

Geodesy in Australia – National Report 1991-1995

Positioning

In Australia, research in geodesy is undertaken through University establishments, principally funded by grants from the Australian Research Council (ARC). Activities in support of the national geodetic infrastructure are coordinated through the State and Federal government agencies by the Intergovernmental Committee on Surveying and Mapping (ICSM). This committee has established a working level Geodesy Group, chaired by Geoscience Australia, with representatives from State and Federal 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 Geoscience Australia's information service using the World Wide Web (../..), gopher service (gopher.auslig.gov.au or IP 143.174.18.227) or through a telephone modem bulletin board (phone 61 2 6201 4375).

Geocentric Datum of Australia (GDA94)

In 1988, the ICSM resolved to adopt an earth-centred coordinate system to be implemented by the year 2000, replacing the regional Australian Geodetic Datum (AGD) which was introduced in 1966. The GDA is realised through the estimated positions of the Australian Fiducial Network and the Australian National Network (see Sections 1.2 and 1.3). The GRS80 ellipsoid has been adopted to provide geodetic curvilinear coordinates.

The Australian Fiducial Network (AFN)

The AFN consists of eight permanent, continuously operating, Roving receivers on the Australian mainland, including Tasmania. The network was initially observed during the International GPS Service for Geodynamics (IGS) Epoch '92 campaign, July-August, 1992. The AFN, in conjunction with six additional sites beyond the Australian mainland, forms the Australian Regional GPS Network (ARGN). Figure 1.1 shows the location and distribution of the AFN and ARGN.

Data from all the ARGN sites are automatically downloaded to Geoscience Australia in Canberra using a variety of dedicated phone lines, Internet and/or satellite communications. These data are being used for a range of scientific, geodynamic and other projects including integrity monitoring and legal traceability.

Two independent solutions of the AFN were determined by Govind (1994) and Morgan et al. (1994b). The AFN (and hence GDA94) station coordinates are based on the ITRF92 at epoch 1994.0 and are estimated to have a precision of a few centimetres (2-4 parts in 10^{**9}).

The Australian National Network (ANN)

Figure 1.2 shows the ANN, consisting of seventy eight (78) GPS campaign points spaced at approximately 500 km intervals across Australia. This network was observed between 1992 and 1994; the first GPS observation campaign being conducted during the IGS Epoch '92 period and followed by a further nine days of observations during August-September, 1993. The solution for the ANN is given by Morgan et al. (1994b) and has an estimated coordinate precision of a few centimetres (1 part in 10^{**8}), with some stations, primarily those that participated in both the 1992 and 1993 epochs, approaching the precision of the ARGN sites. The method of determining the positions of these ANN sites was via a Kalman filter procedure that used the full variance-covariance structure of all available information including station velocity information. The major uncertainties in position stem from the fact that the stations are not, in general, permanent monuments, but ground marks.

[Figure 1.1 : Distribution of ARGN Sites](#)

[Figure 1.2 : Distribution of ANN Sites](#)

State/Territory GPS networks

Most States and Territories have observed (with the exception of Western Australia who will observe their State network during 1996-97) an approximately 100 km GPS network. These networks have been designed to integrate with the ANN and AFN and will provide the control for future densification projects. The GPS baselines were generally computed using vendor proprietary software and have precisions of about 0.5-1.0 ppm.

The State/Territory networks are connected to the existing conventional geodetic (terrestrial) control - Australian Geodetic Datum (AGD66/ AGD84). A geodetic readjustment will be undertaken in July-August 1995, using the AFN and ANN coordinates to constrain the terrestrial data and State/Territory GPS networks in terms of GDA94.

Conventional networks

The labour intensive, traditional methods of geodetic surveys have basically ceased with the advent of GPS. No major field work activities have been undertaken except in some areas of new urban development, particularly in Western Australia and Queensland.

Following the December 1989 earthquake in Newcastle, LIC carried out a precise re-survey of the surrounding geodetic network, containing 22 stations at 10 km density. No conclusive evidence of any permanent earth movement was detected, given the comparable precisions of the initial epoch EDM survey and the subsequent epoch WM101/Trimble 4000-SST GPS (single-frequency) data sets (Kinlyside and Moss, 1991).

Local survey connections at fundamental Geodetic sites

The MOBILAS 5 satellite laser ranging (SLR) telescope at Yarragadee was replaced with a refurbished unit early in January 1992. A pre and post survey was conducted to determine the exact relationship between the old and new installations. During this survey, the three terrestrial calibration ranges were also re-measured, using Leica DI 2000/3000 EDM's.

A detailed analysis of the local survey connections at the VLBI sites Tidbinbilla and Hobart and the SLR site at Orroral has been completed (Stolz et al., 1995). These surveys include the 26 km GPS baseline that connects the VLBI reference frame at Tidbinbilla and the SLR reference frame at Orroral. This line was remeasured by GPS in February 1995 and again in May 1995 with a precision of a few millimetres (Stolz et al., 1995). These GPS results differed by only a few millimetres horizontally and a few centimetres in height from the results of a minimally constrained adjustment of the conventional network (J. Steed, personal communication, 1995).

