoring network to the Australian Regional GPS Network (ARGN). Height precisions in the range of ±5-6 mm were routinely achieved using the Bernese 5 GPS processing software. These precisions satisfied the requirements of the project brief which called for standard deviations of ±10 mm per point per epoch. A series of reports detailing the GPS processing and deformation analysis have been prepared for AAMHatch which were subsequently incorporated into consultant's reports for the client (Collier and Fuller, 2004, 2005, 2006, 2007).

Geoscience Australia has contributed to the TIGA project with data and analysis products. GA has processed GPS data from more than 70 sites from a regional network including Southeast Asia, Australia, South Pacific, New Zealand and Antarctica. GA has contributed to the TIGA pilot project by providing 520 weekly solutions (from 1997 to 2007). Recent CGPS coordinate time series analysis results are reported in SPSLCMP CGPS semi-annual report February 2007.

3.3 Geophysical fluids

Studies of global sea level were made using tide gauge and satellite altimeter data to estimate the regional patterns of sealevel rise for the period 1950-2000 (Church et al., 2004), as well as a comparison of historical sea level records (1841-42) with new data (1999-2002) at Port Arthur, Tasmania (Hunter et al., 2003). Loading effects of the atmosphere on an ice shelf were studied by Padman et al (Padman et al., 2004).

Improved determination of site-specific mean sea-level prediction from tide gauge records with data gaps was examined with neural networks by Makarynskyy et al. (2004a,b, 2005b). Future sea level change has been simulated from a climate dynamics model (Makarynskyy et al. 2005a), showing that these models are rather variable when extrapolated (Makarynskyy et al. 2007).

A collaborative project between Curtin University and the University of Stuttgart, Germany, is looking at sea level change due to the partial or complete melt of land-based ice masses. This sows that melting of all currently land-based ice masses will raise global average sea level by about 64 m (the water equivalent of all ice masses) instead of an often-reported value of 80 m. Due to gravitational feedback of the changing masses sea-level change is not uniform, but highly variable depending on the location (Figure 7). Furthermore, the research shows considerable changes in the Earth's centre of mass and length of day as well as the flooding of extensive coastal areas in the event of a total meltdown.

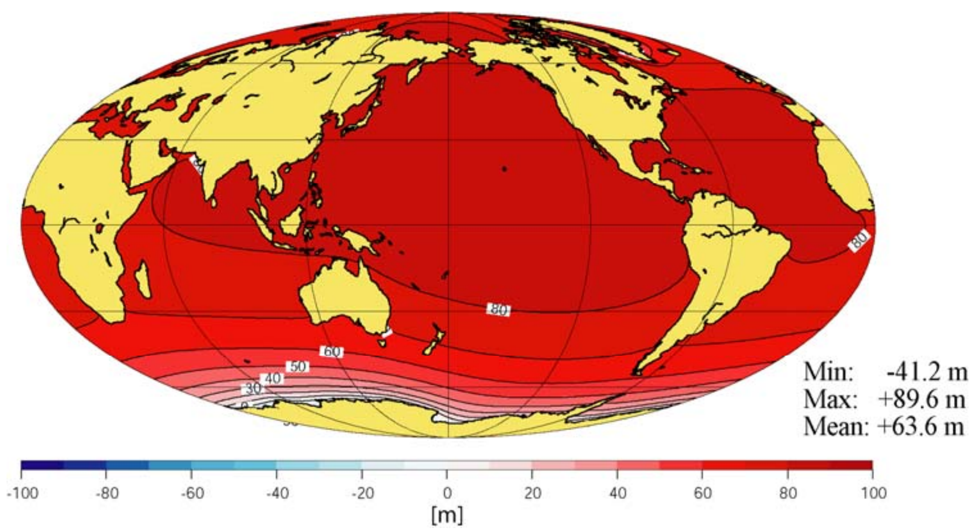

Figure 7: Global sea level distribution under the assumption all land-based ice masses located above the current mean sea level are melted and the water-equivalent is distributed over the oceans. The gravitational feedback effect causes the spatial variability.

