Toitu te whenua
Land Information
New Zealand

Realisation of Ross Sea Region Geodetic Datum 2000

OSG Technical Report 15

Office of Surveyor-General

3 December 2000

Contents

Foreword

Land Information New Zealand (LINZ) (Toitu te Whenua) was established in July 1996. It is a government department with roles and responsibilities in the following key areas:

Regulatory Responsibilities	**LINZ Regulatory Groups**
National spatial reference system and cadastral survey infrastructure	Office of the Surveyor-General
Topographic and hydrographic information	National Topographic/Hydrographic Authority
Land Titles	Office of the Registrar-General of Land
Setting rules for rating valuations	Office of the Valuer-General
Crown Property	Office of the Chief Crown Property Officer (Crown Property)
Assisting the government address land related aspects of Treaty of Waitangi issues	Office of the Chief Crown Property Officer (Crown Property)

The main role of the department is a regulatory one, to set guidelines and standards and manage contracts for carrying out the day to day business associated with each of the key areas.

LINZ also offers a range of services to customers related to land titles, survey plans and Crown property. Land Titles and Survey services are carried out by the Operations Group based in LINZ regional offices throughout New Zealand.

The LINZ overarching objective is to be recognised as a world leader in providing land and seabed information services.

Chief Executive:
Dr Russ Ballard
Land Information NZ
P O Box 5501
Wellington
Phone: 0-4-460 0110
Fax: 0-4-472 2244
Email: info@linz.govt.nz
Internet http://www.linz.govt.nz/

REALISATION OF ROSS SEA REGION GEODETIC DATUM 2000

1 Project Team

The development of a new datum in Antarctica has involved many personnel in the collection of field data both from New Zealand and the United States of America. Without their input this project would never have been realised. Larry Hothem, US Geological Survey, is thanked for his support for this project and the provision of survey data from the TAMDEF project. Contribution to the realisation of the new datum has involved:

Matt Amos	Land Information New Zealand
Graeme Blick (report author)	Land Information New Zealand
Merrin Pearse	Land Information New Zealand
John Ritchie	Land Information New Zealand
Paul Denys	University of Otago
Chris Pearson	University of Otago

Any queries regarding this project should be directed to:

The Surveyor-General
Office of the Surveyor-General
Land Information New Zealand
PO Box 5501
Wellington.

2 Introduction

The Land Information NZ Geodetic Strategic Business Plan [*Office of the Surveyor-General* 1998] identified as Goal 1 'To provide a cost-effective system that can generate current geometric coordinates of points in terms of a globally accepted system to an acceptable and defined accuracy'. The purpose of this goal is to provide an accurate geometric spatial reference framework covering New Zealand's area of land and seabed interests (including New Zealand, Pacific Islands and the Ross Dependency) and facilitate the department's commitment to geodetic and cadastral automation.

In line with this goal LINZ implemented a new geocentric datum for New Zealand, New Zealand Geodetic Datum 2000 (NZGD2000), in August 1999 [*Pearse* 2000]. The relationship between NZGD2000 and the International Terrestrial Reference System (ITRS) has been realised through the International Terrestrial Reference Frame 1996 (ITRF96) coordinates, specified at epoch 2000.0 (a reference date of 1 January 2000).

A report by Blick [1999] recommended that a new datum for the Ross Sea Region of Antarctica be implemented in line with that developed in New Zealand. This was adopted as a LINZ policy as detailed in OSG Policy 99/4.

In November 2000 a new datum, Ross Sea Region Geodetic Datum 2000 (RSRGD2000) was realised for the Ross Island area of the Ross Sea Region of Antarctica. This report details the parameters for, and realisation of, RSRGD2000.

3 Requirements for a Spatial Infrastructure in The Ross Dependency

Through the Scientific Committee on Antarctic Research (SCAR) Geodesy in Antarctica (GIANT) working group there is coordination of geodetic activities in Antarctica, with a major objective to develop an Antarctica wide geodetic infrastructure [*refer internet site http://www.scar-ggi.org.au/geodesy/giant.htm*]. New Zealand contributes to this overall infrastructure. GIANT developed a 1998-2000 geodetic programme with its objectives to:

- provide a common geographic reference system for all Antarctic administrators, scientists and operators;
- contribute to global geodesy for the study of the physical processes of the earth and the maintenance of the precise terrestrial reference frame;
- provide information for monitoring the horizontal and vertical motion of the Antarctic.

In addition to the SCAR requirements there are significant efficiency gains through the provision of a uniform common survey infrastructure in Antarctica as detailed by Grant and Belgrave [1996]. Future New Zealand specific requirements include the provision of a spatial infrastructure in the Ross Dependency that will support:

- continued mapping (both topographic and hydrographic);
- the ability to spatially reference different data sets into a common GIS system;
- the NZ Antarctic Programme whose uses will include spatial referencing for safety, rescue, environmental protection, navigation, monitoring change, and science.

The lack of physical and manmade features in Antarctica, particularly in those areas covered by ice and snow, means that spatial referencing of most activities relies heavily on a survey infrastructure. The provision of such a spatial infrastructure also supports the similar activities of other nations working in the Ross Dependency.

Land Information NZ's activities in the Ross Dependency must now focus on the development of an infrastructure that satisfies Primary Users as discussed in the New

Zealand Geodetic Strategic Plan [*Office of the Surveyor-General* 1998]. A survey infrastructure that supports Primary Users through core Government activities (i.e. mapping to support science and hydrographic charting to meet Government objectives and reduce risk to Government from its activities in Antarctica) will often support other Secondary Users such as tourists.

In view of the need to maintain a uniform spatial infrastructure to satisfy both national and international requirements, it was necessary to update the current spatial infrastructure that consisted of numerous local and often unconnected datums.

4 Defining Parameters for RSRGD2000

To meet LINZ and SCAR requirements Blick [1999] recommended that the defining parameters for RSRGD2000 be the same as for NZGD2000. The recommendation was adopted and accordingly the following parameters as detailed in OSG Policy 99/4 were defined.

1. The new datum for the Ross Dependency of Antarctica will be know as 'Ross Sea Region Geodetic Datum 2000' (RSRGD2000).

2. The ellipsoid associated with RSRGD2000 will be the Geodetic Reference System 1980 (GRS80 ellipsoid).

3. RSRGD2000 will be based on and aligned with the International Terrestrial Reference Frame 1996 (ITRF96) at epoch 1 January 2000 (2000.0) which has a geocentric origin.

4. All points coordinated in terms of RSRGD2000 will have coordinates defined at epoch 1 January 2000 (2000.0).

5. Coordinates of geodetic marks in terms of RSRGD2000 will not be fixed. Coordinates will be updated as required to account for new observations or localised mark movement.

Unlike New Zealand, the Ross Sea Region does not straddle a tectonic plate boundary, accordingly it was not considered necessary to develop a specific velocity model for the Ross Sea Region but rather use the NUVEL1A velocities to model coordinates and data to the reference epoch of 2000.0.

5 Geodetic Network and Data

Rather than utilise existing survey data to develop a new datum for the Ross Sea Region it was decided to use new high precision GPS observations to develop the high level framework for the new datum. As a later step it is proposed to incorporate and transform into this framework the earlier data and separate datums such as Camp Area Datum.

