Australian National Report to the International Association for Geodesy, 2015

INTRODUCTION

Geodetic research in Australia over the past four years is described in this report. The contributions represent the works of:

- *University groups:* The Australian National University, Curtin University, RMIT University, The University of Newcastle, Queensland University of Technology, The University of Melbourne, The University of New South Wales, The University of Tasmania.
- *State/Territory and Federal Government agencies:* the Victorian Department of Environment, Land, Water & Planning (Office of the Surveyor-General); the NSW Department of Finance, Services & Innovation (Land & Property Information); Queensland's Department of Natural Resources & Mining; WA's Landgate; lands departments in other States and Territories; and Geoscience Australia, the national geodetic agency.

Operational geodesy activities in Australia are coordinated by the Intergovernmental Committee on Surveying and Mapping's *Permanent Committee on Geodesy* (PCG), which includes representatives from all the Australian States, Territories, and the Commonwealth and New Zealand responsible for government surveying and mapping, as well as representatives from academia. The PCG is chaired by Geoscience Australia (GA). GA senior staff also play significant roles in regional and international geodetic initiatives, including: Co-chair of the United Nations Working Group on the Global Geodetic Reference Frame (http://ggim.un.org/UN_GGIM_wg1.html) which led to the adoption of the United Nations General Assembly Resolution titled *A Global Geodetic Reference Frame (GGRF) for Sustainable Development* in February 2015; Chair of the geodesy working group of the United Nation Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP); and Chair of the Governing Board of the International GNSS Service (IGS).

Australian participation in the IAG over the 2011-2015 reporting period was extensive, and included: president of the IAG; vice-presidents of Commission 1 and Commission 4; chairs of Sub-Commissions 1.3e, 2.4e, 2.5, 3.4, 4.2; chair of Joint Study Group 3.2; chairs of Working Groups 1.3.2, 4.1.1, 4.1.3, 4.2.2, 4.5.2, 4.5.4; and members of Working Groups 1.3.1, 1.3.2, Joint Working Groups 1.1, 1.2, 1.3, 2.1, 2.3, 2.8, Joint Study Group 3.1, and Sub-Commissions 2.4f, 3.2, 3.4.

In July 2014 the first Australian National Geodetic Workshop was held at the Research School of Earth Sciences, Australian National University. Presentations of research activities, including student presentations, were made over two days. A follow-up meeting is scheduled for 1-2 December 2015.

Activities over the 2011-2015 period reported here include the use of all space-geodetic techniques, geodetic Earth observation techniques, as well as reference frame, gravity, precise positioning, mass displacement, and altimeter studies. This report also contains a comprehensive list of publications.

1. REFERENCE FRAMES

1.1 Coordination of Space Techniques

Geoscience Australian (GA) owns, operates and/or manages a number of geodetic instruments on the Australian continent, in Antarctica and across the South Pacific.

Global Navigation Satellite System (GNSS)

GA maintains GNSS networks of approximately 120 Continuously Operating Reference Stations (CORS) across the Australian region and the South Pacific, some of them in cooperative arrangements, including (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/gnss-networks):

- The *Australian Regional GNSS Network* (ARGN)
- The *South Pacific Regional GNSS Network* (SPRGN)
- The *AuScope GNSS Network*

The ARGN provides the geodetic framework for the spatial data infrastructure in Australia and its territories. The ARGN consists of a network of permanent geodetic-quality GNSS receivers and antennas, on geologically stable marks in Australia and its territories. Figure 1.1 shows the CORS at the Mawson Base, Antarctica. These sites provide input for the measurement of Earth processes, such as crustal dynamics and sea level change. The ARGN network also provides GNSS data to the International GNSS Service (IGS – http://www.igs.org).

Figure 1.1: Mawson, Antarctica, GNSS CORS

The SPRGN was established in 1991 as an Australian Government response to concerns raised by member countries of the South Pacific Forum about the potential impacts of human-induced global warming on climate and sea levels in the Pacific region. Its aim is to monitor vertical movement of the Earth's crust in conjunction with tidal measurements as part of the SEAFRAME network located in the South Pacific Ocean. The SPRGN consists of 13 CORS located in close proximity to sea level monitoring stations, and measures vertical and horizontal movements of the land in an accurate, global, geocentric terrestrial reference frame. Combining this data with precise levelling surveys between the tide gauge sensor and the CORS station determines the vertical stability of the gauge and the absolute sea level change.

On the Australian continent itself the *AuScope* GNSS Network was established under the *National Collaboration Research Infrastructure Strategy* (NCRIS) to characterize the structure and evolution of the Australian continent (http://auscope.org.au).

The GNSS tracking data from these networks is available to national and international researchers, and supports many projects and initiatives, some referred to elsewhere in this report. In particular GNSS data from Australian CORS are making significant contributions to the IGS's *Multi-GNSS Experiment* (Raziq et al., 2012; Rizos et al., 2013).

There is an increasing recognition that CORS are a critical part of the Australia's *National Positioning Infrastructure* (NPI – Hausler & Collier, 2013a, 2013b, 2011), because the GNSS technology is the primary means of defining, maintaining and accessing the geodetic reference frame, at global (Section 1.2), regional (Section 1.3) and national scales. The establishment of new CORS continues at a rapid pace, involving a variety of Government agencies as well as private industry. While not tightly coordinated, in general there is a hierarchy of stations, defined principally by the stability of the GNSS monument, from the highest "tier" (those that follow the IGS site standards, intended to provide ultra-stable geodetic services) to lower tiers (established to support user-oriented precise positioning services). Figure 1.2 shows two CORS with different monument designs.

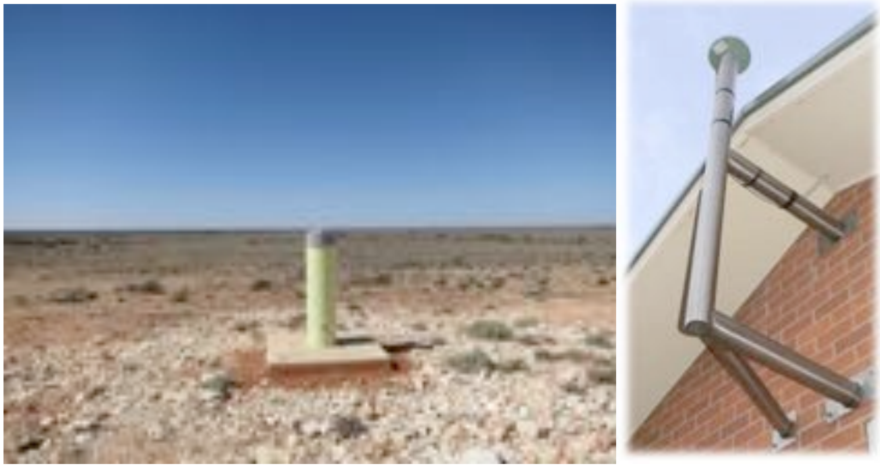

Figure 1.2: Tier 1 CORS established by GA (left); Tier 3 CORS on building (right)

CORS networks are vital for the provision of precise positioning services, in particular using "real-time kinematic" (RTK) and network-based RTK techniques. While service provision is understood to be the role of industry (Docherty & Nix, 2011), Government CORS provide the raw data for such services, as well as quality monitoring of the precise positioning services and datum stability.

The design of CORS networks and the nature of enhancements or augmentations to support next generation GNSS-based precise positioning services have been studied by a number of researchers. Choy et al. (2015a, 2013c), Harima et al. (2015a, 2015b, 2014a, 2014b), Zhang et al. (2013d), and others, have discussed how the L-band experimental signal transmitted by the Japanese *Quasi-Zenith Satellite System* (QZSS) could support future real-time *precise point positioning* (PPP) services in Australia. The manner in which data from nearby CORS could improve standalone PPP convergence was reported in Teunissen & Khodabandeh (2015), and Zhang et al. (2012). New modes of precise positioning that take advantage of next generation multi-frequency GNSS were discussed in Feng et al. (2013). GPS/GNSS-derived time series of (apparent) station movement are important an information source on possible ground deformation (secular and time-variable), but only if not contaminated by GNSS signal errors such as multipath or arising from antennas, monuments or cabling, or by local ground instability issues (Haasdyk & Roberts, 2013; Moore et al., 2014). Gazeaux et al. (2013)

reported on a blind assessment of automated GPS time series offset detection techniques, concluding that no present automated technique is as accurate as an expert user, with velocity errors from automated techniques commonly exceeding 0.5mm/yr. Montillet et al. (2012) reported on statistical analysis techniques, and results, of GPS time series.

Satellite Laser Ranging (SLR)

SLR observatories at Mount Stromlo (Canberra) and Yarragadee (Western Australia) have continued to operate continuously. The two SLR observatories contribute to the *International Laser Ranging Service* (ILRS) where they are consistently ranked in the top three stations in the world (ILRS – http://ilrs.gsfc.nasa.gov). Figures 1.3 and 1.4 show the main facilities at Yarragadee and Mount Stromlo respectively.

Figure 1.3: Yarragadee fundamental geodetic observatory, with GNSS in left of image, SLR station centre, and VLBI antenna rear-right of image

Figure 1.4: Mount Stromlo fundamental geodetic observatory, with GNSS in foreground of image, and SLR station centre of image

Very Long Baseline Interferometry (VLBI)

AuScope funded the establishment of three new radio telescopes. The radio telescopes at Mt Pleasant (Tasmania), Katherine (Northern Territory) and Yarragadee (Western Australia – Figure 1.5) have been operating as a geodetic VLBI array since 2011 (Lovell et al., 2013) from the AuScope Operations Centre at the University of Tasmania (UTAS). They are the most active geodetic telescopes in the world at the moment, currently observing for 232 days per year with 112 days dedicated to global *International VLBI Service* (IVS – http://ivscc.gsfc.nasa.gov) programs and 120 days of "AUSTRAL" sessions with telescopes Warkworth, New Zealand, and Hartebeesthoek, South Africa (Figure 1.6, left). The AUSTRAL observations are focussed on:

1. *Densifying the VLBI baseline time series in the south*. As a result of the high cadence observing in global sessions, the results for southern baselines could be significantly improved, overcoming the previously significant north-south imbalance (Plank et al., 2015).
2. *Improving the southern hemisphere celestial and terrestrial reference frames*. All three AuScope telescopes contributed to the latest realisation of the International Terrestrial Reference Frame (ITRF), and the next realisation of the International Celestial Reference Frame (ICRF) will benefit enormously with additional constraints from observations of southern quasars.
3. *Improving and developing techniques to enhance data quality*. The AuScope VLBI array is seen within the international VLBI community as a leader in the development of observational techniques essential to the next generation VLBI Geodetic Observing System (VGOS).

The AUSTRAL session data are processed at the AuScope correlation facility by Curtin University. The current VLBI observing rate is providing insight into some of the challenges of the *Global Geodetic Observing System* (GGOS – http://www.ggos.org) paradigm which will include continuous 24/7 VLBI operations. Continued improvements in scheduling and observing techniques are improving the quality of results, with a factor of two decrease in baseline measurement error, from 10mm to 5mm across the Australian continent and from 20mm to 10mm between Australia and South Africa (Figure 1.6, right).

