Australian National Report to the International Association for Geodesy, 2011

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INTRODUCTION

Research in Australia - related to or utilising geodesy - over the past four years is described in this report. The contributions below represent the work of Geoscience Australia, university groups (The Australian National University, Curtin University, RMIT University, The University of Melbourne, The University of New South Wales, The University of Tasmania), and the Victorian Department of Sustainability and Environment. Other national institutes and universities conduct geodesy-related studies but have not contributed to this report. Activities over the 2007-2011 period have included the use of all space-geodetic techniques as well as terrestrial gravity. The report contains a comprehensive list of reports and peer-reviewed published works.

AuScope Pty Ltd was established in 2007 to facilitate the implementation of world class infrastructure for Earth science. Since this time, the geospatial component of AuScope has received a total of $27.7M in funding for geodetic infrastructure. In 2007, the Australian federal government awarded $15.4M for geodetic infrastructure through the National Collaborative Research Infrastructure Strategy (NCRIS) and the State/Territories and universities co-invested $5M. In 2010, AuScope funding was augmented with $7.3M from the Education Infrastructure Fund (EIF) for the Australian Geophysical Observing System (AGOS).

The investment has funded new geodetic VLBI installations at Hobart (Tasmania), Yarragadee (Western Australia) and Katherine (Northern Territory). Upgrades to the satellite laser ranging (SLR) system and refurbishment for a new gravity building at Mt Stromlo were funded along with the acquisition of a FG5 absolute gravimeter and three gPhone tide meters. Additionally, a network of 100 GNSS sites is being installed and operated with the funding, in conjunction with significant co-contributions from State/Territory government departments. 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 Global Geodetic Observing System (GGOS).

1. REFERENCE FRAMES

1.1 Global reference frames

GNSS

The most significant GNSS activity of the last four years has been the expansion of the Australian GNSS network through federal government investment in geospatial infrastructure through AuScope. This funding has seen the construction of 48 GNSS sites with a 52 under construction. Significant research has also been undertaken by a number of Australian researchers investigating systematic error sources and mitigation strategies within analyses of global GNSS networks. Tregoning and Watson (2009) investigated atmospheric effects (including a priori zenith hydrostatic delay, mapping functions and non-tidal and tidal atmospheric loading), highlighting the potential for spurious periodic signals and increased noise when adopting inadequate modeling strategies. King and Watson (2010) studied multipath and time variable geometry to explain possible noise structures within geodetic analyses. This work follows King et al (2008) who further investigated sub-daily signal aliasing which has been shown to be a significant driver of low frequency error in GPS time series, directly influencing the ability to accurately determine 3D velocities from GPS. This work forms a component of a body of work in the recent literature that seeks to understand the limitations, and further improve the GPS contribution to the reference frame at the 1 mm/yr level or better.

SLR

Satellite Laser Ranging (SLR) at the Mount Stromlo (Canberra) and Yarragadee (Western Australia) facilities have continued throughout the 2007-2011 period. In 2008, $80K of AuScope funding was used to upgrade power of the laser in the Mt. Stromlo SLR system. This allows ranging to high Earth orbit satellites such as GNSS. 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

Since 2007, AuScope funding has been used to establish three new 12 m Patriot radio telescopes at Yarragadee, Katherine and Hobart. Geoscience Australia (GA) is an International VLBI Service (IVS) Analysis Center. Currently the GA IVS Analysis Center contributes nutation offsets, three Earth orientation parameters (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 2011 are available the IVS. Also the CRF catalogues using a global set of VLBI data since 1979 are regularly submitted.

Research using geodetic VLBI includes investigating improvements to the International Celestial Reference Frame (ICRF) (e.g. Titov 2009) and VLBI measurements of the secular aberration drift (Titov et al., 2011).

Terrestrial Surveys at Co-located Observatories

Geoscience Australia has completed precision terrestrial connection surveys at:

- Tidbinbilla, ACT – 2007
- Ceduna, South Australia – 2007
- Mt. Stromlo, ACT – 2007, 2010
- Mt. Pleasant, Hobart - 2009,
- Parkes, ACT – 2009
- Katherine, Northern Territory – 2011

These solutions in SINEX format were supplied to the IERS for inclusion into the ITRF and are available from the ITRF product centre.

New AuScope geodetic VLBI network

Three new geodetic VLBI stations have been constructed in Australia – Hobart, Katherine and Yaragadee – funded by the Australian government NCRIS scheme. Each VLBI observatory is equipped with a 12.1 m diameter antenna designed and constructed by COBHAM Satcom, Patriot Products division. The characteristics are: 0.3 mm of surface precision (RMS), fast slewing rates (5 deg/s in azimuth and 1.25 deg/s in elevation), and acceleration (1.3 deg/s/s in both axes).

Figure 1: The three AuScope VLBI sites: Hobart (Tas), Katherine (NT), Yarragadee (WA)

All three sites are equipped with dual polarization S and X-band feeds from COBHAM with room temperature receivers, developed at the University of Tasmania by Prof. Peter McCulloch. The receiver systems cover 2.2 to 2.4 GHz at S-band and 8.1 to 9.1 GHz at X-band. System Equivalent Flux Densities (SEFDs) are 3500 Jy in both bands. Data digitisation and formatting is managed by the Digital Base Band Converter (DBBC) system from HAT-Lab, and data are recorded using the Conduant Mark5B+ system. Each site is equipped with VCH-1005A Hydrogen maser time and frequency standards from Vremya-CH.

Construction and commissioning of all three observatories is now complete. The Hobart site commenced geodetic observations in September 2010 with Yaragadee and Katherine following in May and June 2011, respectively. The first geodetic observation involving all three telescopes was made on June 16, 2011.