The new network covers an area approximately 500 kilometres by 300 kilometres in the vicinity of Ross Island, Antarctica (Fig 1). Land Information NZ and the US Geological Survey (USGS) have collected the data used as part of a joint survey programme in the Ross Dependency since 1996. It encompasses observations made by USGS from approximately 36 Trans-Antarctic Deformation Survey (TAMDEF) sites over a four-year period, approximately 75% of which have been observed during multiple campaigns. Observations from approximately 36 additional sites in a LINZ campaign in 1996/1997 are also used. Ground marking consists of either brass pins grouted into rock or for the TAMDEF stations a stainless steel rod with 5/8 inch Whitworth threaded top grouted into rock and with a yellow plastic identification marker.

The McMurdo Sound GPS continuous tracking station was assigned a Zero Order status. All marks that had been occupied in at least three successive 24-hour sessions over multiple years were assigned First Order status, marks that had at least one 24 hour session were assigned Second Order status and other marks Third Order status.

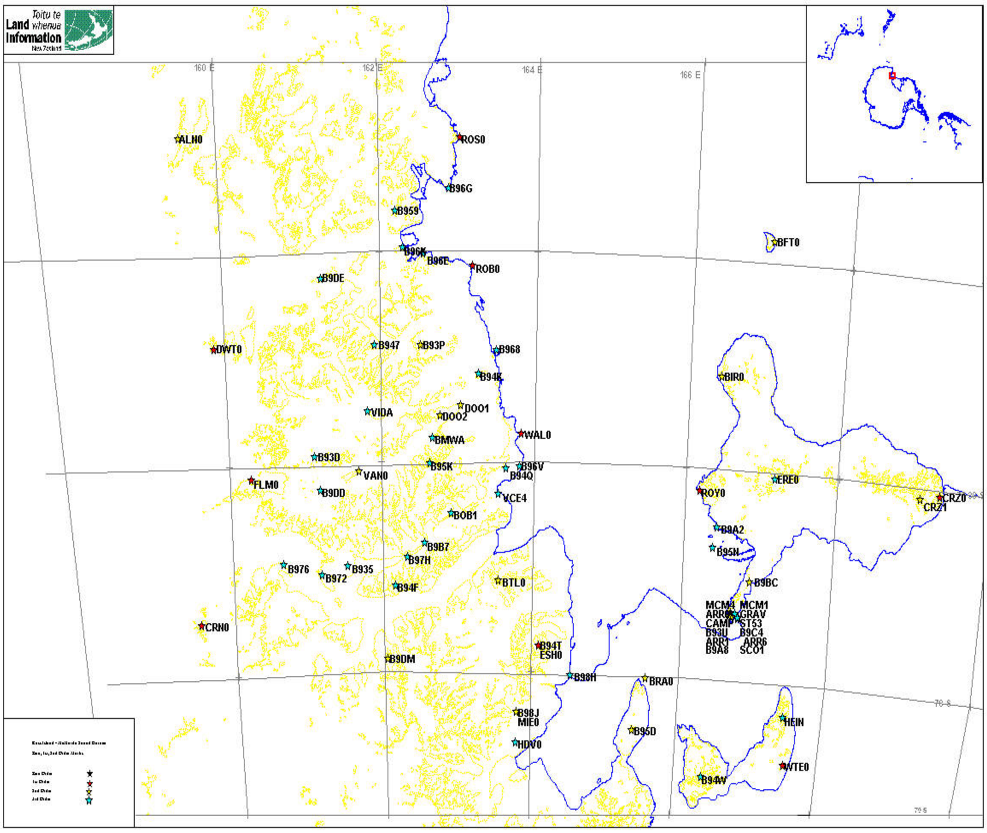

Fig. 1. Ross Sea Region geodetic network.

6 Realisation of Zero, First, Second and Third Order Stations

The processing of the data and realisation of the Zero, First, Second, and Third Order 2000 coordinates were carried out to OSG specifications by the School of Surveying, University of Otago under contract to Land Information New Zealand. A comprehensive report on this processing is attached as ANNEX A.

In total data from 86 stations were processed. These were:

- 10 Zero Order stations;
- 17 First Order stations;
- 17 Second Order stations;
- 42 Third Order stations.

The 10 Zero Order stations were IGS permanent GPS stations located around the perimeter of the Antarctic continent and in the Southern Hemisphere. These were used to connect the network to the ITRS and realise ITRF96 coordinates. The 17 First Order stations observed in three or more campaigns were used to determine epoch 2000 coordinates and velocity estimates. The Second and Third Order stations were transformed to epoch 2000 coordinates using the NUVEL1A velocity field model (refer to ANNEX A). The resulting coordinates at epoch 2000.0 form the basis of RSRGD2000 and have been loaded into Land*online*.

Data from earlier surveys will be readjusted in terms of these stations or transformed to RSRGD2000 coordinates to form a unified datum in the Ross Island area of the Ross Sea Region. As further data is made available it will also be incorporated into the new datum.

7 Summary

High precision GPS observations collected over the past four years in the Ross Island area of the Ross Sea Region of Antarctica have been utilised to develop the Zero, First, Second, and Third Order framework for the Ross Sea Region Geodetic Datum 2000. Coordinates have been calculated in terms of ITRF96 and generated at epoch 2000.0. These coordinates are now available through Land*online* and the Geodetic Database.

8 References

Blick, G. 1999: Ross Dependency (Antarctica): Current and future geodetic activities. *Land Information New Zealand, Office of the Surveyor-General Technical Report 7*.

Grant D.B. and D.V. Belgrave 1996: Antarctic Survey Requirements. *Report held on Land Information NZ file ANT/04/00/03-ZNO*

Pearse, M. 2000: Realisation of the New Zealand Geodetic Datum 2000. *Land Information New Zealand, Office of the Surveyor-General Technical Report 5*.

Office of the Surveyor General 1998: New Zealand Geodetic Strategic Business Plan: *Land Information New Zealand, Office of the Surveyor-General Technical Report 3*.

Annex A

Details of processing, realisation of RSRGD2000.

Paul Denys
Chris Pearson

Department of Surveying
Otago University

Department of Surveying

The Realisation of Zero, First and Second-Order Stations for the Ross Sea Region Geodetic Datum 2000

Paul Denys
Chris Pearson

Prepared for:

Land Information New Zealand
National Office
Lambton House
PO Box 5501
Wellington
New Zealand

Tel: +64 (04) 460 0110
Fax: +64 (04) 472 0575

Prepared by:

Department of Surveying
Otago University
PO Box 56
Dunedin
New Zealand

Tel: +64 (03) 479 7585
Fax: +64 (03) 479 7586

October 2000

Final Report
Report Number 2000/0728 - version 2.2

Contents

Glossary

ARP	Antenna Reference Point
BPE	Bernese Processing Engine
DOSLI	Department of Survey and Land Information
IGS	International GPS Service
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
LINZ	Land Information New Zealand
MRP	Mark Reference Point
QIF	Quasi Ionosphere-Free Algorithm
rms	Root mean square
TAMDEF	Trans-Antarctic Deformation Network
UNAVCO	University NAVSTAR Corporation

1 Executive Summary

The realisation of a network of stations to form the Ross Sea Geodetic Datum 2000 has been completed. GPS data observed during four campaigns (1996 – 1997, 1997 – 1998, 1998 –1999, and 1999 – 2000), from the Trans-Antarctic Deformation Network (TAMDEF) has been processed. In addition, GPS data observed by the Department of Survey and Land Information (DOSLI) during the 1996-1997 campaign as part of the Antarctic Datum Unification Project has also been processed. A location diagram of the region, including ten IGS continuous tracking stations, is given in **Figure 1**.