Figure 1.5: Yarragadee VLBI

The GA IVS Analysis Centre is located in Canberra, contributing nutation offsets, three EOPs and their rates on a regular basis for the IVS-R1 and IVS-R4 networks. The CRF catalogues, based on global set of VLBI data since 1979, are regularly submitted. The most recent CRF solution (submitted on May,

2015) comprises accurate coordinates of 3406 reference radio sources with at least three or more successful observations. Daily positions of the three AuScope radio telescopes (Hobart, Yarragadee, Katherine) and Warkworth since 2011 are obtained and are available for further scientific analysis. Activities of the GA IVS Analysis Centre also include the development of the standard reduction models, in particular for general relativity and structure delay (Titov & Girdiuk, 2015). Titov (2011), Titov et al. (2011a) and Titov & Lambert (2013) discovered a secular aberration drift effect caused by the instantaneous acceleration of the Solar System Barycentre with respect to the centre of the Galaxy. This leads to an appearance of a systematic effect in the reference radio source proper motion with a magnitude of ~6 microarcsec/year.

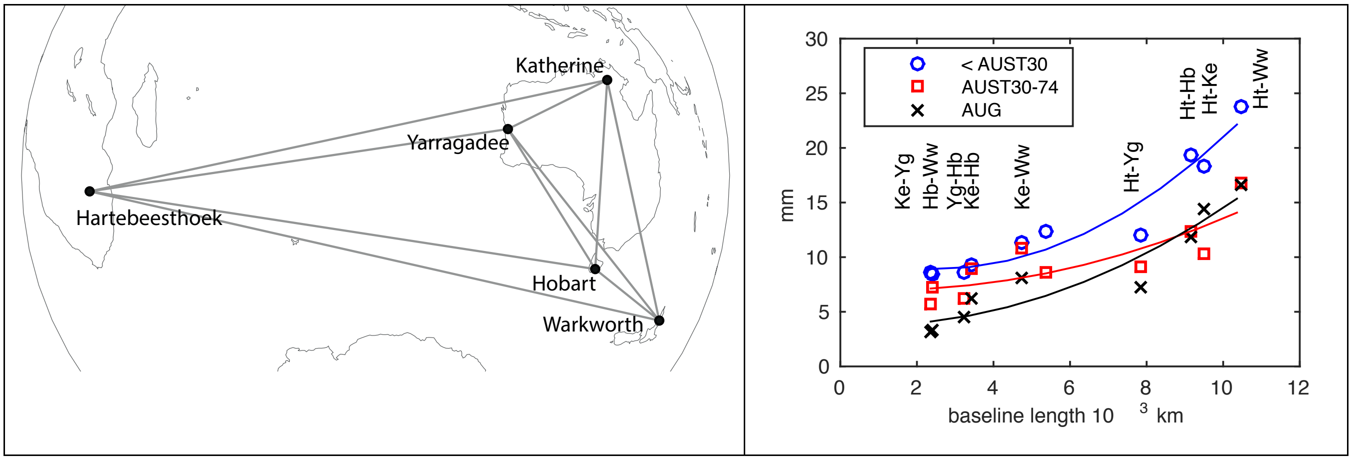

Figure 1.6: Left: The AUSTRAL array comprising the AuScope telescopes at Hobart (Hb), Katherine (Ke) and Yarragadee (Yg) with the Hart 15m (Ht) and Warkworth 12m (Ww). Right: a factor of 2 improvement in baseline length repeatabilities (wrms) as a result of revision and optimization of scheduling strategies. The blue circles cover the initial 12 months of the AUSTRAL program, the red squares cover six months following a revision of the source catalogue and the black crosses show results from the first six months of 2015 after sensitivity target levels and catalogue flux density limits were revised. Baselines between telescope pairs are indicated.

A dedicated program for optical identification and spectroscopy of the reference radio sources has undertaken since 2010 with a number of large optical facilities: Nordic Optical Telescope (Spain), Big Telescope Azimuthal (Russia), Gemini-North (USA, Hawaii), Gemini South (Chile), New Technology Telescope (Chile). A proper identification and redshift was found for about 300 radio sources (Titov et al., 2013, 2011b).

A significant focus of the VLBI program in the past four years has been on the effects of quasar structure on derived geodetic parameters. In collaboration with TU Wien, UTAS has constructed the first geodetic quasar structure simulator (Shabala et al., 2015), and used it to show that the effects of quasar structure on the TRF can be significant at the millimetre-level, and therefore must be considered in the next generation VGOS. Researchers have investigated a number of mitigation strategies in addition to the classical corrections for quasar structure. Promising options include careful selection of quasars (Schaap et al., 2013; Shabala et al., 2014a), observing quasars at suitable times (Shabala et al., 2014b), or in favourable VLBI array configurations (Shabala et al., 2014b; Plank et al., 2015b).

Work has commenced on improving observing and scheduling strategies though intra-session optimizations, or Dynamic Observing (Lovell et al., 2014). The main concept is to use monitoring of antenna performance, local conditions (e.g. wind stows) to provide feedback to a central operations centre so that the observing schedule can be modified in real-time to optimize the data quality.

Simulations of scenarios such as poorer than expected sensitivity have shown that a vast majority of data can be recovered from an affected antenna if real-time adaptation is applied.

DORIS

Geoscience Australia in partnership with the Centre National d'Etudes Spatiales (CNES) and Institut national de l'information géographique et forestière (IGN) operated two DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite) beacons at Mount Stromlo and Yarragadee. Data is provided to the *International DORIS Service* (IDS – http://ids-doris.org).

Terrestrial Connections at Co-located Observatories

Since 2011, GA has undertaken precision terrestrial tie surveys at Yarragadee (Western Australia – 2014), Mt Pleasant (Tasmania – 2014), Mt Stromlo (Australian Capital Territory – 2014), and Katherine (Northern Territory – 2015). The solutions of these surveys have been provided to the *International Earth Rotation and Reference System Service* (IERS – http://www.iers.org/IERS/EN/Home/home_node.html) for inclusion in the ITRF computations (http://itrf.ensg.ign.fr).

1.2 Global Reference Frames

Through recent re-processing, the GNSS data collected by GA from the ARGN and SPRGN over the period of the report were included in the computations for the new realisation of the ITRF. In collaboration with the Massachusetts Institute of Technology IGS Analysis Center and GA, researchers at the Australian National University (ANU) analysed 14 years of GPS data to produce the MIT IGS REPRO2 solution. The data were processed on the National Computing Infrastructure (NCI) computing system using the GAMIT software, updated to include all the state-of-the-art models required for the REPRO2 solution (including general relativity, 2nd order ionospheric effects, updated antenna and satellite phase centre models, VMF1 mapping function and a priori hydrostatic delay, etc).

Australia has played a significant role in the UN-GGIM's Working Group on the Global Geodetic Reference Frame (GGRF) (http://ggim.un.org/UN_GGIM_wg1.html). The WG is currently developing a roadmap for progressing the GGRF resolution to ensure action is taken by UN States with respect to investment in geodetic infrastructure, adoption of the GGRF for national datums, and increased levels of geodetic data sharing.

In May 2012, several Australian geodesists made contributions to the combined IAG, FIG and ICG workshop "Reference Frames in Practice" held in Rome prior to the FIG Working Week. Similar workshops were also run in June 2013 as part of the South-East Asian Surveyors Congress in Manila (The Philippines), and in Suva (Fiji), in September 2013 at the FIG Pacific Small Island Developing States Symposium. In August 2015 an IAG-FIG workshop on vertical datums was presented as part of the South-East Asian Surveyors Congress in Singapore.

1.3 Regional Reference Frames

One initiative of the UN-GGIM-AP is the definition and maintenance of the *Asia-Pacific Reference Frame* (APREF). APREF is a densification of the ITRF in the AP region (Sub-Commission 1.3e). GA has continued to act as the Central Bureau of the APREF which is now incorporating GNSS data from a CORS network of approximately 600 stations, contributed by 28 countries in the AP region. Data are routinely processed by four analysis centres and made available (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame). GA has also continued to coordinate an annual regional GNSS campaign known as the *Asia Pacific Regional Geodetic Project* (APRGP).

AuScope Initiative

On the Australian continent itself the AuScope GNSS Network was established under the *National Collaboration Research Infrastructure Strategy* (NCRIS) to characterize the structure and evolution of the Australian continent (http://auscope.org.au). AuScope includes a geospatial component that enhances the accuracy and resolution of the *National Geospatial Reference System*. AuScope has continued to fund geodetic science infrastructure through the *Australian Geophysical Observing System* (AGOS) Program which is focused on delivering the understanding of the physical state of the accessible crust of the Australian continent that is crucial to meeting secure, sustainable future energy needs. Specifically, the capability has provided the research community with access to state-of-the-art geodetic instruments that support the highest precision measurement of deformation of the solid Earth. The AGOS geospatial infrastructure includes: GNSS ground stations and receivers, three VLBI antennas, an upgrade of the SLR, and absolute gravity instrumentation. The AGOS also funded a "GNSS in Schools" program, with development of four worksheets for use in lower high schools.

A deployable pool of GNSS instruments for episodic campaign surveys in Australia. This includes 80 GNSS instruments, 10 ionospheric receivers and three RTK kits. The geospatial equipment is suitable for GNSS-related geospatial and geophysical experiments. While characterizing deformation of the Earth's crust is the targeted application of the equipment, other novel uses have been encouraged. This instrument pool is fully operational and well utilized, with projects being undertaken in Australia, Indonesia and Antarctica. The GNSS instrument pool represents a significant new capability to measure subsidence caused by crustal services, particularly those in the energy sector. An access committee makes equipment available on the basis of scientific merit.

A geodetic survey mark network, including co-located radar corner reflectors, to enable the precise measurement of surface deformation at a regional scale using Interferometric Synthetic Aperture Radar (InSAR) and GNSS techniques has been established in the Surat Basin, Queensland. A broad scale experiment to measure subsidence related to Coal Seam Gas extraction has commenced and is expected to conclude within a decade. The reflector array is currently being used by five individual space agencies for satellite radar mission calibration and validation. The locations for three corner reflectors in the Perth Basin are being investigated (Feathertstone et al., 2012a).

A robotic GNSS antenna calibration facility, the only one of its kind in the southern hemisphere, has been established. The facility includes two components: the outdoor robot facility located in Canberra (Figure 1.7) and an indoor, anechoic chamber located at the National Measurement Institute (NMI) in Sydney. The NMI component of the GNSS antenna calibration facility is highly complementary to the AGOS robotic GNSS calibration facility located in Canberra. The infrastructure has enabled inter-comparisons between the two systems and has confirmed the operations of the Canberra facility.

