GEODETIC FIXING OF TIDE GAUGE BENCHMARKS OF THE AUSTRALIAN BASELINE SEA LEVEL MONITORING ARRAY: RESULTS OF THE MAY 1995 GPS CAMPAIGN.

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ABSTRACT

In order to monitor changes in absolute sea level, the vertical motion of the crust at the tide gauge location must also be monitored in an accurate, global terrestrial reference frame. During the last week of May 1995, five days of GPS data was observed at over 30 inland and coastal sites related to the tide gauge array. In addition, the data set includes 10 Australian Fiducial Network (AFN) sites, 3 Australian Antarctic Territory sites and 17 global sites of the International GPS Service for Geodynamics (IGS). The computations are undertaken in stages that comprise the precise orbit determination of the GPS satellites from the IGS/AFN global data set and, then estimating the positions of the inland and coastal tide gauge benchmarks. The data set and the computation procedure (including observable, orbit, and station modelling) are briefly described and the results for this epoch are presented.

1. INTRODUCTION AND OVERVIEW:

Fourteen bench mark tide gauges designated the Australian Baseline Sea Level Monitoring Array (ABSLMA), shown in figure 1.1, are deployed along the coast of the Australian continent.

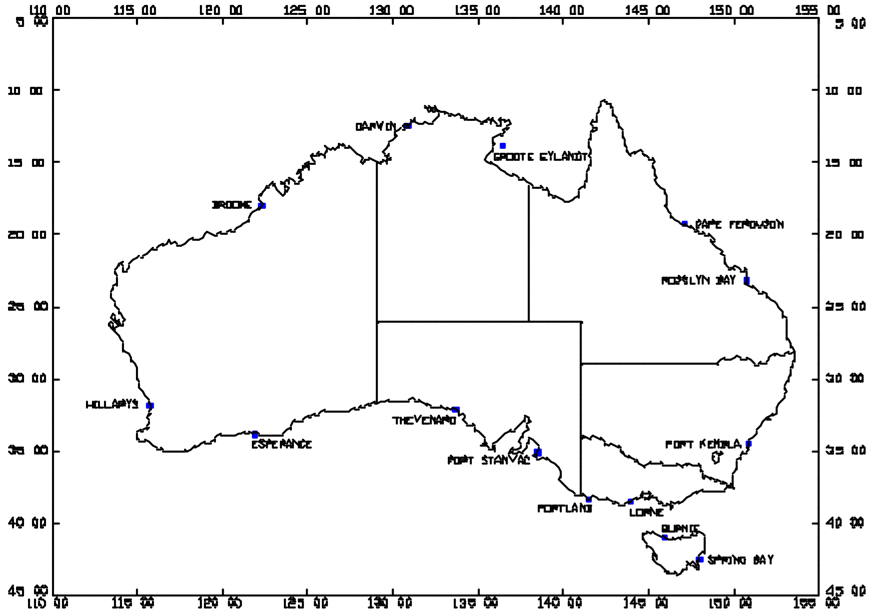


Figure 1.1 Australian Baseline Sea Level Monitoring Array (ABSLMA)

Tide gauge records of data collected over long periods have been studied by researchers to determine long term (eustatic) changes in sea level and neo-tectonic trends (including glacio-isostasy). These records indicate a rise in global sea level of 10-30 cm during the past century (Carter et al., 1989). However, there are large discrepancies in the rates of change of sea level indicated by different tide gauges, or groups of tide gauges spanning particular regions. These differences are considered to be largely caused by vertical land motion resulting from phenomena such as glacial rebound, tectono-physics, subsurface fluid withdrawal and sediment consolidation.

Neo-tectonics cause changes in the position of the crust relative to the oceans. This Earth signal may be misinterpreted as a local sea level change. As an example Carter et al. (1989) state that the redistribution of the mass in the mantle of the Earth associated with glacial rebound causes maximum rates of uplift of more than one centimetre a year in regions of Canada and Scandinavia. Further examples of rates of vertical crustal motion over the globe of a few millimetres or less are also given.

In order to decipher the signals from a global tide gauge network from vertical crustal movement, so that absolute sea level changes could be monitored, it is necessary to establish the positions of the tide gauges in an accurate, global, geocentric terrestrial reference frame, such as the International Earth Rotation Service (IERS) Terrestrial Reference Frame (TRF).

Measurements of vertical crustal movement together with the establishment of global benchmark tide gauges in this global geocentric reference frame will satisfy some fundamental aims. It will lead to the establishment of a world vertical datum, by providing the means to accurately connect national, continental and international vertical datums. This will provide the means to estimate past and current rates of change in global mean sea level, which will lead to better understanding of the causes that may accelerate this change; in view of the current debate that sea level changes may be related to global warming as pollution intensifies the Greenhouse Effect. Since changes in sea level average about one to three mm. per annum any vertical motion of the crust must be monitored at this level of accuracy, and within short time spans (three to five years).

The technical conclusions of Carter et al. (1989) for monitoring absolute sea level changes further require (in addition to establishing and observing tide gauge benchmarks in a global geocentric reference frame) (i) A local network of benchmarks that are re-surveyed annually by precise spirit levelling or GPS, (ii) Continuous GPS monitoring of the relative positions of regional tide gauge networks and, (iii) Repeated Absolute gravity measurements at the primary stations in the network, and at as many tide gauge bench marks as possible, such that any secular changes in gravity may be detected. Changes in absolute gravity of one to three micro gals per year represent height changes of 3 to 10 millimetres per year.

Following the “Woodshole” meeting (Carter et al., 1989) on Geodetic Fixing of Tide Gauge Benchmarks, a meeting of Australian Oceanographers, Surveyors/ Geodesists, members of the Permanent Committee of Tides and Mean Sea Level (PCTMSL) of the Inter-Governmental Advisory Committee for Surveying and Mapping (ICSM) and others, was convened in January 1990 at the National Tidal Facility, Flinders University, Adelaide, to discuss the implementation of the “Woodshole” recommendations with respect to the ABSLMA..

The original proposal was to establish a network of "zero order or fiducial" stations across the continent at approximately 1000 Km distances using mobile VLBI and SLR observations. Subsequently, these fiducial sites would be connected to the tide gauges using GPS. In addition, absolute gravity measurements would be colocated with the fiducial and the tide gauge GPS sites. Precise spirit levelling will further connect the GPS tide gauge sites to the tide gauges themselves. This proposal was further discussed in August 1990 at a meeting of scientists and members of the Geodesy sub-Committee of the Australian Academy of Sciences, to seek their support and participation. An ICSM Geodesy Working Party was then formed to further investigate and establish a “zero order” network for absolute sea level monitoring.