In 1994, a correction to the height of the IGS core site at Tidbinbilla was provided to IERS (B. Murphy, personal communication, 1995). This was subsequently reflected in ITRF93.SSC (December 27, 1994).

At Hobart, local high precision survey connections have been made to establish the spatial relationship between the Hobart 26 m VLBI radio telescope reference point, the former CIGNET (MiniMac GPS) reference point and the IGS core site (TurboRogue GPS) reference point. Preliminary analysis has confirmed the existence of differences in the spatial relationship between the VLBI reference point and the former CIGNET reference point, as compared to the values currently held in the International Earth Rotation Service (IERS) database (R. Coleman, personal communication, 1995). The main difference is about 24 cms in the local vertical component.

In August-September 1995, a high precision survey will be done at Tidbinbilla to rigorously define the local tie between the JPL 34 m VLBI radio telescope and the nearby IGS core site (Rogue GPS) reference point.

Levelling Networks

The Australian Height Datum (AHD 71) remains unaltered as the basis of the national levelling network but will continue to be reviewed during the next four years. A number of major studies on the reliability of AHD 71 have been undertaken since 1991. Morgan (1992) confirmed that the AHD was consistent with third order levelling standards (closures of $12 \text{ mm } \sqrt{K}$, where K is the distance along the level route in km), although several regions were identified as being suspect. The second study, by Kearsley et al. (1993), used a Bayesian filtering technique to combine height information from a number of different sources. The technique was trialled in areas deemed suspect by Morgan (1992). Kearsley et al. (ibid) were able to pinpoint sections and stations of doubtful quality, but in all instances, the data were found to be consistent with third order levelling standards. Pearse et al. (1994) compared GPS-derived orthometric heights and levelled heights at 51 ANN sites across the continent. They concluded that there were outliers of several metres, but in general AHD 71 is consistent at the $12\sqrt{K}$ mm level. However, a significant warping of the datum was detected due to the nature of the AHD 71 definition.

Some regional levelling surveys were carried out to support specialised requests, such as a first order levelling network surrounding the Newcastle 1989 earthquake zone (done by LIC) and an extensive traverse of precise levels was observed throughout the Adelaide metropolitan area by DENR to serve as a basis for monitoring coastal deformation on the adjacent littoral areas.

The primary geodetic levelling activity during 1991-94 was to support the National Tidal Facility (NTF), Flinders University of South Australia, in monitoring vertical crustal movement at and around the baseline sea level monitoring stations (SEAFRAME) - see Section 1.9 for more details.

National Geodetic Database

The National Geodetic Database (NGDB) is an archive of National and State/Territory geodetic information held by Geoscience Australia. It contains information on some 23,000 horizontal geodetic stations and over 100,000 benchmarks from sites throughout Australia and its territories, including the Australian Antarctic Territory. Each site in the NGDB may have its position stored in a number of different coordinate systems and datums.

Australian Baseline Sea Level Monitoring Array (ABSLMA)

The NTF has established an array of high precision tide gauge stations (SEAFRAME) to monitor absolute sea level changes due to the greenhouse effect. A total of 14 SEAFRAME gauges have been distributed around the Australian coastline. Figure 1.3 shows the location and distribution of the ABSLMA sites.

[Figure 1.3 : Australian Baseline Sea Level Monitoring Array \(ABSLMA\)](#)

Each SEAFRAME station is equipped with a Bartex *Aquatrak* acoustic-in-air sensor, secondary water level transducer, anemometers, air and water temperature thermistors, an atmospheric pressure transducer and Sutron programmable data loggers. All data are telemetered to NTF on a daily basis.

To help in monitoring the vertical datum stability of these ABSLMA stations, a geodetic survey program has been carried out under ICSM jurisdiction by Geoscience Australia and the State Government and Territory survey agencies. At each site, three clusters of marks - an inland bench mark array, a coastal bench mark array, and ad hoc reference stations for the recovery of heights at the tide gauge sites - have been connected, using high precision levelling, at varying time intervals over the last four years. A preliminary analysis of levelling for the South Australian stations (Thevenard and Port Stanvac) was reported by Ananga et al. (1993). GPS observations between the arrays have also been observed several times, almost annually.