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Figure 1.7: The Geoscience Australia antenna calibration facility, Canberra

New National Geodetic Datum

Australia is preparing for a new national datum. The Permanent Committee on Geodesy (PCG) has been engaged in planning for many years, with a view to modernizing the current Geocentric Datum of Australia (GDA94 – http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/geodetic-datums/gda). GDA94 is based on holding the ITRF92 coordinates of the Australian Fiducial Network (a sub-set of the ARGN) at reference epoch 1994.0 fixed and adjusting all other GPS baselines and terrestrial-geodetic measurements to derive the GDA94 coordinates of control marks.

GDA94 is a conventional "static" datum in that the coordinates do not take into account the Australian continent's tectonic motion. This means that the continental motion since 1994 is not reflected in the published GDA94 coordinates, and hence the WGS84 and ITRF coordinates of the control marks are at present approximately 1.5m different to the GDA94 coordinates. There are also several other shortcomings of GDA94 that are driving the modernization process (Donnelly et al., 2014a). Several issues were investigated, including whether the new datum would be "static" or "dynamic", what the reference epoch date should be, the nature of the transformation models, how to incorporate ground deformation information, the methodology for the simultaneous datum adjustment, and implementation plans (e.g. Donnelly et al., 2014b; Haasdyk et al., 2014; Stanaway & Roberts, 2015; Stanaway et al., 2015, 2014, 2012).

Transition to the new datum will be a two-stage process which concludes in 2023. In Stage 1, with user implementation commencing on 1 January 2017, a new and more rigorous national adjustment will be undertaken with the coordinates projected to a reference date of 1 January 2020 as a conventional static datum (possible designation the *Geocentric Datum of Australia 2020* – GDA2020). Horizontal coordinates will shift by approximately 1.8 metres; however the new datum will be more closely aligned to the ITRF such that residual coordinate differences will be small enough to be ignored for most users. In Stage 2, with an implementation commencement of 1 January 2020, it is proposed that the new reference frame will be time-dependent and highly accurate with respect to ITRF (possible designation the *Australian Terrestrial Reference Frame* – ATRF). Importantly, the conventional static datum will also be retained in perpetuity, unless it becomes obvious that it is no longer needed.

Much of the technical work to develop the datum has already been completed by the PCG. GNSS and terrestrial observations from all Australian government jurisdictions has been provided to GA who are working to combine and optimize a phased network adjustment on Australia's NCI. Part of this activity has been conducted under the auspices of a project funded by the Cooperative Research Centre for Spatial Information.

Absolute Gravity

Geoscience Australia continued to conduct a national absolute gravity program using an FG5 absolute gravimeter at around 10 geodetic sites across Australia. These sites are co-located with GNSS CORS and are observed annually with sessions of 24 to 48 hours. The program aims to provide an independent measure for vertical movements of the crust and/or other long-term gravity signals of interest.

The Australian Height Datum (AHD)

Featherstone & Filmer (2012) arguably may have put to rest the cause of the North-South slope in the AHD, later suggesting a combined least squares adjustment of heterogeneous data (with appropriate weights in variance component estimation; Filmer at al., 2014) to form a new scientific version of the AHD (Filmer & Featherstone, 2012a; Featherstone et al., 2012b). With a view to providing Helmert orthometric corrections, as opposed to normal-orthometric corrections to levelled heights, in any new scientific AHD, Filmer et al. (2013) have looked at predicting gravity for benchmarks that do not have gravity observed at them. Error propagation formulas are given in Filmer & Featherstone (2011). Filmer & Featherstone (2012b) revisited the vertical datum offset between the Australian mainland and Tasmania using geodetic and oceanographic techniques. Filmer (2014) used oceanographic models of mean dynamic topography to add redundancy in outlier detection in levelling networks. Keysers et al., (2013) investigated vertical datum transformations across the Australian Littoral Zone.

eGeodesy Standard Development

Representatives from the Australian and New Zealand governments have been developing a standards-based approach for the exchange of geodetic data and metadata. The aim is to provide the geodetic community with a standard that makes geodetic data and metadata discoverable and interoperable, easily transferable via web services, and is based on internationally recognised data exchange methods. *GeodesyML* is a proposed Application Schema of the existing Geography Markup Language (GML) which is an ISO Standard (19136:2007). Being an Application Schema simply means GeodesyML extends GML using GML specifications to meet the specific needs of the geodetic community. GeodesyML has been raised in discussions with GGOS and the IGS Data Center Working Group as a proposed model to be adopted internationally. Part of this activity has been conducted under the auspices of a project funded by the Cooperative Research Centre for Spatial Information.

2. GRAVITY FIELD

2.1 Gravimetry and Gravity Networks

New regional gravity surveys are mostly contracted by State/Territory and Federal Government geological mapping agencies as part of resource exploration initiatives. After consultation with various stakeholders and release embargoes, these gravity data eventually appear in the national gravity database. Australia makes these data freely available to the scientific community via the *Geophysical Archive Data Delivery System* (GADDS) http://www.geoscience.gov.au/cgibin/mapserv?map=/nas/web/ops/prod/apps/mapserver/gadds/wms_map/gadds.map&mode=browse. Aspects of gravity data processing were included in a book chapter by Swain & Kirby (2011). The absolute gravity observation program is undertaken by Geoscience Australia (GA) and The Australian National University (ANU). It incorporates regular repeat measurements over the Australian Geodetic Gravity Network to provide a time series for vertical deformation studies. Measurements are made using a Micro-g LaCoste FG5 absolute gravimeter which was purchased 2008 using funding from the *National Collaborative Research Infrastructure Strategy* (NCRIS). Since 2011, NCRIS funding has also been used by GA to complete construction and/or upgrade of the *Australian Geodetic Gravity Network* (AGGN), Table 2.1.

Table 2.1: AGGN sites & the years in which they have been observed –
AGGN core sites are shown in bold

Site	2011	2012	2013	2014	2015
Alice Springs (DH)					O
Alice Springs (JGGRS)	O	O			O
Ceduna	O	O		O	
Dampier	O				
Darwin	O	O		O	
Eidsvold				O	O
Fitzroy Crossing			O	O	
Georgetown				O	O
Hobart		O	O		O
Mainoru		O		O	
Melbourne		O			
Mt Stromlo	O	O	O	O	O
Perth	O	O			
Tidbinbilla					
Tom Price			O	O	
Townsville		O		O	
Wagin	O	2O		O	
Yarragadee	O	O		O	

This included the construction or retrofit of powered gravity huts at each site. New sites at Alice Springs (NT), Eidsvold (Qld), Fitzroy Crossing (WA), Georgetown (Qld), Mainoru (NT), Tom Price (WA), Wagin (WA) and Yarragadee (WA) have augmented the AGGN and ensured that all AGGN core sites are high stability, and in the majority of cases co-located with GNSS CORS. At least two sets of measurements have been taken at all new / upgraded sites since 2011 except for the Alice Springs

Dynamite Hill site at which a second set of measurements will be taken in 2016.

2.2 Spatial and Temporal Gravity Fields and Geoid Modelling

Recent topographic datasets describing land topography, ocean and lake bathymetry, ice thickness and bedrock (sub-ice-topography) were used to create a new 1 arc-min resolution layered topography model named *Earth2014* (Hirt & Rexer, 2015), Figure 2.1. Compared to the widely used ETOPO1 model, the Earth2014 model offers improved information on Earth's shape, topography and uppermost masses, as sensed through comparisons with gravimetry (Hirt, 2014; Hirt et al., 2015). The Earth2014 topography models were analysed into ultra-high degree spherical harmonics (to degree 10,800), for use for example in global gravity and geoid modelling (Hirt & Rexer, 2015).

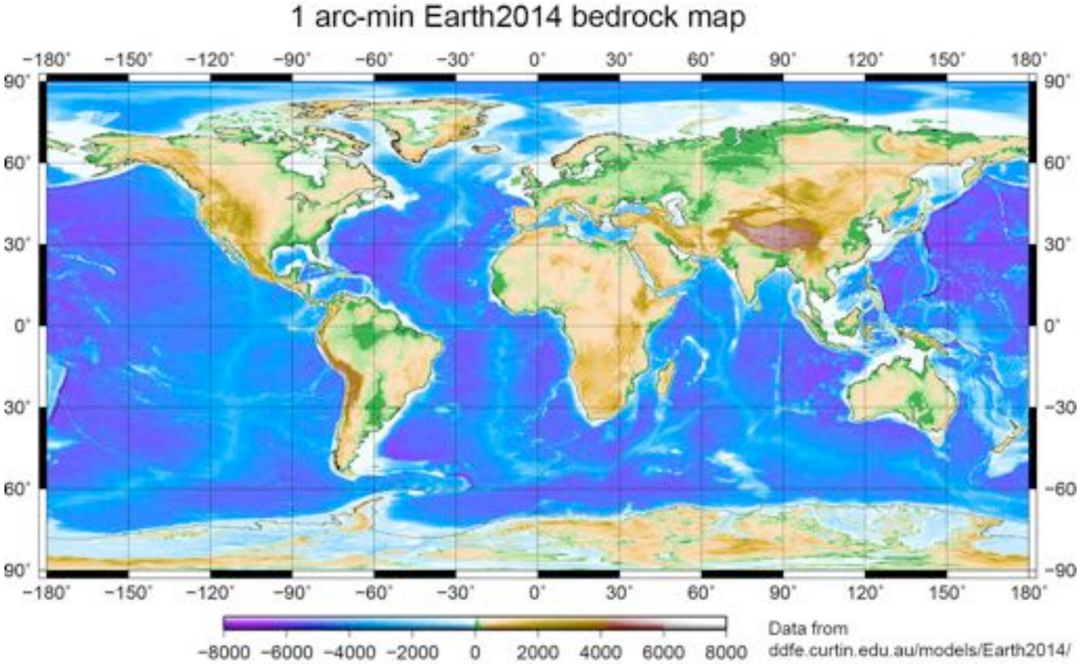


Figure 2.1: Global map of Earth's bedrock at 1 arc-min resolution (from the Earth2014 model, Hirt & Rexer, 2015) – map shows the Earth's surface in the absence of ice and water masses and is based on new compilations of bathymetry over the oceans and recent bedrock data over Antarctica and Greenland

Australian geodesists have validated the new static gravity field models from the European Space Agency's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission over Australia and surrounding areas with various datasets available, ranging from point gravity data (Hirt et al., 2011a), global geopotential models such as EGM2008 and spherical harmonic models newly derived from Australian gravity data (Rexer et al., 2014), to mass-models constructed from high resolution topography (Hirt et al., 2015, 2012a). As key result, the final generation GOCE gravity models provides full resolution to ~90km spatial scales, and partially resolves gravity features to ~70km scales which were never measured before from space over Australia and elsewhere (Hirt et al., 2015).

Research focussed on spectral forward modelling methods, i.e. spherical harmonic techniques for the computation of the gravitational field that is generated by the topographic masses. The spectral forward modelling method was applied as a means to validate GOCE gravity fields (Hirt et al., 2012a). The importance of including higher-order terms for series convergence was demonstrated for high-degree modelling (Hirt & Kuhn, 2012). Further, the spectral forward modelling approach was enhanced to capture very short-scale gravity signals, resulting in a much improved agreement (at the microGal-level) with classical Newtonian integration (Hirt & Kuhn, 2014).

