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Preface

This National Report gives a brief review of the geodetic activities carried out in Australia over the period July 1995 to June 1999. The report summarises the activities of the Federal and State government survey organisations and the universities.

Information from the following organisations is presented in this report:

1) AUSLIG: Australian Surveying and Land Information Group, Canberra, ACT.
2) AGSO: Australian Geological Survey Organisation, ACT.
3) NTF: National Tidal Facility, Flinders University of South Australia, SA.
4) DNR: Department of Natural Resources, Survey Infrastructure Services, Coorparoo, Qld.
5) LIC: Department of Information Technology and Management, Land Information Centre, Bathurst, NSW.
6) OSG: Office of the Survey General, Melbourne, Vic.
7) DPIWE: Department of Primary Industry, Water Resources and Environment, Hobart, Tas.
8) DENR: Department of Environment and Land Management, Geodetic Services Section, Adelaide, SA.
9) DOLA: Department of land Administration, Mapping and Survey Division, Perth, WA.
10) ISD: Department of Lands, Housing and Local Government, Information Services Division, Casuarina, NT.
11) DELP: Department of Environment, Land and Planning, Land Information Office, Canberra, ACT.
12) UNSW: School of Geomatic Engineering, The University of New South Wales, Kensington, NSW.
13) UMelb: Department of Geomatics, The University of Melbourne, Parkville, Vic.
14) Curtin: School of Spatial Sciences, Curtin University of Technology, Perth, WA.
15) UNewcastle: Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Newcastle, NSW.
16) UniSA: School of Geoinformatics, Planning and Building, The University of South Australia, Adelaide, SA.
17) RMIT: Department of Land Information, Royal Melbourne Institute of Technology, Melbourne, Vic.
18) UniTas: School of Geography and Environmental Studies, The University of Tasmania, Hobart, Tas.
19) UniCanberra: Faculty of Information Science and Engineering, The University of Canberra, Canberra, ACT.
20) ANU: Research School of Earth Sciences, The Australian National University, Canberra, ACT.
21) QUT: Queensland Institute of Technology, Space Center for Satellite Navigation, Faculty of Engineering, Brisbane, Qld.

Geodesy in Australia

In Australia, research in Geodesy is undertaken through University institutions, principally funded by grants from the Australian Research Council (ARC). Activities in support of the National geodetic infrastructure are coordinated through the Federal and State government agencies by the Intergovernmental Committee on Surveying and Mapping (ICSM). This committee has established a working level Geodesy Group, chaired by AUSLIG, with representatives from Federal and State agencies. Representatives from the Geodesy Sub-Committee and the National Tidal Facility participate as observers. The Geodesy Group plans and implements approved national projects. Information about the national geodetic infrastructure can be obtained from AUSLIG's information service using the World Wide Web (http://www.auslig.gov.au/welcome.htm). Links to the University institutions can be obtained via http://www.isaust.org.au/links.htm .

1. Positioning

1.1 GDA94

The Geocentric Datum of Australia (GDA) is Australia's new GPS compatible datum, realised through the International Terrestrial Reference Frame (ITRF) 1992 positions (at an epoch of 1994.0) of the Australian Fiducial Network (AFN) of permanent GPS stations. The AFN stations, forming part of the larger Australian Regional GPS Network (ARGN), cover Australia and its offshore Territories. The AFN station coordinates were adopted by the Intergovernmental Committee on Surveying and Mapping (ICSM) in November 1994 and were published in the Commonwealth of Australia Government Gazette on 6 September 1995. These positions are the result of a global GPS solution by Morgan et al. (1996), who also provided ITRF92 positions for a further seventy eight (78) geodetic sites of the Australian National Network (ANN). The report by Morgan et al. (1996) describes the processing methodology used to establish the zero order GPS network for Australia, that of a multi-campaign data processing strategy as conventionally employed by the *GAMIT* software system.

A detailed technical manual has been produced for the GDA, containing background information, formulae, transformation parameters and worked examples. It was released on the World Wide Web in May 1998 (http://www.anzlic.org.au/icsm/gda/index.htm) and continues to be updated based on user feedback. Although the GDA94 re-adjustments were 3 dimensional, only the horizontal positions from the adjustment were adopted. The Australian Height Datum (AHD) remains unchanged.

The concepts behind the different Australian datums, and their map projections and transformations, was reviewed by Featherstone (1996b) and Featherstone and Langley (1997). A review of the transformation parameters existing in 1997 was conducted by Featherstone (1997a and 1997b) and transformation software developed based on the seven-parameter model (White, 1996; Barrington and Featherstone, 1995 and 1996; Featherstone and Barrington, 1996). As many users of spatial data rely upon hard-copy maps, a modified map projection was developed to preserve map grid coordinates (Featherstone and Reit, 1998a and 1998b; Featherstone et al., 1999). With the change of datum, the geoid must also be reconsidered in the reduction of terrestrial survey data (Featherstone, 1997d).

1.2 The Australian Regional GPS Network

The Australian Regional GPS Network (ARGN) consists of fifteen (15) permanent, geodetic quality GPS receivers, on geologically stable marks, in Australia and its offshore Territories - see Figure 1. It provides the fundamental framework for spatial data in Australia and provides data for Australia's contribution to global geodesy and the study of earth processes, such as crustal dynamics and sea level rise. Seven of these sites are accepted as IGS global sites (Casey, Cocos Is, Davis, Hobart, Macquarie Is, Yaragadee and Tidbinbilla) and data from the other sites are frequently used by IGS processing centres

TurboRogue SNR-8100 receivers operate at most sites and all sites use a Dorne Margolin choke ring antenna. Many of the ARGN remote sites have two GPS receivers in place. This backup strategy was instigated for the most remote sites (the Antarctic stations of Davis, Mawson and Casey, Macquarie and Cocos Islands) but is also being extended to other ARGN sites. Currently, the backup receiver is an Ashtech Z12, connected to the same antenna as the Rogue via an in-line amplifier and antenna splitter.

Each site collects data at 30 second epochs and transmits data, by a combination of modems and phone lines or Internet, to AUSLIG Canberra. At AUSLIG, data are validated, converted to Rinex format and made available on the World wide web (http://www.auslig.gov.au/geodesy/argn.htm). A time series analysis of some of these ARGN sites was done by Digney (1998).

In October 1998, two Ashtech Z18 GPS/Glonass receivers were deployed at Mt Stromlo and Yaragadee, to provide data for the International Glonass Experiment (IGEX) (Slater et al., 1998). A third receiver, operated by the National Measurement Laboratory in Sydney, also contributed to this project. Although the initial observation period for IGEX is complete, these receivers continue to acquire data that are available to IGS. From September 1998 to January 1999, two Ashtech GG24 GPS/Glonass receivers, owned by a University consortium, also contributed data from sites in Hobart and Perth.

1.3 State/Territory GPS Networks

Between July 1995 and March 1997, the combined State and Territory geodetic networks were re-adjusted in terms of the new geocentric datum, holding fixed the gazetted positions of the AFN and the Australian National Network. The final data set used for the adjustment consisted of: (a) the AFN and ANN GDA94 fixed positions; (b) all terrestrial observations (directions, distances etc) that were used in the previous AGD66 and AGD84 national adjustments; (c) the additional terrestrial measurements observed since 1984 and; (d) the State and Territory GPS networks, which typically have a spacing of about 100 km and an accuracy of the order of 1 part per million.

This adjustment of almost 8,000 stations was contracted to Dr J.S. Allman, who had previously carried out the AGD84 national adjustment (Allman & Veenstra, 1984). The data were divided into twelve blocks and were adjusted using the Section method (Pinch & Peterson, 1974) in the *NEWGAN* geodetic adjustment software. The results are a considerable improvement over the previous AGD84 adjustment, due mainly to the inclusion of the large number of high quality GPS observations.