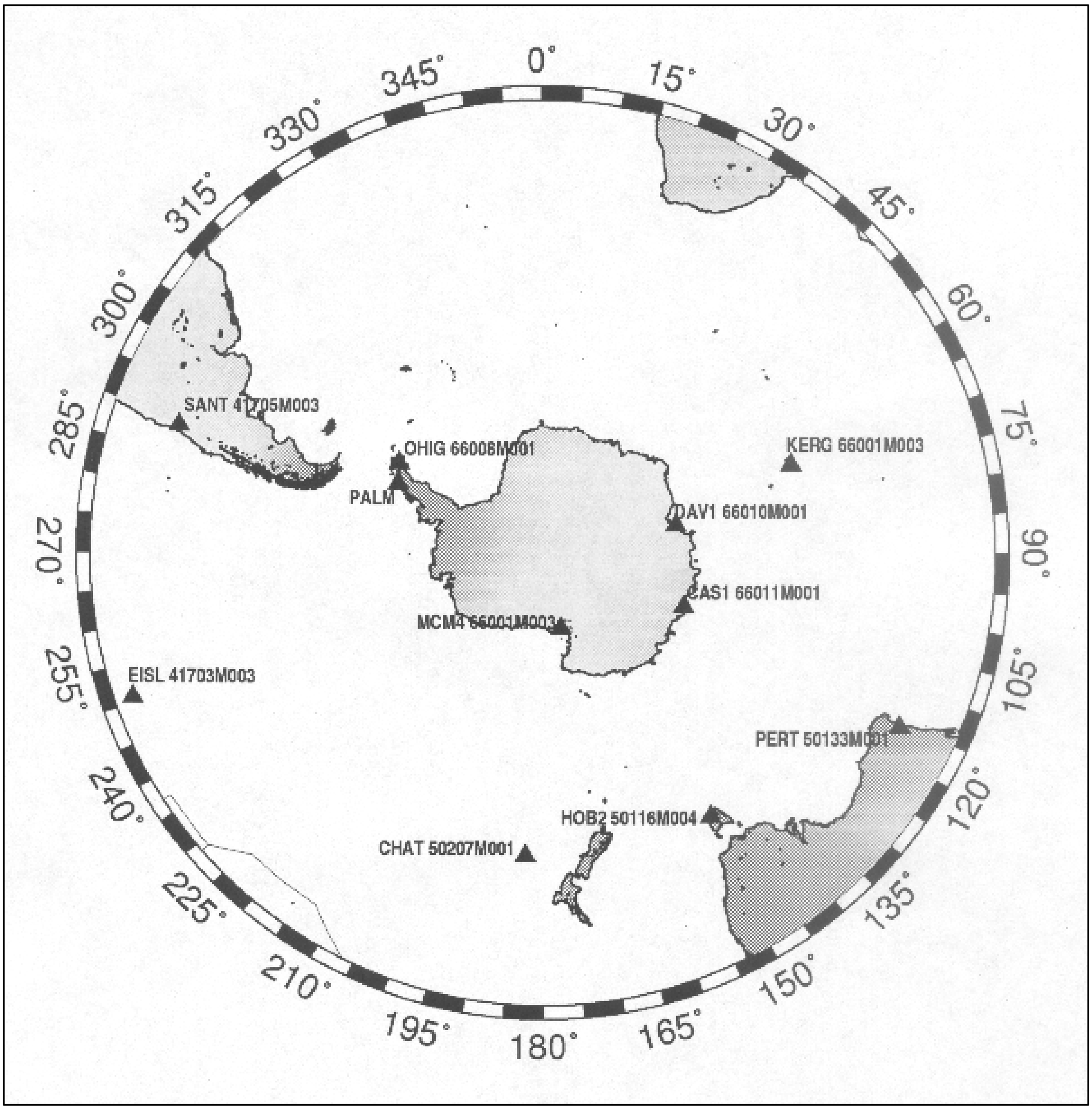

Figure 1: Location of the Ross Sea Region network

In total, data from a total of 86 sites has been processed, including ten IGS permanent GPS stations located around the perimeter of the Antarctic continent and elsewhere in the Southern Hemisphere. Of the remaining sites, 34 stations form the TAMDEF network and 42 sites are included as part of the Antarctic Datum Unification Network.

The data has been processed as a series of daily network solutions. The principal steps taken include:

1. Baseline selection;
2. Clean GPS data;
3. Daily session network solution;
4. Campaign (or epoch) network solution; and,
5. Epoch 2000 coordinate and velocity estimates (using four epochs).

The daily sessions are then combined to form a campaign network solution. For sites that were observed in three or more campaigns (17 stations), the campaign solutions were used to determine epoch 2000 coordinates and velocity estimates. The remaining sites (59 stations), most of which were occupied only once, were transformed to epoch 2000 using the NUVEL1A velocity field model.

Two solutions were initially computed. These two solutions processed the observed GPS data using a 10° elevation mask and a 20° elevation mask. The horizontal coordinates from the two solutions agreed well, the mean difference being 1-2mm and the maximum difference being less than 5mm. The vertical coordinates agree at the 10-20mm level, with the maximum difference being in the order of 50mm.

Generally, there is little difference between the two solutions (10° and 20° elevation masks) in both the horizontal coordinate and velocity components. However, the solution using the lower elevation satellite data (10° elevation mask) does produce more precise vertical coordinates and velocity estimates. On the basis of this analysis, and in agreement with LINZ personnel, it was agreed that only the 10° elevation mask solution would be provided in this report.

This work, the Ross Sea Geodetic Datum 2000, has been commissioned by Land Information New Zealand (LINZ) in order to satisfy a milestone for the Minister of Land Information. The work has been carried out by the Surveying Department, University of Otago.

2 GPS post processing

2.1 Post processing software

All GPS data was processed in a SUN SPARC Station environment (Operating System 5.6) using the Bernese Post Processing Software (Rothacher and Mervart, 1996). Within the Bernese software, the Bernese Processing Engine (BPE) was utilised to automate the GPS data processing. The velocity estimation was carried out using software developed at the University of Otago[1].

Software	Version
Bernese GPS Post Processing Software	4.0
Velocity and Coordinate Estimation Software	2000

The Bernese software consists of a series of programs that provide the following operations:

1. Transfer — decode GPS observational data; decode satellite ephemeris data
2. Orbit — create satellite orbits
3. Pre-processing — single point positioning; detect and correct cycle slips; detect and delete bad data
4. Processing — baseline solutions; network solutions

2.2 Processing methodology

The processing methodology is displayed diagrammatically as a structure diagram given in Figure 2.

The transfer and orbit processing stages are normally executed once for each observing session. This procedure decodes the GPS observations and satellite orbit data from the data format in which the data was supplied and enables the user to create satellite orbits for a specific time period.

The pre-processing stage starts with the computation of a single point position for each station, this giving an initial indication of the quality of the data. In addition to the absolute position, the receiver clock error is also estimated.

[1] Software program developed by Mark Henderson as part of his PhD studies. The software has been compared and tested against a similar program, ADJCOORD, developed at the former DSIR (Crook, 1992).