A software correlator facility has been developed by Curtin University. It is an implementation of the DiFX correlator, described in Deller et al. (2007). The DiFX correlator has been used extensively for radio astronomy and is starting to make a global impact in the geodetic community. DiFX has been compared to the geodetic correlator at MPIfR in Bonn and shown to be capable of generating geodetic-quality results (Tingay et al. 2009). The software correlator is installed at Curtin University on a 20 node Beowulf cluster, each node containing two quad-core Intel processors, 8 GB of RAM, at least 2 TB of disk space per node, and interconnects using 1 Gbps ethernet. In addition, mass storage is provided by five Apple Xraid chassis, each capable of holding 9 TB in raid5 configuration. Three Mark5B+ VLBI playback units are integrated into the cluster, for compatibility with the AuScope VLBI recording systems. The cluster has a 10 Gbps connection to the iVEC petabyte store, for additional storage and staging of large volumes of data.

The correlator is capable of e-VLBI observations and, if high capacity network connections are made available to the AuScope antennas in the future, real-time correlation and extraction of geodetic parameters will become possible.

All three observatories were designed and constructed to be controlled remotely and monitored to keep operating costs at a minimum. Operation of the AuScope VLBI array is being carried out from a dedicated operations room on the Sandy Bay campus of the University of Tasmania.

Terrestrial Surveys at Co-located Observatories

1.2 Regional reference frames

In 2010 the first Asia-Pacific Reference Frame (APREF) product was made available. The APREF project is an initiative that recognises the importance of improving the regional geodetic framework in the Asia-Pacific region. Coordinated by Geoscience Australia with contributions from Curtin University and the University of NSW as well as each of the State and Territory Governments (Huisman et al 2011), the APREF project provides a weekly regional GNSS solution. This contains weekly estimates of the coordinates of the participating Asia-Pacific GNSS tracking stations and their covariance information.

The APREF product provides a reliable time-series of a regional reference frame in the International Terrestrial Reference Frame and a quality assessment of the performance of the GNSS CORS stations included in the network. APREF is mandated by Resolution 1 (Regional Geodesy) of the 18th United Nations Regional Cartographic Conference (UNRCC) for Asia and the Pacific, 26 – 29 October 2009, Bangkok, Thailand. Demonstrating a broad community desire to improve the reference frame, it is also endorsed by the International Global Navigation Satellite System Service (IGS), the United Nations Office for Outer Space Affairs (UNOOSA) and the Federation of International Surveyors (FIG). The APREF combined solution is contributed to the IAG Regional Dense Velocity Field Working Group.

Research in this field undertaken includes comparing the precise point positioning (PPP) GNSS technique with a network solution in south-western Australia as an alternative approach to establish a geodetic control network (Ebner and Featherstone, 2008). This has proven to be viable provided that sufficient continuous data are collected. Furthermore, studies relating to the analysis of International Terrestrial Reference Frame (ITRF) coordinates have included a new estimate of the spreading rate of the African-South American plate boundary (Jin & Wang, 2008). Stanaway & Roberts (2009, 2010) have been investigating the application of the newly established CORS infrastructure in Australia on a national scale and how best to deal with long-term tectonic movements for real time operational users at the cm-level. "Dynamic datum" considerations were discussed in Wang et al (2008). Rigid plate transformations to support Precise Point Positioning were discussed in Stanaway & Roberts (2011).

2. GRAVITY FIELD

2.1 Gravimetry and gravity networks

In 2006, the Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS) awarded $15.4M over four years towards geospatial infrastructure, with co-investment funding of $5M from State and Australian Government departments and universities. $2.67M of the NCRIS funds were awarded to the Australian National University for use for:

1. The purchase of a precision absolute gravimeter.

2. The purchase of one or more precision relative gravimeters.
3. The establishment of a building at Mount Stromlo for gravimeter calibrations and inter-comparisons.
4. The operation of these instruments and the existing super conducting gravimeter at Mount Stromlo through to July 2011, which has now been extended to July 2013.

Separately Geoscience Australia continues to maintain the Australian fundamental gravity network (AFGN) and Australian National Gravity Database (ANGD), including over 1.4 million gravity observations. (Bacchin. M., *et al.*, 2008), and continues to maintain the AFGN with Geoscience Australia's A10 absolute gravimeter (http://www.ga.gov.au/afgn/).

Geoscience Australia has released AUSGeoid09 which is an order to magnitude more accurate than AUSGeoid98 due to the inclusion of a geometric component to model the spatially variable offset between the AHD and gravimetric quasigeoid (Brown et al., 2011).

Australian ship-track gravity data has been shown to be in error (Featherstone, 2009), and attempts to adjust it using cross-over data are ill conditioned because of the sparse coverage in some regions. Instead, the data was dispensed with in favour of satellite-altimeter-derived marine gravimetry in the generation of AUSGeoid09 (Featherstone et al., 2011).

Spherical Bouguer gravity anomalies were computed from a combination of the Bouguer shell and spherical terrain correction (Kuhn et al., 2009) and were found to be very similar to planar Bouguer gravity anomalies.

Precise absolute gravity measurements

A Micro-g LaCoste FG5 absolute gravimeter was purchased and delivered in March 2008. Training was provided in Canberra to 4 staff members from The Australian National University and Geoscience Australia.

The absolute gravity observation program is operated by The Australian National University in collaboration with Geoscience Australia. It incorporates regular repeat measurements over a network of existing absolute gravity sites throughout Australia to provide a time series for vertical deformation studies. Evaluation of the existing network has resulted in newer gravity stations being constructed and/or planned to replace less suitable sites and fill gaps in the existing network. The new Australian Geodetic Gravity Network (AGGN) sites have been selected for high stability and precision and will be collocated with GNSS CORS. To date, observations have been made at Townsville, Mt Stromlo (SLR), Tidbinbilla Tracking Station, Sydney, Melbourne, Hobart (VLBI), Perth, Ceduna, Darwin, Alice Springs and Yarragadee (SLR and VLBI).

Precise relative gravity measurements for ocean tide loading deformation studies

The first Micro-g LaCoste gPhone portable earth tide relative gravimeter was purchased and delivered in June 2008. An additional two gPhone instruments were received in September 2009. These instruments are being used to study and assess the adequacy of ocean tide loading models at existing key geodetic sites within Australia. At mid 2011, measurements have been completed at 4 sites with observation spans of between 6 and 12 months. These observations will form the beginning of a program to measure ocean tide loading in many locations around Australia for 6-12 month spans.