Directions	Distances	Azimuths	GPS Baselines	GPS Multi-baselines	GPS Multi-station	Total Observations
46,412	13,698	1,167	4,044	5,839	230	71,390

Table 1: Observations in the GDA94 readjustment of the Australian geodetic networks

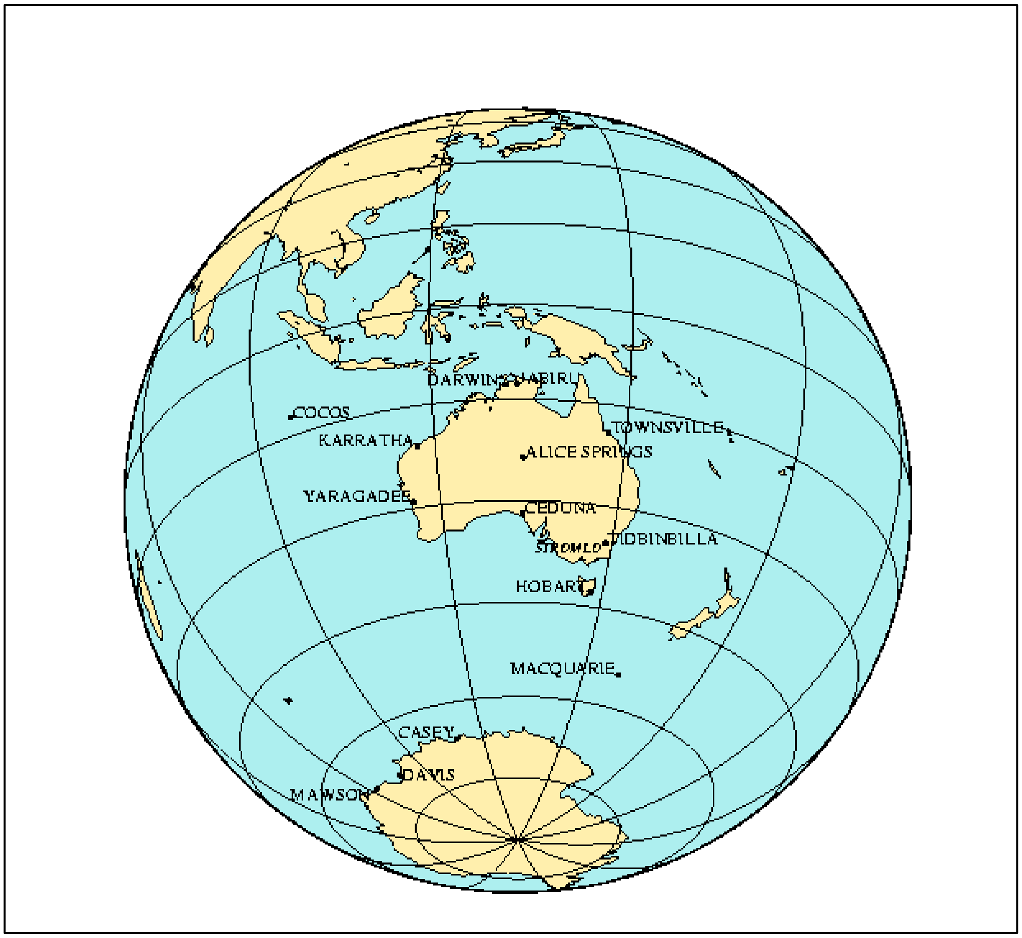


Figure 1: The Australian Regional GPS Network as at January 1999.

As a continuation of the GDA implementation, the results from the GDA adjustment have been used by the State and Territory authorities to constrain their supplementary survey control networks.

Western Australia was not included in the combined State and Territory re-adjustment, as their GPS networks were not completed at the time of the GDA adjustment. However, Western Australia have since completed their STATEFIX GPS network, which was also constrained to the GDA94 AFN and ANN positions, and they are now re-adjusting their subsidiary networks to this framework (Stewart et al., 1997 and 1998b). The final results indicate that the network is accurate (relative to the ANN) to better than 2 cm in the horizontal component (95% confidence), and 6 cm in the vertical component (95% confidence). The processing also allowed an evaluation of antenna phase-centre models (Stewart, 1998b). The STATEFIX network has also been considered adequate as a framework for GPS height determination (Stewart, 1998a) and has indicated the possibility of distortions in the Australian Height Datum (AHD) in Western Australia (Featherstone and Stewart, 1998). The Tasmanian GPS and height network was investigated by King (1997), using GPS, levelling and geoid data.

1.4 Levelling Networks

The Australian Height Datum (AHD) remains unchanged since its introduction in 1971. It is the result of a simultaneous adjustment of 97,230 kilometres of two-way levelling. In this adjustment, mean sea level for the period 1966-1968 was fixed at zero on the Australian Height Datum at thirty (30) tide gauge sites around the Australian coast. During 1995-1998, a number of repeated precise levelling surveys were carried out by the State government agencies to connect the NTF high-precision tide gauges and their associated coastal benchmark clusters.

1.5 The National Geoid

In November 1998, the latest in a series of national gravimetric geoid models was released by AUSLIG. Known as AUSGeoid98, it is the result of an Australian Research Council grant that included Curtin University, University of NSW and the University of South Australia. It was computed using the FFT technique with a modified integration kernel and a 1° cap size (Johnston and Featherstone, 1998) and used the latest available data including:

- The complete expansion of the EGM96 Global Geopotential Model, which was produced by the US National Imagery and Mapping Agency (NIMA) and NASA's Goddard Space Flight Centre (Lemoine et al., 1997).
- The 1996 Australian Gravity database from the Australian Geological Survey Organisation (AGSO).
- AUSLIG / AGSO / National Heritage Commission GEODATA 9" Digital Elevation Model (DEM) (Carrol and Morse, 1996).
- Satellite altimeter-derived free air gravity anomalies offshore, which were produced by Scripps Institute for Oceanography using a combination of several satellite altimeter missions. (Sandwell et al., 1995)

AUSGeoid98 consists of a 2' by 2' grid (approximately 3.6 km) of geoid-ellipsoid separations, and deflections of the vertical, in terms of the GRS80 ellipsoid. The GRS80 ellipsoid is also used for the new Geocentric Datum of Australia. The AUSGeoid98 values may be computed interactively or from data files using interpolation software (called *Winter*). The interpolation software may be downloaded from the World Wide Web (http://www.auslig.gov.au/geodesy /geoid.htm).

To validate AUSGeoid98, an absolute comparison was carried out at 906 sites, each site had both gravimetric and geometric (GPS minus AHD) geoid-ellipsoid separations. These points were chosen because they had third-order or better optically levelled AHD heights, as well as ellipsoidal heights derived from a three-dimensional least-squares adjustment of all geodetic quality GPS data spanning Australia. This comparison validated the chosen cap size and showed that AUSGeoid98 was an improvement over its predecessor (AUSGeoid93), with a standard deviation of 0.364 m.

1.6 Transformation from AGD to GDA94

Australia’s new datum (GDA) produces positions about 200 m away from its predecessor (the Australian Geodetic Datum – AGD). To assist with the implementation of GDA, transformation parameters have been computed between the two datums.

Initially, Australia-wide parameters were computed to transform from both the 1966 and the 1984 versions of AGD (AGD66 & AGD84) to GDA94, using the abridged Molodensky formulae. This was done using sites with GPS-determined coordinates from the combined State and Territory adjustment, which also had AGD66 or AGD84 coordinates. One hundred and sixty one (161) points were available for the computation of the AGD66 parameters and 327 points for the AGD84 parameters. The resulting parameters supersede those previously published by the United

States National Mapping and Imagery Agency (DMA, 1987) and are applicable for low accuracy applications. For higher accuracy applications, of the order of a metre, a national set of similarity transformation parameters was computed using the same 327 points mentioned above, but these are only available from AGD84.