New mathematical solutions for forward modelling of topography with respect to a mass ellipsoid were derived (Claessens & Hirt, 2013) and used for the development of a high resolution ellipsoidal topographic potential model (dV_ELL_RET2012). The *dV_ELL_RET2012* model is a "topographic counterpart" to the EGM2008 geopotential model and allows accurate computation of Bouguer gravity from geopotential models (such as from GOCE or EGM2008) directly in spherical harmonics (Claessens & Hirt, 2013; Hirt, 2015a), Figure 2.2.

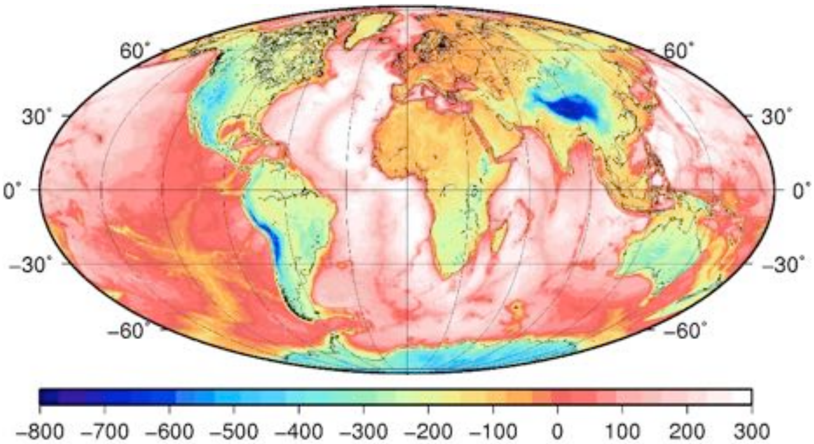


Figure 2.2: Global map of Bouguer gravity anomalies computed from the EGM2008 geopotential and dV_ELL_RET2012 topographic potential model in spherical harmonics and ellipsoidal approximation –map offers a resolution of up to 10km (Claessens & Hirt, 2013)

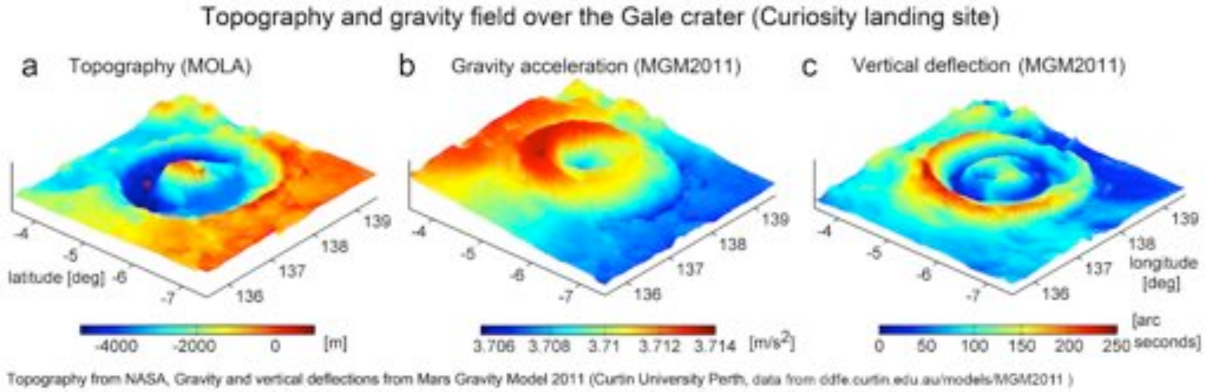
The residual terrain modelling (RTM) method for approximation of the short-scale gravity field was refined with combined topography and bathymetry data, and tested for coastal zone gravity field modelling (Hirt, 2013). Using Western Australia's iVEC supercomputing facility, the RTM forward gravity modelling was applied near-globally with local resolution (~220m) for the first time (Hirt et al., 2014a). The resulting model ERTM2160 helps reduce the omission error of global geopotential models, and can be used to study the characteristics of the Earth's short-scale gravity field (Hirt et al., 2014a; Rexer & Hirt, 2015).

Hirt (2012b) investigated a gradient-based technique for efficient spherical harmonic synthesis at varying heights (3D-synthesis). The 3D-synthesis technique takes into account the effect of gravity attenuation with height while reducing synthesis computation times by 2-3 orders of magnitude. It was used for gravity computations from topographic potential models (Hirt & Kuhn, 2012) and geopotential models (Hirt et al., 2013).

By combining global geopotential models (GOCE, GRACE, EGM2008) with RTM data (ERTM2160), estimates of common gravity field functionals (gravity accelerations, gravity anomalies, vertical deflections, quasi-geoid undulations) were obtained at over 3 billion points covering most of the Earth's surface at 220m resolution. The new gravity field maps were released under the name *GGMplus* (Global Gravity Model plus) (Hirt et al., 2013).

The properties of Earth's gravity field at short spatial scales were studied based on GGMplus. A new potential degree variance model (power spectrum) was computed that is data-based to ultra-high spherical harmonic degree of 90,000 (Rexer & Hirt, 2015).

Australian geodesists became active in planetary gravity field modelling in 2011. Methods for Earth gravity field modelling (e.g., 3D-synthesis and RTM) were adopted along with topography data from laser altimetry to produce gravity maps for the Moon (LGM2011 – Hirt & Featherstone, 2012), and Mars (MGM2011 – Hirt et al., 2012b, 2012c) which offer spatial resolution of a few km. The *MGM2011* gravity map was used by JPL for software validation and by NASA for detection of inflight anomalies during the landing phase of their Curiosity rover mission over the Gale Crater (Figure 2.3). Band-limited Bouguer gravity was used to detect about 280 candidate locations for basins and craters on the Moon (Featherstone et al., 2013).


Topography and gravity field over the Gale crater (Curiosity landing site)

a Topography (MOLA)

b Gravity acceleration (MGM2011)

c Vertical deflection (MGM2011)

Topography from NASA, Gravity and vertical deflections from Mars Gravity Model 2011 (Curtin University Perth, data from ddfe.curtin.edu.au/models/MGM2011)

Figure 2.3: panel a: Topography, panels b and c: Gravity field functionals from the MGM2011 gravity model (Hirt et al., 2012b) over the Gale Crater, the landing site of NASA's curiosity mission

2.3 Dedicated Satellite Gravity Mapping Missions

Nothing to report.

2.4 Regional Geoid Determination

AUSGeoid09 remains the national standard for the transformation of GNSS-computed ellipsoidal heights and ellipsoidal height differences to the *Australian Height Datum* (AHD). Though it was computed in and released in 2009, several papers appeared in 2011 (Featherstone et al., 2011; Brown et al., 2011). The most significant philosophical change from *AUSGeoid98* was to adjust the gravimetric quasi-geoid model AGQG2009 to GNSS-AHD values using least squares collocation so as provide a direct transformation product for GNSS surveyors. Both *AUSGeoid09* and AGQG2009 can be downloaded from the GA website (ftp://ftp.ga.gov.au/geodesy-outgoing/gravity/ausgeoid/), as well as interpolation software (http://www.icsm.gov.au/gda/tech.html). There is also an online computation facility (http://www.ga.gov.au/ausgeoid/nvalcomp.jsp). Claessens et al. (2011), under contract to Land Information New Zealand, computed the *NZGeoid09* quasi-geoid model using an iterative data reduction to account for disparate vertical datums for that nation.

The implementation of the new national geodetic datum (see Section 1.3) will see a change in ellipsoidal heights, in some cases as much as 70mm because of the antenna phase centre modelling chosen in the AFN and ANN. Therefore, a new gravimetric quasi-geoid model will be computed using new gravity and terrain data over Australia and improved software (Hirt et al., 2011b). As for *AUSGeoid09*, the gravimetric quasi-geoid will be fitted to the GDA2020-AHD values using least squares collocation so as provide a direct transformation product for GNSS surveyors.

Given the increasing number of GNSS-coordinated land gravity surveys, Featherstone (2013) proposed numerous modifications to Hotine's kernel for quasi/geoid determination from gravity disturbances instead of gravity anomalies. The Australian synthetic gravity field has been applied to test the geoid computation schemes developed by the University of New Brunswick, Canada (Vanicek et al., 2013), showing some remaining deficiencies. Fellner et al. (2012) computed a global synthetic field based solely on Newtonian forward modelling.

Over Antarctica a 10km resolution GOCE-based geoid model was computed from a combination of satellite data with forward-modelled gravity based on new bedrock, ice and bathymetry data (from the Bedmap2 product). The geoid and gravity model *SatGravRet2014* is a significant improvement over previous efforts (such as EGM2008) by adding the fine structure of the field based on Bedmap2 forward-modelling (Figure 2.4). It could be demonstrated that geoid signals as large as 1m were neglected in previous models (Hirt et al., 2015). GOCE gravity was used as a new validation tool to sense improvements in Antarctic bedrock and mass models, as available through the Bedmap2 data compilation (Hirt, 2014).

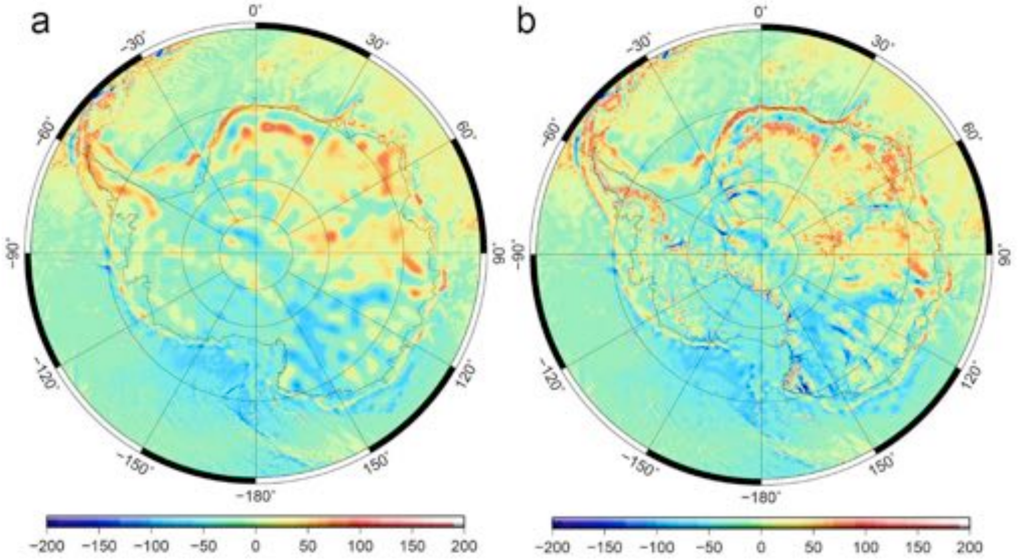


Figure 2.4: Gravity anomalies over Antarctica, from EGM2008 (left), and from SatGravRET2014 (right) – left image the gravity field over Antarctica is based on the GRACE mission (110km resolution) – use of recent GOCE data and topographic gravity from Bedmap2 increases the resolution to 10km spatial scales (right)

2.5 Satellite Altimetry

The University of Tasmania, working closely with the sea level group within CSIRO Marine and Atmospheric Research, and part-funded by the *Integrated Marine Observing System*, have continued to develop approaches to the validation and calibration of ocean satellite altimeter missions. This includes the ongoing absolute calibration facility in Bass Strait and most recently extended to include new observations in Storm Bay south of Hobart, Tasmania (Watson et al., 2011). A new "relative" calibration technique was developed and applied to the Jason-class altimeter missions to produce a revised global-mean sea level time series (Watson et al., 2015), showing a smaller overall rate of sea-level rise of 2.6-2.9mm/yr but with a quadratic term of opposite sign to previous estimates (although still not significantly different to zero). A major review of sea level changes around Australia's coastline was reported by White et al. (2014), while Burgette et al. (2013) examined the noise properties of tide gauge sea level data and developed an approach to reduce noise by considering differenced time series. They report increases in the rates of Australian sea level rise through the 20th Century.