High precision gravity measurements with a super conducting gravimeter

This Superconducting Gravimeter continues to provide a high precision record of the time variation of gravity at the Canberra site of the worldwide GGP network for studies of Earth deformation and internal structure. Data is shared with other observers in the Global Geodynamics Project (GGP) network through the ICET data archive facility. Operation of the instrument requires routine maintenance, annual refilling of the liquid helium Dewar and refurbishment of the cold head. Regular calibration against the FG5 absolute gravimeter is also performed by simultaneous observation on adjacent piers through a number of tidal cycles. In March 2008 the National Astronomical Observatory of Japan transferred ownership of the GWR Instruments compact tidal superconducting gravimeter operating at Mt Stromlo to The Australian National University.

Gravity building for calibration and inter-comparison of gravimeters

The Reynolds Telescope building at Mt Stromlo, Canberra, was damaged during the 2003 Canberra bushfire. It was refurbished during 2010 for use as a facility for calibration and inter-comparison of gravimeter instruments. Four concrete piers tied to bedrock have been constructed in the ground floor of the building. Absolute gravity measurements with the FG5 instrument commenced in this facility during 2011.

This facility is collocated with the super conducting gravimeter installation and a gravity observation pier containing 2 stand points located in the Commonwealth Solar Observatory building, which also required refurbishment following the 2003 Canberra bushfire.

Figure 2: Reynolds Dome gravity building at Mt Stromlo (left) and the FG5 absolute gravimeter (right)

2.2 Dedicated satellite gravity mapping missions and modelling of geoid and spatial and temporal gravity fields

Products from the GRACE space gravity mission have been used by Australian researchers to study geophysical processes associated with continental hydrology, melting of polar regions and glacial isostatic adjustment. The annual tide in the Gulf of Carpentaria as estimated from GRACE products was found to agree well with tide gauge observations at Groote Eyreland (Tregoning et al., 2008). The drought in the Murray-Darling Basin was characterised, with inter-annual decreases in total water storage estimated by GRACE found to correlate strongly with measured decreases in groundwater levels (Leblanc et al., 2009), while Brown and Tregoning (2010) found that leakage effects of distant geophysical signals (such as the Amazon River system, melting in Greenland etc) had little effect on the estimates of total water storage in the Murray-Darling Basin.

The application of Gravity Recovery and Climate Experiment (GRACE) data to study hydrology in Australia pose some challenges because of the noise in the GRACE products compared to the small hydrological signals in the predominantly dry continent (Awange et al., 2009). A comparison of the 4-degree mascons-based GRACE models with rain gauge data showed that this parameterisation has some potential (Awange et al., 2011) for hydrological studies.

Spatial leakage effects in GRACE models have been reduced using Newtonian forward modelling and applied to Greenland (Baur et al., 2009), resulting in better agreements with InSAR-derived ablation estimates. Newtonian forward modelling (Kuhn et al., 2010) and numerical climate models (Makarynskyy et al., 2007) have been applied globally to demonstrate that sea level does not change uniformly.

Spatial and temporal changes of the Earth's gravity field have been analyzed by Anjasmara et al. (2010) using five years (April 2002 to May 2007) of GRACE-derived surface mass changes. A principal component analysis (PCA) revealed that on a global scale more than 80% of the overall variability can be modeled by the first 5 PCA modes. These include all major hydrological, cryospheric and crustal deformation (e.g. post-glacial rebound and earthquakes) signals. As expected the study confirms that, globally, the most dominant temporal variation is an annual signal followed by a secular trend. Apart from these well-known signals, the study also shows that the PCA is able to reveal other periodic and a-periodic signals (e.g. Sumatra-Andaman Earthquake in December 2004).

Tregoning et al (2009) showed that crustal deformation derived from GRACE are not always stationary in nature because of the presence of deformation caused by from hydrological processes. Consequently, deriving estimates of glacial isostatic adjustment by fitting linear trends through GRACE time series was shown to yield incorrect results. In particular, the positive anomaly seen in GRACE products in the region of Enderby Land (East Antarctica) was shown to not be caused by unmodelled glacial isostatic adjustment.

Funding through the Australian Space Research Program was provided to a consortium led by The Australian National University to contribute to the GRACE Follow On mission. The aims of the project are to develop a capability in Australia to exploit observations from the GRACE space gravity mission to study continental hydrology, ocean/continent exchanges of water and melting of polar regions. A substantial part of the funding is being used to develop components of the inter-satellite laser ranging system that will be flown on GRACE Follow On as a technology demonstrator.

Complete spherical Bouguer gravity anomalies have been derived over the whole of Australia (Kuhn et al. 2009). These are based on ~1 million land gravity observations extracted from the Australian national gravity database (June 2007) and high-resolution spherical terrain corrections. The spherical terrain corrections, residual to each Bouguer shell, were computed on a 9-arc-sec by 9-arc-sec grid (~250 m by ~250 m spatial resolution) from global Newtonian integration using heights from version 2.1 of the GEODATA digital elevation model over Australia and the GLOBE and JPP95E global DEMs outside Australia. Comparison to complete planar Bouguer gravity anomalies revealed that the planar model provides a reasonable approximation in flat or moderately elevated areas but is insufficient in mountainous areas

A new iterative mass optimization algorithm has been developed by Fellner et al. (2010) used to construct synthetic - but realistic - Earth gravity models (SEGMs). The optimization algorithm iteratively improves a synthetic mass distribution as long as the induced gravity signal fits given gravity observations. The effectiveness of the algorithms has been demonstrated by fitting a mass model to EGM08-induced geoid heights over Austria producing an overall RMS-fit of 5cm.

2.3 Regional geoid determination

AUSGeoid09 (Featherstone et al., 2011; Brown et al., 2011) was released by Geoscience Australia as the new national standard for transforming GNSS-derived ellipsoidal heights (referred to the GDA94) to the Australian Height Datum (AHD) and *vice versa*. Unlike previous AUSGeoid models, a newly computed gravimetric quasigeoid model was fitted to around 7,000 GNSS-AHD points using least-squares collocation (LSC), which delivered a fit of ~30 mm (Brown et al., 2011). The gravimetric component was based on EGM2008 and the terrestrial contributions of gravity, topography and satellite altimetry were added via a deterministically modified kernel (Featherstone et al., 2011). Careful consideration was given to the quality of the GNSS-levelling data used.