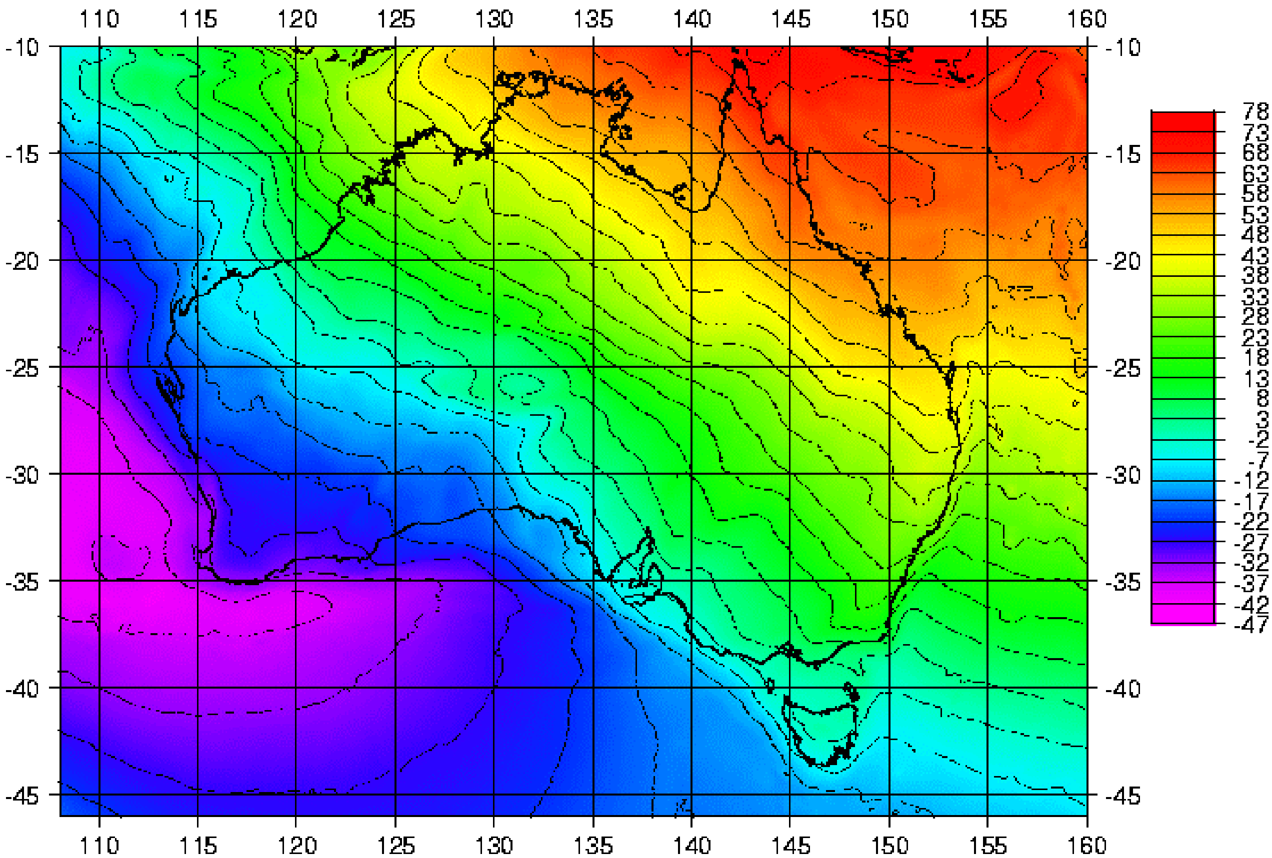


Figure 2: The Australian national geoid – AUSGeoid98

To satisfy the most accurate applications, ICSM has agreed to produce an accurate national grid of coordinate shift values, calculated from many thousands of common points using the collocation technique. This will not only transform coordinates from AGD to GDA94, but will also remove much of the distortion in the old AGD coordinates (Collier, 1997). In areas of dense data, an accuracy of better than 10 cm is anticipated. Individual grids have been or are being computed by State and Territory authorities. On completion in early 2000, they will be amalgamated into a single national grid that will be available on the World Wide Web. Work on implementation of GDA has been documented in Collier et al. (1996, 1997a, 1997b, 1997c, 1997d, 1998a, 1998b), Collier and Bowden (1999), Collier (1998a, 1998b) and Mitchell and Collier (1998a, 1998b).

1.7 Local Geodetic Connections

Accurate 3-dimensional connections between nearby geodetic facilities (e.g., GPS, SLR, and VLBI sites) are essential to monitor possible local movement and to provide accurate linkages in the development of the International Terrestrial Reference Frame.

A summary and assessment of 3-dimensional local connections at Australian fundamental geodetic facilities was compiled in 1997 (Stolz et al., 1997) and in 1998 a campaign was commenced to re-measure the connections using a Leica TC2003 Total station and a Topcon DL101C digital level.

The ITRF positions of the IGS GPS and IGEX monuments and the centre of the axes of rotation of the Satellite Laser Ranger (SLR) telescope at Yaragadee were re-measured in September 1998. A redundant local network, based on a GPS-derived ITRF position, was observed and all observations were rigorously reduced and then adjusted using *Geolab*. The centre of the axes of rotation of the SLR were measured by multiple observations, from two stations to several targets on the horizontal and vertical axes of the telescope. Each axis of the telescope was incrementally rotated. The adjusted observations to the axes, with their full variance matrix were used to rigorously determine the 3-dimensional centre of the horizontal and vertical axes.

In November 1998, the Orroral SLR observatory was permanently closed, and replaced by a new facility at Mt Stromlo, near Canberra. Just prior to the closure of Orroral, the relationship of all monuments and geodetic equipment was rigorously determined by observing a high precision local network. Once again, the observations were rigorously reduced and then adjusted using *Geolab*. The results indicate good agreement with the previous survey, carried out in 1989.

As part of the establishment of the new SLR facility at Mt Stromlo, a high precision local survey of all monuments and equipment was undertaken. A permanent GPS antenna is now in place and a follow-up survey of all monuments and facilities at this facility is planned in June 1999.

When completed, the results from all of these surveys will be documented in a final report that will be available from AUSLIG's World Wide Web site.

1.8 The Australian Antarctic Geodetic Network

The Australian Antarctic Geodetic Network consists of about 360 permanent marks on solid rock in the Australian Antarctic Territory. The bulk of the network is in the Southern Prince Charles Mountains, south of Mawson, but it also extends to the west into Enderby Land and to the east to Davis. The bulk of the observations in this network are terrestrial angles and distances observed over the last forty years, but in recent years it has been strengthened by the addition of geodetic quality GPS. Wherever possible, these new GPS observations have been on new, stable GPS antenna ground marks, so that the results not only strengthen the geodetic network, but also provide a base observation for possible future epoch surveys for geodynamic movement. The strengthened network has been readjusted and constrained to the ITRF96 coordinates (at epoch 1998.0) using AUSLIG's permanent GPS base stations at Mawson and Davis. These ITRF96 results are available from AUSLIG's World Wide Web site (http://www.auslig.gov.au /geodesy/ antarc/antmarks.htm).

1.9 The National Geodetic Database

The national archive of geodetic coordinates continues to be held in AUSLIG's National Geodetic Data Base (NGDB). This archive of almost 25,000 stations for Australia and its offshore Territories (including Antarctica) has been updated to include the new GDA coordinates, as well as the previous AGD coordinates. Original, hardcopy station summaries for about 5,000 geodetic stations, established by the Commonwealth Government over the last forty years, have been scanned so they can be archived in digital form. These images are to be made available on AUSLIG's World Wide Web.

2. Advanced Space Technology

2.1 Satellite Altimetry

Satellite altimetry data have been used in the solution of the geodetic boundary value problem (Kirby, 1997; Kirby and Hipkin, 1996), merged with marine gravity anomalies offshore Australia as part of the computation of the AUSGEOID98 gravimetric geoid model (Kirby and Forsberg, 1998; Zhang, 1998). Satellite altimeter measurements over land have been used to validate digital elevation models (Berry et al., 1998a and 1998b). Satellite altimeter measurements have been used over the North Sea to provide control on a gravimetric geoid model in that region (Stewart et al., 1998c).

2.2 GLONASS

Since 1994, the commercial availability of combined GPS/GLONASS receivers has led to an increase in GLONASS research. In Australia, theoretical work has been led by Curtin University where the first independent GPS/GLONASS software processing package has been developed (Forward, 1998; Stewart and Tsakiri, 1998). A number of GLONASS applications have been tested, including marine positioning (Kealy et al., 1998), real time kinematic positioning in the urban canyon (Stewart and Tsakiri, 1997), urban fleet monitoring (Tsakiri et al., 1998; Pantall et al., 1999) and legal traceability (Stewart et al., 1998). Theoretical work has covered GLONASS ambiguity resolution and mathematical modelling (Wang, 1998b).

2.3 GPS

Applications of kinematic GPS positioning over very long baselines (base-mobile receiver separations of the order of 1000 kms) have been investigated by several investigators (Dickson, 1996; Colombo and Rizos, 1996; Feng and Han, 1996; Feng et al., 1996). The status and trends in high precision kinematic GPS positioning have been described in Han and Rizos (1997d) and Rizos and Han (1998a, 1998b, 1998c). A new technique for GPS attitude determination was described in Han et al. (1997). Other kinematic GPS investigations for route mapping were produced by Seager (1995a, 1995b, 1998), Seager and Judd (1995) and Leahy and Judd (1996).

The use of GPS measurements to determine the ionospheric Total Electron Content (TEC) and to model regional ionospheric TEC activity were given in Lin (1997, 1998), Lin and Rizos (1996, 1997a, 1997b), and Lin et al. (1996, 1998). Further studies are underway in the use of wavelets to detect ionospheric scintillation.

The use of GPS for automatic, continuous deformation monitoring has been dealt with in Rizos (1996) and Rizos et al. (1996). Algorithms for data processing using a combination of an outer "fiducial", dual-frequency GPS network, and an inner, single-frequency GPS network are discussed in Han and Rizos (1996g), Rizos et al. (1997c), and Roberts and Rizos (1998). Tests using some permanent GPS stations in Japan and Taiwan are described in Rizos et al. (1998a). A permanent test network is being established in Singapore in a joint UNSW-NTU (Nanyang Technological University) project commenced in 1999.