4. POSITIONING AND APPLICATIONS

4.1 Multi-sensor systems

A long term study involving the absolute calibration of satellite altimeters TOPEX/Poseidon and Jason-1 through the use of tide gauge and GPS buoy data has continued at the Bass Strait calibration site (Watson et al., 2003, 2004). These studies have developed an improved in-situ calibration technique for the two satellite altimeters, cementing the Bass Strait calibration site as the sole calibration facility outside of the National Aeronautics and Space Administration (NASA) and the French Centre National d'Etudes Spatiales (CNES) structure, and the sole site in the Southern Hemisphere. This work has provided a significant contribution to the NASA/CNES science team and will continue into the future with the planned launch of Jason-2.

In a project funded by the Australian Cooperative Research Centre for Spatial Information, research activities at UNSW have focused on the design, development and testing of a generic GPS/INS hardware/software integration "platform" that can be used in the future as the basis to build customisable integrated positioning/mapping systems (Ding et al, 2005; Li et al., 2006; Mumford et al., 2006). Theoretical analysis and algorithm development for sensor integration have been conducted over the past few years (Lee et al., 2003; Moore and Wang, 2003; Wang et al., 2003a, b; Hwang et al., 2005; Li et al., 2005a, b, 2006). Realistic stochastic modelling for measurements and the dynamic noise is one of the fundamental and challenging issues for a wide range of scientific problems. A new adaptive stochastic modelling methodology was developed to improve the accuracy and reliability of integrated positioning results (Ding et al., 2006, 2007).

Research related to the integration of GPS with "pseudolites" (or "pseudo-satellites") was conducted both in a theoretical sense - modelling of measurements, algorithm implementations, systematic error propagation studies, etc. (Wang et al., 2005a, 2006) - and in field tests directed to specific applications (Soon et al., 2003; Barnes et al., 2004; Wang et al., 2004; Lee et al., 2004b, 2005b).

System design and implementation has also been carried out for the triple-integration GPS/Pseudolite/INS in several graduate student projects (Yi et al., 2003; Lee et al, 2004a, 2005a; Lu et al., 2005; Wang et al, 2006). Such triple-integration work is aimed at addressing the shortcomings of both GPS (vulnerable to signal obstructions in certain application environments) and INS (rapid growth of navigation errors if no GPS measurements can be made). This work continues but with the replacment of the pseudolite technology with an Australian-developed terrestrial RF-based ranging system known as "Locata" (Barnes et al., 2003a, b, 2006).

Ultra-tight integration of GPS, pseudolites and inertial sensors has been investigated, whereby the GPS receiver tracking loops are helped using inertial measurements of dnamic motion so as to improve the tracking performance of the receiver (of the GPS or pseudolite signals). Efficient filtering algorithms for signal acquisition and tracking, which can effectively suppress RF interference and enhance weak ranging signal tracking, have been developed (Babu and Wang 2005a,b; Li and Wang, 2006; Li et al., 2006).

Integration of Global Navigation Satellite Systems (GNSS), such as GPS, Glonass, Galileo, is critical for applications with stringent requirements for high precision and integrity. Research has been conducted into combined GNSS measurement modelling, ambiguity resolution, etc. (Isshiki & Wang, 2007; Wang et al., 2005b), and especially into reference network-based positioning algorithms to support network-RTK (Dai et al., 2003a, b, 2004; Musa et al., 2003, 2004). Algorithms and methodologies have also been developed for GNSS receiver autonomous integrity monitoring and quality control (Hewitson et al., 2004; Hewitson and Wang, 2006a, b; 2007). Studies on the possible impact of next generation GNSS on high accuracy applications have also been conducted (Rizos et al., 2005; Feng et al., 2006).