Considering both the physical, logistical, and financial constraints of undertaking experiments with mobile VLBI and SLR in Australia, and the growing evidence of the high accuracy capability of GPS, a network of permanently tracking GPS receivers -- constituting the Australian Fiducial Network (AFN) -- was established to provide the geodetic framework for absolute sea level monitoring; and to continually monitor any vertical crustal movement -- so that the signals from the tide gauges can be differentiated from any other tectonic phenomena. This implies that the precision and accuracy of these coordinates should be such that any tectonic phenomena at the mm. level should be detectable.

1.1 GEODETIC TECHNIQUES :

Currently utilised space based geodetic techniques that can meet the required positioning accuracy's for sea level monitoring are, in the main, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and the Global Positioning System (GPS).

1.1.1 GEODETIC VERY LONG BASELINE INTERFEROMETRY (VLBI)

Geodetic VLBI is described by, for example, Herring (1983), Harvey(1985), Lambeck (1988) and Robertson (1991). The analysis of VLBI measurements by Ma et al. (1992) show that baselines that are accurate to a few centimetres (over transcontinental distances) are routinely obtained. The global repeatability of baseline lengths for the 1991 solution (ibid.) is 14.3 mm. The precisons continue to improve as new state of the art VLBI data is incorporated into the solutions. It is projected that baseline accuracies of better than 1 cm could be achieved with a repeatability at the 1 to 2 mm level. This capability of VLBI to determine the vector components of transcontinental baselines with accuracies at the centimetre level promises to produce a global reference frame at this level of accuracy. However, VLBI does not provide geocentric positions of stations; at least one station must be known from another technique, such as SLR, which provides coordinates relative to the centre of the Earth or, the VLBI solutions must be transformed into the SLR (geocentric) system.

1.1.2 SATELLITE LASER RANGING (SLR):

A complete description of the geodetic SLR is given by Dedes (1987) and Smith et al. (1991). Of particular interest to the measurement of absolute sea level is the inherent ability of SLR measurements to determine the coordinates of ground based laser tracking instruments in a coordinate system with an origin that is theoretically coincident with the Earth's centre of mass. Range measurements are now made routinely to a number of geodetic satellites. with a precision of 1 cm or better (Carter et al. 1989). SLR sites are usually not located near suitable tide gauges for sea level monitoring. SLR systems, however, contribute global geocentric coordinates to an accuracy of a few centimetres in each component. This is significant for absolute sea level monitoring. Further, the colocation of SLR and VLBI provide transformation parameters for the VLBI coordinates to be transformed into a geocentric reference frame, establishing an accurate global terrestrial reference frame. The process and establishment of the global terrestrial reference frame through Satellite and Lunar Laser Ranging and VLBI is further discussed in section 4 and figure 4.1.

1.1.3 GLOBAL POSITIONING SYSTEM:

The precision and accuracies of GPS surveys have evolved from one part per million, (for example, Bock et al. 1985, and Wanless and Lachapelle 1988) to a few parts in hundred million (Soler et al. 1992) of baseline lengths. The precision and accuracy achieved by, for example, Beutler et al. (1985, 1987 and 1989), Bertiger (1988), Dong and Bock (1989), Lindqwister et al. (1991), Larson and Agnew (1991) and Soler et al. (1992) is unambiguous evidence of the capability of GPS as a technique for high precision regional size geodetic surveys comprising line lengths of up to about 4000 Km (Beutler et al. 1987; Soler et al. 1992). King and Blewitt (1990) in summarising the accuracies (compared to VLBI) that were achieved by the various regional (line lengths of between 50 and 1000 Km) GPS campaigns concluded that the "accuracy of GPS measurements in the Southwestern US is no worse than 5 mm plus one part in 10^8 of the baseline lengths in the horizontal components and 20 mm in the vertical from the equivalent of a few days observations". They further concluded that the accuracy and repeatability of these results provide clear evidence of the utility of GPS for monitoring crustal deformation in plate boundary regions.

At the Global level, Hefflin et al. (1992) and Blewitt et al. (1992) have demonstrated the attainable accuracies of GPS in their analyses of the GPS experiment for the IERS and Geodynamics (GIG'91) (Ibid.) data comprising 21 globally distributed sites. Hefflin et al. (1992) report a daily repeatability of 2 mm plus 4 parts per billion of the baseline length for baselines in the Northern Hemisphere. A comparison to VLBI determined baselines gave an agreement of 2.1 parts per billion for these Northern Hemisphere baselines. Blewitt et al. (1992) compared the results of 12 GPS stations to ITRF90 (Ibid.) coordinates. The difference in Northern Hemisphere stations (Europe and North America) with respect to ITRF90 station coordinates is at the 1 cm level. For the Northern Hemisphere stations the rms of the differences is 9 mm, 13 mm and 20 mm in the north, east and vertical components respectively.

2. IGS, ARGN AND ABSLMA CAMPAIGN DATA.

In relation to each tide gauge shown in figure 1.1, an inland and a coastal array of benchmarks were established. During the five day period from 28 May to 1 June 1995, the 29 tide gauge benchmarks (with their GPS receivers types) listed in Table 2.1 were occupied by continuously tracking GPS receivers. In order to determine the accurate positions of the tide gauge benchmarks within the Australian Regional GPS Network (ARGN) and in a global terrestrial reference frame, accurate global orbits for the GPS satellites must also be determined. To accomplish this, data from the ARGN stations and a selected subset of the International GPS Service for Geodynamics (IGS) network of globally distributed permanently tracking sites were required. Figures 2.1 and 2.2 show the distribution of the ARGN and the IGS stations used in the computations. Tables 2.2 and 2.3 show the availability of GPS data from the ARGN and ABSLMA benchmarks.

Table 2.1 Tide Gauge Benchmarks and GPS Receiver Types.