2.4 Satellite Laser Ranging

Three sites have been active in satellite laser ranging:

(1) Orroral near Canberra. It ceased operation on 1 November 1998 after 25 years of distinguished service. The site was vacated on 1 December 1998, and the 1.5 metre telescope was removed from the site on 11 May 1999 for transportation to White Sands, New Mexico for use in a Laser Lightcraft project of the NASA Marshall Space Flight Center. A high-precision local

survey was performed by AUSLIG early in 1999, supplemented by GPS observations, to verify the adopted relationships between the SLR, GPS and DORIS reference points, the internal and external calibration targets, and the local monuments.

(2) Mount Stromlo, nearer Canberra. A contract for its construction and operation was let by AUSLIG to Electro Optic Systems (EOS) on 3 November 1997, and it came into full operation on 29 October 1998. From 9 July to 28 October, an intensive campaign of observing was conducted at Stromlo and Orroral to ensure the best possible transfer of coordinates from the old to the new site. The campaign was supplemented by high-quality continuous GPS observations. A high-precision local survey was performed in March 1998 to establish the relationships between SLR, GPS and DORIS reference points, the internal calibration target, the four external ground targets, and the local monuments. The survey will be repeated by AUSLIG in June 1999. This new laser station is producing excellent results.

(3) Yarragadee, Western Australia. This NASA MOBLAS 5 station continued its excellent performance unabated throughout the reporting period. A high-precision local survey was performed in August 1998 to verify the relationships between SLR, GPS and DORIS reference points, the external ground targets, and the local monuments. Under a formal agreement with NASA, AUSLIG assumed responsibility for its operational funding from 1 March 1998 until 30 June 2002. Serious discussions are under way with several parties, to try to secure continuation of SLR from Western Australia after that date.

In addition, a Portable Satellite Laser Ranging System (PSLR), developed jointly by the University of Latvia, Riga and SLR Research Ltd. of Western Australia, was installed and tested at the Yarragadee site in 1995-6. It was removed to Riga in 1997 for further development.

A SLR system has been designed for operation in Antarctica, and a project plan was developed. To date, the proposal is not funded.

Laser ranging from the Australian stations contributed to the following programs:

(a) IERS and ITRF ongoing programs, through LAGEOS 1 & 2 and ETALON 1 & 2;
(b) TOPEX/POSEIDON ocean altimetry, including Bass Strait calibration passes, supplemented from 1999 by GFO-1;
(c) Ocean and Glacier altimetry, through ERS 1 & 2;
(d) Gravity field, through STARLETTE, STELLA and GFZ-1, and a finite GEOS-3 reactivation campaign;
(e) Reference frame comparisons, through GPS 35 & 36 and various GLONASS satellites;
(f) IGEX'98, through a number of GLONASS satellites nominated by the newly-formed International Laser Ranging Service (ILRS);
(g) Satellite performance experiments by campaigns to METEOR 2-21 ("Fizeau"), METEOR-3 ("Prare"), and ZEYA, and by routine tracking of AJISAI and of WESTPAC which is owned by EOS, Australia and was launched on 10 July 1998;
(h) Remote sensing programs, through ADEOS/RIS and RESURS-01-3;
(i) Special-purpose campaigns, including OPTUS B1 & B3 (time transfer – proof of concept was successfully demonstrated (Luck and Woodger, 1994); DIADEM-1C & 1D (not successful in the southern hemisphere), TiPS (Tether Physics and Survivability mission), MSTI-2 (US Navy) and SUNSAT.

There was no productive lunar laser ranging in the reporting period.

Careful attention is paid to system calibration techniques and the elimination of site-dependent systematic errors. Ground-target ranging was routinely performed at each station several times per day throughout the period. An algorithm to correct for the intensity of received signals was implemented at Orroral in 1996 (Luck et al, 1997), and is a feature of the CSPAD detector at Mt Stromlo. Concomitant care is taken in the ground surveys referred to above, which are designed to satisfy the criteria of the IGN/ITRF, DOMES, and the CSTG Geodetic and Geophysical Sites Subcommission (GGSS), to establish the stations as fundamental multi-technique global sites, and to connect to surrounding geodetic networks.

In particular, the following activities were performed in the context of perceived discrepancies between SLR, VLBI, GPS and classical survey baseline vectors in this region (Stolz et al., 1997) - ground surveys at Orroral and Mt Stromlo, common SLR observing periods at both sites, continuous GPS campaigns at both sites and at Tidbinbilla, and an imminent re-observation of the local connections at Tidbinbilla, supplemented by several GPS campaigns earlier in the period, and optical levelling at Mt Stromlo and re-levelling over older suspect lines.

The Australian stations conform to ILRS tracking priorities, performance criteria and data standards, but retain the right to vary them to satisfy local requirements. Tracking data in the form of normal points are routinely transmitted within 24 hours of observation to the Data Centres at CDDIS and EDC, from where they are immediately accessible to Analysis Centres for (*inter alia*) rapid earth orientation and orbit estimation, and where they are archived. Full-rate data are archived in perpetuity on-site. A complete archive of all of the Orroral normal-point and full-rate data is retained on CD by AUSLIG, with a copy held by the Matera station in Italy. Full-rate data is made available upon request for special investigations, which have included such projects as spin rates of AJISAI and LAGEOS, retroreflector characteristics of AJISAI, WESTPAC, RESURS-01-3 and FIZEAU, satellite centre-of-mass determinations, and a EUROLAS study of optimum data filtering and characterization procedures.

AUSLIG played a key role in the establishment of the ILRS arising from the CSTG SLR/LLR Subcommission. It currently provides a member of the ILRS Governing Board, the Coordinator of its Data Formats and Procedures Working Group, and a member of its Analysis Working Group.

AUSLIG provides a member of the Executive Committee of the Western Pacific Laser Tracking Network (WPLTN) which coordinates the activities of its member stations and promotes their development and conformance to standards. EOS continues to provide the Chairman. Considerable support has been given by AUSLIG to the Changchun SLR station in north-east China, resulting in dramatic improvement in its productivity and quality, which is flowing on to the other stations in China. AUSLIG, in collaboration with EOS, commenced an effort to repair and reactivate the SALRO system in Riyadh, Saudi Arabia, in which compatible ex-Orroral parts were made available. EOS entered negotiations with the Indian Space Research Institute to establish a modern SLR capability in India. WPLTN Executive Committee meetings were held in December 1995 (Moscow), June 1996 (Moscow), November 1996 (Shanghai) and September 1998 (Deggendorf). WPLTN Plenary meetings were held in conjunction with the International Laser Ranging Workshops in Shanghai and Deggendorf.

AUSLIG provides a member of the Management Board of the Asia-Pacific Space Geodynamics (APSG) project, and a Co-Convenor of its SLR Measurement Technique Panel. For more information, see http://center.shao.ac.cn/APSG/.

AUSLIG and WPLTN coordinated the SLR contribution to two major Space Geodesy campaigns for the Permanent Committee on GIS Infrastructure for Asia and the Pacific, in October 1997, called APRGP97 (Luton et al., 1998) and November 1998 (APRPG98).

2.5 Space Analysis Centre

The AUSLIG Space Geodesy Analysis Centre undertakes GPS, SLR, DORIS and GLONASS data processing and analysis, and the combination of these techniques. In addition, development of the combination solutions have further progressed to include VLBI results (SINEX files), which are produced by VLBI Analysis Centres.

GPS data processing activity focuses on AUSLIG's obligations as an IGS RNAAC, the Regional Geodetic Networks Working Group of the Permanent Committee for GIS Infrastructure for Asia and the Pacific (PCGIAP). The RNAAC computes daily station coordinates for the ARGN stations (including Antarctic sites) using IGS products for GPS satellite ephemerides and Earth Orientation Parameters (EOP). These are submitted as weekly solutions to the IGS for combination by the IGS GNAACs. Typical time series of the weekly solutions for the ARGN computed by AUSLIG are shown in Manning et al. (1998).

The Space Geodesy Analysis Centre also determine their own orbits and EOP products together with station position estimates. The satellite trajectories and estimated EOPs compare at the accepted standards with the IGS combined products. The computation standards, processing techniques, results and comparisons are documented in Govind et al. (1996), AUSLIG (1998), Govind et al. (1998) and Dawson et al. (1998). A fundamental regional geodetic objective is the densification of the ITRF and its relationship with local and national geodetic datums (AUSLIG, 1998). Manning and Govind (1997) presented the concept of a regional geodetic network and an initial multi-technique observation campaign. The results of the APRGP97 campaign are given in AUSLIG (1998), Govind et al. (1998) and Dawson et al. (1998). A high precision GPS geodetic network comprising eight stations (observed in August 1997, November 1997 and May 1998) was computed for the General Department of Land Administration, Socialist Republic of Vietnam. The results of the subsequent (and significantly larger) APRGP98 campaign observed during November 1998 are being prepared for presentation at the meeting of Working Group 1 to be held 12 – 13th July 1999, Ho Chi Minh City, Vietnam and in Govind at al. (1999b).