Research at the University of Newcastle mainly focused on coastal altimetry and its application on (1) the development of altimeter waveform retrackers for accurate retrieval of sea level measurements, and (2) studies of sea level changes and sea level extremes. Waveform retracking is an important means of improving the retrieval of sea surface heights for all satellite altimetry applications. To optimise the sea level measurements from multiple retracking solutions near the coast (Gommenginger et al., 2011), Idris & Deng (2014, 2013, 2012a, 2012b) developed a new *Coastal Altimetry Waveform Retracking Expert System* (CAWRES). The system aims to achieve the highest possible accuracy of coastal sea levels, and bring radar altimetry data closer to the coast. The system first reprocesses altimeter waveforms using the optimal retracker based on the analysis from a fuzzy expert system. Then the system minimises the relative offset in the retrieved sea levels caused by switching from one retracker to another, using a neural network. The sub-waveform retracker by Idris & Deng (2012a) is one of significant contributions to CAWRES. It can be used to effectively retrack waveforms near the coastline. This system has been validated against geoid height and tide gauge data in two different regions: the Great Barrier Reef in Australia and the Prince William Sound in Alaska USA, for the Jason-1 and Jason-2 satellite missions. The results demonstrate that the CAWRES can effectively enhance the quality of 20Hz sea level data, and recover up to 70% more data than the existing retrackers.

The accurate retrieval of sea levels from altimeter range measurements in the coastal zone also involves a number of corrections for geophysical signals (e.g. tides and sea state bias) and atmospheric attenuations (e.g. wet and dry tropospheric delay and inverse barometer effects). Near coasts, these corrections require special attention because they are usually less accurate. In this regard, Idris et al. (2014) investigated the importance of coastal altimetry retracking and de-tiding through a case study in the Great Barrier Reef. The investigation demonstrates the importance of optimal tide modelling using the response method as well as careful use of the dynamic atmosphere correction delivered by the MOG2D model.

The sea levels and sea level extremes were investigated using altimetry and tide gauge data around Australian coastal regions. The sea level fields with and without non-linear components were modelled using the multivariate regression method and the Multi Adaptive Regression Splines (MARS), respectively (Deng et al., 2013, 2012; Gharineiat & Deng, 2015). The 20 years of data (1993-2012) from multiple altimeter missions (e.g. Topex, Jason-1 and Jason-2) and 14 tide gauges are combined to provide a consistent view of sea levels. MARS is chosen because it is capable of dividing measured sea levels into distinct time intervals where different linear relationships can be identified, and of weighting individual tide gauge according to the importance of their contributions to predicted sea levels. In the northern coasts of Australia, the predicted sea levels during six tropical cyclones are validated against sea level observations at three independent tide gauge sites. The results show that both methods, especially MARS, can be used for efficiently monitoring sea level extremes. The results also suggest that altimetry is able to capture high sea levels induced by storm surge (and cyclones). This study open the way for further altimetry research into monitoring of extreme sea level events (Stewart & Deng, 2015).

Australian researchers contributed two chapters to a book on satellite altimetry (Deng et al., 2011; Bonnefond et al., 2011).

Khaki et al. (2015) improved gravity field anomalies from retracked satellite altimetry data over the Persian Gulf and Caspian Sea. Sharifi et al. (2013) used satellite altimetry to monitor the fluctuations of the Caspian Sea level.

2.6 Gravity and Mass Displacements

The ANU's Gravity Recovery and Climate Experiment (GRACE) team have developed software to generate estimates of the temporal gravity field from the Level-1B GRACE observations. The software uses the classical approach of orbit dynamics, estimating initial position/velocity of each satellite along with calibration parameters of the accelerometers onboard each satellite. The temporal gravity field is parameterized using mass concentration elements (mascons) that can vary in both size and shape. It is anticipated that time series for all existing GRACE observations (since 2003) will be generated by the end of 2015.

In addition, an interactive website was developed where users could generate time series and/or spatial maps using the French GRGS GRACE solutions in the form of spherical harmonics. The intent of the web site was to make the data accessible to users who may not have had the requisite knowledge as to how to extract geophysical signals from the spherical harmonic fields themselves. Users can choose to generate results in terms of geoid changes, elastic deformation of the Earth's crust, visco-elastic deformation or as an estimate of the load in terms of an equivalent water height. A full explanation of the capabilities of the website is given in Darbeheshti et al. (2013), along with several examples.

McGrath et al. (2012) synthesised both GRACE observations and vegetation indices to conclude that the significant loss of water mass in Western Australia, SE of Karratha, was due to a drying out of the region after abnormally high levels of cyclone activity in the years preceding the launch of the GRACE satellites. They showed that the so-called "Big Dry" was in fact a continent-wide reduction in water storage, vegetation and rainfall and can be attributed to inter-decadal variability in the Indian Ocean Dipole.

New estimates of ice sheet contribution to recent sea level change were obtained for the Antarctic and Greenland Ice Sheets. UTAS contributed to the NASA/ESA-funded Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) with results published in *Science* in 2012 (Shepherd et al., 2012), following an independent study led by UTAS published in *Nature* (King et al., 2012a). Temporal correlations in GRACE ice mass change time series were shown to exhibit temporal correlations, with "white noise" uncertainties underestimating uncertainties of trends and accelerations by factors 2-6 (Williams et al., 2014). Andrews et al. (2014) simulated GRACE spherical harmonic and mascon solutions within the same processing framework, testing the relative merits of the two approaches in the presence of noise and systematic error and showing clear benefits to the mascon approach when spatial constraints are introduced that consider prior knowledge of spatial correlation of mass changes (such as hydrological or ice sheet drainage basins). Memin et al. (2014a) investigated mass transport over Antarctica using a combined analysis of GRACE and EnviSat altimeter data, and when considering inter-annual timescales. Memin et al. (2015) used similar datasets to show evidence for accumulation changes that vary with the Antarctic Circumpolar Wave.

Baur et al. (2013, 2011) used GRACE and Newtonian forward modelling to assess how much water may be stored on land away from the oceans. Baur et al. (2012) looked for linear and non-linear trends in GRACE time series. Other GRACE related research was reported in Awange et al. (2014c), Doubkova et al. (2011), Forootan et al. (2014b), Purcell et al. (2011), Tregoning & McCluskey (2011), and Tseng et al. (2014).

The 2012 Indian Ocean earthquake sequence (Mw 8.6, 8.2) is a rare example of great strike-slip earthquakes in an intraoceanic setting. With over a decade of GRACE data, Han et al. (2015b) were able to measure and model the unanticipated large co-seismic and post-seismic gravity changes of these events. It was revealed that the gravity changes are produced predominantly by co-seismic compression and dilation within the oceanic crust and upper mantle and by post-seismic vertical motion. The results suggest that the co-seismic positive gravity from GRACE and the co-seismic subsidence from GPS are the result of spontaneous compression, and thus density increase in the compressional quadrant. The post-seismic positive gravity from GRACE and the post-seismic uplift from GPS are due to the gradual uplift associated with viscoelastic relaxation with little perturbation in density. In addition to the recent great mega-thrust ruptures in 2004, 2010, and 2011, this earthquake is a rare example from which we can advance our understanding on the Earth's response to these large episodic stress changes under different environments by testing various hypotheses and physics of post-seismic processes.

Water storage changes in Africa, Asia, and Australia were investigated, and reported in Awange et al. (2015a, 2015b, 2014c, 2014d, 2013a, 2013b, 2011) and Forootan et al. (2014a, 2014b, 2012), while the associated impacts of climate change were treated in Andam-Akorful et al. (2015), Endris et al. (2013), Fleming & Awange (2013), Fleming et al. (2011), Khandu et al. (2015), Omondi et al. (2014, 2013, 2012), Omute et al. (2012), and Tregoning & McCluskey (2011).

3. EARTH ROTATION AND GEODYNAMICS

3.1 Earth Tides and Geodynamics

A review of global ocean tide model accuracy found that significant progress had been made in the accuracy of ocean tide models over the period since the last major reviews more than 10 years earlier. Nonetheless, significant errors remain in coastal regions and at high latitudes (Stammer et al., 2014).

3.2 Crustal Deformation

Separating present-day mass balance from ongoing glacial isostatic adjustment (GIA) is an essential component of using space-geodetic observations to study mass balance changes. Purcell et al. (2011) presented a new methodology by which the GIA component of vertical deformation could be derived from dimensionless Stoke's coefficients of GRACE temporal gravity field solutions. Their approach is valid for a broad range of Earth and ice models and reproduces to within 0.3mm/yr the rigorous computations of uplift rates computed using full glacial ice sheet modeling code. Fleming et al. (2012) studied the changes in sea level around the Australian continent caused by ongoing GIA, by present-day melting of polar ice sheets and a hypothetical complete melting of Greenland and Antarctic ice sheets. The increase in sea level was found to not be uniform, with greater increases in Western Australia and southeastern Australia.

Memin et al. (2014b) considered the non-tidal ocean loading associated with Tropical Cyclone Yasi that crossed the Australian coast in January/February 2011 and showed reduction in GPS time series scatter over this period when modelling the combined atmospheric and non-tidal ocean loading. They also identified seasonal variations in noise as a limiting factor in analysis of low latitude GPS sites, suggesting the need for improved models of atmospheric effects in these regions. Santamaría-Gómez et al. (2015) showed that geodetic site vertical velocities may be substantially biased by elastic deformation due to changes in surface loading. They suggest biases in velocities derived using 5-year-long time series are commonly 0.5mm/yr and are dominated by hydrological loading (aside from Antarctica, where atmospheric loading dominates). Uncertainties in loading models means decade-long time series are currently required to accurately study vertical land movement. King et al. (2012b) considered GPS vertical velocities at sites globally, and especially near to tide gauges, and identified regionally coherent differences to predictions based on models of glacial isostatic adjustment or elastic deformation. The pattern, which approximated a degree 2,1 deformation, suggested an over-estimation of true polar wander in models of GIA, such as would result from errors in ice load change distribution.