Australian geodesists were also involved in the computation of the NZGEOID09 model for New Zealand (Claessens et al., 2011) using an iterative quasigeoid computation technique (Amos and Featherstone, 2009).

Related work has been undertaken on the application of non-stationary LSC (Darbeheshti and Featherstone, 2010a) for the gridding of terrestrial gravity data (Darbeheshti and Featherstone, 2009) and fitting a gravimetric quasigeoid to GNSS-levelling (Darbeheshti and Featherstone, 2010b). Techniques from the spatial statistics literature were adapted for geodetic LSC to account for cases when non-stationary signals have to be modelled, instead of relying on the current implicit assumption of stationarity. Experiments to fit a geoid model to vertical deflections (Featherstone and Lichti, 2009) were unsuccessful because of the poor quality of the historic deflection data (cf. Featherstone and Morgan, 2007; Hirt and Seeber, 2008; Hirt et al. 2010).

A general framework for the accurate numerical evaluation of geodetic convolution integrals was developed and applied to Stokes's integral (Hirt et al., 2011a), showing that Gauss-Legendre quadrature can be used to evaluate the high-frequency geoid with a precision of ~1mm for error-free data. Supplementary studies are on the computation of mean gravity anomalies (Hirt and Claessens 2011) and modified kernels (Hirt 2011).

Residual terrain modelling (e.g., Hirt 2010) has been used to model the omission error in global geopotential models in areas where data are sparse (Hirt et al., 2010a) and to assess EGM2008 over

Europe (Hirt et al., 2010b). Other assessments of EGM2008 by Australian geodesists have been conducted for Australia (Claessens et al., 2009, 2010), parts of Antarctica (Morgan and Featherstone, 2009), Sri Lanka (Abeyratne et al., 2009, 2010) and Germany (Hirt, 2011). Assessment of the new GOCE static gravity field models is described in Hirt et al. (2011b), showing improvements in spherical harmonic degrees ~160-190.

2.4 Height systems and vertical datums

A medium-term study on the integrity of the Australian Height Datum (AHD) is nearing completion. Half-metre distortions were quantified over Western Australia (Featherstone and Filmer, 2008). Loop closure analysis of the current version of the Australian National Levelling Network (ANLN) identified deficiencies in the ANLN and was also used to show that errors of up to ~0.5 m can remain undetected in the long levelling traverses in the interior of the continent (Filmer and Featherstone 2009). Helmert orthometric, normal and normal-orthometric corrections to differential levelling were tested in the Australian context (Filmer et al., 2010; Filmer and Featherstone 2011) with a supplementary conclusion that the normal-orthometric height system is not strictly compatible with a quasigeoid model. Attempts to retrospectively apply refraction corrections to levelling led to a correction to Angus-Leppan's approach (Filmer et al., 2009). The issues surrounding height determination in Australia were reviewed by Featherstone (2008).

3. GEODYNAMICS AND EARTH ROTATION

3.1 Crustal deformation

Studies on contemporary seismicity in the southwest seismic zone of Western Australia has continued with an aeromagnetic survey of geological structures that influenced the 1968 Meckering earthquake (Dentith et al., 2009) and paleoseismic trenching of the Hyden Fault scarp (Clark et al., 2008).

A simulation study was undertaken to determine which of Australia's recorded earthquakes would have generated sufficient surface deformation as to have been detectable in an InSAR study (Dawson and Tregoning, 2007). Deformation of the 2005 Kallani and 2007 Katanning earthquakes was subsequently detected. Both earthquakes occurred in the top 1 km of crust, and the slip distribution of the latter was resolved even though the earthquake magnitude was only Mw=4.7 (Dawson et al., 2008).

The flexural isostatic state of the lithosphere has been investigated using wavelets (e.g., Kirby and Swain, 2008, 2011) with applications in North America (Kirby and Swain, 2009) and South America (Tassara et al., 2007; Perez-Gussinye et al., 2009) to show that the effective elastic thickness is thinner than previously thought and that it varies spatially.

Estimates of hydrologically induced surface deformation derived from GRACE surface load changes were compared with those measured directly by continuous GPS sites (Tregoning et al., 2009). A far better agreement was found than in previous studies, which was attributed to the more accurate modelling strategies used in the analysis of the GPS observations (Tregoning and Watson, 2009; Tregoning et al., 2009). However, there remain significant periodic differences between the GRACE- and GPS-derived deformation estimates, in particular in the horizontal coordinate components.

A novel study investigating changes to sea level and land level over the twentieth century on

Macquarie Island was undertaken by Watson et al (2010). This study used historical sea level data from Sir Douglas Mawson's 1911-14 expedition, coupled for the first time with modern sea level data, space geodetic estimates of land motion and co- and post-seismic deformation modeling to constrain estimates of sea and land level change. The study revealed absolute sea level rise over the period of 2 mm/yr and, surprisingly, highlighted that the Island is subsiding at approximately 2.5 mm/yr. A further important finding was the spatial extent of co- and post-seismic deformation induced by the Mw ~8.0 great earthquake (23 December, 2004) north of Macquarie Island. Deformation was observed throughout the south-eastern Australian GPS sites, with important ramifications for the realization of the reference frame. This work informs current studies that are underway by Australian researchers to further understand the magnitude of far field deformation (and thus its impact on the reference frame) from recent great earthquakes.

3.2 Geophysical fluids

As part of the global effort to better quantify the ice sheet contributions to sea level rise, a group of Australian researchers are involved in projects based around Law Dome and the Totten Glacier in East Antarctica. This work contributes to the European Space Agency (ESA) Calibration, Validation and Retrieval Team (CVRT), for the CryoSat-II altimeter mission. In-situ quantities derived from GPS include ice velocity and tidal motion, ice elevation and its change over time, and water content of the atmosphere. These measurements are paired with airborne data (LiDAR and ASIRAS) flown by the Alfred Wegener Institute over the study site to validate various components of the CryoSat-II data stream. The ESA ASIRAS instrument is an airborne radar sensor that closely replicates the CryoSat-II instrument - allowing the identification of spatial variations in snow/ice density – and is thus critical in interpreting changes in surface elevation over time.