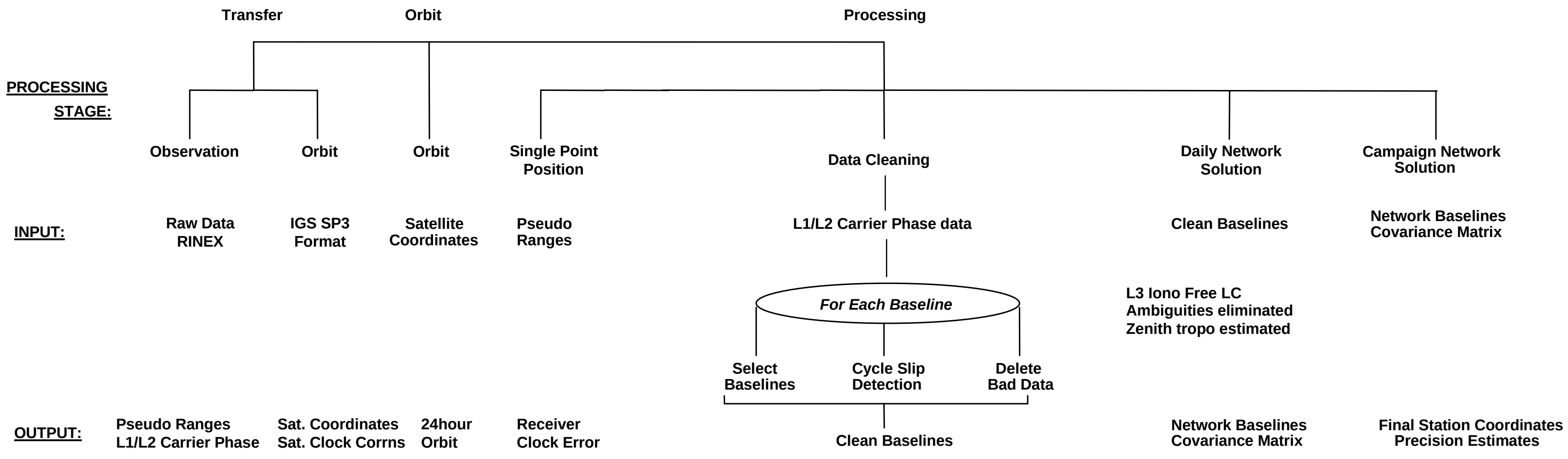

Figure 2: Structure diagram of the Bernese GPS post processing methodology

The following steps are performed for every baseline formed in the network including baseline selection and data cleaning. The criteria used are given in Sections 0 and 0 and can be summarised as:

- **Baseline selection**
  - Determined by selecting the baselines with the maximum number of observations
  - Select independent baselines only

- **Clean GPS data**
  - Analyse triple difference residuals (ionosphere free linear combination)
  - Fix cycle slips
  - Delete bad observations

When the baselines are cleaned, a daily network solution is created using the ionosphere free linear combination. Seven daily network solutions are then combined to form a weekly solution. For each of the weekly solutions, the troposphere parameters are re-estimated thereby ensuring continuity between the daily solutions. See also Section 0.

- **Daily session network solutions**
  - Least squares daily network solutions
  - Carrier phase ambiguities pre-eliminated
  - Estimation of zenith troposphere delay parameters (1 parameter per 2 hours)

- **Weekly network solutions**
  - Least squares weekly network solutions
  - Solve for zenith troposphere delay parameters (1 parameter per 2 hours)
  - Troposphere parameters post-eliminated

The final step is to combine all of the weekly network solutions to form a campaign network solution. This solution uses both the final coordinates, and the coordinate covariance matrix from each network solution, to estimate the final campaign solution.

- **Campaign network solution**
  - Least squares solution by combining all weekly network solutions
  - Coordinates constrained to the mid epoch of the campaign
  - Estimated coordinate covariance matrix
  - Data and coordinate precision analysis

2.1.1 Cycle slip detection and repair

The Bernese GPS software checks data for cycle slips on an epoch-by-epoch basis. It does this by forming the triple difference residual for each epoch, and tests this against a user defined tolerance given in terms of the apriori L_1 and L_2 carriers phase standard deviations. If the test fails, that is, the null hypothesis that "`No Cycle Slip Has Occurred`" is false, then a search is implemented in the ambiguity space for a whole number of cycles. If the carrier phase ambiguity is found, then this is applied to all the remaining observations. If no such integer is determined, the observation is deleted.

2.1.2 Data deletion

The GPS data can be "flagged as bad" for a number of reasons. These include:

- **Indeterminate Cycle Slip:** If a cycle slip cannot be repaired using the strategy given in Section 0, the observation is deleted. This is based on the standard deviation of a carrier phase observable with σ_{L1} = 1.1 mm and σ_{L2} = 1.2 mm.
- **Unpaired Observations:** Data that does not have the corresponding second frequency observation.
- **Low Elevation Satellite:** Observed satellites below 10°.
- **Small Data Group:** Data in a group of less than 300 seconds (5 minutes) is considered too small to process. Each data group must be separated by a gap of greater than 150 seconds (2.5 minutes).

2.1.3 Network solution characteristics

After each baseline has been cleaned by eliminating bad data and correcting cycle slips, all baselines for each observing session are combined into a single daily network solution using the ionosphere free linear combination. Characteristics of this solution are shown in Table 1.

- **Daily Network Solution Characteristics**

Observable :	$\phi_{L3} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2}\phi_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}\phi_{L2}$	Ionosphere free linear combination
Input :	ϕ_{L1}, ϕ_{L2}	L1 and L2 carrier phase observables
	300 seconds (5 minutes)	Epoch interval
	10°	Elevation angle
Parameters :	ΔX, ΔY, ΔZ	Baseline components
	dr	Zenith troposphere path delay 1/2hours (12 / 24 hours)
	N	Carrier phase ambiguities Pre-eliminated
Output :	Daily set of normal equations	Baseline components Zenith troposphere parameters
	Station coordinates Zenith troposphere estimates	

Table 1 : Daily network solution variables

In addition to the estimation of the baseline components (ΔX, ΔY, ΔZ), the zenith troposphere path delay is also estimated in order to parameterise the residual troposphere delay.

Standard GPS processing techniques provide several ambiguity resolution techniques, such as wide laning and the Quasi Ionosphere Free (QIF) algorithm. However, for this set of GPS data, the carrier phase ambiguities have not been resolved, but rather pre-eliminated from the solution. Ambiguity resolution was not carried out owing to the quantity of data and the reasonably short time to undertake the processing, analysis and reporting. It is not considered that this will significantly reduce the precision of the final coordinates or velocity estimates since the observing sessions are generally long with a corresponding large data quantity. It does improve considerably the processing productivity.

The weekly network solution is essentially the same as a daily network solution, except that the troposphere parameters are continuous over the whole week.

- **Weekly Network Solution Characteristics**

Observable :	$\phi_{L3} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2}\phi_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}\phi_{L2}$	Ionosphere free linear combination
Input :	Seven daily sets of normal equations	Baseline components Zenith troposphere parameters
	300 seconds (5 minutes)	Epoch interval
	10°	Elevation angle
Parameters :	ΔX, ΔY, ΔZ	Baseline components
	dr	Zenith troposphere scale factors 1/2hours (12 / 24 hours) Post eliminated
Output :	Weekly set of normal equations Station coordinates Covariance matrix Zenith Troposphere estimates	Baseline components

Table 2 : Weekly network solution variables

The final campaign network solution combines all weekly network solutions in the same manner. The only parameters estimated are the three components, ΔX, ΔY, ΔZ for each baseline.