Inertial Positioning

The Litton LLN-83 was extensively tested by J. M. Rueger (UNSW) (with W. Caspary and H. Heister of the University of the Bundeswehr, Munich) for its suitability for general purpose inertial surveying applications. Initial laboratory tests

indicated already sub-metre precision, despite the least count of 1 m in the displayed UTM coordinates. Field tests in Germany on a 1 km linear course, on a sealed road with nine marks (average spacing of 118 m), achieved a double-run accuracy of 0.3 - 0.5 m in E and N and 0.2 - 0.3 m in elevation. A new procedure was employed to effectively centre the Inertial Reference Unit over the road marks. Field tests on two 7 km linear courses on the unsealed roads of the Inertial Surveying System Testnet, Ebersberger Forst (30 km east of Munich, Germany), with average point spacings of 1.0 km, showed a pooled double-run accuracy of about 1.2 m in E and N and about 0.4 m in elevation after using very simple adjustment techniques onto the given coordinates of the endpoints. The results and performance of the LLN-83 strap-down system are given in Rueger et al. (1993) and Rueger (1995).

Advanced Space Technology

VLBI

Geodetic VLBI has been restricted to the 26 m antenna in Hobart, operated by The University of Tasmania, and the 34 m antenna at NASA's Tidbinbilla Deep Space Centre. The latter only participated in an average of 9 global experiments per year whereas the Hobart antenna participated in an average of 34 global experiments. Many of the more important global experiments have coincided with other intensive observation campaigns, such as the IGS Epoch '92 campaign with the Hobart antenna participating in all major Southern Hemisphere campaigns involving antennae located at Santiago, O'Higgins, and Hartebeesthoek. A particularly unique experiment with the Japanese Antarctic Expedition took place in 1992 when a successful experiment was run between Tidbinbilla, Kashima and the Japanese Syowa base in Antarctica.

SLR/LLR

Two sites have been active in laser ranging: Orroral near Canberra and the NASA site at Yarangadee in Western Australia.

AUSLIG continues to operate the Laser Ranging Observatory at Orroral. A substantial system upgrade during 1991-94 resulted in significant improvements in production and precision. Terrestrial target ranging demonstrates an internal system accuracy in the vicinity of 3 mm and the rms precision of ranging to satellites is now at the sub centimetre level.

Ranging to LAGEOS satellites in support of the NASA Dynamics of the Solid Earth (DOSE) and the IERS programs remains a major activity. Calibration passes for the TOPEX/Poseidon mission were also given priority. Currently, Orroral Observatory collects more than 200 passes per month and laser ranging is undertaken to the following satellites: LAGEOS 1 and 2, ETALON 1 and 2, AJISAI, STARLETTE, ERS 1 and 2, STELLA, GPS SV35 and 36, TOPEX/Poseidon, METEOR. In addition, laser ranging to the Australian OPTUS geostationary communication satellites, at an altitude of 38,000 km, has been successful.

During 1991-94, Yarangadee has operated continuously and consistently, ranging to all geodetic satellites in the NASA program with sub centimetre rms precision. Excellent observations have been produced from this MOBLAS 5 system and it is arguably the most productive system in satellite laser ranging.

The laser ranging observations from Orroral and Yarangadee are transmitted to NASA Goddard Space Flight Centre (GSFC) for analysis, archive and distribution through the Crustal Dynamics Data Information System (CDDIS), and to the Center for Space Research, University of Texas (CSR/UT) for Earth Orientation Parameter estimation.

The Ninth International Laser Ranging Workshop was held in Canberra between November 7-11, 1994. There were 148 attendees representing 21 countries. A significant outcome of the workshop was the formation of the steering committee of the Western Pacific Laser Tracking Network (WPLTN) with the major participating

countries being Australia, China, Japan and Russia. The first post-workshop meeting of the steering committee was held in February 1995 in Tokyo.

In March 1995, AUSLIG began doing geodetic data analysis for the LAGEOS satellites. Thirty-day arcs of LAGEOS data, starting from January 1995 onwards, are being processed.

Curtin University of Technology, in collaboration with the University of Latvia and the commercial sector, is developing a mobile satellite laser ranging system (Abele et al., 1994a;b).

Time

Responsibility for civil time was assumed by the National Standards Commission (NSC) in 1993, in preparation for a National primary standard of legal time under the National Measurement Act. By arrangement with the NSC, AUSLIG has maintained a de-facto primary time standard, UTC(AUS), since January 1, 1994, and coordinates the relationship between Australian atomic clocks and International Atomic Time/Universal Coordinated Time promulgated by the International Bureau of Weights and Measures UTC(BIPM). AUSLIG administers this responsibility for NSC utilising a bank of cesium standards at the Ororol laser ranging observatory. Up to 20 Australian clocks contributed regularly to UTC through daily GPS Time comparisons, while up to 50 clocks are linked to the time scale UTC(AUS). Weekly clock comparisons are made between Tidbinbilla and Goldstone by VLBI within the NASA Deep Space Network but these are not linked into the National Time System directly. For UTC(BIPM)-UTC(AUS) comparisons, the free-running time-scale TA(AUS) is calculated from clock comparison by satellite TV, local TV and GPS commonview within Australia and New Zealand. It is independent of UTC, but compared regularly to it by GPS Time Transfer.