The calibration and performance of airborne and terrestrial laser scanners has been investigated over the last few years (Lichti et al. 2003, Bae and Lichti 2007a,b, Gordon 2005, Gordon and Lichti 2004, Lichti 2004, Lichti and Jamtsho 2006, Lichti and Licht 2006, Lichti et al. 2005, Skaloud and Lichti 2006). This has been extended to automated registration from laser scan point clouds (Bae and Lichti 2004, Bae 2006, Bae et al. 2005, Belton and Lichti 2005, 2006, Lichti 2005).

At The University of Melbourne, research in multi-sensor systems area has focused on the development of new algorithms and techniques for augmenting GNSS during periods of partial and complete satellite unavailability. Specifically, this work has revolved around evaluating the performance of low cost MEMS-based inertial sensors and assessing their potential for augmenting GNSS. Low cost inertial sensors pose new challenges with regards to error and bias modelling and new approaches have been developed and evaluated. The algorithmic approach adopted is based around a smart, constrained, centralised Kalman filter. Appropriate constraints are generated from additional sensor measurements or from environment specific characteristics derived from logical navigation rules and database relationships. The sensor measurements and constraints are then integrated through smart stochastic models that optimises their effect on the final position and orientation solution.

The approaches developed here for integrating GNSS measurements with those of low cost inertial sensors have been successful in demonstrating cost and reliability improvements for geo-referencing in mobile mapping systems. This work is being extended to address the more practical constraints of size and power emerging for localization problems across ad-hoc wireless sensor networks for applications such as environmental monitoring.

What has emerged through this research, offering greater potential for improving the performance of multi-sensor systems, is the capability to integrate topological relationships (inherent in spatial databases) and the outputs of human spatial cognition studies as synthetic measurements to the integration models. These investigations are stimulating new research initiatives into augmented reality applications and advanced in-vehicle navigation systems.

Researchers at RMIT in collaboration with the Australia Institute of Sport (AIS), the recently closed CRC for microTechnology and Griffith University have developed an integrated miniaturized smart athletic tracking system which integrates high-rate GPS measurements, INS/IMU, accelerometers, physiological sensors and magnetometer (Zhang et al., 2007, Zhang et al., 2005, Zhang et al., 2004).

The ability to measure and record athlete physiological and positional information associated with athlete movement in real-time is critical in the process of athlete training and coaching, particularly for outdoor activities. Blood oxygen, respiration, heart rates, velocity, acceleration/force, changes in direction and position, and many other factors are required in elite athlete training and coaching. The position, movement and force information plays an important role in an effective analysis of the athlete performance, especially for rowers. Currently, the stroke information can only be measured in either well-controlled situations in dedicated sports laboratories or using simulation devices. Much of the equipment is either too heavy, expensive or obtrusive and multiple factors which are difficult to control have restricted the use of sport-specific field-testing. Therefore, smart real-time monitoring during training and competition to help elite athletes to improve their performance and avoid injuries is critical for both athletes and coaches.

A prototype of the GNSS rower tracking system was used extensively by elite Australian athletes prior to and during the Athens Olympics and other major international events (e.g. Lucerne Regatta). The continuous monitoring of three-dimensional position, velocity and acceleration of the rowing boat with a high frequency and accuracy is achieved through an integration of GPS, a multi-sensor system for athlete physiological and movement information, a wireless communication mechanism and interactive visualisation tool. This is the first of its kind, a typical multisensor system and patented internationally. The prototyped system is now being commercialized by Catapult Innovations Ltd. RMIT GPS research group continues this effort in collaboration with AIS and Catapult Innovations to further develop the system a joint project of "Improving the precision of position and velocity determinations provided by low-cost GPS devices".

4.2 Applications of geodesy in engineering

A detailed study of the behaviour of a cable-stayed bridge, using GPS, traditional survey data and computational models, was made by Watson et al. (2007). This study took an innovative approach towards validating existing structural deformation models using GPS techniques combined with additional in situ observations.