The computation and analysis of GPS observations at the ABSLMA tide gauge sites for absolute sea level monitoring is undertaken on an opportunity basis, that is, when a coordinated, long occupation observation campaign is undertaken. A one week occupation at ABSLMA tide gauge benchmarks was undertaken during May 1995. The results and analysis are given in Govind et al. (1996).

SLR computations for POD, SSC and EOP with Lageos-1, Lageos-2, Stella and Starlette have been routinely undertaken over the last four years. Combined solutions for these four geodetic satellites have also been produced (AUSLIG, 1998 and Govind et al. 1998). Although there exists a significant interest in using Etalon data for determining geodetic parameters, only a limited number of solutions have been produced, mainly due to the very low volume of observed data since Etalon tracking is generally at low priority. As an Associate Analysis Centre of the International Laser Ranging Service (ILRS), Lageos-1 and Lageos-2 solutions for SSC and EOP are submitted to the IERS, currently as a participant in the Continuous Time Series Project (Boucher, 1999). As part of the routine data processing, SLR station performance is monitored by estimating the range and time biases. Some results of the performances of SLR stations in the Asia Pacific region are shown in Govind et al. (1998). In addition, some data processing of SLR observations to the two GPS satellites equipped with retro-reflectors was performed and simple comparisons were made to the AUSLIG determined orbit trajectories using microwave data. An optimisation study for determining high precision heights for the Keystone SLR Network of the Communications Research Laboratory in Japan was undertaken and reported in Govind (1997).

DORIS data for the Spot-2 satellite is processed for determining the satellite orbit and geodetic parameters. In particular, intense processing for the APRGP97 and then again for the APRGP98 campaigns have been completed. For both of these campaigns, one-month solutions using the Spot-2 data were produced. The results for the AUSLIG-determined station coordinates and EOP for the APRGP97 are given in AUSLIG (1998) and Govind et al. (1998) as comparisons to both the ITRF96 SSC and as comparisons to the GPS solutions at the co-located sites. It is proposed to increase the number of DORIS beacons in Australia with at least one additional beacon.

As a participant in the IGEX-98 campaign, SLR GLONASS orbits have been computed and compared with the microwave determined orbits of the other IGEX Analysis Centres. The results are given in Govind et al. (1999c,d). The processing of GLONASS microwave data has only just commenced.

A major activity of the Space Geodesy Analysis Centre is the combination of high precision space geodetic techniques. The AUSLIG combination of GPS, SLR and DORIS for the APRGP97 campaign is given in AUSLIG (1998) and Govind et al. (1998). The results of subsequent combination solutions of GPS and SLR are given in Govind et al. (1999a). The capability to combine VLBI results of other analysis centres with AUSLIG GPS, SLR and DORIS computations has been developed - see Govind et al. (1999b). Research and development activity towards providing the optimum solutions from co-location and combination of high precision space geodetic techniques continues. Solutions for the variation in the position of the geocentre are determined by estimating a set of transformation parameters with respect to the ITRF.

Software has been developed to determine the reference points (intersection of axis) of the SLR and VLBI telescopes and to relate them to the ground monuments. Past and recently observed survey data at Orroral, Tidbinbilla, Mount Stromlo and Mount Pleasant is being computed to determine and continually monitor the telescope reference points.

2.6 Time

Time was accepted as an Australian legal unit of measurement on 30 June 1997 by an Amendment to the National Measurement Act 1960. The CSIRO National Measurement Laboratory (NML) is charged “to maintain, or cause to be maintained, Coordinated Universal Time as determined by the International Bureau of Weights and Measures (BIPM)”. The National physical standard, known as UTC(AUS), was in fact kept by a HP5071A Cesium Standard at AUSLIG’s Orroral Observatory until 1 September 1998, when a similar standard at NML took over. By agreement with the National Standards Commission (NSC), UTC(AUS) is kept within 1 microsecond of UTC(BIPM) at all times, by quasi-continuous GPS Common-View time transfer.

Along with the closure of Orroral, the function of maintaining the National Time Scale Service was transferred to NML on 1 July 1998. Prior to this date, Orroral had been responsible for coordinating the contributions of Australian clocks to the computation of International Atomic Time (TAI) and its derivative UTC, for computing the national free-running time-scale TA(AUS) based on some 45 atomic clocks around the country and New Zealand. The clocks were intercompared daily by terrestrial TV, OPTUS TV (from geostationary communications satellite) and GPS Common-View, and results published in Bulletins summarizing these comparisons and reporting on the HF radio time signal service transmissions on VNG at 2.5, 5.0, 8.636, 12.984 and 16.0 MHz.

AUSLIG still provides the Chairman of the NSC National Time Committee. It has agreed to close the VNG time service by the end of 2003. It has prescribed methodologies for determining frequency and time using GPS as a transfer medium in manners that are legally traceable to the national standards, since GPS is not permissible as an Australian national standard. It is attempting to encourage the various States and Territories to amend their Standard Time Acts to refer to UTC(AUS) in place of the current definitions arising from around 1890 and involving mean (solar) time at specified meridians east of Greenwich. It is also most concerned to develop a low cost, low precision (in the order of 0.1 seconds), commonly accessible and legally traceable time signal service to replace VNG.

For many years, comparisons of the wholly southern-hemisphere TA(AUS) against the predominantly northern-hemisphere TAI had shown an annual cycle with an amplitude about 200 nanoseconds. This has disappeared since the new commercial HP5071A cesium standards have come to dominate the time-scales.

Despite much work and equipment acquisition, the planned Pacific Rim International Time Transfer Experiment (PRITTE) did not come to fruition. However, as a spin-off, a Two-Way Satellite Time and Frequency Transfer (TWSTFT) link has been established between NML and Communications Research Laboratory (CRL), Japan yielding sub-nanosecond precision and stability in its twice-weekly measurement sessions. NML entered into negotiations to expand this link to include China, Korea, Taiwan and other Japanese laboratories; and to activate the original link between NML and the US National Institute of Standards and Technology (NIST) in Boulder, Colorado, USA.

Further research into time transfer methods has concentrated on applications of relatively low-cost GPS engines operating in multi-channel mode (Fisk et al., 1997a) and adapting them to common-view mode (Armstrong et al., 1999). Time transfers are showing 5 nanosecond levels of precision over baseline lengths maximized at Sydney-Wellington. Receiver calibration and accurate geodetic coordinates are now serious issues. Australians participate in the IGS/BIPM Pilot Project to study GPS Carrier Phase Methods in Time Transfer by operating some GPS geodetic receivers with traceable external frequency inputs. AUSLIG also participates in data analyses and in the time transfer aspects of IGEX'98 through a 3S Navigation R-100/30T GPS/GLONASS receiver at NML. A watching brief is being held on the opportunities afforded by the Atomic Clock Ensemble in Space (ACES) mission, planned for the International Space Station to be launced in 2002-3. Time comparisons between the on-board super-clocks and similar ground clocks will be needed to 30 ps, and the position and velocity of the flying clocks to 0.5m and 0.6mm/sec respectively. Laser ranging, TWSTFT-like microwave and GPS methods for both the time transfers and the orbital determinations will be included.

Research in frequency standards continues at NML, where laser-cooling of a Ytterbium ion-trap standards is yielding parts in 10^{15} stability (Fisk et al., 1997b), and at the Frequency Center of the Physics Department, University of Western Australia whose work is based on ultra-cold sapphire microwave cavities.

3. Determination of the Gravity Field

3.1 Geoid Computations

Researchers from Curtin University, the University of New South Wales and the University of South Australia have investigated the theoretical and practical basis for the determination of a new Australian gravimetric geoid (Featherstone et al., 1996d, 1997a, 1997b, 1997d, 1997e; Zhang et al., 1996a and 1998). The methods, data and computer software have been used by AUSLIG, who released the results to the Australian public as AUSGeoid98 (Johnston and Featherstone 1998a and 1998b). This model and associated deflections of the vertical can be downloaded free of charge from AUSLIG's web page at http://www.auslig.gov.au/geodesy/geoid.htm.

AUSGeoid98 uses the complete expansion of the EGM96 global geopotential model, the 1996 release of AGSO's gravity database, satellite-altimeter-derived gravity anomalies and the national 9" digital elevation model. The gravity data have been validated and processed according to geodetic requirements (Featherstone, 1995; Featherstone et al., 1997a, Featherstone and Dentith, 1997). These data were gridded using tensioned splines (Kirby et al., 1997; Zhang, 1997). The EGM96 global geopotential model was chosen since it provided a slightly better fit to the Australian gravity field (Kirby et al., 1998; Zhang and Featherstone, 1995). Gravimetric terrain corrections and their indirect effects, which have never been included in previous Australian geoid models, have been included (Zhang, 1996; Zhang and Featherstone, 1996a; Zhang and Featherstone, 1997; Kirby and Featherstone, 1999).