A collaborative study between Curtin University and Darmstadt University of Technology, Germany examined the impact of steric sea level changes on the Earth's gravity field (Roedelsperger et al. 2008). In this study projected future steric sea level changes have been modeled under two extreme CO_2 emission scenarios over the next 2000 years. In contrary to common assumptions that steric sea level changes do not produce a gravity signal results show that considerable steric sea level changes of several meters have a very small (~10^{-3} m^2s^{-2} in terms of gravitational potential) but non-zero effect. This is due to the fact that water masses are re-distributed without having a net mass change.

Continuation of a collaborative project between Curtin University and the University of Stuttgart, Germany is looking at deglaciation-induced future sea level changes, associated changes in Earth's rotation and geo-centre and change in global coastline (Kuhn et al. 2010). For example a complete melt of all land-based ice masses (most prominently the Greenland and Antarctic ice shields) will result in a global average sea level rise of about 64 m affecting almost 30% of the current world population living in low-lying coastal areas (Figure 3).

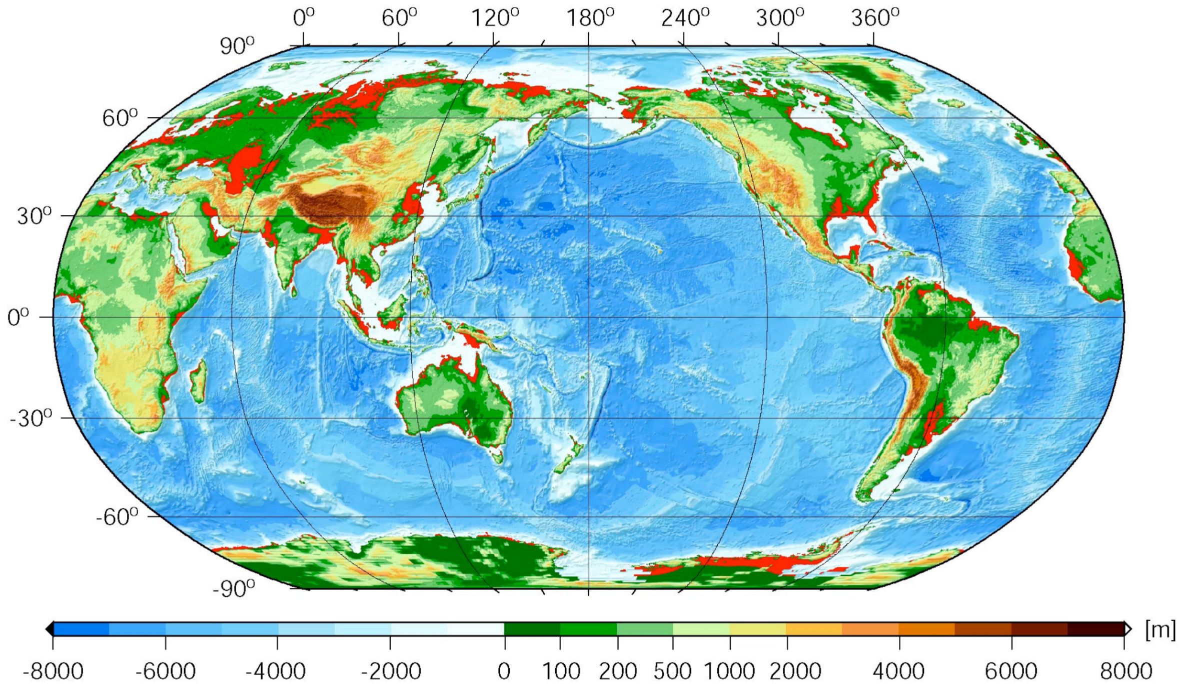

Figure 3: Global change in land-ocean distribution due to a complete melt of all land-based ice masses. The flooded regions (indicated in red) are the result of matching the raised sea level with the topographic heights and ocean depths from the global 5-ar-min by 5-arc-min DEM JGP95E.

A collaborative study between Curtin University, Graz University of Technology, Austria and Technical University München, Germany looked the relation between GRACE-derived surface mass changes and precipitation over Australia using multiple linear regression analysis and principal component analysis techniques (Rieser et al. 2010). Apart from revealing the most dominant spatial and temporal changes the study also provides their statistical significance. Results suggest a significant decrease in water storage in the southeast of Australia (e.g. Murray Darling Basin) and a dominant annual cycle over the majority of the continent. Furthermore, a direct relation between surface mass changes and precipitation has been revealed further suggesting that only about a fourth of the precipitation's water masses remain sufficiently long in an area to be detected as a gravity change.

4. POSITIONING AND APPLICATIONS

4.1 Multi-sensor systems

A long-term study involving the absolute calibration of the TOPEX/Poseidon, Jason-1 and OSTM/Jason-2 satellite altimeters continues at the Bass Strait calibration site (Watson et al. 2011; Bonnefond, Haines and Watson, 2011). This work provides an important and internationally valued contribution to the National Aeronautics and Space Administration (NASA) and the French Centre National d'Etudes Spatiales (CNES) missions, their science team and international user community. These ocean altimeters are recognized as the tool-of-choice for the determination of global and regional sea level change, reinforcing the need for rigorous calibration in order to derive these important climate variables. The calibration activities and delivery of its data stream, both in terms of absolute bias, and bias drift, is supported through the Australian Integrated Marine Observing System (IMOS) established under the Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS).

Further work in the marine domain includes the development of a novel strategy to calibrate coastal tide gauges using GPS buoys (Watson, Coleman and Handsworth, 2008). This approach is now routine implemented by the Australian Antarctic Division at each of its sub-Antarctic and Antarctic tide gauge locations (Watson, Handworth and Brolsma, 2008).