Research into time series analysis of outputs of structural monitoring systems based on GPS, accelerometers and other sensors has been conducted by several graduate students at UNSW (Moore et al., 2003; Ogaja et al., 2003; Li et al., 2005, 2006a, b, c). The use of GPS networks, made up of a mixture of dual-frequency and single-frequency receivers, for monitoring deformations of volcanoes has been a study topic of several graduate projects, including Janssen and Rizos (2003a, b; 2005). The use of "pseudolites" was also investigated in a number of papers (Meng et al., 2004; Barnes et al., 2005).

The University of Melbourne has been conducting research into measuring long-term structural deformation as well as the high frequency components of structural movement (Raziq and Collier, 2006; 2007). The work is demanding from the perspective of the precision that needs to be achieved as well as the difficult environmental conditions causing signal obstructions and multipath that impact on the quality and completeness of the collected data.

4.3 GNSS measurement of the atmosphere

Investigations into the effect of tropospheric delay on GPS positioning were carried out in the context of research into network-RTK techniques (Dai et al., 2003b; Musa et al., 2004; Roberts et al., 2004). The impact of stochastic modelling improvements on ZTD estimation was studied by Jin et al. (2004a, 2005). Ionospheric studies were conducted by Jin et al. (2004b, 2006), Zhang et al. (2005).

Using CHAMP satellite data, the numerical algorithm used to process bending angles for GPS meteorology was analysed and compared to analytical solutions (Awange et al. 2004). Glowacki et al. (2006) used GPS to estimate integrated water vapour for the Australian region.

New mapping functions (VMF1) based on time-dependent ray-traced values were assimilated into the GAMIT GPS software, yielding improved height estimates in GPS analysis (Boehm et al., 2007a). An empirical version, GMF, was also developed and validated from an analysis of global GPS data (Boehm et al., 2006). Studies of the effect of choice of a priori hydrostatic delay models were made (Tregoning and Herring, 2006), including the implementation of the Global Pressure and Temperature (GPT) a priori atmospheric modelling into the GAMIT software (Boehm et al., 2007b). The use of ray-traced slant tropopspheric delays is the subject of a PhD study at ANU.

A collaborative project between the Australian Bureau of Meteorology and The University of Melbourne is investigating the required spatial and temporal resolutions for GNSS derived zenith tropospheric delays (ZTD) to reliably support weather forecasting activities. In this work, a communications module has been developed to enable the real-time streaming of raw GNSS data from each site within Victoria's regional network of reference stations (GPSnet). A computation module uses the Bernese (Version 5) GNSS processing software to automatically produce hourly estimates of ZTD and Integrated Water Vapour (IWV). These values are then uploaded to a webserver for subsequent analysis for weather prediction. Validation of the ZTD values based on variation of the spatial and temporal resolutions of the GNSS data is currently under investigation. The system developed is scalable to include real-time data streams from any active GNSS site across Australia.

Various independent software processing packages and algorithms have been developed at RMIT University and research undertaken spans modelling both the spatial and temporal variation of the ionosphere in a network-RTK environment, the use of GPS measurements to determine the ionospheric Total Electron Content (TEC) both in absolute and differential sense, TEC above LEO satellite, limitations during severe weather events, the potential of exploiting GNSS as a remote sensing tool for meteorology and space weather applications and atmposheric density modelling for precise space debris tracking and collision warning purposes.

GPS radio occultation is a new technique of imaging the atmosphere with the potential for providing high vertical resolution of temperature, pressure and water vapour profiles of the atmosphere. Preliminary research has been undertaken jointly by RMIT University and The Australian Bureau of Meteorology to improve the forecast accuracy of numerical weather prediction and climate system studies, to reveal the height and shape of the tropopause on a global scale (an important goal in atmospheric and climate research), to investigate cyclone and El Nino events and to investigate the global water vapour distribution and map the atmospheric flow of water vapour.