2.3 ITRF coordinate frames

All data processing has been carried out using the ITRF97 coordinate and velocity field. The coordinates of the IGS stations (MCM4, CAS1, DAV1, OHIG, EISL, HOB2, KERG, PERT, SANT) were transformed to the epoch of the GPS data and constrained during the data processing. Because the ITRF realisations agree with each other at the centimetre level after about 1993, it is not critical that the satellite orbits and ground station coordinates are based on identical ITRFyy realisations (Gurtner *et al.*, 1997). Therefore, it is preferable that the latest and best realisation should be used for densification purposes, namely ITRF97.

The daily networks are combined into weekly coordinate sets, which are subsequently combined to form a campaign solution. It is at this stage that the IGS sites are constrained to their appropriate ITRF96 coordinate at the mean epoch of the campaign using the ITRF96 velocity model. The mean epochs are tabulated in Table 3.

Campaign	Mean Epoch
1996 – 1997	23 – 11 – 1996 (1996.899)
1997 – 1998	13 – 12 – 1997 (1997.951)
1998 – 1999	02 – 01 – 1999 (1999.005)
1999 – 2000	09 – 01 – 2000 (2000.025)

Table 3 : Campaign mean epochs

For each campaign a set of station coordinates and an associated covariance matrix was generated.

3 The data set

3.1 The Ross Sea data set

GPS stations have been occupied in the Ross Sea Region during four Antarctic summer field seasons of 1996 – 1997, 1997 – 1998, 1998 – 1999 and 1999 – 2000. These sites have been classified as zero-order, first-order, second-order and third-order sites. During this time, data from up to ten IGS continuous tracking sites have been utilised in order to tie the network of stations into the ITRS/ITRF system. These sites are listed in Table 4.

IGS Station	Site Identification	Data Usage
Casey	CAS1 66011M001	Daily
Chatham Island	CHAT 50207M001	3 days / campaign
Davis	DAV1 66010M001	Daily
Easter Island	EISL 41703M003	3 days / campaign
Hobart	HOB2 50116M004	3 days / campaign
Kerguelen Islands	KERG 91201M002	3 days / campaign
McMurdo	MCM4 66001M003	Daily
O'Higgins	OHIG 66008M001.	Daily
Perth	PERT 50133M001	3 days / campaign
Santiago	SANT 41705M003	3 days / campaign

Table 4 : IGS sites and data usage. (Data usage is nominal, provided data is available.)

Provided that the GPS data is available, the four IGS sites located on the Antarctic plate, (CAS1, DAV1, MCM4, OHIG), have been incorporated into the network on a daily basis. To strengthen the tie between the Ross Sea Region network and the global reference frame, data from six additional IGS sites located in the Southern Hemisphere (CHAT, EISL, HOB2, KERG, PERT, SANT) have also been incorporated into the network. This data is for three different days, which are separated at approximately equal intervals, during each of the four campaigns. (See also Table 5.)

Most of the Ross Sea Region sites that have been re-occupied during the four field campaigns are the TAMDEF stations. Between 18 and 23 sites have been re-occupied each year, including new marks that were installed. There are 34 TAMDEF marks with, 17 sites designated as first-order and 17 sites as second-order. These sites are displayed in Figure 3 and Figure 4 respectively. The site PALM, located on the Antarctic Peninsular, is included in this set of first-order marks (but not included in Figure 3).

The remaining marks (42 sites) were mostly occupied as part of the DOSLI (now LINZ) Antarctic Datum Unification Network. The majority of these marks were occupied once during the first campaign in 1996 – 1997. These sites are shown in Figure 5.

A summary of the sites occupied during each campaign is tabulated in Table 5 – Table 7. This information is collated for each GPS week. Thus, a site is marked as being occupied if it was observed during a GPS observation session irrespective of whether that session was for 12 hours, one day (24 hours) or seven days. Hence, most of the four primary IGS sites have data for the majority of each field campaign. One exception is OHIG during the 1998 – 1999 campaign and data for DAV1 was only available for the last three weeks during the 1997 –1998 campaign.

Some of the first-order marks have also been occupied on a semi-continuous basis during each campaign, for example ARR0, ROB0. The station PALM is operated as a permanent site although it does not appear to be part of the IGS network of stations.

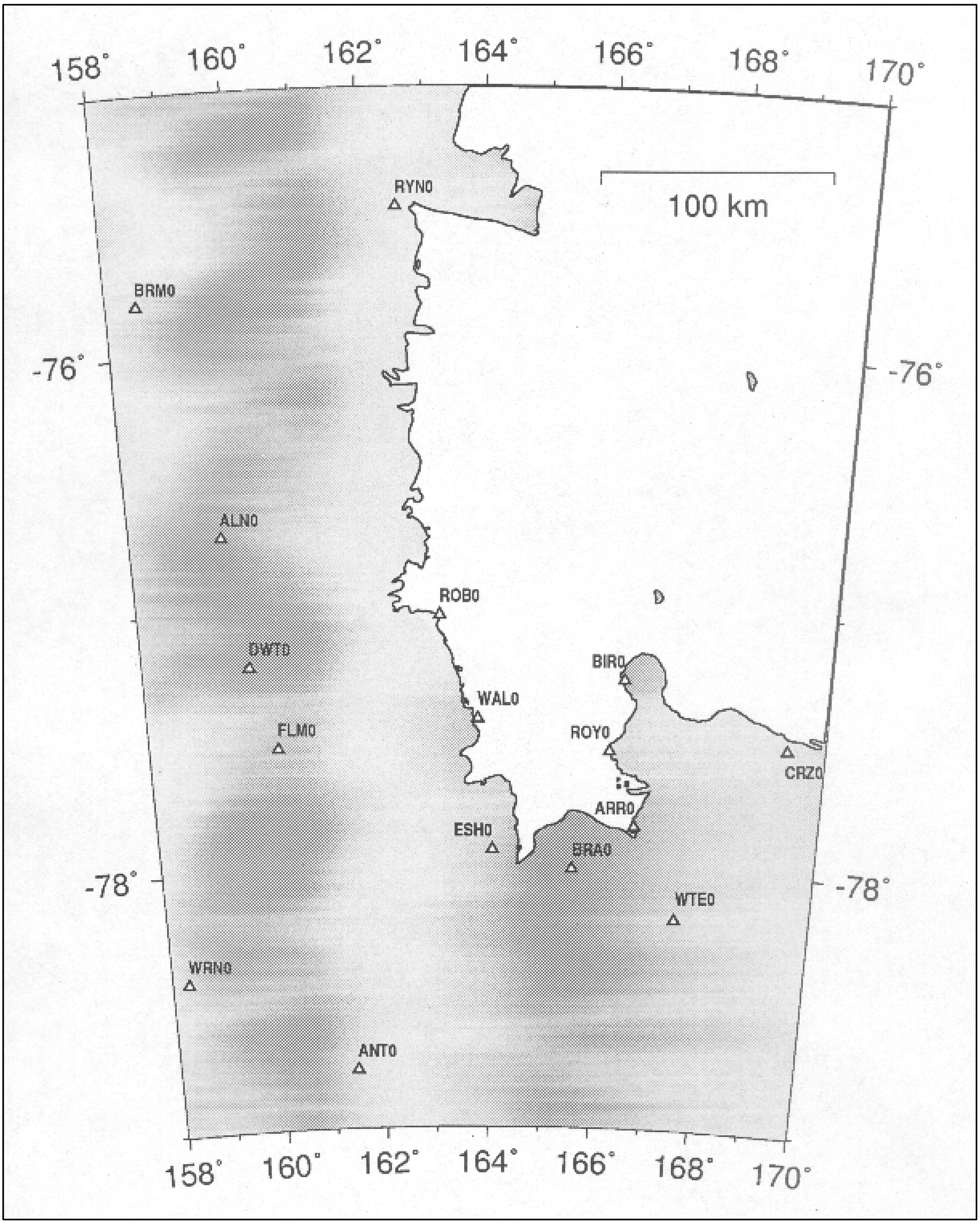

Figure 3: Ross Sea Region, first-order stations.
(Excluding PALM, Antarctic Peninsular, (65°S, 64°W).)