Hardware research at UNSW has focused on two main topics: the use of low-cost, micro-electro-mechanical systems (MEMS)-based inertial sensors (accelerometers and gyroscopes), and the integration of additional sensors to the standard "GPS plus INS" (Inertial Navigation System) multi-sensor configuration. In the case of the former applications include low-cost integrated GPS/INS systems for farm machinery (Geng et al, 2007; Li et al, 2007a, 2009), urban navigation (Li et al, 2008c), and mobile mapping (Li et al, 2010b). Additional navigation sensors include vision/optical systems, pseudolites and the Locata technology.

The use of optic flow measurements in multi-sensor systems was reported in Ding et al (2009, 2010, 2011) and Wang et al (2008b), in particular for Unmanned Aerial Vehicle (UAV) navigation applications. Integration of GPS with "pseudolites" (or "pseudo-satellites") was pioneered at UNSW with research that was begun in the late 1990s. In the reporting period of this National Report further research was conducted for airborne mapping applications by Wang et al (2007d) and for aircraft approach and landing by Lee et al (2008). Pseudolite research at UNSW has been largely supplanted by investigations into an Australian developed terrestrial RF-based ranging system known as "Locata" (Politi et al, 2007).

A test Locata was established on the UNSW campus in 2007. Locata observation tropospheric modelling was discussed in Choudhury et al (2009a), and UNSW researchers have conducted considerable research into the Locata signal structure (all of it published in the IEEE literature and not cited here). The most recent Locata results include first investigations into indoor positioning using Locata (Rizos et al, 2011), and tests on its application for structural deformation monitoring (see section 4.2). During 2010 and 2011 Locata has also been used for aircraft flight approach tests, wide-area (tens of km) kinematic aircraft positioning and in machine automation applications within deep open-cut mines (Rizos et al, 2011).

Theoretical analysis and algorithm development for GPS/INS sensor integration have been conducted in the reporting period of this National Report (Almagbile et al, 2010; Ding & Wang, 2007; Han & Wang, 2009, 2010b; Li et al, 2008a, 2009b; Wang et al, 2007c, 2007e, 2009c; Xu et al, 2010), in particular the challenges of using MEMS-based INS (Han & Wang, 2010a; Han et al, 2009; Wang et al 2009a, 2009b; Zhou et al, 2009). New error modelling techniques were discussed in Han & Wang (2011).

The era of multi-GNSS is providing new impetus for research into observation modelling, error analysis, the application of the theory of reliability for fault/outlier detection and Receiver Autonomous Integrity Monitoring, as reported in Jiang et al (2010), Knight et al (2009, 2010), Wang & Ober (2010), and Wang & Wang (2007). This is a fertile area of research funded by current research grants. Progress on multi-sensor (GPS/INS) integration RAIM was reported Hewitson & Wang (2010). As the GNSS RAIM algorithms are relatively well developed, they have been adapted to multi-sensor systems, and referred to as "extended-RAIM" (eRAIM). eRAIM procedures are able to detect faults in the dynamic model and isolate them from the measurement model. The analysis includes outlier detection and identification capabilities, reliability and separability measures of integrated GNSS/INS systems. Fault detection analyses for multi-sensor systems were also reported in Almagbile et al (2011).

Zhang et al. (2010) performed an investigation of tags in Radio Frequency IDentification (RFID) systems that meet the needs of PNT using location fingerprinting algorithms. It is limited by the large amount of work required to establish a fine Received Signal Strength (RSS) distribution pattern in a large area in the training phase and the variations of RSS in dynamic environments of the positioning phase.

Zhu et al. (2011) developed algorithms for the low-cost and portable indoor personal positioning system using RFID based multi-sensor techniques, such as integrating with Micro-Electro-Mechanical Systems (MEMS) Inertial Navigation System (INS) and/or GPS. Various indoor/outdoor experiments have been conducted using the RFID/MEMS INS/low-cost GPS integrated technique. The techniques integrated with the low-cost GPS, can be used to provide continuous indoor/outdoor positions to approximately 4m accuracy with the iterated Reduced Sigma Point Kalman Filter (RSPKF).

Xu et al. (2011) developed an approach utilizing fractal analysis and wavelet transforms to enhance GSM-based positioning accuracy. Fractal theory and analysis is introduced into the research of Global System for Mobile (GSM) Communication downlink multipath fading. The GSM base station signal strength data are converted into representations in terms of wavelet bases. The approach performs real-time signal strength processing. Based on strength data of the signals from different base stations, the distances between the receiver and base stations are estimated and then the position estimation of the receiver is determined.

4.2 Applications of geodesy in engineering

Research into time series analysis of outputs of structural monitoring systems based on GPS, inclinometers, accelerometers and other sensors has been conducted by Yigit et al (2010a, 2010b) for the case of a building in Turkey, and Li et al (2008b, 2010a) for the case of a building in Japan. The use of network-based GNSS techniques for structural monitoring during periods of active ionosphere was discussed in Rizos et al (2010b). The testing of the Locata technology for deformation monitoring applications was reported on by Choudhury et al (2009b, 2010) and Choudhury & Rizos (2010, 2011).

4.3 GNSS measurement of the atmosphere

A comprehensive study of the effect on site coordinates of using different mapping functions and a priori hydrostatic delays was undertaken (Tregoning and Watson, 2009). Conclusive evidence was found that not using the most sophisticated, time-varying models leads to not only increased error at annual and semi-annual frequencies but also greater amplitude noise at high frequencies. Thus, high accuracy GNSS positioning must include the use of the time-varying parameterisations of the atmospheric effects.

A modified MINQUE technique has been used to deliver more realistic uncertainties from GNSS-derived zenith wet delays (Lo et al., 2010). The refraction coefficient of the lower atmosphere has been estimated using automated theodolites (Hirt et al., 2010a).