4.4 Applications of satellite and airborne imaging systems

A system has been developed for re-tracking satellite radar altimeter waveform data (Deng and Featherstone 2006), which has improved geodetic parameter estimation in the notoriously problematic coastal zone (Deng 2003, Deng and Featherstone 2005). The performance of various altimeter-derived gravity anomalies was evaluated around Australia (Featherstone 2003c), showing significant differences in the coastal zone. Spatial variations in sea level over the Atlantic were studied by Kuhn et al. (2005). Satellite altimetry over land has also been used to validate digital elevation models (Hilton et al. 2003).

Investigations into the modelling of small-scale surface deformation using satellite radar interferometry (INSAR) have been performed (Baran 2004), which has led to a new filtering technique for the processing of interferometric data (Baran et al. 2006) and a functional model to determine the range of deformation that can be detected using satellite radar interferometry (Baran et al. 2005). Simulation studies quantified the magnitude/depth characteristics of Australian earthquakes likely to be detected from InSAR in the Australian region (Dawson and Tregoning, 2007). Differential radar interferometry (InSAR) was used for mine subsidence monitoring with data from the ERS-1/2, JERS-1, Radarsat-1, Envisat (Chang et al., 2003; Ge et al., 2003a, 2005, 2007a, b; Chang et al., 2004b, 2005a, b). Atmospheric corrections for radar interferometry (Janssen et al., 2003, 2004), the accuracy assessment of InSAR digital elevation models and comparison with photogrammetric and lidar DEMs (Trinder et al., 2003; Chang et al., 2004a; Lee et al., 2005a, b) were undertaken. The integration of InSAR with GPS and GIS (Ge, 2003; Ge et al., 2004a, b; Rizos et al., 2003a), filtering for InSAR Xu et al., 2005a, b; Meng et al., 2007) and differential radar interferometry for monitoring earthquakes, geothermal site etc (Ge et al., 2003b, Chang et al., 2005c, d) were studied.

The UNSW team has recently commenced research on Persistent Scatterer InSAR (PSInSAR), and results for several cities in Australia and China have been generated. Studies of inter-seismic, co-seismic and groundwater extraction deformation in Western Australia are being undertaken at ANU in a cooperative program with Geoscience

Australia.

4.5 Next Generation RTK

Research into the development of a robust stand-alone point positioning framework to provide high positional accuracy (both static and kinematic) using low cost GPS receivers in the context of Next Generation GNSS and local GPS CORS network, is being undertaken by RMIT University (Choy et al., 2007, Wu et al., 2006). Both algorithms and independent software packages have been developed with investigations into the concept of using a low-cost single frequency GPS receiver to achieve decimetre-level positioning accuracy, the contribution of precise orbit and clock correction products (in terms of Next Generation Satellite Systems) to single frequency PPP, the application of the atmospheric delay estimation model based on a local GPS CORS network in standalone point positioning, the positioning limitations of using a low cost GPS receiver and to design a robust observations model and algorithm, which can be used to improve the accuracy of standalone point positioning particularly in static and kinematic scenarios.

To date, precise real-time GPS positioning has only been possible using differenced carrier phase observations and the RTK or network-RTK method over local areas. The critical limitation of this technique is the availability of expensive user ground-based infrastructure. However, the new developments of precise International GNSS Services products, the advances in receiver technology and the advent of new space infrastructure have given GPS users an innovative way to eliminate GPS errors and to performance high precision point positioning without a user ground-based infrastructure. RMIT researchers have recently developed a robust Precise Point RTK Positioning technology that can offer high-precision positioning using single receiver observations for airborne geophysical survey (Wu et al., 2006). The primary results demonstrate that the Precise Point RTK Positioning technology provides robust technology for easy positioning at the centimetre level of accuracy without the need for expensive independent user ground infrastructure for airborne geophysical survey applications.