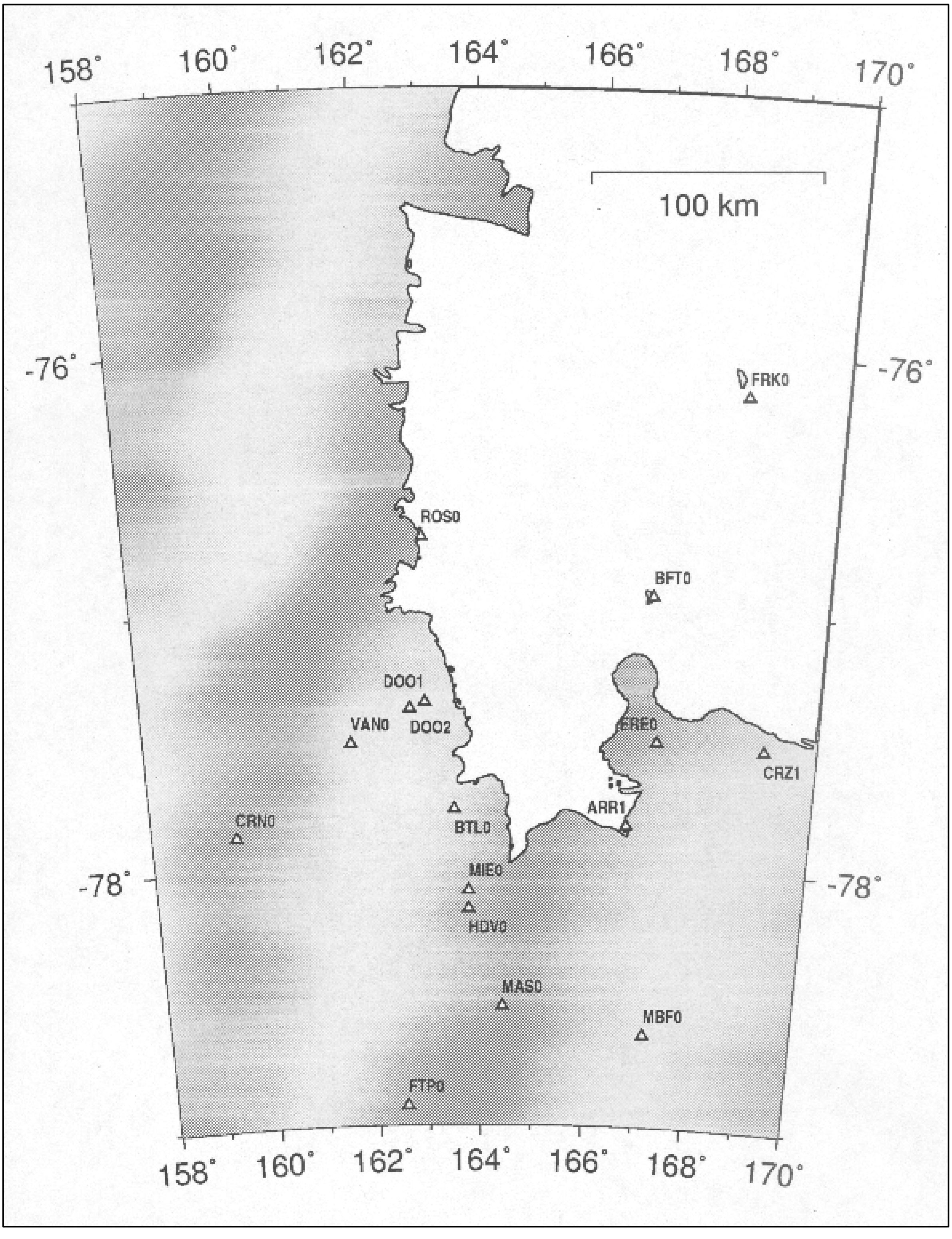

Figure 4: Ross Sea Region, second-order stations

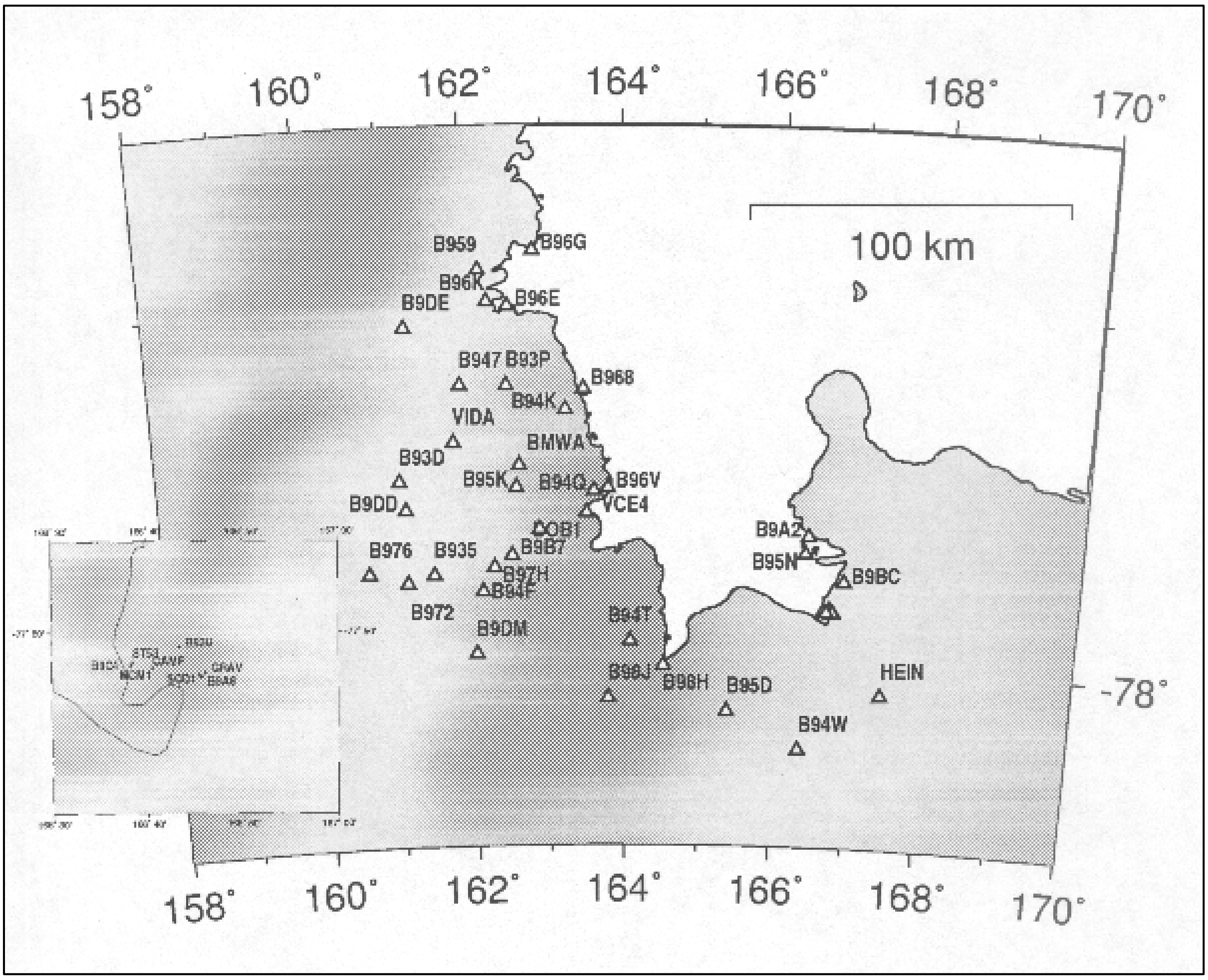

Figure 5: Ross Sea Region, third-order stations

Campaign		**1996 – 1997**							**1997 – 1998**								**1998 – 1999**						**1999 - 2000**							
GPS Week		880	881	882	883	884	885	886	932	933	934	935	936	937	938	939	988	989	990	991	992	993	1040	1041	1042	1043	1044	1045	1046	1047
Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Station	Weeks Occupied																													
Zero Order Stations																														
MCM4	29	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
CAS1	28	F	F	F	F	F	F		F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
DAV1	23	F	F	F	F	F	F							F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
OHIG	21	F	F	F	F	F	F		F	F	F	F	F	F	F								F	F	F	F	F	F	F	F
CHAT	12		F		F		F			F		F			F			F		F		F		F			F		F	
EISL	12		F		F		F					F			F			F		F		F		F			F		F	
HOB2	12		F		F		F			F		F			F			F		F		F		F			F		F	
KERG	12		F		F		F			F		F			F			F		F		F		F			F		F	
PERT	12		F		F		F			F		F			F					F		F							F	
SANT	12		F		F		F			F		F			F			F		F		F		F			F		F	
First Order Stations																														
ALN0	7		X	X							X	X	X											X	X					
ANT0	9			X	X				X	X	X														X	X	X	X		
ARR0	20	X	X	X	X	X	X	X	X	X					X	X		X	X	X	X	X			X	X			X	X
BIR0	6		X	X							X													X	X	X				
BRA0	6	X					X												X	X				X	X					
BRM0	6			X					X	X								X									X	X		
CRZ0	7			X							X								X	X				X	X	X				
DWT0	7		X	X	X						X	X												X	X					
ESH0	7											X							X	X	X				X	X	X			
FLM0	7	X	X								X	X							X		X	X								
PALM	22								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ROB0	27	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ROY0	9		X	X				X		X	X								X					X	X	X				
RYN0	12			X	X				X	X				X	X	X		X									X	X	X	X
WAL0	10	X	X	X		X					X	X									X		X	X	X					
WRN0	5				X				X	X									X	X										
WTE0	10			X	X	X	X	X	X	X															X	X	X			

Table 5 : Zero and first order station occupations

3.1.1 GPS receivers and antennas

Geodetic, dual frequency receivers have been used throughout all four campaigns with the receiver/antenna descriptions included in the RINEX data files using standard IGS naming conventions. These have been predominately the Trimble 4000SSE, 4000SSSI and Ashtech Z12 receivers with Dorne Margolin Choke Ring antennas. In 1997-1998, some of the antennae used were Ashtech Geodetic L1/L2 and one was a Trimble Geodetic Compact L1/L2.

Further information (exact equipment models used, serial numbers and instrument owners) for the last three campaigns (1997 - 1998, 1998 - 1999, 1999 – 2000), is provided in the data documentation.

The IGS sites have used a variety of receivers during the four campaigns. These have mostly been Rogues, Turbo Rogues, the SNR 8100 and Ashtech receivers. The same Dorne Margolin Choke Ring antennas have been used at all sites.

The receivers and antennas for the Antarctic Datum Unification points were not consistently described in the RINEX files. Often the IGS naming conventions were not adhered to and even the same receiver/antenna combination at a single site could differ from day to day. These have been translated as accurately as possible.

Campaign		**1996 – 1997**							**1997 – 1998**								**1998 – 1999**						**1999 - 2000**							
GPS Week		880	881	882	883	884	885	886	932	933	934	935	936	937	938	939	988	989	990	991	992	993	1040	1041	1042	1043	1044	1045	1046	1047
Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Station	Weeks Occupied																													
Second Order Stations																														
BFT0	4														X	X													X	X