The Ororol Observatory with the NSC and the National Measurement Laboratory is collaborating with US Naval Observatory and the National Institute of Science and Technology in a two-way time experiment with a view to improve the correlation of UTC(AUS) with UTC(BIPM) from 50 nanoseconds to less than 10 nanoseconds and to ascertain the causes of daily and long-term anomalies observed in GPS Time Transfer. The availability of the stable free-running time scale TA(AUS) is a key factor.

A permanent national standard frequency and time signal service VNG, transmitting on 2.5, 5, 8.636, 12.984 and 16 MHz commenced in July 1991. But increasingly, time is being distributed across Australia using common view GPS signals. A method of clock comparisons using passive reception of TV signals from the geostationary satellite system OPTUS has also been trialled for distribution of UTC(AUS) within Australia. Its precision capability is better than 10 nanoseconds. A set of retro-reflectors on the OPTUS B-series spacecraft, launched in August 1992, will enable laser ranging from Ororol Observatory to compute precise orbits for the satellite to significantly improve the accuracy potential of the TV time transfer system.

GPS

The AUSLIG ground network of permanent tracking GPS receivers will form the fundamental stations in the Australian GPS monitoring network for near real-time navigation applications and to establish a legal traceability system for GPS applications (see sections 1.2, 1.3, 1.4, 1.9).

A large number of institutions were involved in GPS activities. The main research projects were :

- The determination of AFN, ARGN, ANN and SEAFRAME positions and velocities (Morgan et al., 1994a;b)
- Crustal deformation in Papua New Guinea (McClusky et al., 1994)
- Rate of subduction between Australasia and Eurasia along the Java Trench (Tregoning, 1994)
- Efficient handling of cycle slip errors (Chu, 1993)
- Improvements to the ambiguity function (Rizos and Han, 1995b;c)
- Long range DGPS (Colombo et al., 1995a;b)
- Transformations from AGD66/84 to geocentric WGS84.
- Geoid modelling for GPS heighting using least squares collocation (Collier et al., 1994).
- 3D (integrated) network adjustment by least squares collocation.
- Dynamic adjustment and maintenance of large networks.
- Automated network segmentation for dynamic adjustment.
- Phased adjustment of large networks (Collier and Leahy, 1992b).
- Monitoring structural deformation and ground subsidence with kinematic GPS (Collier, 1993; 1994).
- Integration of GPS and other sensors for rapid rail and road mapping (Leahy et al., 1993).
- On-line integration of GPS and other sensor data using a Kalman filter.

Geodetic Positioning and Monitoring of Tide Gauge Datums

The geodetic positioning of high precision and other tide gauges has been an area of considerable interest in Australia after the Federal Department of the Environment, Sport and Territories (DEST) adopted sea level monitoring, through tide gauge recorders, as a core component of Australia's contribution to Global Change. This contribution by DEST was further augmented by the South Pacific Sea Level Program, that is administered by AUSAID, formally AIDAB, as a result of the South Pacific heads of state agreements to monitor sea level change. In all, there are 14 SEAFRAME sites (see Section 1.9) and a further 10 tide gauge sites in the South Pacific. Most of these gauges have both local and far arrays for control purposes, although the South Pacific gauges normally have only a single close array point. The connection between the close array stations and the far or inland array stations is monitored with both classical spirit levelling and high precision GPS techniques.

A wide range of investigations have been undertaken ranging from theoretical studies aimed at understanding the tidal signatures and loadings that the arrays experience (Morgan, 1994b), through to the integration of terrestrial and space derived data (Ananga, 1993).

Experimental work in this area began in 1990 to determine the relationship between some of the gauges across Bass Strait (Rizos et al., 1991). This was followed by the determination of the positions of the principal inland array mark and a near array mark as part of the Epoch '92 data exercises. The solutions made by Govind (1994), which simulated the inland array with AFN sites, are in agreement with the unpublished University of Canberra solutions. This agreement between the two independent solutions indicates that the positions of these points is accurate to a few centimetres. Morgan (1994b) suggests that the minimum attainable precision level is 2 cm. This figure appears to be realizable with the currently available GPS units, observable, orbit and station modelling.

Since precise geometric estimates of position are but one measure of processes affecting the interpretation of tide gauges, the Australian program will shortly begin to augment precise GPS positions with absolute gravity determinations at selected stations. Other sites, e.g., Mawson, are to be equipped with precision recording, gravity meters, which means that continuous GPS, gravimetric, tidal and atmospheric signals will be available for correlation studies.

Altimeter Calibrations

As a check on the total system accuracy of the TOPEX/Poseidon satellite, a verification study was undertaken at Burnie, northern Tasmania. This was the first-ever southern hemisphere calibration of an altimeter mission and involved collaborative work between CSIRO Division of Oceanography, NTF, AUSLIG, DELM and the Universities of Canberra and Tasmania. The Burnie site is one of the SEAFRAME stations and the GPS observations were made during the Epoch '92 campaign, being part of the AFN survey. The estimate of the altimeter bias was consistent with the official NASA and CNES calibration sites, full details of the experiment are reported in White et al. (1994).