The analysis of GNSS observations to determine TEC (Total Electron Content) and VED (Vertical Electron Density) of the ionosphere was reported in a number of publications (Ouyang & Wang, 2008a, 2008b, 2009; Ouyang et al, 2008, 2008; Wang & Ouyang, 2011). Techniques used included the Abel inversion algorithm, combined LEO satellite and ground-based GPS data sets, and tomography. The spatial and temporal variation of the GNSS tropospheric delay was studied in the context of network-based real-time kinematic (RTK) precise positioning techniques such as the Virtual Reference Station

(VRS) method (Al-Shaery et al, 2007; Feng & Rizos, 2009). The ionospheric effects on network-RTK based structural monitoring were reported from tests in Hong Kong by Rizos et al (2010b). Pavelyev et al., (2010a; 2010b) developed analytical expressions for the excess phase path and refractive attenuation of electromagnetic waves propagating through the disturbed ionosphere.

Funding through the Australian Space Research Program was provided to a consortium, led by RMIT University, to develop advanced platform technologies for space-related research, including in-space tracking and navigation, precise positioning, space weather, weather forecasting, atmospheric modelling and climate monitoring. New algorithms and enhanced atmospheric models will be developed in the context of new generation navigation and geo-environmental satellite programs to enhance Australia's capability in space research.

The Global Navigation Satellite System (GNSS) atmospheric profiles derived from radio occultations (RO) have great potential to overcome many limitations of existing atmospheric observation methods. Statistical results show that the difference in average temperature is less than 0.05˚C with a standard deviation of 1.52˚C and the difference in average pressure is -1.06 hPa with a standard deviation of 0.91 hPa. GNSS RO derived atmospheric profiles show good agreement with radiosonde observations (Fu et al., 2008).

GPS RO has been recognized as an alternative atmospheric upper air observation technique due to its distinct features and technological merits. RO technique is best used for meteorological studies in remote and/or difficult-to-access areas such as the polar regions (Pavelyev et al., 2011; Zhang et al., 2011). The accuracies of GPS RO retrievals from both CHAMP and COSMIC were evaluated by comparing satellite-derived data with radiosonde observation over Antarctica (Zhang et al., 2011). In the Antarctic region a warming trend during 2001–2008 was found over the West Antarctic and Peninsula and a cooling trend over the East Antarctic. A general warming trend was identified in winter seasons but a cooling trend in summer seasons.

Zhang et al., (2010) investigated ionospheric correction using the RO Processing Package (ROPP) in the Australian region. The MSISE-90 model with the statistical optimization method produced the best results for altitudes greater than 40 km. The influence from the ionosphere can be removed using the generic linear combination method, which produced the best results for altitudes less than 40 km.

It has recently been demonstrated (Le Marshall et al., 2010) that data from GPS and constellations of Low Earth Orbit (LEO) satellites equipped with RO receivers can be used to improve weather forecasting and climate monitoring in the Australian region. Forecasts when using RO data were improved in the lower, middle and upper troposphere.

4.4 Applications of satellite and airborne imaging systems

An evaluation of recent digital elevation models (DEMs) was conducted by Hirt et al. (2010), showing stripes and cloud-caused artefacts in the ASTER satellite-derived DEM. Comparisons with well-positioned benchmarks in Western Australia showed that the Australian DEM-9S model is good to ~9m, SRTM v4 to ~6m and ASTER to ~15m.

Research into satellite radar altimetry applications in marine geodesy at the University of Newcastle has continued, culminating in two book chapters in Coastal Altimetry (Deng et al., 2011; Gommenginger et al., 2011). The chapters comprise combined input from geodesists and oceanographers. The chapter by Deng et al. (2011) provides an overview of recent research applications utilising satellite altimetry around Australia. The approaches use altimetry synergistically with all available oceanic data including other remote sensing techniques, drifting buoys, geoid models and in-situ data such as coastal tide-gauges. The results presented include improving the quality of altimeter sea surface height data in coastal regions, observing and understanding the structure and variability of the major boundary current systems, estimating regional sea-level changes, and determining and verifying the marine gravity field using altimetry in the Australasian region. Work on re-tracking altimeter waveforms has been described in Gommenginger et al. (2011), providing a review of waveform retracking methods and examples of the application of waveform retracking methods in coastal regions around the world. It also explores some of the new ideas to yield unbiased parameter estimation for land-contaminated waveforms much closer to the land/water interface.

In addition, marine geoid models (Deng et al. 2009) and ocean boundary currents (Deng et al. 2008) have been assessed in using geoid-models and satellite radar altimeter data. Through a collaborative project with researchers in the US funded by NASA, Jason-2 satellite altimeter sensor geophysical data records were validated by retracking 20-Hz radar waveforms over the California coastal ocean for the period September 2008 - June 2009 (Lee et al., 2010). Research commenced in early 2011 to analyse sea level rise along the New South Wales coast, funded by NSW Environmental Trust. Sea-level rise in the region has been determined using data from Topex/Poseidon, Jason-1 and -2 altimeters and tide-gauges over the period January 1993 to December 2010. The preliminary results will be presented in IUGG 2011.

Synthetic Aperture Radar research at UNSW has focused on:

a) differential radar interferometry (DInSAR) for ground subsidence monitoring with data from satellites such as ERS-1/2, Radarsat, Envisat, Cosmo-Skymed (Chang et al, 2008; Ge et al, 2009; Ng et al., 2008a, 2008b, 2009, 2010; Yu et al, 2008);
b) theoretical studies into SAR observation modelling and analysis (Ge et al, 2008a; Hu et al, 2011);
c) accuracy assessment of InSAR-derived digital elevation models (DEMs), and comparison with photogrammetric- and Lidar-derived DEMs (Yu & Ge, 2010; Yu et al, 2007, 2011a, 2011b); and
d) DInSAR for monitoring deformations associated with volcanoes and earthquakes (Dong et al, 2009; Ge et al, 2008, Hu et al, 2009; Qiao et al, 2011; Wang et al, 2007a, 2007b; Zhang et al, 2008, 2010a, 2010b).

An Australian Space Research Program (ASRP) grant funded the commencement of a project on designing a SAR formation-flying satellite mission for a range of applications, including for ground deformation monitoring. Enabling technologies such as satellite-borne GNSS receivers are being researched, as well as modified receivers for GNSS "reflectometry" observation of the sea state.

Full waveform Lidar analysis for remote sensing forest biomass density has recently commenced at UNSW (Lim et al, 2011) funded by an ARC grant.