The integration was performed using the one-dimensional FFT technique (Featherstone and Sideris, 1998; Featherstone et al, 1996) in conjunction with a determinsitically modified integration kernel (Featherstone et al., 1998b). A spherical cap was used instead of the whole data area since this provides better results (Forsberg and Featherstone, 1998), probably due to noise in the Australian gravity data. The separation between the geoid and quasi-geoid was considered small and thus neglected (Featherstone and Kirby, 1998). A zero-degree term was included in the computations (Kirby and Featherstone, 1998), which was independently verified using GPS and AHD data over the continent (Johnston and Featherstone, 1998a and 1998b).

Several analyses of GPS height determination have been conducted in Western Australia (Featherstone and Alexander, 1996) and the geoid been used to deduce geological structure in the north-west region of Western Australia (Featherstone, 1997c).

3.2 Combined gravimetric-GPS geoid determination

Primarily due to the practical realisation of the AHD, low-frequency differences between the gravimetric geoid and the vertical datum are evident (Featherstone, 1998; Featherstone and Stewart, 1998). Initially, geometrical interpolation of GPS-AHD heights were used to transform GPS heights to the AHD, but these proved unsucessful (Friedlieb and Featherstone, 1996; Friedlieb et al., 1997). Therefore, combined techniques have been used, where the gravimetric geoid model is warped to fit the vertical datum in the area of interest (Featherstone, 1996c; Alexander and Featherstone, 1996). This has been used for regional gravity surveys (Featherstone et al., 1998a; Rout et al., 1995a and 1995b) and the guidance of mining vehicles (Featherstone et al., 1997c).

Near Perth in Western Australia, the geoid is dramatically deflected due to the presence of the Darling Fault, which is the juxtaposition between the very dense Yilgarn Craton and less dense Perth Basin. As such, the geoid departs from the reference ellipsoid very steeply and the gravimetric method cannot recover the undulations to sufficient precision. Instead, a combined gravimetric/geometric method, based on least-squares collocation, has been used to optimally model the separation between the Australian Height Datum and the reference ellipsoid, specifically for GPS levelling (Featherstone, 1998c). This has been included in the AUSGeoid98.

3.3 Gravimetry

A number of GPS-based gravity surveys have been conduced for geophysical exploration in Western Australia (Rout et al., 1995a and 1995b) and to place constraints on a meteorite impact structure (Dentith et al., 1996; Dentith et al., 1999). GPS gives great productivity gains in geophysical data acquisition and the accuracy of the reductions (Featherstone, 1995b). A mobile, GPS-based gravity data acquisition system has been designed that includes a quality assurance procedure (Bilick et al., 1998). Other gravity-related studies have looked at the gridding of gravity data (Zhang and Featherstone, 1996b and 1996c).

3.4 Absolute Gravity

A new gravity benchmark station has been established at Mt Stromlo Observatory in Canberra. In February 1996, three high precision absolute gravimeters were deployed on newly established benchmarks in the Observatory at the Australian National University. This work was conducted by the Japanese Geographical Survey Institute (GSI) and the CSIRO Division of Exploration and Mining, with the assistance of AUSLIG and AGSO. Two Japanese FG5 Absolute Gravimeters, #104 and #201, were used along with the CSIRO instrument #110. These measurements established the absolute value of g at the site and demonstrated the consistency between the instruments on the three neighbouring benchmarks to within 1 microgal (Murukami et al., 1997). As part of the same project, the GSI instruments also made absolute gravity determinations on benchmarks at Tidbinbilla in the ACT and Mt Pleasant in Hobart. Details of the campaign are recorded on the AUSLIG CD "Australia 1996 Absolute Gravity Campaign".

Shortly afterwards, the Research School of Earth Sciences at ANU began a collaborative effort with the Japanese National Astronomical Observatory (JNAO), in Mizusawa, for the installation and operation of a GWR Instruments Compact Tidal Superconducting Gravimeter SG-CT031. The gravimeter was installed in a basement laboratory at the Observatory in January 1997. Operating at liquid helium temperatures, it is the most sensitive gravimeter ever operated in Australia, capable of monitoring variations in gravity at the nanogal level. Raw and filtered gravity, pressure and associated data are collected on a 1 second cycle triggered by a GPS clock (Sato et al., 1998).

The site is now one of 18 currently reporting to the data centre of the Global Geodynamics Project, a world-wide array making precise observations of faint signals from the interior of the earth in an attempt to detect motions in the deep interior, infer details of earth's internal structure, and provide information on a range of problems in global geodynamics. It is also a component of the Japanese Poseidon Project, also aimed at detecting signals related to the convective motions in the Earth's mantle and core. In addition to contributing to international programs, the deployment of a superconducting gravimeter in Australia is of intrinsic value to Australian Geodesy and Geophysics. Results of the work are intended to provide a basis for distinguishing the mechanisms causing changes in relative sea-level around Australia, and along with the absolute gravity determinations contribute to a more accurate reference frame for gravity measurements in Australia.

The Superconducting Gravimeter has been operating successfully with few interruptions for over the past two and a half years. A new GGP gravity filter card and an enhanced data acquisition system were installed at the site at the beginning of 1998. Data collected over the first two years operation indicate that the Mt Stromlo site has very low noise characteristics relative to other sites around the world and a relatively low incidence of instrumental offsets. These data have been used in studies of the excitation of free oscillations in the earth and analysis of the response of the earth to tidal forcing in the Australian region.

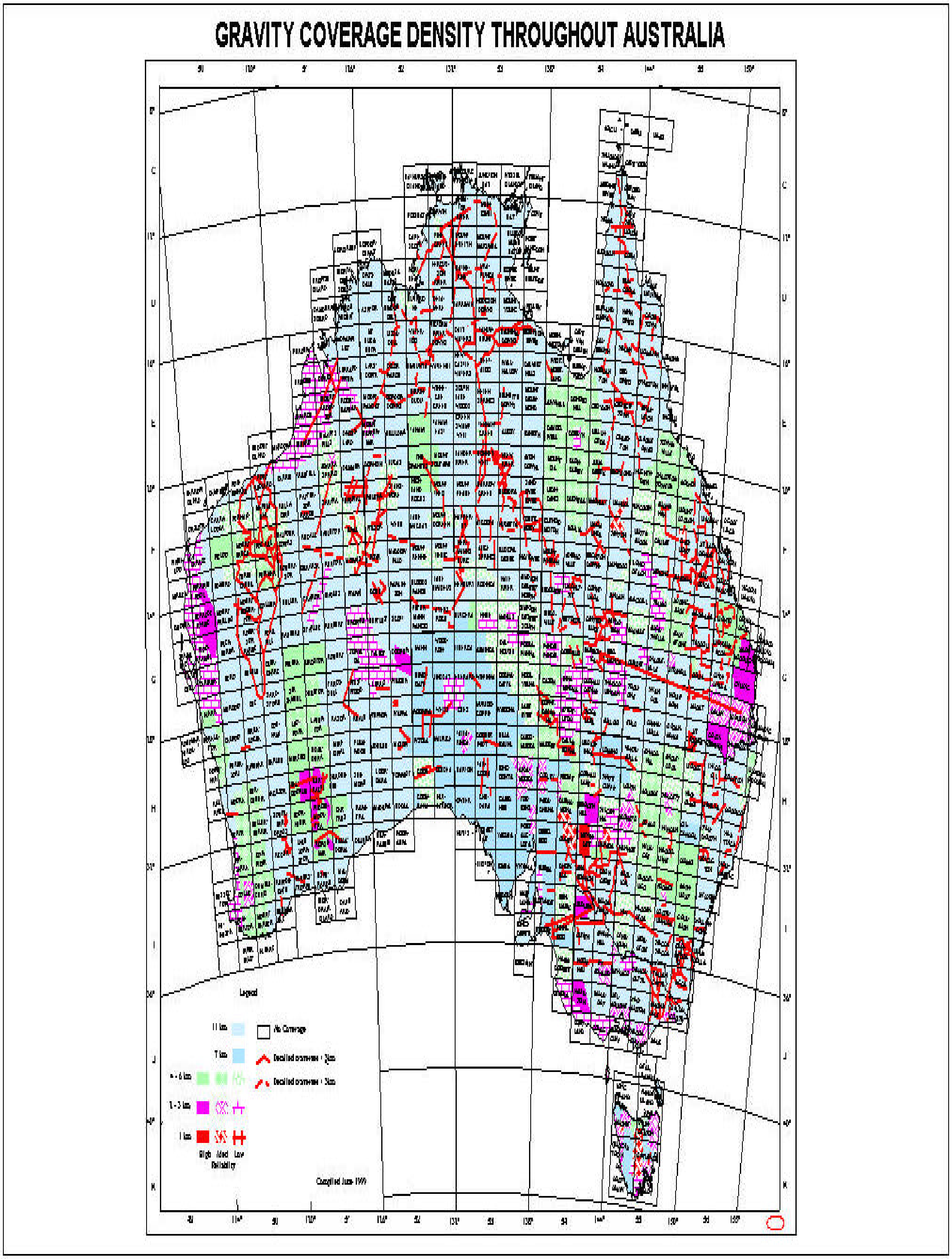
Repeated absolute gravity determinations on nearby benchmarks are essential for full calibration of the superconducting instrument and to the continuing process of monitoring its drift characteristics and the secular change of gravity at the site. In September 1998, five days of absolute gravity determinations were carried out using the FG5 #110 absolute gravimeter of the CSIRO Division of Exploration and Mining. A Lacoste-Romberg Gravimeter from JNAO Mizusawa was also operated on the site for most of 1998, providing an independent, though less accurate, calibration. Another absolute gravity observation was carried out over 12 days in February 1999, using FG5 #206 of the Université Louis Pasteur in Strasbourg, with support from AUSLIG and ANU. Results for the absolute gravity value at Mount Stromlo are given in Amalvict et al. (1999). Further observations are being planned to improve the calibration and extend the observation record to enable the drift and secular change determination.