Determination of the Gravity Field

Gravity Networks

The Australian Fundamental Gravity Network (AFGN) consists of about 400 gravity stations situated at 180 widely spaced localities throughout Australia, offshore islands and Australian Antarctic Territory. These stations provide the framework for all gravity surveys in Australia. The AFGN is connected to the International Gravity Standardization Net (IGSN) by absolute measurements carried out by Russian and United States survey teams in 1979 and 1991 respectively, and by international ties using relative gravimeters. A continuous program of maintenance and enhancement of the AFGN has been a high priority. In the last five years, refurbishment, replacement and augmentation of stations has been carried out in Western Australia, Northern Territory, Tasmania and South Australia.

The regional gravity coverage over Australia is basically at an 11 km spaced grid (7 km spacing in South Australia and Tasmania) with areas or traverses of more detailed coverage scattered around the country where surveys have been conducted by private companies, state mines departments, universities and the Australian Geological Survey Organisation (AGSO). The offshore coverage around Australia has been systematically obtained by AGSO over the last 25 years and by a number of foreign private and governmental marine surveys. Satellite altimetry also provides useful regional gravity coverage over marine areas. Densification of the regional gravity coverage to a grid spacing of 4 to 5 kms is proceeding in areas of exploration and geological interest. The distribution of gravity stations over the continent is shown in Figure 3.1

The gravity data held in the Australian National Gravity Database comprise 800,000 point values in the area bounded by 8-48 deg S and 108-162 deg E, excluding data in Papua New Guinea. These data are available from AGSO in digital format as a catalogue of the point observation parameters and as a gridded data set having a mesh size of 0.025 deg of latitude and longitude. Computer drawn Bouguer anomaly (density 2670 kg m⁻³) contour maps at a scale of 1:1,000,000 are available for onshore Australia and the adjoining offshore areas of these maps. Selected areas of the country are covered by 1:250,000 station plot and Bouguer anomaly contour maps.

Geoid Computations

Geoscience Australia is responsible for the dissemination of the National gravimetric geoid model and provides it to all users. This ensures that only a single geoid model is used for geodetic operations over the continent. Over the 1991-94 period, Geoscience Australia has produced two national geoid models using software developed at the University of New South Wales (UNSW). AUSGEOID91 was superseded in 1993 by AUSGEOID93, which uses the OSU91a geopotential model, AGSO's 1980 gravity data set, and is gridded at 10' resolution over the continent (Kearsley and Govind, 1991a,b; Steed and Holtznagel, 1994). The absolute accuracy of the AUSGEOID93 values is estimated to be better than 0.5 m, while the relative accuracy has been estimated at 2-5 parts per million.

Figure 3.1 Australian Gravity Stations

Featherstone et al. (1994) have an Australian Research Council (ARC) funded research project, entitled "A new generation gravimetric geoid of Australia to support GPS geodetic applications". The results of this project will eventually be included in future AUSGEOID models.

The AUSGEOID models were tested in Western Australia by Featherstone and Dentith (1994) and Featherstone and Alexander (1994), by comparing the resulting GPS-derived orthometric heights with the known AHD values. The former study showed an agreement of within 4 cms. The latter study showed precisions that were equivalent to levelling misclosures of $12 \sqrt{K}$ mm, where (K) is distance of the line in km.

Digital elevation model's (DEM's) have been incorporated into software at UNSW to provide terrain corrections and to improve the value of the mean gravity anomaly for the compartments used in the evaluation of the ring integration around the point of computation. A geoid computed for the Australian Capital Territory (ACT), which has the roughest terrain in Australia, indicated an improvement of about 1.5 ppm in the rms of the agreement of the gravimetric dN with the AHD heights (A.H.W. Kearsley, personal communication, 1995).

Other geoid computations have been carried out in South Australia using a precise GPS control network in the Flinders Ranges (Gilliland and Jaksa, 1994; Jaksa et al., 1991) and in Melbourne (Gilliland, 1994b).

With the advent of the new GDA94 network, using the AFN and ANN GPS Networks, there are 78 stations evenly spread over the continent, many of which have spirit levelled heights, and can be used to provide a geometric determination of the geoid. Initial comparisons at 25 of the ANN stations shows an agreement of between 5 and 80 cm with respect to AHD values (J. Steed, personal communication, 1995). Smaller scale GPS campaigns has been observed in New South Wales and Victoria (Dickson and Zahra, 1992) to determine the geoid.