BTL0	5				X	X		X																	X	X				
CRN0	4				X				X	X	X																			
FRK0	4														X	X													X	X
FTP0	5								X	X	X														X	X				
MAS0	6																X	X	X						X	X	X			
MBF0	5										X						X	X			X	X								
ROS0	4								X								X	X	X											
ARR1	2																							X	X					
ARR6	2																							X	X					
CRZ1	2		X	X																										
DOO1	3																				X		X	X						
DOO2	3																				X		X	X						
ERE0	1																		X											
HDV0	1										X																			
MIE0	3			X			X	X																						
VAN0	4			X	X	X															X									

Table 6 : Second order station occupations

Campaign		1996 – 1997							1997 – 1998								1998 – 1999						1999 - 2000							
GPS Week		880	881	882	883	884	885	886	932	933	934	935	936	937	938	939	988	989	990	991	992	993	1040	1041	1042	1043	1044	1045	1046	1047
Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Station	Weeks Occupied																													
Third Order Sites																														
B935	1					X																								
B93D	1				X																									
B93P	2				X	X																								
B93U	1						X																							
B947	1				X																									
B94F	1					X																								
B94K	1					X																								
B94Q	1					X																								
B94T	2						X	X																						
B94W	1							X																						
B959	1				X																									
B95D	2						X	X																						
B95K	1					X																								
B95N	1							X																						
B968	1					X																								
B96E	1				X																									
B96G	1				X																									
B96K	1				X																									
B96V	1					X																								
B972	1					X																								
B976	1					X																								
B97H	1					X																								
B98H	1						X																							
B98J	1						X																							
B9A2	1							X																						
B9A8	1						X																							
B9B7	1					X																								
B9BC	2						X	X																						
B9C4	1						X																							
B9DD	1				X																									
B9DE	1				X																									
B9DM	3			X		X		X																						
BMWA	1					X																								
BOB1	1					X																								
CAMP	1																	X												
GRAV	1						X																							
HEIN	1						X																							
MCM1	1						X																							
SCO1	1						X																							
ST53	1						X																							
VCE4	1					X																								
VIDA	1				X																									

Table 7 : Third order station occupations

3.1.2 Antenna heights

Except for the IGS sites, all the TAMDEF sites used a levelling mount (compact UNAVCO spike mount). The advantage of this system is that all antenna heights are given directly as vertical measurements (no reductions necessary), and thus they are the same for all occupations. The levelling mounts were individually measured and an average antenna height value was determined to be 0.0794m. This is the distance between the monument reference point (MRP) and the antenna reference point (ARP).

In October 1999, the levelling mount structures were re-measured and found to be 0.686mm shorter, on average, than the height determined previously. The method used to make the original measurement cannot be confirmed, but irrespective of this, there does appear to be a small difference, some of which may possibly be wear and tear.

All stations have used the antenna heights as recorded in the RINEX data files. The only exception is the station PALM, which had a change of height during the campaign. See also Section 0.