3.5 Gravity Measurements

The Australian Fundamental Gravity Network (FGN) consists of 900 gravity reference stations in about 250 localities throughout Australia, its offshore island territories and the Australian Antarctic Territory. These stations provide a common basis for all gravity surveys carried out in Australia. The FGN is connected to the International Gravity Standardisation Net (IGSN) by absolute measurements at Alice Springs, Broome, Canberra, Darwin, Hobart, Perth and Sydney; variously made by United States, Japanese, French and Russian survey teams since 1979. International ties have also been made with relative gravimeters on numerous occasions.

The maintenance and augmentation of the FGN has continued with a new network being established in Victoria in 1996, a series of new stations between Alice Springs and Halls Creek in northern Australia in 1999 and refurbishment of stations in Canberra, Hobart, Kalgoorlie and Sydney.

The regional gravity coverage of Australia has been significantly enhanced in central New South Wales, Victoria, eastern Queensland and the Yilgarn province of Western Australia by the in-fill surveying of gravity at 4 km spacing or closer. About 25% of the continent is now covered by observations spaced at 7 km or less compared with the complete continental coverage spaced at 11 km. Many surveys covering smaller areas with denser coverage have been conducted by private exploration companies, universities, AGSO or State governments. A schematic diagram of the gravity coverage over Australia is shown in Figure 3.



The Australian National Gravity Database (NGD) now contains about 900,000 onshore point observations, derived from 1,000 surveys dating back to 1938. An equal or greater volume of data over offshore areas will soon be incorporated into the database as soon as the marine traverses have been levelled and the network adjusted. Large areas of the continent have been gridded at a 1 km cell size from the compilation of onshore, levelled marine and satellite gravity coverage. In

1997, a new gravity anomaly map of the continent at 1:5,000,000 scale was released. This map displays the onshore data as Bouguer anomalies, using a density of 2.67 tm^{-3}, combined with the offshore satellite-derived, free-air anomalies. A gridded dataset of the continent is available with a mesh size of 1.5 minutes of arc (about 2.5 km). Digital point data and gridded data at a mesh size of 0.5 minutes of arc (800 m) covering the continent by 1:1,000,000 sheet areas (6º by 4º) will be released progressively over the next two years.

4. General Theory and Methodology

4.1 GPS

The broad issue of "quality control" (QC) of GPS measurements for demanding applications such as kinematic GPS positioning was addressed in several papers - Han (1996, 1997c); Han and Rizos (1998b); Mertikas and Rizos (1996, 1997, 1998); Rizos et al. (1998d). Chen and Wang (1996) and Jia et al. (1996 and 1998a) have studied the reliability issues as they relate to dynamic system QC.

A study of carrier phase and pseudo-range multipath in mine environments, and its mitigation through the use of digital filters, was described in Han and Rizos (1997e). The topic of wavelets and their possible application to GPS was introduced in Fu and Rizos (1997b), with further studies presently being undertaken in relation to the detection of ionospheric scintillation. The use of Doppler measurements for high precision applications, as an alternative to carrier phase, was discussed in Fu (1995), and Fu and Rizos (1996c).

Considerable research has been undertaken in achieving ambiguity resolution (AR) for various GPS applications - Rizos et al., 1997a; 1997b; Han and Rizos (1996f, 1997a, 1997b); Han (1995a); Han and Rizos (1995a, 1996b, 1996c, 1996e); Han and Mok (1997); Han (1997a); Wang et al. (1997a and 1998b).

Algorithms for high precision kinematic GPS positioning over medium-range baseline lengths (defined as being of the order of 40-100 km) are described in Han and Rizos (1997c, 1998a). These are based on "wide-area" carrier phase corrections being generated by a network of GPS base stations. Significant progress has been made in long-range, kinematic GPS positioning, primarily due to advances in the algorithms for ambiguity resolution (Han, 1995b; Han and Rizos, 1996a), for cycle slip repair "on-the-fly" (even when the baseline lengths are many hundreds of kilometres) (Han, 1997b), and when external information is provided, in the form of laser-derived sea level heights (Han et al., 1998a; 1998b).

The principles of integrating GPS with other technologies have been dealt with in several papers and reports (Wong, 1995; Fu, 1996; Fu and Rizos, 1996a; 1996b; 1997a; Logan, 1997a; 1997b, Logan and Leahy, 1998).

A number of studies were made of antenna phase centre modelling (Stewart, 1998b), multipath analysis (Stewart et al., 1996b; Tsakiri et al, 1996) and stochastic modelling of GPS measurements (Ding et al., 1998a; Wang et al., 1998a; Stewart et al., 1998a; Wang, 1998a).

The use of Kalman filters and other filters have been used to integrate GPS and GLONASS positions with other positioning sensors (Dumville and Tsakiri, 1997; Jia et al., 1997 and 1998b; Tao et al., 1997; Wang et al., 1998c). These have been applied in the marine environment (Forward et al., 1997; Wang, 1997; Wang et al., 1997b), on land (Tsakiri and Dumville, 1996) and for collecting spatial data in areas of restricted sky visibility (Forward et al., 1998; Tsakiri and Stewart, 1998; Tsakiri et al., 1998b).

Ananga et al. (1995) described a methodology for combining GPS campaign results in order to monitor tide gauge benchmarks. Other studies have looked at the problem of GPS heighting, especially in the engineering environment (Collier and Croft, 1997a, 1997b; Croft, 1997).

Han & Rizos (1995b, 1995c) define the optimal means of combining baseline determinations, including selecting independent baselines and scaling the VCV matrices. New methodologies

have been suggested in these papers, but extensive field testing is still required to demonstrate whether or not the network results will be significantly affected.
A new GPS field and data processing technique was described in Han and Rizos (1996d, 1996h). This technique has been referred to as "GPS traversing" because of its similarity to terrestrial traversing techniques.

The use of differential GPS (DGPS) for "low-cost", sub-metre positioning applications is discussed in Lin (1995). The development of a hardware system, and its testing, has been described in several papers, including Han et al. (1998), Rizos et al. (1998b, 1998c), Subari (1995, 1997), and Subari & Rizos (1995a, 1995b).

A monograph, dealing with the principles and practice of GPS surveying, was prepared by Rizos (1997). This publication is predominantly used for supporting undergraduate teaching of high precision GPS to geomatics/surveying students. An HTML (web-based) version is presently under development.

A number of contributions to geoid computation have been made. These include a technique to validate geoid computation software (Featherstone and Olliver, 1997a), the deterministic modification of Stokes's kernel (Featherstone et al., 1998b), the adaption of the filtering properties of these kernels (Vanicek and Featherstone, 1997 and 1998), the treatment of the singularity in Stokes's kernel (Zhang et al., 1995) and the determination of boundary values for the Stokes-Helmert problem (Vanicek et al., 1999), an investigation of the use of DEM's to provide high-frequency information about the gravity field for the geoid computation, the proof that limiting and/or optimising the cap size of integration in the geoid integration was important in all N computations using Stoke's, and not just an artifact of ring integration, and tests on the use of airborne gravimetry in geoid computations to provide offshore data, where ship-borne and altimetrically derived data was either not avialable, or subject to systematic errors (Kearsley et al., 1998).

4.3 Fundamental Constants

Featherstone (1997) gave a review of constants relevant to Australian geodesy. Rüeger (1998, 1999) reviewed the refractive index formulae for electro-optical distance measurement units.