TIDE GAUGE	BENCHMARK	4-CHAR-ID	INLAND/COASTAL	RECEIVER TYPE
BROOME	Broome 184	BI84	coastal	Ashtech Z-XII3
	Broome 173	BROO	inland	Ashtech Z-XII3
BURNIE		SPM9	coastal	(no observations)
CAPE FERGUSON	PSM112150	AIM4	coastal	Trimble 4000SSE
	AU028 RM2	TOR2	AFN RM	Trimble 4000SST
	DD 83469	3469	inland	Trimble 4000SSE
DARWIN	NTS302 NMG21 Darwin Pillar	PILL	coastal	Leica SR299
	BM4563	WINN	inland	Leica SR299
	NTS664	RAAF	inland	Leica SR299
ESPERANCE	Esperance 171	ESPE	coastal	Ashtech Z-XII3
GROOTE EYLANDT	NTS652	ALYA	coastal	Leica SR299
	NTS653	GROO	inland	Leica SR299
HILLARY’S	Hammersley 164	HILS	coastal	Ashtech Z-XII3
	Gnangara 73	PER2	inland	Ashtech Z-XII3
LORNE	Lorne Pedestal	LAAC	coastal	Trimble 4000SSE
	P206-34H Lorne PM76	BENW	inland	Trimble 4000SSE
PORT KEMBLA	PM70948	948_	coastal	Leica SR299
	Flag	FLAG	inland	Leica SR299
PORT STANVAC	6527/8432	RFNP	coastal	Trimble 4000SSE
	6627/22981	STNP	inland	Trimble 4000SSE
PORTLAND	Henty TS Pillar	HENT	coastal	Trimble 4000SSE
	P204-1 Trewalla PM80	PORT	inland	Trimble 4000SSE
ROSSLYN BAY	PSM82477	KIO_	coastal	Trimble 4000SST
	PSM95189 Mulara	MULA	inland	Trimble 4000SSE
SPRING BAY	SPM9404	9404	coastal (tide gauge)	Leica SR299
	SPM9259 RM4	SBCP	coastal	Leica SR299
	SPM9261 RM4	TRIP	inland	Leica SR299
THEVENARD	5633/1680	MURP	coastal	Trimble 4000SSE
	AU019 RM3	CER3	AFN RM	Trimble 4000SSE
	5633/1679	THVP	inland	Trimble 4000SSE

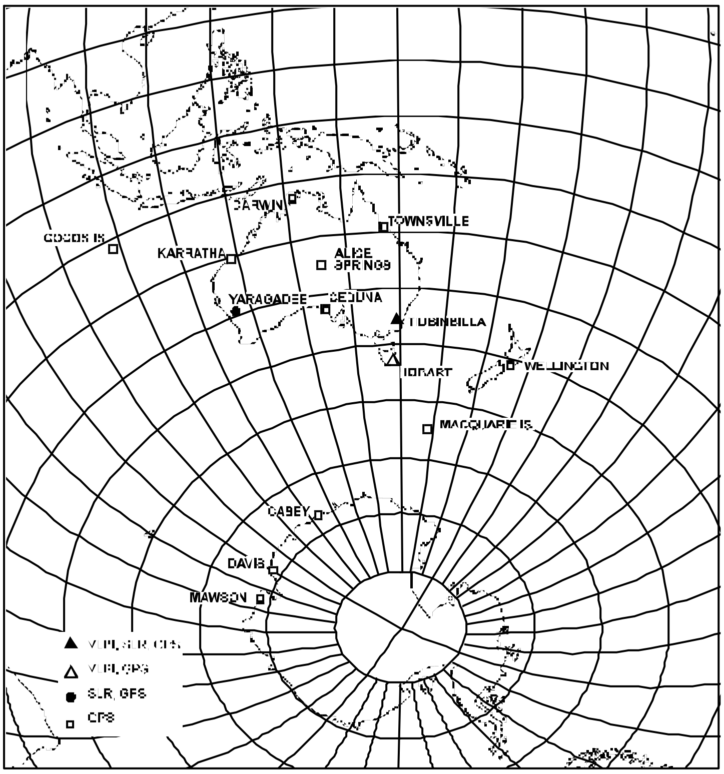
Table 2.2 Data Availability at the TGBMs

BENCHMARK 4-CHAR-ID	95148*	95149*	95150*	95151	95152
BI84	X	X	X	X	X
BROO	X	X	X	X	0
SPM9	X	X	X	X	X
AIM4	X	X	X	X	X
TOR2	X	X	X	X	X
3469	0	0	X	X	X
PILL	X	X	X	X	X
WINN	X	X	X	X	X
RAAF	X	X	X	X	X
ESPE	X	X	X	X	X
ALYA	0	0	0	0	0
GROO	0	0	0	0	0
HILS	X	X	X	X	X
PER2	X	X	X	X	X
LAAC	X	X	X	X	X
BENW	X	X	X	X	X
948_	X	X	X	X	X
FLAG	X	X	X	X	X
RFNP	X	X	X	X	X
STNP	X	X	X	X	X
HENT	X	X	X	X	X
PORT	X	X	X	X	X
KIO_	X	X	X	X	X
MULA	X	X	X	X	X
9404	X	X	X	X	X
SBCP	X	X	X	X	X
TRIP	X	X	X	X	X
MURP	X	X	X	X	X
CER3	X	X	X	X	X
THVP	X	X	X	X	X

* Year,day of year

Table 2.3 Data Availability at the AFN Sites

AFN SITE	95148	95149	95150	95151	95152
TIDBINBILLA	X	X	6 hrs	X	X
YARAGADEE	X	X	X	16 hrs	X
HOBART	X	X	X	X	X
DARWIN	X	X	X	X	X
TOWNSVILLE	X	X	X	X	X
WELLINGTON	0	0	X	X	X
CEDUNA	X	X	0	X	X
ALICE SPRINGS	X	0	X	X	0
KARRATHA	X	0	0	X	X
COCOS ISLAND	X	X	X	X	X
DAVIS	X	X	X	0	0
CASEY	X	X	X	X	X
MAWSON	X	X	X	X	X



Figue 2.1: Distribution of the ARGN Sites.

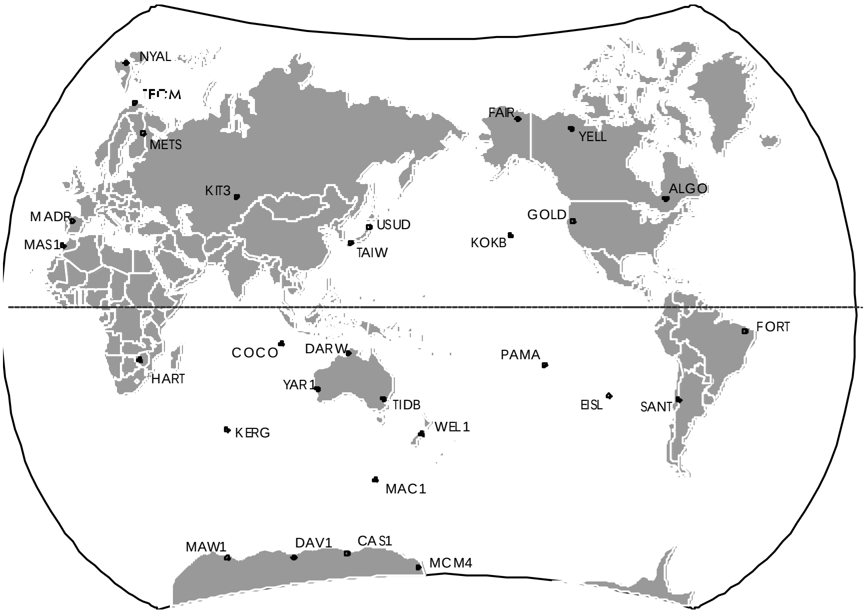


Figure 2.2: Distribution of the Global IGS and Antarctic GPS Sites Used.