A deformation model for Australia has been developed by Stanaway et al. (2014) and Stanaway & Roberts (2015) (Figure 3.1). This work is being done in close cooperation with geodesists from Land Information New Zealand (LINZ). A *Stable Australian Plate Reference Frame* (SAPRF) has also been developed and was presented at the IAG Commission 1 REFAG Symposium at Luxembourg in October 2014 (Stanaway et al., 2015). Deformation studies of the Papua New Guinea Geodetic Datum 1994 were reported in Stanaway (2014). 4D deformation modeling, as a link between international, national and local reference frames, was discussed in Stanaway et al. (2012).

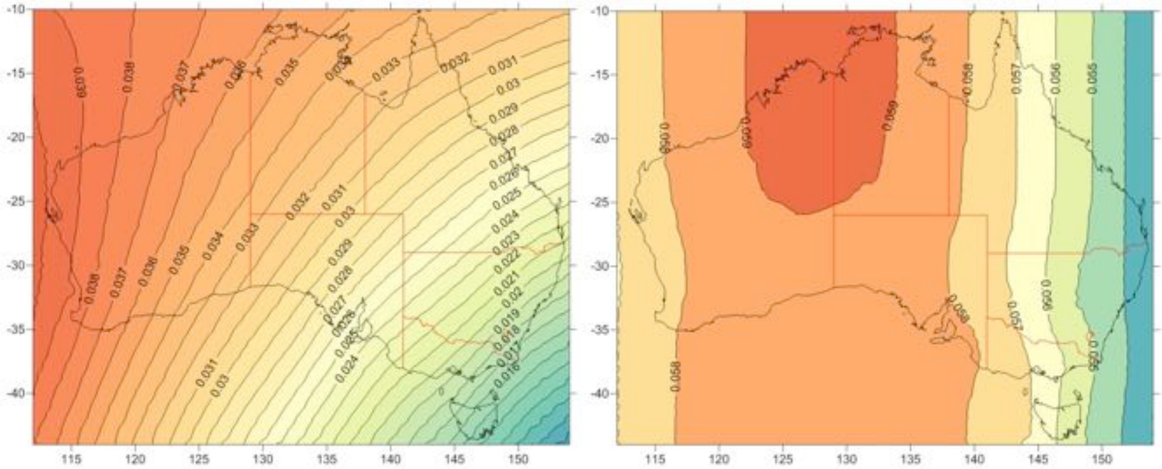


Figure 3.1: Australian Kinematic Model – topocentric East velocity (left) and North velocity (right) in m/yr

3.3 Earth Rotation and Geophysical Fluids

King & Watson (2014) highlighted the IERS (2010) pole tide model (defined by a linear plus cubic model) was insufficient in accounting for actual recent polar motion, reported elsewhere to be driven by increased ice sheet melting. As such, a large-scale bias of up to 0.25mm/yr exist in geodetic vertical velocity estimates. Keller et al. (2012) derived formulas to map polar wander due to deglaciation.

3.4 Cryospheric Deformation

University of Tasmania focused on validating and improving models of GIA in Antarctica. King (2013) provided a review of Antarctic GIA modelling and observations, highlighting the need for increased observations, including geodetic ones. Nield et al. (2014) revealed rapid viscoelastic uplift within the Antarctic Peninsula following the breakup of the Larsen B Ice Shelf in 2002, inferring low upper mantle viscosity in this region from comparison of numerical modelling and GPS uplift data. Bradley et al. (2015) inferred late Holocene readvance of part of West Antarctica, in part based on GPS observations of subsidence within the interior of the ice sheet. Gunter et al. (2014) provided an improved and spatially continuous empirical estimate of Antarctic crustal uplift derived from GRACE, ICESat and a fine densification model. They showed close agreement with GPS uplift rates, where those were available. Pittard et al. (2015) investigated ice velocities of the tributary glaciers feeding the Amery Ice Shelf.

3.5 Tectonics and Earthquake Geodesy

Tectonic studies at the Australian National University (ANU) included both regional and global deformation investigations. An assessment of great earthquakes in the 21st Century showed that the majority of the Earth's surface has been deformed. Modelled horizontal deformation was found to agree with estimates of co-seismic deformation from the ANU's analysis of global GPS data. It was shown that not accounting for far-field earthquake deformation can lead to errors in estimates of plate rotations and that, when accounting for offsets caused by instrument changes and earthquakes, the majority of the Australian continent is not deforming by more than 0.2mm/yr. On the other hand, significant post-seismic deformation is occurring in southeastern Australia as a result of the 2004 Macquarie Ridge earthquake (Tregoning et al., 2013).

Koulali et al. (2015) has identified new active plate boundaries in Papua New Guinea, with significant convergence (as much as 13mm/yr) occurring on the New Guinea Trench and south of the Highlands. Active convergence is occurring north of the city of Lae (not south, as previously thought) on the Gain Thrust. Wallace et al. (2014) found anti-clockwise rotation of blocks north of the Australian Plate in the d'Entrecasteaux Islands, causing extension of 10-40mm/yr. They also found that the GPS velocities estimated in the region do not require significant locking on the faults, suggesting that much of the relative motion occurs aseismically.

A field program in collaboration with the Indonesian geodetic agency Bandan Informasi Geospasial (BIG) and the Institut for Teknologi Bandung (ITB) aimed at identifying active faults and quantifying levels of seismic strain accumulation and seismic hazard in Java and eastern Indonesia began in 2013. This ongoing project to date has incorporated the historical database of GPS observations made across the region since 1993 with newly measured sites. The resulting dense velocity field spanning 22 years reveals details of crustal deformation resulting from all phases of the earthquake over the last cycle. This velocity field among other things has been used to constrain an elastic block model which for the first time quantifies the petitioning and method of transition of strain accumulation between the Java Trench / Timor Trough mega-thrust interface to the Flores back-arc thrust system.

The University of New South Wales (UNSW), working closely with the Japan Aerospace Exploration Agency (JAXA), mapped in near real-time the co-seismic deformation of the 2015 Nepal earthquake (Ge et al., 2015). UNSW delivered a suite of satellite remote sensing products, such as the differential InSAR interferogram, DInSAR ground displacement map, contour map of ground deformation, horizontal ground displacement based on the pixel offset tracking analysis, and damage map based on coherence difference analysis. This study shows that the mapping products can be released 6–8 hours after the post-event image is acquired using international ground receiving stations, with the direct mapping activities such as DInSAR and GIS processing typically taking only 3–4 hours. UNSW and collaborators also studied several other earthquakes (e.g. Liu et al., 2014e; Meng et al., 2013; Qiao et al., 2011; Zha et al., 2011).

4. POSITIONING AND APPLICATIONS

4.1 Alternatives and Backups to GNSS

The shortcomings of GNSS are well known, and include its poor availability in urban and indoor environments, its vulnerability to jamming and spoofing, and the fact that GNSS cannot provide information on attitude (or orientation) of a platform. In many countries there has been (and continues to be) considerable research and commercialisation activity focussed on alternatives and backups to GNSS, as well as the integration with GNSS of other navigation sensor technologies such as inertial navigation systems (INS), vision/imaging, laser-scanning systems and the Locata ranging technology, in the form of *multi-sensor* systems.

Most of the work undertaken by University of Melbourne (UM) researchers has focused on addressing the challenges for positioning in GNSS difficult environments (Grejner-Brzezinska & Kealy, 2013). This work has contributed to the joint working groups of the FIG Working Group 5 and IAG Sub-Commission 4.1.1 entitled “Ubiquitous Positioning”. In particular UM efforts have focused on collaborative or cooperative positioning techniques and its application to *Intelligent Transport Systems* (ITS) (e.g. Kealy et al., 2013a, 2012; Alam et al., 2013b; Efatmaneshnik et al., 2012a, 2012b, 2011a, 2011b, 2011c). Most notable was a special issue entitled “Ubiquitous Positioning and Navigation Systems” of the *Journal of Applied Geodesy* (Vol.7, No.4; http://www.degruyter.com/view/j/jag) edited by Kealy et al. (2013b).

In 2012 a major activity led by the UM was field experiments at the University of Nottingham (UK). These tests involved collaborations between the University of Nottingham, the University of New South Wales (UNSW), the Ohio State University (USA), the National Technical University Athens (Greece) and the Vienna University of Technology (Austria). The tests revolved around the concept of collaborative navigation, and partially indoor navigation (Kealy et al., 2013a; Hasnur Rabian et al., 2013a, 2013b, 2013c; Alam et al., 2013b). *Collaborative positioning* is an integrated positioning solution, which employs multiple location sensors with different accuracy on different platforms for sharing of their absolute and relative localizations. The employed platforms in the tests include a train on the roof of a UN building, mobile mapping vans, personal navigators from the Ohio State University and University of Nottingham (Alam et al., 2013a, 2013b; Hasnur Rabian et al., 2013a, 2013b).

Three Australian universities (RMIT, UM and UNSW) have established a dedicated indoor positioning laboratory through major funding attracted from the ARC and capital budget from both RMIT and UM. This laboratory is hosted in RMIT’s Design Hub Building in Melbourne and a large number of sensors systems have been procured. Several initial tests that involve smartphones and laptops as a mobile platform and UWB, USRP, RFID, WiFi, magnetometers and IMU as sensors were carried between 2013-2015 (Bai et al., 2014a, 2014b, 2014c).

Research on multi-sensor integration at UNSW during the reporting period has been carried out in areas of multi-sensor hardware systems, data fusion algorithms, new applications of multi-sensor systems, and quality control algorithms. Hardware research at UNSW has focused on such topics as: use of low-cost MEMS-IMU, the integration of additional sensors to the standard “GPS plus INS” multi-sensor configuration, incorporation of WiFi "fingerprinting" techniques, and the supplanting of investigations into the use of pseudolites by Locata technology.

Theoretical studies and algorithm development for GPS/INS sensor integration have been conducted at UNSW. This activity continued in the reporting period of this National Report. In addition to the standard GPS/INS studies, e.g. for agricultural applications (Li et al., 2012a; Cole et al., 2013), these have been expanded to more complex multi-sensor systems (e.g. Grejner-Brzezinska et al., 2011; Jiang et al., 2015; Li, 2014). These studies include the use of image matching techniques that provide additional measurements for multi-sensor systems (e.g. Feng et al., 2012; Li & Wang, 2014c; Li et al., 2011b; Xu et al., 2013), or used on their own (e.g. Li & Wang, 2012a, 2012b, 2012c, 2012d; Li et al., 2011c; Liu et al., 2011b, 2011c; Shi et al., 2011a, 2011b). Improvements to multi-sensor Kalman filter algorithm implementations were reported by Han & Wang (2012), Li (2013), Li & Wang (2013b, 2013c), Wang et al. (2012c, 2012d), and Zhou et al. (2013). A new technique for in-motion alignment of an INS was described in Li et al. (2013e, 2012b). Attention was also focused on attitude determination using INS sub-systems (e.g. Han & Wang, 2011a, 2011b; Li et al., 2011a, 2012a; Sun et al., 2013; Wu et al., 2014; Zhu et al., 2014, 2013).