4.5 High-precision GNSS

Feng (2008) and Feng et al (2008 and 2009) identified the optimal ionosphere-reduced virtual signals to significantly enhance the reliability of three carrier ambiguity resolutions, of which ambiguities of two extra-widelanes can be resolved very easily without distance dependence. Ambiguity-fixed widelanes can be used directly for decimetre level positioning (Feng and Li, 2010) and relative ionospheric delay estimations. Li et al (2009) experimentally demonstrated the success rates of three carrier ambiguity resolution over the baselines of 50 to 155 kilometers using semi-generated three carrier data from five 24h dual-frequency GPS data sets. Feng and Li (2008) also demonstrate that one benefit of multiple carrier GNSS signals for regional scale network-based RTK is that the inter-station distances can be doubled with the base stations that are equipped with triple frequency receivers. This will significantly reduce the infrastructure costs for CORS network.

After carrier phase ambiguities have been determined, a GPS RTK system can usually achieve centimetre level positioning with uncertainty in the vertical component being approximately twice that of the horizontal component. In addition, RTK positioning uncertainty grows as the distance between the reference station(s) and the rover receiver increases, mainly due to the effect of residual tropospheric errors on the positioning solution. Li et al (2010) established a geometry-specified troposphere decorrelation strategy able to achieve 3D sub-centimetre kinematic positioning. The strategy was based on a single reference station and an epoch-by-epoch solution for the rover position, using dual frequency GPS observations. Preliminary results from several baseline solutions have shown that the RTK software can provide sub-cm 3D RMS position accuracy with the vertical RMS of typically better than 0.5 cm.

Feng and Wang (2010) compare the computed success rates of ambiguity resolution to integers with simplified formulas and actual success rates from real data sets. The results demonstrated that the upper bound probability of ILS solutions agrees well with the actual statistic success rate. This potentially simplifies the probability computations of ILS solutions in practice.

A series of investigations have been conducted into such topics as the algorithms of the Virtual Reference Station (VRS) technique of network-based RTK (Al-Shaery et al, 2010), NTRIP and communications protocols/formats (Yan, 2007), new models for providing RTK services (Rizos, 2007), new server-based processing methodologies (Lim & Rizos, 2007a, 2007b, 2008a, 2008b), and performance testing (Feng & Wang, 2008).

Precise GNSS positioning research also included the design of temporary continuously operating reference station (CORS) networks, such as the one deployed in Aceh, Indonesia, for land reconstruction (Adiyanto & Roberts, 2007). The deployment and monitoring of city-wide CORS networks, such as SydNet in Sydney (Roberts et al, 2007), and state-wide CORS networks, such as CORSnet-NSW in the state of New South Wales (Haasdyk et al, 2010), were also topics of study. New algorithms for long-range (up to 100's of km) kinematic positioning were used to determine an aircraft trajectory on a Lidar mapping mission and reported in Colombo et al (2010). The coming era of multi-GNSS is motivating research into triple-frequency ambiguity resolution and the enhanced performance of GNSS-RTK (Feng & Rizos, 2008, 2009; Feng et al, 2007a, 2007b, 2009).

The ARC is also funding the design of multi-GNSS receiver based on a software/FPGA (Field Programmable Gate Array) platform. The majority of the receiver design research is published in IEEE literatire and is not cited here.

Choy et al., (2008) investigated the performance of three different ionospheric error mitigation methods used in single frequency PPP in the Australian Region. They are the GRAPHIC (GRoup And PHase Ionospheric Correction) algorithm, the Global Ionospheric Maps (GIMs) and the Klobuchar model. Numerical results show that the GRAPHIC and GIMs methods are able to provide point positioning accuracy better than 1m for session duration less than an hour using geodetic quality single frequency receivers. For 12 to 24 hours data sets, the positioning accuracy can be better than 0.1m. Single frequency PPP using a low-cost GPS receiver could potentially provide horizontal point positioning accuracy better than 1m with a precision of 1.7m, and 1.5m vertical accuracy with a precision of 3.3m in post-processing mode Choy et al., (2009).

The investigation for COSMIC orbit determination indicated the observed attitude information should be replaced by the nominal in order to improve the orbit accuracy. The orbit overlap analyses suggest that the accuracy of the dynamic and kinematic orbits is at the 2–3 cm level. For atmospheric occultation research using COSMIC, a cm-orbit is over qualified. The potential application of COSMIC kinematic orbits is the determination of temporal variations in the gravity field (Hwang et al., 2009).

Parameter estimation and external correction approaches were investigated by Wang et al. (2009) for the correction of the zenith total delay (ZTD) in the estimation of GPS heights and baseline lengths. Water vapour radiometer (WVR) measurements at each GPS stations were applied in the external correction approach. The results indicate that for the short-medium length of baselines selected, the WVR corrections can improve the precision of the estimated baseline lengths by a few millimetres. In addition, the results of the estimated GPS heights show that the effects from WVR corrections are at the centimetre level.

A new concept was proposed by Sang and Zhang (2010) for the real-time improvement of atmospheric mass density models (AMDM) using space tracking data aiming at better orbit prediction accuracy for low latitude earth-orbiting (LEO) space objects. Preliminary experiments using CHAMP GPS-derived precise orbit solution data have demonstrated encouraging results in the error reductions of orbit prediction for 3 days and 10 days. This suggests that an order of error reduction is achievable using space tracking data in the algorithms.

The differences between the double-differenced (DD) tropospheric and ionospheric errors were investigated by Wu et al. (2009, 2010) using GPS observations from the Victorian CORS network. Both types of the DD atmospheric errors significantly contaminate GPS measurements. These results can be instructive in the determination of the way a NRTK system should be implemented.

5. MATHEMATICAL GEODESY

The spherical Meissl scheme has been generalised for the geodetic ellipsoid (Claessens and Featherstone, 2008), which relates the spectral expressions among various gravity field functionals. A non-iterative approach has been developed to transform directly between geodetic and ellipsoidal coordinates without the need to stage via Cartesian coordinates (Featherstone and Claessens, 2008). Awange et al. (2008) developed a non-iterative approach for the determination of the Affine transformation.

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