3. GPS SOLUTION PROCEDURE.

The three-stage (Global, and Stages 1 and 2) solution procedure to obtain accurate positions for the tide gauge benchmarks is shown in figure 3.1. At the Global stage the precise orbit determination for 25 GPS satellites was undertaken. The ITRF93 coordinate values at epoch 95.4055 for GOLD, YELL, ALGO, KOKB, MADR, SANT, FAIR, MADR, SANT, HART, TIDB and YAR1 were held fixed in these solutions. The coordinates of the remaining IGS sites were estimated, together with the position of the pole, measurement biases and a two hourly tropospheric scale bias at each site. In stage one and stage two of the computations, the estimated orbits of the satellites (together with the non-gravitational parameters), pole position, the coordinates (from the global solution) for DARW and WEL1 and the ITRF93 coordinates for TIDB and YAR1 were held fixed. Also, the estimated tropospheric scale biases for these four sites were held fixed. The positions for all the ABSLMA tide gauge benchmarks, measurement biases and two-hourly tropospheric scale biases at each site were estimated.

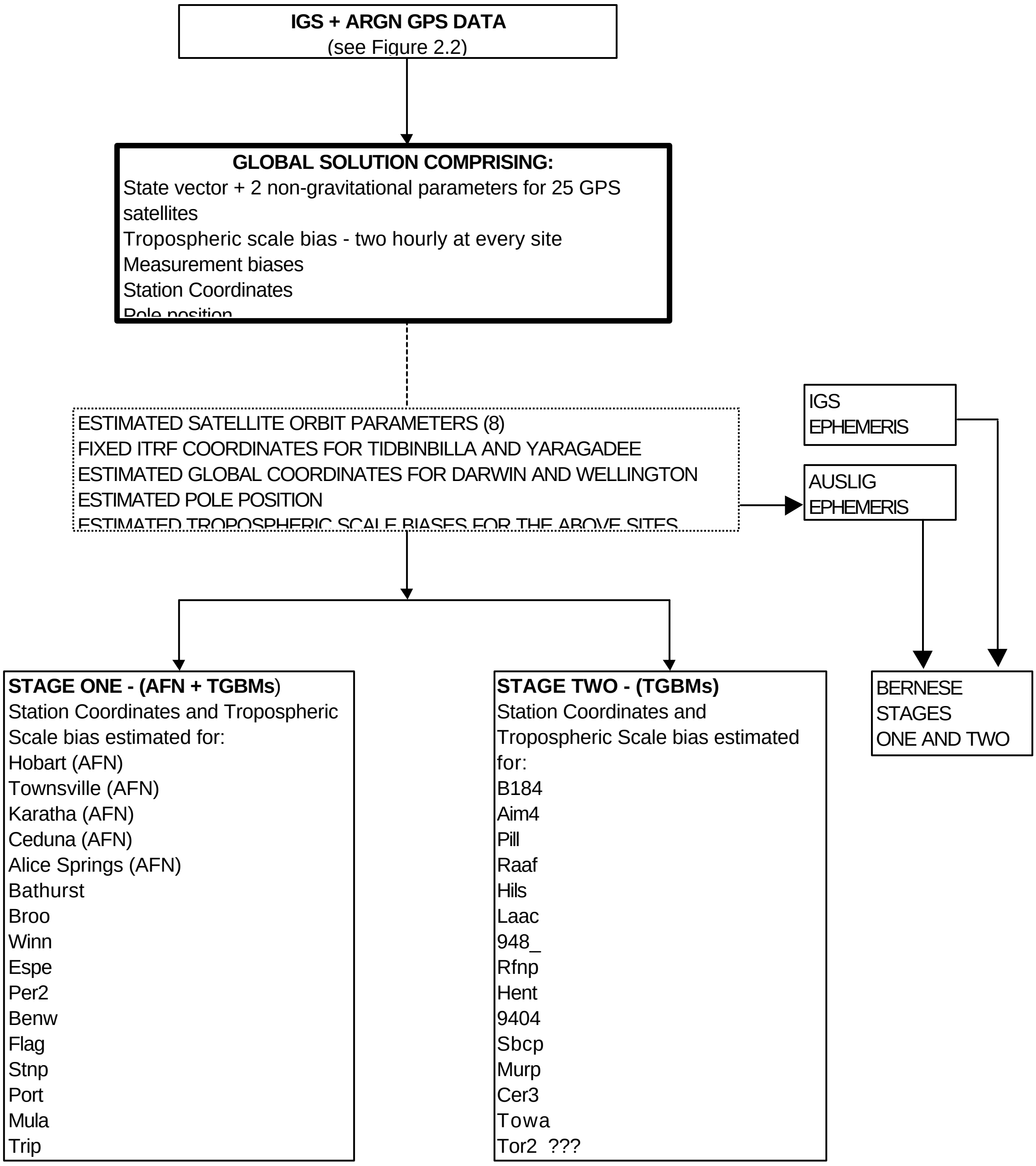


Figure 3.1 Computaion Procedure for the May 1995 ABSLMA GPS Data

4. COMPUTATION STANDARDS.

Using the MicroCosm software package (Martin, 1993) for state-of-the-art satellite orbit determination and geodetic parameter estimation, the computation standards adopted adhered closely to the recommended IERS standards. The computation standards that were followed are set out below as Observable Modelling, Orbit Modelling, Reference System and Station Position Modelling, and Parameters Estimated.

4.1 OBSERVABLE MODELLING

OBSERVABLES	Ionosphere corrected L1 double difference carrier phase
RECEIVER CLOCKS	Receiver clock offsets estimated, time tags and observations corrected.
TROPOSPHERE	Modified Hopfield Model. Meteorological data is generally not available. Therefore, defaults values for temperature, relative humidity and pressure are used. T = 293.16 K (20° C), RH = 40%, P = 1013.5 mb (scaled for the station altitude)
CYCLE SLIPS AND AMBIGUITIES	Cycle slip detection and repair . Ambiguities and cycle slips estimated as measurement biases.
GENERAL RELATIVITY	General relativistic gravitational delay included in the observation model