General Theory and Methodology

Local Scale Parameter Method

The determination of a representative refractive index for the wave path is the main limitation of attainable accuracy in electronic distance measurement (EDM). To overcome this problem and to improve accuracy, the length ratio method was initially proposed and later developed into the local scale parameter (LSP) method. The mathematical model of the LSP adjustment method was derived from first principles of the physics of the atmospheric boundary layer (Brunner and Rueger, 1992). The model does not rely on 'standard atmospheres'. It is shown that atmospheric temperatures and pressures must be observed at instrument stations but not at reflector stations. J. M. Rueger developed appropriate LSP field procedures and tested them in a number of networks. The method consistently produces accuracies of better than +1 ppm (Rueger and Dupraz, 1992; 1993).

Fundamental Constants - Refractive Index of Air

The precision of modern geodetic distance measurements far exceeds its accuracy, the main limitation being the inadequacy of currently used equations for the refractive index in the atmosphere. In recent years, there have been several improvements in data on the density of water vapour and in dispersion equations for air.

There also have been revisions in the temperature scale, change in units, new values for some atomic constants and experimental proof of errors in some old data. J. M. Rueger (UNSW) and P. E. Ciddor (CSIRO), as members of an IAG working group, have critically reviewed these results, together with data on the CO₂ content of the atmosphere. P.E. Ciddor has derived new equations for the refractive index in the visible and near-infrared that cover a wide range of atmospheric parameters with an accuracy of a few parts in 10⁸, which is that of the experimental data (Ciddor and Rueger, 1993; Rueger and Ciddor, 1995).

Geoid-Related Studies

Geoid-related research has investigated the use of the geoid in coordinate transformations in gravimetry (Featherstone, 1993a) and mapping (Featherstone, 1992; 1994), and the effects of kernel modifications (Featherstone, 1993b; Featherstone and Olliver, 1993; 1994) and singularities (Bian and Zhang, 1993) in gravimetric geoid determination.

Gilliland (1994a) has investigated the optimum capsizes to be adopted in geoid calculations for the Australian region. As a general rule, the results indicate that cap sizes of 0.5 deg radius are satisfactory when using a 360 degree geopotential model. This procedure was applied to a 30 x 40 km test area in Melbourne, in which GPS-derived orthometric heights at 32 stations were compared with heights obtained by spirit levelling. An rms of 14 mm for the differences was obtained over the test area with a corresponding total range of 51 mm (Gilliland, 1994b).

A comparison of least squares collocation and numerical integration was made in Melbourne by Armstrong (1993). This showed that the two methods agreed closely and AHD heights could be derived from GPS with precisions of order $12\sqrt{K}$ mm, as in Kearsley et al. (1993).

Ahmad et al. (1992) investigated the combination of the various elements of height information (tide gauge, conventional levelling, absolute and relative GPS heights, and gravimetric geoid heights) in an optimal solution by Bayesian least-squares. The technique has been used to investigate the integrity of large sub-sets of the AHD, and the study concludes that this levelling has, in general, precisions of order $12\sqrt{K}$ mm. Comparisons of GPS-derived orthometric heights were made at 40 of the ANN stations. First results show an agreement of the order of 1.5 m, but this result is skewed, implying the AHD datum contains regional biases, confirming earlier results of free net adjustments of the levelling data.

GPS

GPS theoretical studies at UNSW over the last four years have included the development of algorithms for undifferenced GPS data processing (Hung, 1992; Hung and Rizos, 1992), cycle slip detection and repair procedures (Chu, 1993; Rizos and Chu, 1993), investigations into ambiguity resolution algorithms (Han and Rizos, 1995a;b;c), development and testing of algorithms appropriate for low-cost GPS surveying, investigations into GPS network adjustment methodologies (Rizos and Hung, 1992; Rizos et al., 1993), and development of data management and quality assurance strategies. A new and innovative research project commenced in 1994 in collaboration with Dr. Oscar Colombo (NASA/Goddard Space Flight Center, USA) aims to develop field and analysis procedures for very high accuracy (of the order of 0.1 ppm) kinematic positioning over very long (> 1000 km) baselines. A first data collection experiment was carried out in August 1994. The results of this experiment demonstrated the feasibility of the technique (Colombo et al., 1995a,b) and further tests will be carried out in 1995 and 1996.

Studies of a suitable form of VCV matrix for use in GPS network adjustments was investigated by Ananga (1993) and Ananga et al. (1994c).

Brunner and Tregoning (1994a; b) made several investigations into the repeatability of GPS-determined heights over small baselines, as experienced between the near and far arrays found at the SEAFRAME stations. They found that the stability of these height determinations was 1-2 cms. Considering the nominal baseline length of 10 km, this results in a precision of 1 ppm of baseline length. This precision has been reported by others. It is well inside third order levelling standards, even approaching first order. Nevertheless these researchers concluded that the variability was outside the expected limits and that unmodelled factors were perturbing the result.