Multi-sensor integration continues to provide an impetus for research into observation modelling, error analysis, Receiver Autonomous and Integrity Monitoring (RAIM) techniques, and the application of the theory of reliability for Fault Detection & Exclusion (FDE), as reported in Almagbile & Wang (2011), Almagbile et al. (2011), Alqurashi & Wang (2015), Han et al. (2015a), Jiang & Wang (2011), Knight et al., (2011), Li et al. (2012a, 2011b), Yang & Wang (2011), Yang et al. (2014a, 2013a, 2013b, 2013c, 2012), Wang & Knight (2012), and Wang et al. (2012b, 2013d).

UNSW researchers have conducted *Locata* research since the early 2000s (Rizos et al., 2011b). "Locata" is an Australian-developed range-based positioning system that has similarities to GNSS, except that the RF signal transmitters are located on the ground (Figure 4.1). If enough "LocataLite" (pseudo-satellite) transmitters are covering a service area, then positioning to an accuracy of a few centimetres is possible even without any GNSS measurements. Hence Locata can be used indoors. Alternatively, Locata can augment GNSS in difficult environments (where there are GNSS signal obstructions, as in the case of deep open-cut mines) by providing extra range measurements that can be combined with GNSS within a single multi-sensor configuration.

Figure 4.1: LocataLite transmitter at UNSW (left); White Sands Missile Base (right)

For more than four years integrated GNSS/Locata systems have been used in an open-cut mine in Australia (Rizos et al., 2013, 2011a), being the first commercial use of an alternative to GNSS technology in environments where GNSS on its own could not support precise machine guidance. The feasibility of using Locata for deformation monitoring applications was discussed in Choudhury et al. (2011). The most recent Locata results include first investigations into maritime positioning on Sydney Harbour using Locata by Yang et al. (2015b), Jiang et al. (2013a, 2013c). Flight tests using Locata were described in Jiang et al. (2013b). Indoor positioning and attitude determination experiments were described in Jiang et al. (2014), Rizos et al. (2014), and time transfer experiments were reported in Gauthier et al. (2013). FDE for integrated GNSS/Locata positioning was studied by Yang (2013).

An application that received attention was indoor pedestrian navigation using a combination of WiFi, INS and GNSS (Cheng et al., 2014; Yang et al., 2015a). The challenges of indoor positioning for the blind and vision impaired were discussed in Gallagher et al. (2014). WiFi-based positioning investigations were undertaken by Bai et al. (2014a, 2014b, 2014c), Chen et al. (2013), and Lui et al. (2011). Indoor positioning using geomagnetism was investigated by Li & Wang (2014b), and Li et al. (2013d, 2013g); and using RFID tags by Retscher et al. (2012), Peng et al. (2012), and Zhu et al. (2012, 2011).

4.2 Geodesy in Geospatial Mapping and Engineering

"Geodesy in Geospatial Mapping and Engineering" covers a number of areas, including *mobile mapping technologies and applications*, *geodetic applications in Mining Engineering*, *geodetic applications in Precision Agriculture* (Choy et al., 2015d; Lamb & Collier, 2015), *application of Artificial Intelligence in engineering geodesy*, *applications in civil and structural engineering* (Donets, 2011; Kuckartz, 2015; Kuckartz & Collier, 2013, 2011; Kuckartz et al., 2015, 2011), and *monitoring of landslides and system analysis*. Many of these topics are cross-disciplinary, involving researchers from the fields of geodesy, navigation, sensor development, image processing, computer science, and signal processing, as well as domain experts in mining engineering, geohazards and geomorphology, and machine guidance systems. Furthermore, contributions in some of the other IAG sub-commissions could also be included here, for example, Sub-Commission 4.2 "Alternatives and Backups to GNSS".

Application of geodesy to solving environmental problems was highlighted in publications by Awange (2012), Agola & Awange (2014), Awange & Kiema (2013), Goncalves et al. (2012a, 2012b), and Schloderer et al. (2011). Anwar et al. (2012) investigated the use of workshops in the teaching of surveying to civil engineering.

Australian scientists were involved in the development of a new-generation digital zenith camera system in Hungary that combines a digital star camera with a hexapod-platform for astronomical positioning and measurement of vertical deflections (Hirt et al., 2014b). The role of atmospheric anomalous refraction on geodetic-astronomical observations, particularly vertical deflection measurements was reviewed in Hirt (2012a) showing refraction to be the limiting factor in modern geodetic astronomy.

4.3 Remote Sensing and Modelling of the Atmosphere

Luo et al. (2013) examined the improvement of zenith dry tropospheric delay using regional surface meteorological data. The Australian tropopause was remotely sensed using GNSS in Khandu et al. (2011). Estimation of precipitable water vapour using GNSS data was the subject of research by Choy et al. (2015b, 2013a, 2011), Li et al. (2011d), Musa et al. (2011), Rohm et al. (2014d), Vyas et al. (2011), and Yuan et al. (2014). Tropospheric tomography was investigated by Manning et al. (2014). Rohm et al. (2014c, 2013) described a Kalman filtering technique for tropospheric tomography using GNSS signals.

RMIT University in collaboration with the Australian Bureau of Meteorology (BoM) investigated the GNSS *Radio Occultation* (RO) technique for climate monitoring and weather forecasting in the Australian and Antarctic regions (e.g. Choy et al., 2015c; Norman et al., 2014a; Pavelyey et al., 2015, 2013a, 2013b, 2012a, 2012b, 2011a, 2011b, 2011c; Wang et al., 2014b, 2011b; Zhang et al., 2011a). The research was supported by multi-year *Australian Space Research Project* funding (Zhang et al., 2014, 2013c, 2011c). They showed a beneficial impact on the accuracy of short to mid-term (3-5 days) weather forecasts by up to 8 hours in the Australian region (Le Marshall et al., 2012, 2011). In 2012 GNSS RO data was formally integrated into the BoM's operational Numerical Weather Prediction (NWP) system and is currently considered one of the top 5 of the 30+ data sources used by the BoM in reducing forecast error. This collaborative effort takes advantage of the Victorian ground-based infrastructure GPSnet (Manning et al., 2014; Rohm et al., 2014a, 2014b; Yuan et al., 2014). Numerical and analytic ray tracing techniques (Norman et al., 2014a, 2014b, 2013a, 2013b, 2012a, 2012b, 2012c, 2011) based on geometrical optics have been developed and used for investigating the impact of severe troposphere weather has on GNSS signal paths (Norman et al., 2015). Li et al. (2015b, 2014e), and Liu et al. (2014a) investigated the quantification of residual ionospheric errors in GNSS RO bending angles, and Liu et al. (2015a, 2014b) developed a new dynamic statistical optimisation algorithm for more accurate determination of the GNSS RO bending angles. The RMIT space weather equatorial plasma bubble research has led to predictive mathematical algorithms outperforming the other GNSS scintillation models (Carter et al., 2014a, 2014b, 2014c, 2013a, 2013c, 2011).

The effect of ionospheric errors on GPS RO-derived temperature was reported in Liu et al. (2014a, 2013a). Quality control of RO and ground-based ionospheric parameter estimation was studied by Wang & Ouyang (2011). The possibility of using ionospheric disturbances as precursors for earthquakes was reported by Carter et al. (2013b).

Single-frequency GPS receivers are an alternative to high-end dual-frequency receivers for applications such as GIS data collection, vehicle positioning for lane-level safety applications and UAV mapping. For a single-frequency receiver to achieve positioning accuracy at the decimetre-level, the challenge of estimating the ionosphere delay must be addressed. With around 200 CORS, *Australian Regional Ionospheric Corrections* (AusRIC) were generated with high temporal and spatial resolution of both the slant and vertical total electron content. Liu et al. (2015b) described a station-based *precise point positioning* (PPP) ionosphere estimation method which preserves the integer nature of the carrier phase ambiguity terms in the measurement model. Using test data from 25 CORS in Australia, the single-frequency PPP mode yielded RMS accuracy of better than 10cm and 25cm for the horizontal and vertical component respectively.

4.4 Applications of Satellite and Airborne Imaging Systems

GA has been developing a capability to use the Interferometric Synthetic Aperture Radar (InSAR) technique to map surface deformation. This high resolution geodetic imaging will enable modelling of crustal deformation induced by processes such as resource extraction that are at the regional scale. Regional crustal deformation models are an essential component of the GDA2020 datum in order to ensure that it meets the needs of all stakeholders in all parts of the country. GA has been preparing legacy radar datasets from the European ERS satellites and the Japanese PALSAR satellites for national InSAR analysis using the super-computing facilities at the National Computing Infrastructure

(NCI). To facilitate this analysis, open-source software is being developed in non-proprietary languages and a scalable framework that can take advantage of the substantial computer resources available at the NCI.

A new regional geodetic network that will enable InSAR and other geodetic techniques to be accurately tied together was installed by GA in the Surat Basin, Queensland in November 2014 (Garthwaite et al., 2015). The network consists of forty co-located GNSS survey marks and radar corner reflectors (Figure 4.2) spread across the basin. The radar corner reflectors have also been used to assist the international space agencies to calibrate and validate data from their orbiting radar satellites.

Garthwaite et al. (2013) reported on InSAR-based determination of land surface deformation in the Surat and Perth Basins. SAR has also been applied by Australian researchers to measure ground displacement in other regions (e.g. Hu et al., 2013; Ji et al., 2011; Ng et al., 2012b, 2012c, 2011a, 2011b, 2011c; Zhang et al., 2013b).

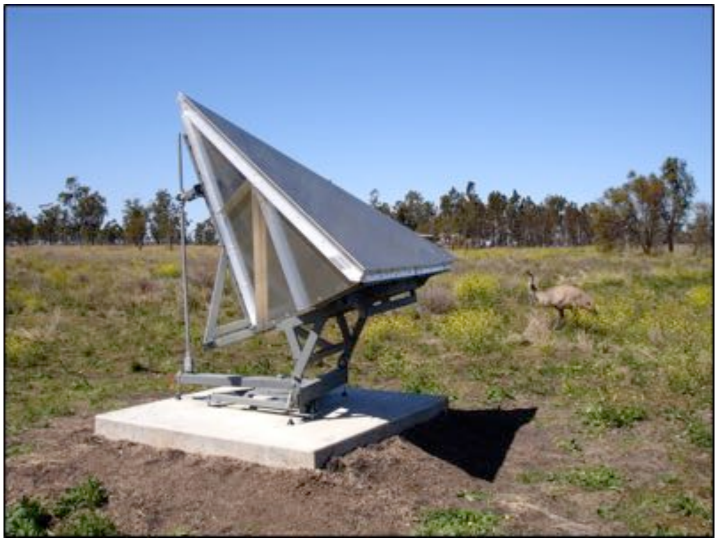


Figure 4.2: Geoscience Australia InSAR Corner-cube reflector established in the Surat Basin, Queensland, for deformation monitoring and satellite calibration and validation

UNSW researchers, working closely with the Victorian Department of Sustainability and Environment (DSE), have mapped land deformation in the Gippsland Basin using the InSAR technique (Ng et al., 2015). The InSAR result has been compared to the ground survey data in several areas, collected with GPS and total station surveys. The comparison of results suggested that the InSAR measurement and the ground survey measurement generally agree with each other.