4.2 ORBIT MODELLING

EARTH'S GRAVITATIONAL POTENTIAL MODEL	Goddard Earth Model-T3 (GEM-T3) to degree and order 8 and adopting the IERS values for C21 (= -0.17E-09) and S21 (= 1.19E-09) coefficients.
SOLID EARTH TIDES POTENTIAL	The model of Christodoulidis et al. (1988) is used to compute the Earth Tide potential at the satellite. The tidal potential is expressed in terms of the amplitude and phase of the tidal constituents. Table 4.1 lists the principal tidal constituents, their Darwinian descriptions and their Doodson Argument Number. The amplitudes are related to their contribution to the elasticity parameter, k_2 , the second degree Love number. The values used for k_2 ,the frequency dependant Love numbers which represent the elastic response of the 1066A Earth Tide Model of Gilbert and Driewonski (1975) are those computed by Wahr (1981).
OCEAN TIDE POTENTIAL	The model of Christodoulidis et al. (1988) together with the principal tidal constituents listed in Table 4.1 is used to compute the Ocean Tide potential at the satellite. The global tidal heights are obtained from the tidal models of Schwiderski (1980a, 1980b, 1983) The major tidal constituents in the long period, diurnal and semi-diurnal bands are available in the form of spherical harmonic coefficients on a 1° X 1° grid.
THIRD BODY PERTURBATIONS	Sun, Moon and Planets are modelled as point masses
SOLAR RADIATION PRESSURE	The GPS Rock 4 and Rock 42 SRP models of Fliegel et al. (1992) are used.
Y-BIAS	Modelled as a general acceleration in the GPS Y-axis direction

4.3 REFERENCE SYSTEM AND STATION POSITION MODELLING

PRECESSION	IAU76
NUTATION	IAU80
POLAR MOTION	IERS Bulletin B - 5 day smoothed values.
EARTH ROTATION	IERS Bulletin B - 5 day smoothed values.
PLATE MOTION	NUVEL NNR-1 (no net rotation) model is used. The ITRF93 velocity field, which comprises a combination of the NUVEL geological model and estimated geodetic model determined from combined SLR, GPS and VLBI observations. Figure 4.1 shows the steps in determining the coordinates of the terrestrial reference frame. The station coordinates are updated to the campaign epoch by applying the ITRF93 station velocities.
PLANETARY AND LUNAR EPHEMERIS	Jet Propulsion laboratory Development Ephemeris 200 (JPL DE200) and Lunar Ephemeris 200 (LE200)
STATION DISPLACEMENT: SOLID EARTH TIDE LOADING	The Love and Shida numbers which characterise the Earth's elastic response are given below: $l_2 = 0.609$ and $h_2 = 0.0852$ respectively.
STATION DISPLACEMENT: OCEAN TIDE LOADING	The method of Schnerneck (1991) is implemented using the Schwiderski (1980a, 1980b, 1983) global ocean tide model. This method uses the load Love numbers of the Gutenberg-Bullen A and the PREM-C Earth models for the elastic response of the Earth to under tidal frequencies. The eleven tidal constituents listed in Table 4.2 are used in the station displacement computations due to ocean tide loading.

Parameters Estimated

GLOBAL	Station coordinates Pole position (if IERS final values are not available)
ARC	Satellite state vector at epoch Solar radiation pressure scaling factor once per arc Y-bias once per arc Measurement biases for ambiguities and cycle slips Tropospheric scale bias every two hours at every station

5. RESULTS AND ANALYSIS.

Figures 5.1 (a-c) show the precisions for ellipsoidal height, east and north components of four daily solutions. The precisions of the east component is generally better than one centimetre. The precisions of the north component is generally better than 0.5 centimetre. The only significant outliers in the east component are at the Wellington and Townsville ARGN sites. The only significant outlier in the north component (2.5 cms.) is at Davis ARGN site. Although the precisions of the estimated heights at most sites were better than two cms., with a significant number of sites having a repeatability of better than 1.5 cms., there were some sites at which the estimated heights had a repeatability of more than two cms. As a test for accuracy, the estimated GPS height differences at a selected number of sites were compared with the precise spirit levelled height differences. The geoid-spheroid separation values were obtained Ausgeoid93. These comparisons are listed in Table 4.1.

The differences in the height comparisons can be attributed to poorly determined GPS ellipsoidal heights, antenna phase centre variations and uncertainty in geoid-spheroid separation value. The first two causes are clearly demonstrated by the 800 metre and 26 metre lines at Cape Ferguson and Thevenard. At both these sites different antenna types were used at very closely place sites and the ellipsoidal heights (from figure 5.1) were poorly estimated -- resulting in large inaccuracy.

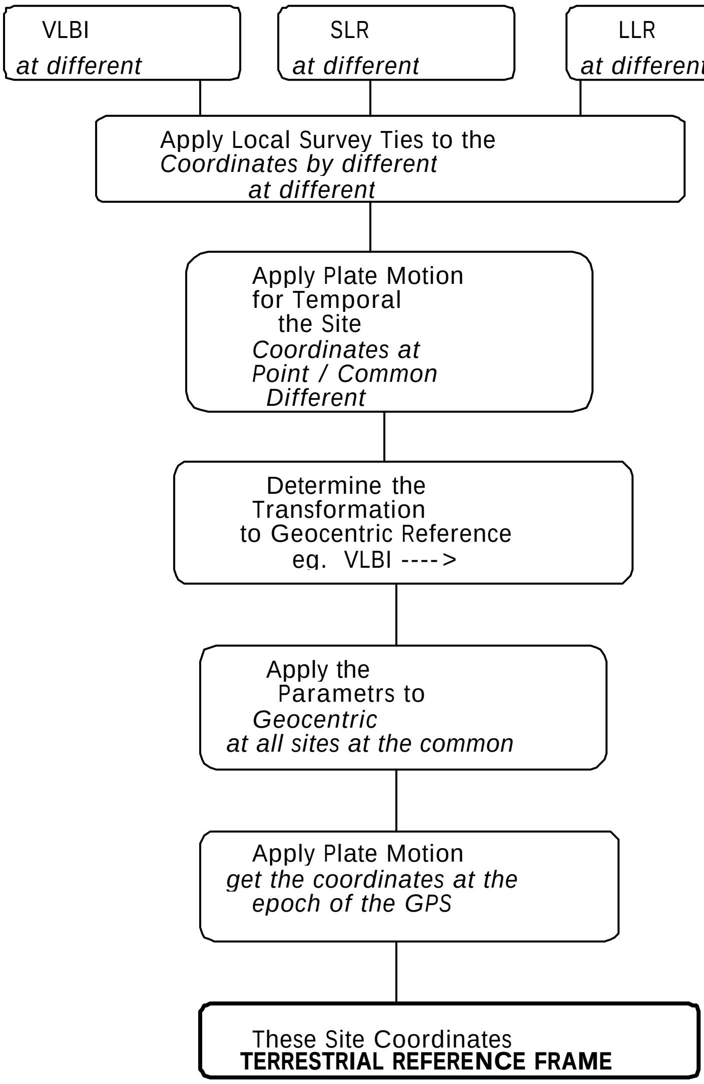


Figure 4.1 Determination of the Global Terrestrial Reference Frame.