4.4 Legal Traceability

In collaboration with Federal surveying and mapping authorities, GPS observation and processing procedures that will enable GPS measurements to be relied upon in a legal framework (i.e., cadastral surveying) are being investigated. The introduction of RTK GPS receivers into the surveying industry (Wylde and Featherstone, 1995 and 1996) has brought with it the need for these measurements to be traced to the Commonwealth standards of length (Ding and Munsie, 1995). It has been found that RTK GPS can satisfy cadastral tolerances at the 95% confidence level when careful observation guidelines are followed closely (Stewart et al., 1998d).

4.5 Linear Estimation

A number of studies were carried out in the general area of linear estimation:

- rigorous least squares adjustment of large geodetic and survey control networks (Chitanukul, 1996; Sakurai et al., 1996).
- dynamic network adjustment procedures (Leahy and Collier, 1998; Leahy, 1999). This software has been commercialised and research is continuing in the application of the automatic segmentation and adjustment processes to the upgrading of cadastral data and the development of a coordinated cadastre.

5. Geodynamics

5.1 Crustal Movements

Australian Intraplate Tectonics

A collaborative project, between Curtin University and the University of Western Australia, is studying the geophysical and geodetic controls on the distribution of earthquakes in south-west Western Australia (Dentith et al., 1998). The factors that control the earthquake activity in the south-west region of Western Australia are not well understood and the region presents a seismic hazard to Perth. Recent geodetic surveys (June 1995) in WA's zone of seismicity were conducted by the WA Department of Land Administration and have been analysed to determine whether there is any surface motion associated with earthquakes in this area. Based on the analysis of a time series of terrestrial and GPS deformation monitoring, no surface motion could be resolved due to the uncertainty inherent to these techniques (Downes et al., 1998; Featherstone, 1998b). Other studies have looked at the crustal stresses derived from GPS measurements and comparisons with geological models (Zhang et al., 1998a and 1998b).

Papua New Guinea

Scientists from ANU and University of Canberra (UCanberra) have continued using GPS measurements to monitor the present-day tectonic motion in Papua New Guinea (PNG). Data from a field campaign conducted in September 1996 was analysed in conjunction with data collected from several earlier campaigns, resulting in velocity estimates for 13 sites spread across PNG. The analysis produced the first geodetically-derived plate tectonic model of the region (Tregoning et al., 1998a). The tectonic model comprises 4 major plates in the region (Australian, Pacific, Woodlark and South Bismarck), and Euler vectors have been estimated which allow site motion on these plates to be predicted.

Additional fieldwork was conducted in September 1998 to investigate the plate boundary zone of the Pacific and South Bismarck Plates in eastern New Britain and southern New Ireland. This is a strike-slip deformation zone, with a predicted relative rate of motion of > 100 mm/yr. GPS measurements were made at several new sites, as well as on some existing geodetic marks that were first observed with geodimeters by the Australian National Mapping Bureau in 1975 and subsequently reobserved using GPS in 1994/95 by PNG institutions. The analysis and combination of these data are currently underway and will lead to a new insight into the deformation zone in this region.

The large-scale pattern of tectonic motion has now been estimated in the PNG region. Densification of the GPS monitoring network is underway in regions of probable deformation zones in order to understand the local-scale interaction of neighbouring plates at plate boundaries. Fieldwork conducted in PNG has been greatly assisted by the staff and students of the Papua New Guinea National Mapping Bureau, the Papua New Guinea University of Technology and the Rabaul Volcano Observatory.

Researchers at ANU have developed a computer program which allows the effects of tectonic motion on geodetically-measured baselines to be computed, thereby allowing surveyors in PNG to estimate how tectonic motion will affect their geodetic measurements.

Solomon Islands

In September 1995, a GPS field survey was conducted by the University of South Australia (UniSA) in the Solomon Islands to commence monitoring of the tectonic motion in this region between the Australian and Pacific Plates. Two sites to the north and one site to the south of the

San Cristobal Trench were observed using Trimble 4000-SSE receivers, thereby spanning the boundary between the two plates. The survey was repeated in September 1997 by UniSA and ANU and expanded to include two new sites in the northeastern region and one new site in the Western Province of the Solomon Islands. The data were analysed with the *GAMIT/GLOBK* software and revealed a small but significant localised decoupling of the Solomon Islands Arc from the Pacific Plate, whilst the site south of the San Cristobal Trench appears to be moving as part of the rigid Australian Plate (Tregoning et al., 1998b). The survey will be repeated in 1999 and will lead to a better understanding of the present-day motion of this region.

Antarctica

A new program was initiated by ANU in 1998 to monitor present-day postglacial rebound in the Lambert Glacier region. Estimates of the amount of rebound range from 5 to 10 mm/yr and should be detectable from a long time series of GPS height estimates at particular sites (Zwartz et al., 1999). A solar-powered GPS system was developed, which operates unattended throughout the summer months, collecting GPS measurements from a quasi-permanent site. In January 1998, the equipment was installed near Beaver Lake, Antarctica by AUSLIG personnel (Tregoning et al., 1999). A choke ring antenna was mounted on a plate, which is connected to rods embedded into the rock. The antenna will not be moved until the end of the 5 year project. The equipment operated unattended until 20 March, 1998, at which time the solar power system failed to generate enough power to maintain the operation. The data have been retrieved and analysed using the *GAMIT/GLOBK* software. In January 1999, the system was replaced with another solar-powered system, and installed by students from UTas. The second system operated successfully for two weeks before being left unattended for the remainder of the summer period. It is not yet known how long the system operated before the power failed. A third system is currently being developed which will integrate solar power with power from a hydrogen-based fuel cell in order to maintain operation throughout the winter period when solar power is unavailable. This system will include a satellite communications system, which will enable the GPS data to be transmitted back to Australia in real-time. There is currently insufficient GPS data to allow a reliable estimate to be made of the postglacial rebound at this site.

Other Antarctic work concentrated on the Amery Ice Shelf looking at strain rates and grounding line definition from a combination of terrestrial and GPS data (Manson et al., 1998), mass balance estimations from GPS traverse data around the Lambert Glacier Basin (Manson, 1995) and the integration of ERS altimeter data with GPS data to produce a digital elevation model of the Amery Ice Shelf region (Phillips et al., 1998). Strain rates were computed in the Frammes Mountain area also using GPS techniques (Dawson et al., 1995, Dawson, 1996).

High Precision Deformation Surveys

Between 1994 and 1998, there has been various research projects in precise engineering deformation monitoring. Quality control analysis was studied by Ding and Coleman (1996a, 1996b and 1996c) and Jia and Ding (1996) whilst terrestrial survey techniques were studied by Ding et al. (1996c and 1996d). The use of kinematic GPS techniques for deformation analysis was studied by Collier (1995; 1997). The application of GPS for slope monitoring, the monitoring of dams, bridges and other man-made structures was the subject of ongoing research (Ananga et al., 1995c; 1996a; 1997; Ananga and Sakurai, 1997; Tsakiri et al, 1996a, 1996b; Stewart and Ding, 1996; Tsakiri and Stewart, 1997; Duckrell and Stewart, 1998; Jia et al., 1998; Watson, and Coleman, 1998). A workshop entitled *'Advances in GPS Deformation Monitoring'* was held at Curtin University in September 1998 (Tsakiri, 1998). The effects of deformation on the gravity field have been investigated in China by Zhang et al. (1996b).

Monitoring of Open Pit walls and Steep Slopes

The resource-rich state of Western Australia relies upon open-cut mining techniques. However, the design of these slopes is achieved to reduce excavation costs, which is associated with an increased likelihood of wall collapse. A number of studies have been used to address this problem using terrestrial survey techniques (Ding, 1995), which have been integrated with complementary sensors (Ding et al., 1995; Ding, 1996; Ding et al., 1996a and 1996b). More recently, satellite-based techniques have been used (Stewart and Ding, 1996; Stewart et al., 1996a; Ding et al., 1998b; Tsakiri et al., 1997). Other areas of investigation have concentrated on the models of deformation (Jia et al., 1996a; Ren and Ding, 1996; Ren, 1998; Tsakiri et al., 1998a) and reweighted filters (Jia et al., 1998c).

5.2 Satellite Altimetry

Researchers at the University of Tasmania, Antarctic CRC and CSIRO Marine Research analysed data from the TOPEX/Poseidon mission, looking at large scale seasonal climate signals (Bindoff et al., 1997; van Gysen and Coleman, 1995; 1996; 1997; Church et al., 1998). Other studies related to theoretical techniques for crossover analysis (van Gysen and Coleman, 1995a, 1995b, 1995c, 1996, 1999; van Gysen et al., 1997).

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