Precise point positioning (PPP) and virtual reference system (VRS) GPS software was developed from scratch for post-mission kinematic positioning of aircraft for airborne mapping applications (Castleden et al. 2004, 2005, Hu et al. 2005). This software is now being used commercially by AAM Hatch Pty Ltd.

A series of investigations have been conducted into data quality assessment (Fantino et al., 2005; Satirapod and Rizos, 2005), carrier phase-based positioning models and methodologies (Wang et al., 2005b), including network-based processing strategies (Chen et al., 2004, 2005; Dai et al., 2003a, b, 2004; Musa et al., 2006; Rizos and Han, 2003) and the evaluation of the effectiveness of RTK under different operating conditions (Lee and Ge, 2006). However, in the last 4-5 years the research has been facilitated by the establishment of a test network of continuously operating reference stations (CORS) in the Sydney basin known as “SydNET” (Rizos et al., 2003b, 2004). The SydNET project is fully funded and managed by the NSW Department of Lands (DoL).

For real-time users, correction data is available in real-time via the Internet. Suitably equipped users (with appropriate GPS receiver and wireless data link to Internet - usually GPRS mobile phone) operating in the coverage area can receive data processed from the network and provide centimetre-level positioning in real-time. Recent limited testing reports data repeatability at 15mm and consistency with existing ground mark infrastructure at a similar level (Roberts, 2005; Roberts et al., 2007). The real-time service is still in beta test mode and has not been released to all users at this stage. Researchers at the UNSW are alpha testing their custom-made Network RTK software and comparing with SpiderNet which is used by researchers at UNSW.

NSW DoL plan to expand SydNet across the entire state a network called NSWNet. SydNet/ NSWNet will link into the national NCRIS-funded Auscope base station network. The first Auscope base station is planned for Port Kembla in 2007. The wider issue of how to plan and implement wide-area CORS networks is under investigation in a number of projects, some funded by the Australian Research Council and others by the Cooperative Research Centre for Spatial Information. These include Rizos et al. (2005), Zhang et al. (2006).

The State of Victoria, through the Department of Sustainability and Environment and its Spatial Information Infrastructure business, coordinates a cooperative RTK CORS network of 30 stations in and beyond the state known as GPSnet (www.land.vic.gov.au/GPSnet). Ten new CORS receivers are to be deployed into the network increasing station density to further increase support and coverage of NRTK services. The Trimble Infrastructure Software is used to process network solutions.

Eighteen CORS in the network have been certified by Geoscience of Australia (as Verifying Authority under the National Measurement Act) as reference standards of measurement of Position (Position is a value standard in Australia) providing legal traceability of measurement from GPSnet CORS antennas to the Australian Fidicial Network (AFN). GPSnet is used to realise the Geocentric Datum of Australia in the State of Victoria.

Currently 400 registered GPSnet users apply corrections to a wide range of applications including, surveying, mapping, remote sensing, engineering, construction, precision farming, emergency services, and resource management. Testing has recently been completed using NRTK solutions to provide high accuracy, dynamic positioning solutions for machine guidance using VSAT and local radio rebroadcast technology.

Supported by the Cooperative Research Centre for Spatial Information (CRC-SI), a model for managing continuously operating networks of GNSS reference stations (CORS) has been developed. The model identifies and validates the core components for establishing, managing and assuring the utility of CORS networks. It provides the essential technical and administrative frameworks for any custodian of CORS networks. Also supported by the CRC-SI is research into determining reliable and useful parameters that describe the quality of GNSS data and derived positions. A real-time quality control

(RTQC) software module has been developed to evaluate the GNSS data measured at regional CORS sites. This software is currently being evaluated across the Victorian CORS network. Another quality control (QC) module is under development to evaluate GNSS data measured at the mobile GNSS receiver. The overall objective is to combine the QC parameters at both the CORS and the rover sites into more reliable and meaningful descriptors of position solutions for GNSS users.