At this stage the causes of poor height estimates (having a repeatability greater than 2.5 cms.) is uncertain. Usually height uncertainties are attributed to the wet troposphere. However, the two-hourly tropospheric scale bias estimates show smooth variations of less than a few percent. A point in case are the two inland array marks (RAAF and WINN) at the Darwin tide gauge which are less than a km. Apart. The daily height estimates for RAAF range from -6 cm. to +5 cm. from the mean value over the four days; having a repeatability of 3.5 cms. The nearby WINN site has a height repeatability of 1.5 cms. Both sites were occupied by identical receiver types.

Alternately, when comparing the good height estimates at the Antarctic sites with the poor estimates at an island site close to the equator (COCOS) indicate that the stability or otherwise of the troposphere poses a limitation to accurate heighting with GPS. Similar arguments can be proposed for DARW and AIM4.

6. CONCLUSIONS.

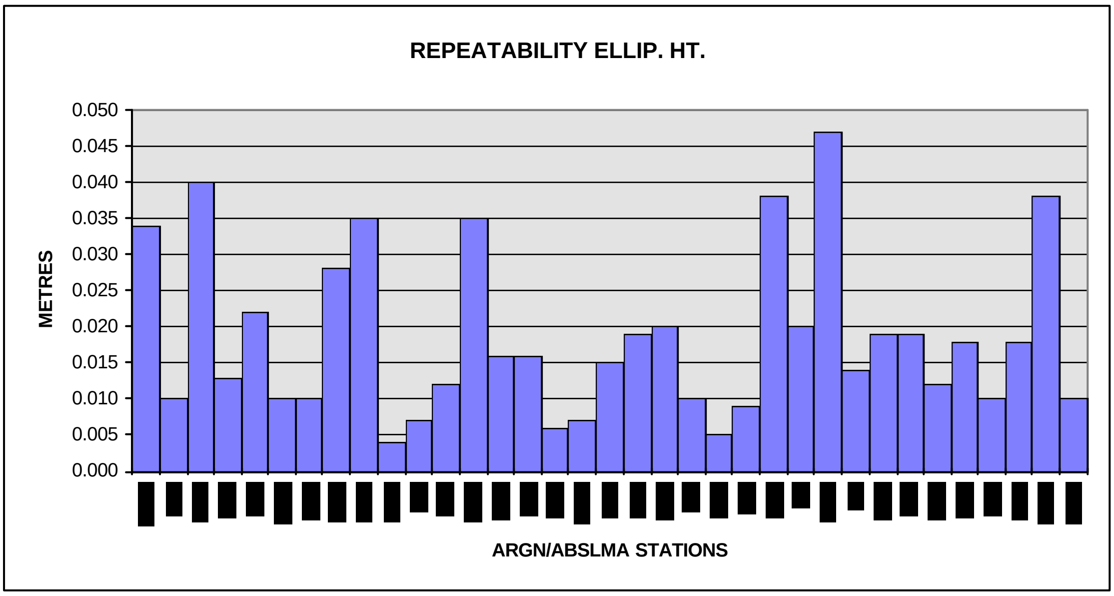
From the analysis of five days of continuous GPS data at the ABSLMA, ellipsoidal heights can be determined at precisions at the 15 to 20 mm level. The precisions can, however, be improved, by longer occupancies at the tide gauge benchmarks -- prefereably permanent. Testing for GPS heighting accuracies by comparing GPS derived orthometric heights differences with precise spirit levelling height differences is significantly limited by the inherent uncertainty in the geoid. It is preferable therefore, to

Table 3.5 Tidal constituents used to compute the Dynamic Geopotential due to Earth and Ocean Tides

DARWIN SYMBOL	**DOODSON NUMBER**	**DESCRIPTION**
Sa	056554	
Ssa	057555	solar semiannual
	058554	
Mm	065455	lunar monthly
Mf	075555	lunar fortnightly
	075565	
Q1	135655	
	145545	
O1	145555	principal lunar diurnal
	155455	
M1	155655	
π1	162556	
P1	163555	principal solar diurnal
S1	164556	
	165545	
K1	165555	lunar/solar diurnal
	165565	
	166554	
	167555	
S1	175455	
OO1	185555	
N2	245655	larger lunar elliptic semidiurnal
	255545	
M2	255555	principal lunar semidiurnal
L2	265455	smaller lunar elliptic
	271557	
T2	272556	
S2	273555	principal solar semidiurnal
R2	274554	
K2	275555	luni/solar semidiurnal
	285455	
	295555	

Table 4.2 Tidal constituents used to compute Ocean Tide Loading.

DARWIN SYMBOL	**DOODSON NUMBER**	**DESCRIPTION**
Ssa	057555	solar semiannual
Mm	065455	lunar monthly
Mf	075555	lunar fortnightly
Q1	135655	
O1	145555	principal lunar diurnal
K1	165555	lunar/solar diurnal
P1	163555	principal solar diurnal
M2	255555	principal lunar semidiurnal
S2	273555	principal solar semidiurnal
N2	245655	larger lunar elliptic semidiurnal
K2	275555	luni/solar semidiurnal


REPEATABILITY ELLIP. HT.