Comparisons of orthometric heights and GPS and conventional heighting over a section of the AHD in South Australia have been carried out at UniSA. Results using proprietary software showed agreement with the AHD between 1 to 1.5 ppm (Jaksa et al., 1991). Further investigations showed that these results are sustainable for baselines up to 500 km in length (Gilliland and Jaksa, 1994). Another study to verify the accuracy of kinematic GPS surveying was undertaken by Tan (1991). A

comparison was made between baselines measured by both the kinematic, static and terrestrial techniques for distances up to 12 km. The results confirmed that kinematic GPS surveying can provide centimetre level accuracy in 3D positioning and is a highly productive and cost-effective tool in routine surveying applications.

High Precision Engineering Surveys

Research into the general field of survey/geodetic network adjustment and analysis was carried out during 1991-94 (Coleman and Ding, 1993; Ding and Coleman, 1994), primarily for applications in precise engineering surveys and deformation surveying and monitoring (Ding et al., 1991; Ding, 1992; Coleman et al., 1992; Coleman and Ding, 1993; Harvey and Coleman, 1993; Ding et al., 1994a,b). Over the last two years, Curtin University has attracted over a quarter of a million Australian dollars in this field of research; from both industry and government.

Linear Estimation

A variety of studies were carried out in the general area of linear estimation. The projects were:

- Evaluation of calculus versus calculation in the context of the efficiency of network adjustment algorithms (Bervoets, 1991).
- Geodetic coordinate transformations by least squares collocation (Deakin et al., 1994).
- Multiple outlier detection and sensitivity analysis in Gauss-Markov models (Ding and Coleman, 1995a,b).

Geodynamics

Crustal Movements

Southwest Pacific region

Australia was involved with the completion of a modern primary geodetic network throughout the Philippine Islands using GPS techniques (Larden, 1992) and the subsequent use of this framework for monitoring regional plate motion and crustal movement along the Philippine fault zone. Similar studies have recently been initiated in the SW Pacific on Vanuatu and throughout the Solomon Islands.

PNG region

Scientists from UNSW, ANU and UniCanberra, and surveyors from the Papua New Guinea (PNG) Geoscience Australia Bureau have used satellite Doppler and GPS measurements to determine plate tectonic motion in Papua New Guinea. A 15-station network, which straddles most of the plate boundaries of the region, was first observed with dual-frequency JMR-1 Doppler receivers in 1981 and 11 of these sites were reoccupied with GPS. The Doppler survey was carried out over 34 days. The lines observed are 200-850 km long. Special field procedures, such as simultaneous observations, multiple site occupations and the use of atomic frequency standards, were employed to guarantee high quality observations. The short-arc method was used to reduce the data, solving for site coordinates, corrections to the orbital state-vectors for each short-arc, residual atmospheric delays, satellite and receiver oscillator offsets and drift rates, receiver clock synchronization errors, frequency variations of the satellite oscillators and initial range ambiguities. The rms precision of the Doppler baseline measurements is 5-7 parts in 10^{**7} (25-35 cm for a 500 km long line) and extensive testing indicates that this is also a measure of the accuracy achieved.

A 9-station network straddling the Papuan Peninsula (PP), Woodlark Basin spreading system (WBSS), Trobriand Trough/New Britain Trench subduction system (TT/NBTSS) and Bismarck Sea seismic lineation (BSSL), was reobserved with GPS in July-August 1990. Four of the sites which span the PP and WBSS, and which were observed in 1990, were again observed in August 1991. In May 1992, the part of the Doppler network which straddles the boundaries between the South Bismarck (SB) and North Bismarck (NB) plates and the NB and Pacific (P) plates was reoccupied and two lines, which respectively span the PP and TT/NBTSS, were remeasured. The GPS measurements were generally taken at night with dual-frequency codeless Trimble receivers, over 4-11 days, using an observing window of 9 hours or more. The Bernese software (Version 3.3) was used for parameter estimation. Site coordinates, atmospheric delay parameters and ambiguity terms were estimated, holding precise orbits fixed. The rms daily repeatabilities indicated that the baseline measurements were accurate to better than one part in 10^7 (5 cm for a 500 km-long line). The 1981 and 1990 data indicate spreading (14.7 ± 13.7 cm/yr) across the BSSL, convergence (-15.1 ± 12.0 cm/yr) across the TT/NBTSS, spreading (8.8 ± 13.2 cm/yr) across the WBSS and zero motion (0 ± 13.5 cm/yr) across the PP. These rates are corroborated by the repeat GPS measurements to within measurement error. The results are consistent with the geological models for the region in which the

South Bismarck and Solomon Sea/Woodlark plates form the principal tectonic elements between the Pacific and Australian plates (McClusky, 1993; McClusky et al., 1994; Stolz et al., 1994).