UNSW also measured land subsidence characteristics of the Bandung Basin, Indonesia, with InSAR using ENVISAT ASAR and ALOS PALSAR data through a collaboration with the Institute of Technology Bandung (ITB), Indonesia (Ge et al., 2014, 2013a). GPS survey data collected between 2002 and 2010 were used to validate the ALOS PALSAR and ENVISAT ASAR measurements. Good correlations were observed between InSAR and GPS measurements. A comparison between the land subsidence measurements and the groundwater level information showed there were some correlations. These studies are based on a range of significant improvements of InSAR techniques by several researchers (e.g. Altin et al., 2012; Du et al., 2015; Hu et al., 2011; Liu et al., 2013c; Ng et al., 2012a; Yan et al., 2014b, 2012; Youtain et al., 2014; Zhang et al., 2013a, 2011c).

The feasibility of using SAR data to monitor pastures in Western Australia was investigated by Wang et al. (2014c, 2013b), and for vegetation and land cover monitoring by Chu & Ge (2012), Li et al. (2013j), and Wang et al. (2012d, 2012e). Li et al. (2013i) used SAR for waterbody detection, and Hu et al. (2012) for flood monitoring. Ge et al. (2013b) used an integration of SAR and Landsat TM data to measure coastal erosion. Beach erosion measurement using Lidar was reported by Middleton et al. (2013). Mitchell et al. (2011) derived terrain characteristics of Heard, McDonald and Macquarie Islands using multi-frequency InSAR data. Wang et al. (2013e) reported results on the use of SAR and optical satellite imagery for locating tropical cyclones.

High resolution digital elevation models (DEM) – an important source for detailed modelling of gravitational fields – were validated using accurate heights from the Australian National Gravity Data Base (Rexer & Hirt, 2014), showing that the 2nd-generation ASTER DEM has improved over Australia, while not quite reaching the quality of SRTM. DEM generation using SAR data was reported by Yu et al. (2014a, 2011a, 2011b). The use of Lidar data for DEM generation, and the extraction of building and road corridor information was investigated by several Australian researchers (e.g. Chang et al., 2014; Lim et al., 2013; Liu & Lim, 2014; Shirowzhan & Lim, 2012).

4.5 High-Precision GNSS Algorithms and Applications

A number of investigations have been conducted into the algorithms and applications of precise point positioning (PPP), e.g. Cheng et al. (2015), Choy (2011), Choy & Silcock (2011), Grinter & Roberts (2013, 2011), Huisman et al. (2012), Odijk et al. (2012b), Rizos et al. (2012), and Teunissen et al. (2012). An outlier detection method for PPP was described in Xu et al. (2011a), and Li et al. (2014b) reported on quality control challenges for reliable ambiguity resolution.

An implementation of combined GPS and BeiDou PPP was discussed in Li et al. (2013b). Hauschild et al. (2012) undertook a characterisation of the (Compass) BeiDou M-1 signals. First studies of the Indian Regional Navigation Satellite System (IRNSS) were reported in Nadarajah et al. (2015).

The L-band Experimental (LEX) signal, or the L6 signal, is a unique signal transmitted by the Japanese regional *Quasi-Zenith Satellite System* (QZSS). The objective of the LEX signal is to enhance the performance of *positioning, navigation and timing* of a GNSS such as GPS, as well as to augment next generation satellite navigation technology to meet the demand for high accuracy real-time positioning. In 2013, an agreement between the Australian Cooperative Research Centre for Spatial Information (CRC-SI) and JAXA has made LEX signal and correction messages available for experimentation in Australia. Research is currently ongoing with the aim to assess the capacity of the signal to deliver a high accuracy real-time positioning service anywhere in Australia. The research team has, as a "proof-of-concept", demonstrated the performance of PPP in Australia using the LEX signal. The use of LEX for PPP has been discussed, and results have been presented, in Choy et al. (2015a, 2013c), Harima et al. (2015a, 2015b, 2014a, 2014b), and Zhang et al. (2013d). The use of QZSS as an augmentation of GPS was described in Li & Rizos (2011a). Results of QZSS L1-SAIF augmented positioning were reported in Choudhury et al. (2015).

Investigations into how to improve convergence of PPP results using information derived from nearby GNSS CORS, in a technique known as "PPP-RTK", were reported by Teunissen & Khodabandeh (2015), and Zhang et al. (2012).

Multi-constellation GNSS studies included research into the many inter-system biases (e.g. Al-Shaery et al., 2013; El-Mowafy et al., 2012; Khodabandeh, 2014; Khodabandeh & Teunissen, 2014; Nadarajah et al., 2014b, 2013; Odijk & Teunissen, 2013; Odijk et al., 2012c), the degree of improvement of GNSS positioning services to users (Feng et al., 2013; Li et al., 2011a), and the challenges of ambiguity resolution (Li et al., 2013c). Combined GPS/GLONASS algorithms continued to be a popular topic of research (e.g. Al-Shaery et al., 2013, 2012, 2011b; Li & Wang, 2011b; Zhang et al., 2011d), as was GPS/BeiDou combined positioning (e.g. Odolinski et al., 2015b, 2014a, 2013b, 2013c, 2013d; Teunissen et al., 2013; Zhang et al., 2011b) and GPS/Galileo (Odijk et al., 2014b, 2014c, 2012a).

Research into ambiguity resolution robustness was undertaken by a number of researchers, including Li & Teunissen (2011), Li & Wang (2015, 2013a, 2012a), Li et al. (2015a, 2013a), Odijk & Teunissen (2011), Teunissen (2013), Teunissen & Khodabandeh (2014), Verhagen & Teunissen (2013a, 2013b, 2013c, 2012a, 2012b, 2011), and Wang & Li (2015). Single-channel multi-frequency GNSS integrity was investigated by Teunissen & de Bakker (2012a), and cycle slip reliability by Teunissen & de Bakker (2012b). The performance of multi-constellation GNSS for baseline determination, including single epoch solutions, was reported by Odijk et al. (2014c), Odolinski et al. (2015a, 2015b, 2014a, 2014b, 2013a, 2013b, 2013c, 2013d), and Teunissen et al. (2013). The theory of reliability control for GNSS ambiguity resolution was investigated by Wang & Verhagen (2015). A general hypothesis test model for ambiguity validation based on ambiguity residuals distribution was proposed by Wang & Feng (2013a). This research pointed out that the difference test is an approximation of the optimal integer aperture estimator, and the proposed test outperforms the popular ratio test in terms of success rate (Wang et al., 2014a). A new threshold function method for the difference test was described, which enables the calculation of the fixed failure rate threshold directly (Wang et. al, 2014a; Wang & Verhagen, 2015). Rubinov (2013) investigated stochastic modelling for real-time GNSS positioning. Part of this research activity has been conducted under the auspices of projects funded by the Cooperative Research Centre for Spatial Information.

Multi-constellation PPP was an area of intense investigation, e.g. Choudhury & Rizos (2015), Choy et al. (2013b), and Odijk et al. (2015, 2014a, 2014b, 2012a). An easy to implement weighting model for phase observations was reported in Luo et al. (2014). Integrated GNSS attitude and position determination was reported in Nadarajah & Teunissen (2013), and Nadarajah et al. (2014a, 2014c). Lu et al. (2013) in particular studied attitude determination using BeiDou measurements.

Precise GNSS positioning research also included the design of CORS network infrastructure and network-RTK algorithms (e.g. Al-Shaery et al., 2011a, 2011b; Charoenkalunyuta et al., 2012; Docherty & Nix, 2011; Haasdyk & Roberts, 2013; Odijk & Teunissen, 2011; Rizos & Satirapod, 2011; Zhang et al., 2011d). Feng et al. (2013) contributed to the design of new GNSS algorithms and a new computing mode to support distributed computing with the goal of unifying PPP and RTK solutions. The current GNSS commercial data processing systems for PPP and/or RTK services are based on centralised and sequential computing modes. The new computing mode will enable processing data streams of a large number of reference stations in real time, and address the "Big Data" problems in GNSS technologies and applications.

Advances in GNSS-RTK technology have paved the way for centimetre-resolution object tracking. One such application is the study of fine-scale flow dynamics at higher temporal resolution compared to existing drifters. This work was carried at Queensland University of Technology since 2012 (Suara, et al., 2014). The GNSS-based Lagrangian drifters allow for more realistic quantification of fluid motion and dispersion coefficients than Eulerian techniques because such drifters are analogs of particles with the relevant field and pollutant dispersion characteristics. The drifters have been designed to be small in size and are subject to lower wind drag, so as to better follow the subsurface flow that characterises dispersion in shallow waters. Single particle statistical analysis of field deployments in a shallow estuarine zone yielded estimates of dispersion coefficients comparable to those of dye tracer studies. In addition the drifters capture the tidal elevation in a tidal estuary, and the vertical position coordinates of the GPS-tracked drifters are useful for flood height monitoring.

4.6 GNSS-Reflectometry and Applications

The analysis of GNSS signals reflected from the ocean or land surface, and received by a device mounted on an airborne, satellite borne or on the ground, for a range of remote sensing applications has been researched during the last Reporting Period. This technique is known as *GNSS Reflectometry* (Yu et al., 2015a, 2015b).

The design of an appropriate GNSS receiver that can be installed on a small satellite platform such as a CubeSat has been a significant topic of R&D at UNSW (Glennon et al., 2015). This development was undertaken as part of a multi-year *Australian Space Research Project*.

A new approach to obtaining ellipsoidal heights of mean sea surface was demonstrated by Santamaría-Gómez et al. (2014) through the use of GPS reflection off ocean surfaces, with early results showing accuracy at the 0.1m level, although with evidence of elevation-dependent errors that promise improved results with ongoing developments. Use of airborne GNSS reflectometry for sea state, sea wind and sea surface height determination was reported by Alam et al. (2013) and Yu et al. (2014b, 2012a, 2012b, 2012c, 2012d, 2012e, 2011), for soil moisture by Yan et al. (2014a), and for forest change detection by Yu et al. (2013).

5. MATHEMATICAL GEODESY

Grafarend & Awange (2012) considered the problem of linear and non-linear models in geodesy, Awange et al. (2014a) looked at the application of the Groebner basis to geodesy, while the algebraic handling of maximum likelihood function in the case of Gaussian mixture distribution was treated in Awange et al. (2014b). The Pareto optimality problem was treated in Palancz et al. (2013) and Palancz & Awange (2012), while Palancz et al. (2011) solved the affine transformation problem.

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