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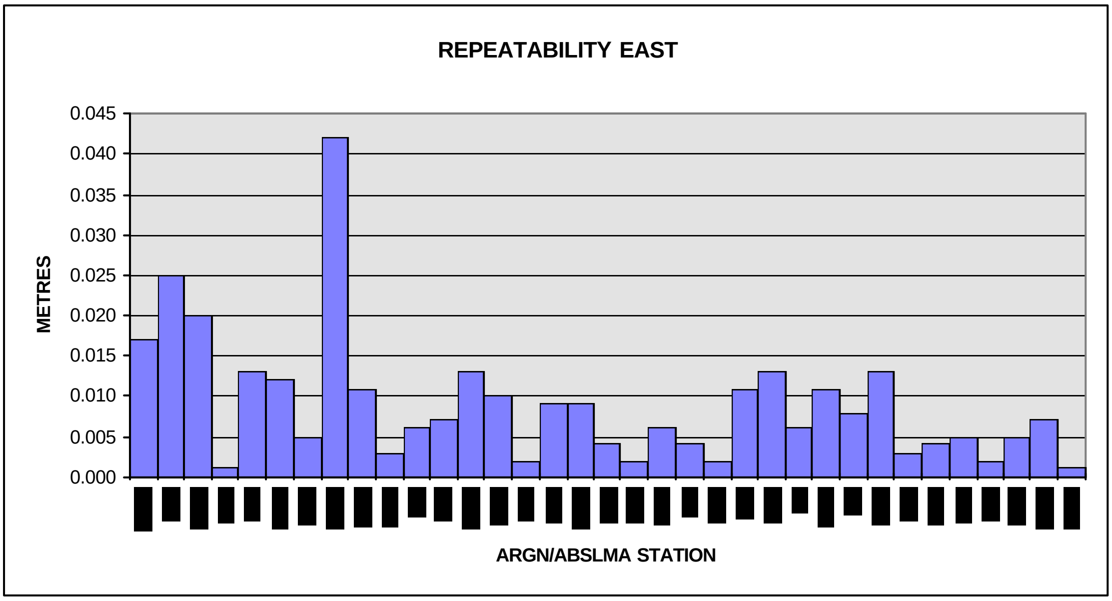
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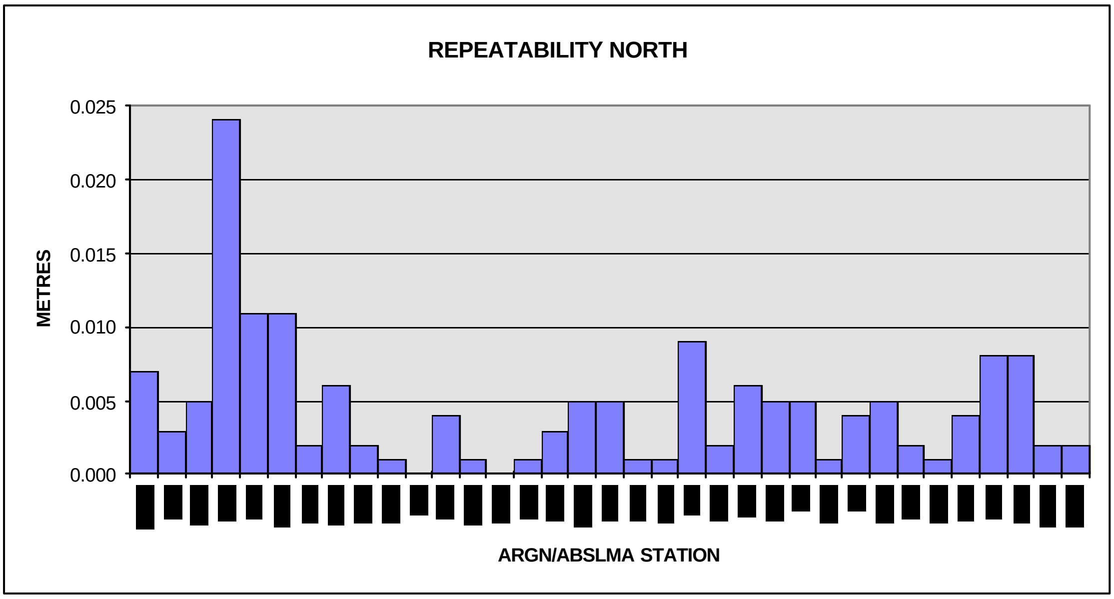
REPEATABILITY NORTH

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Table 5.1 Comparison: Estimated GPS Height Differences and Levelled Height Differences.

Tide Gauge	Line	½D Height ½ GPS	½D Height ½ Levelling	Line Length
Spring Bay				
	9404 - SBCP	0.216	0.217	1.6 Km
	SBCP - Trip	10.233	10.238	4 Km
Broome				
	B184 - Broo	1.265	1.255	1.6 Km
Hillary's				
	Hils - Per2	42.271	42.346	14 Km
Port Kembla				
	948_- Flag	43.753	43.789	5.86
Cape Ferguson				
	AIM4 - TOW2	23.870	23.974	800 metres
Thevenard				
	Murp - Thvp	27.371	27.396	13 Km.
	Cedu - Cer3	0.131	0.265	26 metres

establish GPS ellipsoidal heighting accuracies by long term or permanent GPS occupations. In this regard, it is preferable (and more meaningful) to compare changes (from epoch to epoch) in GPS determined ellipsoidal height differences with changes in precise spirit levelled height differences. It is also preferable to compare GPS determined ellipsoidal heights with ellipsoidal heights determined from another ultra-high precision satellite geodetic technique such as, Satellite Laser Ranging (SLR).

GPS ellipsoidal height estimates are still limited by tropospheric refraction effects -- as can be seen by the precisions obtained at the Antarctic sites (stable troposphere) verses those at say at the Darwin and Cocos Island sites (varying tropospheric conditions).

An additional limiting factor in GPS ellipsoidal height accuracies is the phenomena of "antenna phase centre variation". This is demonstrated by the larger discrepancies in the orthometric height differences at the Cape Ferguson and Thevenard tide gauge benchmarks; where different GPS antenna types were used over very short baselines.

With the current developments in SLR, it is proposed that in the short and medium term, colocated GPS, mobile SLR, Absolute Gravity measurements and precise spirit levelling experiments be undertaken by establishing at least two "laboratory" sites on a semi-permanent to permanent basis.

BIBLIOGRAPHY.

Baker, T. F. (1990) "GPS Measurements of Absolute Mean Sea Levels." Workshop on Geodetic Fixing of Tide Gauge Bench Marks, Flinders University, Adelaide, 22-23 January 1990.

Bilham, R. (1991) "Earthquakes and Sea Level: Space and Terrestrial Methodology on a Changing Planet" Reviews of Geophysics, 29, pages 1-29.

Blewitt, G. (1989) "Carrier Phase Ambiguity Resolution for the Global Positioning System Applied to Geodetic Baselines up to 2000 km" JPL Geodesy and Geophysics Preprint No. 172, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

Blewitt, G. (1990) "An Automatic Editing Algorithm for GPS Data" JPL Geodesy and Geophysics Preprint No. 192, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

Blewitt G., M.B. Heflin, F.H. Webb, U.J. Lindqwister and R.P. Malla (1992) "Global Coordinates with Centimeter Accuracy in the International Terrestrial Reference Frame Using GPS" Geophysical Research Letters, Vol. 19, No 9, Pages 853-856.

Bock Y, R.Abbot , C.C. Counselman, S.A. Gourevitch and R.W. King (1985) "Establishment of Three-Dimensional Geodetic Control by Interferometry With the Global Positioning System" Journal of Geophysical Research, Vol. 90, No 89, Pages 7689--7703.

Carter, W.E., W. Scherer and J.M. Diamante (1987): "Measuring Absolute Sea Level", Sea Technology.

Carter, W., D. Aubrey, T. Baker, C. Boucher, C. LeProvost, D. Pugh, W. R. Peltier, M. Zumberge, R.H. Rapp, R.E. Schultz, K.O. Emery and D.B. Enfield (1989) " Geodetic Fixing of Tide Gauge Bench Marks.", Woods Hole Oceanographic Institution, Technical Report WHOI-89-31.

Carter, W.E., G. Peter, G. Sasagawa, F. Klopping, K. Berstis, R. Hilt, P. Nelson, G. Christy, T. Niebauer, W. Hollander, H. Seeger, B. Richter, H. Wilmes and A. Lothammer (1994): "New Gravity Meter Improves Measurements" EOS, Transactions, AGU, Vol. 75, No. 8.