Further expansion and densification of the geodetic network is in progress, which should lead to improved estimates of plate motions as well as provide evidence for deformation across some of the presently unsurveyed boundaries. Specifically, four main areas are of interest: (1) the region to the east of Rabaul, including Nuguria and Carteret and extending out onto the Ontong Java Plateau as far as Tasman Island; (2) the region bounded by Milne Bay, Goodenough Bay and Misima and Guasopa islands; (3) the region straddling the Wewak Trench and Bismarck Sea seismic lineation roughly between 143 deg and 146 deg E longitude; and (4) the region to the north of Cairns linking the Australian and New Guinea mainlands and straddling the Bismarck Range in New Guinea. Future surveys are planned in one of these areas in 1995.

Antarctica

Australia chairs both the [Geoscience Standing Scientific Group](#) (GSSG) and Expert Group on Geospatial Information of the Scientific Committee for Antarctic Research (SCAR). Geoscience Australia has responsibility for the cooperative [Geodetic Infrastructure of Antarctic \(GIANT\)](#) program of the GSSG. The main activity for the GIANT program has been the epoch surveys to establish geodetic infrastructure points for the Antarctic crustal dynamics/plate tectonics project involving GPS observations in the Austral summers of 1991/92, 1992/93 and in conjunction with Germany in 1994/95.

Analysis of some of the SCAR GPS data for vertical movement was done by Ananga (1993) and Ananga et al. (1994d). These studies showed that height precisions of 2 to 3 cms are possible from well reduced data. Morgan (1994a) and Morgan et al. (1994c) have made more comprehensive analyses of the available data. These studies have been able to determine the movement of ice cap stations over 20 days, including correct determinations of the settling or firnification process. The procedures were also used by Phillips (personal communication, 1995) to reinterpret some early data on the Amery Ice Shelf. There was excellent correlation between the glaciological nature of the station and the vertical changes. While these studies all used a single season's data, studies to unify the various campaigns have been rather limited. This has been partly due to the state of the reference frame and partly due to the very different geometries and error sources in each of the surveys. Close collaboration has been established between the University of Canberra team and the German University consortium for Antarctic Research, which should see many of the network problems diminish.

Satellite Altimetry

Researchers at the Universities of New South Wales, Sydney and Tasmania, in collaboration with scientists at CSIRO, Division of Oceanography, Hobart, analysed data from a number of altimeter missions (Geosat, ERS-1, TOPEX/Poseidon missions) for extracting information on the variability of the global oceans. New techniques were developed for resolving surface eddy statistics from crossover data

and understanding the dynamical balances in the Southern Ocean (Morrow et al., 1992a,b; 1994). A wave climatology of the Southern Ocean was prepared using the Geosat altimeter data (Lee et al., 1995). Work currently in progress is aimed at mapping the large-scale, seasonal variations of the ocean surface and comparing the altimeter results to numerical ocean models.

In collaboration with Prof. Herman van Gysen, much progress was made on the development of rigorous and efficient computational procedures for analysis of collinear and crossover altimeter data (van Gysen et al., 1992; van Gysen and Coleman 1994a,b; Coleman and van Gysen 1993; Coleman et al., 1992).

International Geodynamics Service (IGS)

Australia has made major contributions to the IGS. Mr John Manning of AUSLIG and Assoc. Prof. Peter Morgan of University of Canberra were members of the Steering Committee responsible for the establishment of IGS.

AUSLIG has now become a regional data centre in the acquisition and distribution of Southern Hemisphere data, while the University of Canberra has continued to reduce epoch campaigns of interest to the Southern Hemisphere. The University of Canberra also has a unique collection of RINEX files from 1992 onwards, with a speciality for Southern Hemisphere data that is not stored on one of the major global archives.

Recent IGS activity has paved the way for AUSLIG to become an Associative Analysis centre.

AUSGeoid

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Contributors to Geodesy in Australia

National Report 1991-1995

This National Report gives a brief review of the geodetic activities carried out in Australia over the period 1991-1995.

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 :

- **AUSLIG** : Australian Surveying and Land Information Group, Canberra, ACT.
- **LANDCARE** : Department of Lands, LANDCARE, Woolloongabba, Qld.
- **LIC** : Department of Conservation and Land Management, Land Information Centre, Bathurst, NSW.
- **S&M** : Department of Finance, Survey and Mapping, Melbourne, Vic.
- **DELM** : Department of Environment and Land Management, Office of the Surveyor General, Hobart, Tas.
- **DENR** : Department of Environment and Natural Resources, Geodetic Services Section, Adelaide, SA.
- **DOLA** : Department of Land Administration, Mapping and Survey Division, Perth, WA.
- **ISD** : Department of Lands, Housing and Local Government, Information Services Division, Casuarina, NT.
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- **UniSA** : School of Surveying, The University of South Australia, Ingle Farm, SA.
- **RMIT** : Department of Land Information, Royal Melbourne Institute of Technology, Melbourne, Vic.
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- **UniCanberra** : Faculty of Information Science and Engineering, The University of Canberra, ACT.
- **ANU** : Research School of Earth Sciences, The Australian National University, Canberra, ACT.