Supported by the Australian Research Council (ARC), The Department of Sustainability and the Environment, Victoria (DSE) and the Department of Lands, New South Wales, a collaborative project between researchers at UNSW, RMIT University and The University of Melbourne, aims to undertake research into improving models that currently limit the range over which network RTK algorithms can currently operate.

The areal extents of the Australian continent makes it unfeasible to realise the density of CORS sites required for national RTK coverage. At The University of Melbourne a component of this collaborative research is focused on improving estimates of the atmospheric biases computed at CORS sites. It is hypothesised that if better estimates of these biases can be obtained then the interpolated biases used in computing a rover position solution can be extended to cover longer ranges. An undifferenced GNSS processing algorithm has been developed that demonstrates improvements in bias computations at CORS sites across Victoria. Through additional simulation and real-world investigations, future work will focus on combining these improved biases with enhanced stochastic modelling approaches.

RMIT University, in collaboration with UNSW and University of Melbourne, is developing a software platform of an Australian network RTK system on the suite of software jointly developed by UNSW and Nanyang Technological University for the Singapore Integrated Multiple Reference Stations Network (SIMRSN) (Chen *et al*. 2000; Goh, 2002). The software is a VRS-style system which provides RTK users with virtual reference station data anywhere within the network's "triangle" coverage. The performance of the platform is being tested using both Sydnet in NSW and GPSnet in Victoria.

A high precision temporal model for the ionospheric bias for Network RTK applications has been investigated. The model is developed and analysed for the state of Victoria under solar maximum conditions. Given advanced knowledge of the temporal nature of the differential ionospheric bias, it should be possible to design Network RTK ionospheric correction messages that meet high precision GNSS user requirements including: to quantify the temporal trend in the ionosphere during a period of solar maximum over the State of Victoria; to compare other empirical ionospheric models (Klobuchar 1986, IRI 1995, Bent & Llewellyn, 1973, Bent et al 1975; Schaer,1999) against observed values, in order to investigate the quality of these models; to provide a means of modelling the double differenced ionospheric bias in a network-RTK environment, by testing a number of different extrapolation techniques, together with different data sampling rates; to use the GPSnet sites and the data they collect to form the basis of the corrections derived for the ionosphere; and to use GPSnet as a test bed for the development of a unique ionospheric correction model to be used to improve the efficiency of Network-RTK correction distribution.

With the rapid development of spatial infrastructure in US, Europe, Japan, China and India, there is no doubt that the next generation Global Navigation Satellite Systems (GNSS) will improve the integrity, accuracy, reliability and availability of the position solution. GNSS is becoming an essential element of personal, commercial and public infrastructure and consequently part of our daily lives. However, the applicability of GPS in supporting a range of location-sensitive applications such as LBS in an urban environment is severely curtailed by the interference of the 3D urban settings. The RMIT group is investigating how to accurately quantify and reliably evaluate these improvements in typical 3D Australian urban context, where most human activities are taking place.

To characterize and gain in-depth understanding of such interferences and to be able to provide location-based optimization alternatives, a high-fidelity 3D urban model of Melbourne CBD, built with ArcGIS, and large scale high-resolution spatial data sets is used to support a comprehensive simulation study of current and future GNSS signal performance, in terms of signal continuity, availability, strength, geometry, positioning accuracy and reliability based on a number of scenarios. The design, structure and major components of the simulator are also outlined. Useful time-stamped spatial patterns of the signal performance over the experimental urban area have been generated which are very valuable for supporting location-based services applications, such as emergency responses, the optimisation of wireless communication infrastructures and vehicle navigation services.

The improved high fidelity 3D urban model forms the foundation for a range of important location-sensitive applications such as assessing and enhancing GPS location signal performance over the CBD of Melbourne, simulating the spatial dispersion of physical and chemical substances or biological agents across the 3D urban environment and supporting emergency response operations within the 3D urban environment by police, ambulance, fire brigade, and other relevant agencies.

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