Christodoulidis, D.C., D.E. Smith, R.G. Williamson, and S.M. Klosko (1988): " Observed Tidal Braking in the Earth/Moon/Sun System", JGR,Vol. 93, No. B6, pages 6216-6236.

Dedes, G.C. (1987) "Baseline Estimation from Simultaneous Satellite Laser Tracking", OSU Report No. 384, Dept. of Geodetic Science and Surveying, Ohio State University, Ohio.

DeMets, C., R.G. Gordon, D.F. Angus, and S. Stein (1990): "Current Plate Motions", Geophys. J. Int., 101, pages 425 - 478.

Dong, D. and Y. Bock (1989) " Global Positioning System Network Analysis With Phase Ambiguity Resolution Applied to Crustal Deformation Studies in California". JGR Vol. 94, No B4, Pages 3949-3966.

Dziewonski, A.M. and D.L. Anderson (1981): "Preliminary Reference earth Model", Phys. Earth Planet. Interior, 25, 297-356.

Fliegel, H.F., W.A. Feess, W.C. Layton and N.W. Rhodes (1985) "The GPS Radiation Force Model", Proceedings, First International Symposium on Precise Positioning with the Global Positioning System, Rockville, Maryland.

Fliegel, H.F. and T.E. Gallini (1989) "Radiation Force Models for Block II GPS Satellites", Proceedings, Fifth International Symposium Satellite Positioning, Las Cruces, New Mexico.

Fliegel, H.F. and T.E. Gallini (1992) "Global Positioning System Radiation Force Model for Geodetic Applications", JGR, Vol. 97, No B1, pages 559-568.

Gilbert, F. and A.M. Driewonski (1975): " An Application of Normal Mode Theory to the Retrieval of Structural Parameters and Source Mechanisms for Seismic Spectra", Phil.Trans R.Soc, 278A, pages 187-269.

Govind, R. (1994): “Absolute Sea Level Monitoring in Australia: The Geodetic Fixing of Tide Gauge Benchmarks using the Global Positioning System”, PhD. Dissertation, University of Colorado, Boulder, USA.

Heflin, M.,W. Bertiger, G. Blewitt, A. Freedman, K. Hurst, S. Lichten, U. Lindqwister, Y. Vigue, F. Webb, T. Yunck and J. Zumberge (1992) "Global Geodesy Using GPS Without Fiducial Sites", Geophysical Research Letters, Vol. 19, No 2, Pages 131-134.

Herring, T.A. (1983) "The Precisions and Accuracy of Intercontinental Distance Determinations Using Radio Interferometry", P.hD. Dissertation, MIT.

King, R.W. and G. Blewitt (1989) "Present Capabilities of GPS for High Precision Regional Surveys", JPL Geophysics and Geodesy Preprint No. 190, presented IAG, Edinburgh, Scotland.

Kleusberg, A. (1986) " Ionospheric Propagation Effects in Geodetic Relative GPS Positioning", Manuscripta Geodaetica Volume 11 Number 4 Springer International.

Klopping, F.J., G. Peter, D.S. Robertson, K.A. Berstis, R.E. Moose and W.E. Carter (1991): "Improvements in Absolute Gravity Observations", JGR, Vol. 96, No. B5, pages 8295-8303.

Lambeck, K. (1988) "Geophysical Geodesy: The Slow Deformations of the Earth" , Oxford Science Publications.

Larson, K. and D. Agnew (1991), "Application of the Global Positioning System to Crustal Deformation Measurement: Precision and Accuracy". JGR Vol. 96, No B10, Pages 16,547-16,565.

Lindqwister, U., J. Zumberge, F. Webb and G. Blewitt (1991), "Few Millimeter Precision For Baselines in the California Permanent GPS Geodetic Array". Geophysical Research Letters Vol. 18, No 6.

Ma, C., J.W. Ryan and D.S. Caprette (1992) "Crustal Dynamics Project Data Analysis -- 1991 VLBI Geodetic Results 1979-1990", NASA Tevh.Mem. 104552.

Martin, T.V. (1993) "MicroCosm", Vols. 1-4, Van Martin Systems, Rockville, Maryland.

Minster, J.B. and T.H. JOrdan (1978): "Present Day Plate Motions", JGR, 83, pages 5331 - 5354.

Rabbel, W. and J. Zschau (1985): " Static Deformations and Gravity Changes at the Earth's Surface due to Atmospheric Loading, J. Geophys., 56, 81-99.

Ray, J.R., C. Ma, J. Ryan, T.Clark, R. Eanes, M. Watkins, B. Schutz and B. Tapley (1991)", Comparison of VLBI and SLR Geocentric Site Coordinates". Geophysical Research Letters, Vol. 18, No 2, Pages 231-234.

Scherneck, H-G (1991): "A parametrized Solid Earth Tide Model and Ocean Tide Loading Effects for Global Geodetic Baseline Measurements" Geophys.J.Int. No. 106, pages 677-694.

Schwiderski, E.W. (1980a): "Ocean Tides, Part I: Global Ocean Tidal Equations", Marine Geodesy, Vol. 3, pages 161-217.

Schwiderski, E.W. (1980b): "Ocean Tides, Part II: A Hydrodynamical Interpolation Model", Marine Geodesy, Vol. 3, pages 219-255.

Schwiderski, E.W. (1983): "Atlas of Ocean Tidal Charts and Maps, Part 1: The Semidiurnal Principal Lunar Tide M2", Marine Geodesy, Vol. 6, Numbers 3-4 pages 219-265.

Smith, D., R. Kolenkiewicz, P.Dunn, S. Klosko, J. Robbins, M. Torrence, R. Williamson, E. Pavlis, N. Douglas and S. Fricke (1991) "LAGEOS Geodetic Analysis -- SL7.1" NASA Tech. Memo. 104549, Goddard Space Flight Center, Greenbelt, Maryland.

Soler, T., W. Strange and L. Hothem (1992) "Accurate Determination of Cartesian Coordinates at Geodetic Stations using the Global Positioning System", Geophysical Research Letters, Vol. 19, No. 6, pages 533-536.

Stolz, A. and D. Larden (1979) "Seasonal Displacement and Deformation of the Earth by the Atmosphere", J. Geophys. Res., 84, 6185-6194.

Wahr, J.M. (1981): "Body Tides on an Elliptical, Rotationg, Elastic Oceanless Earth", Geophys.J.Ast.Soc.64, pages 677-703.

Wahr, J.M. (1981): "The Forced Nutations of an Elliptical Rotationg Elastic and Oceanless Earth", Geophys.J.Ast.Soc.64, pages 705-727.

Wanless, B. and G. Lachaplle (1988) "NOVAS - an Automated Program for the Precise Reduction of GPS Static Carrier Phase Observations" Manuscripta Geodaetica, 13, pages 201-209.