The antennae used in the Antarctic Datum Unification project were mounted with tripods and therefore the antenna heights were not constant. Again, the value as given in the RINEX file has been used.

3.1.3 Phase centre eccentricities

The standard IGS antenna phase centre correction table has been used. This table assumes that the Dorne Margolin Choke Ring antenna is the standard antenna and applies corrections to other antenna to the choke ring antenna. These corrections account for antenna phase centre variations in azimuth and elevation.

3.1.4 Precise ephemeris and earth rotation parameters

The IGS computed precise ephemeris has been used for all data processing. This is a weighted combination of the post-processed ephemeris generated by the (seven) IGS analysis centres. In addition, the set of IGS earth rotation parameters that are derived in conjunction with the IGS precise ephemeris are also used. The set of earth orientation parameters includes the earth rotation offsets from the origin of the rotation axis and the UT1-UTC time difference.

3.2 Processed GPS data

3.2.1 Problem GPS data and stations

Several stations did exhibit problem data that was caused by either the hardware or by firmware problems in the field. These problems had already been identified and noted within the documentation or "READ.ME" files that accompanied the data. This data was not processed.

Difficulty was experienced in translating the OHIG RINEX data for the 1996 – 1997 campaign. Some of the header information needed to be removed. No other difficulty was experienced with the data from this site in later campaigns.

The station PALM had a change in the antenna height on the 31st December 1999 that was not noticed during the initial processing. The height change was made by the receiver's data logging software and was not caused by a physical change in the antenna. Apparently this site is also used for DGPS and RTK applications and it is therefore of benefit to these users to have the correct (L1 phase centre) antenna height recorded in the station logging software. The antenna height was changed from 0.1894m (L1 phase centre height) to the original value of 0.794 (ARP) for the remainder of the campaign.

3.2.2 Deleted GPS data and stations

Some of the initial and final data at a particular site was not processed. Some site occupations were sometimes started a few hours (1 – 3 hours) before 00:00 UT or continued for a few hour after the end of the UT day. These small sessions generally did not contain useful data and so, if noticed, were not processed.

In general, this problem did not affect many of the TAMDEF sites. However, it occurred frequently with the Antarctic Datum Unification project sites.

BTL1 was also removed as the mark was destroyed and was considered unreliable.

4 Network realisation and analysis

4.1 Campaign coordinate repeatability analysis

All observing sessions for each campaign (1996-1997, 1997-1998, 1998-1999 and 1999-2000), were combined to form a single campaign network. An estimate of the relative precision of the GPS data can be made by comparing the coordinate repeatability of the combined campaign network. This has been computed for each of the coordinate components (latitude, longitude, height) as well as the 3Drms value. This coordinate variance data for the 10° elevation mask solution is graphically displayed in **Figure 6**.

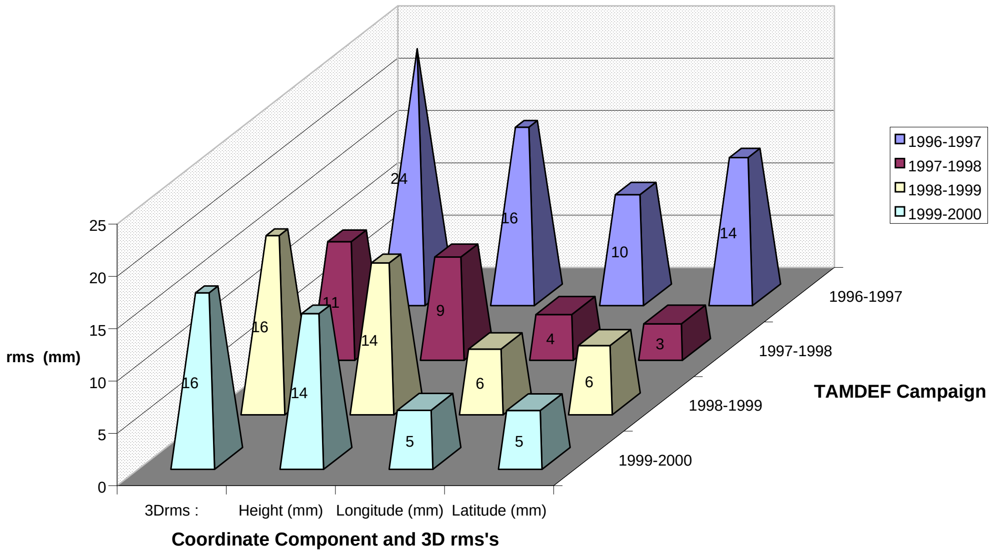

Figure 6 : Coordinate component repeatability and 3D rms for the 10° elevation mask solutions

The general trend has been for an improvement in the coordinate repeatability between 1996 and 2000. The best data was obtained during the 1997-1998 campaign. It is noticeable that there is little difference between the last two campaigns (i.e. 1998-1999 and 1999-2000).

Table 8 to Table 11 list the numerical data for the 10° elevation mask solution. Tabulated is the variance (given as a standard deviation) of the coordinate repeatability (and 3D rms), plus the maximum, minimum and range of the coordinate residuals.

	Elevation Mask 10° Latitude (mm)	Longitude (mm)	Height (mm)
Std Deviation :	14	10	16
3Drms :	24		
Count :	168		
Maximum :	46	36	66
Minimum :	-51	-32	-37
Range :	97	68	103

Table 8 : Coordinate repeatability for epoch 1996-1997

	Elevation Mask 10° Latitude (mm)	Longitude (mm)	Height (mm)
Std Deviation :	3	4	9
3Drms :	11		
Count :	195		
Maximum :	7	12	24
Minimum :	-31	-21	-50
Range :	38	33	74

Table 9 : Coordinate repeatability for epoch 1997-1998

	Elevation Mask 10° Latitude (mm)	Longitude (mm)	Height (mm)
Std Deviation :	6	6	14
3Drms :	16		
Count :	182		
Maximum :	23	21	51
Minimum :	-29	-30	-65
Range :	51	52	116

Table 10 : Coordinate repeatability for epoch 1998-1999

	Elevation Mask 10° Latitude (mm)	Longitude (mm)	Height (mm)
Std Deviation :	5	5	14
3Drms :	16		
Count :	321		
Maximum :	24	17	65
Minimum :	-51	-21	-52
Range :	75	38	117

Table 11 : Coordinate repeatability for epoch 1999-2000

Some of the maximum and minimum residuals are large (height component maximum 66mm, epoch 1996-1997). On inspection, most of these large residuals have been caused by part-day observation sessions (e.g. 1-3 hours) at the start of a multi-day site occupation. The data has corresponding large standard deviations and therefore does not significantly affect the network solution.

Figures 8 to 11 (Appendix A) give plots of the coordinate repeatability residual frequency distributions using 5mm bins for the 10° elevation mask solution. Overall, each graph does have a bell shape (normal distribution curve) that trends towards a peak in the centre (a greater number of smaller residuals) and flatten outs towards the edges.

4.2 Network coordinate and velocity estimates

The final epoch 2000 coordinate estimates and velocities were estimated (10° elevation mask) for sites occupied in more than three campaigns, and transferred to epoch 2000 (1^{st} January 2000) using the estimated velocity field. The input data included coordinate and covariance matrices from each campaign network.

For those sites that were not observed in multi-epochs, the final epoch 2000 coordinates were derived using the NUVEL1A plate motion velocity field.

The order of the marks is as follows:

Zero Order	The IGS permanent GPS sites.
First Order	TAMDEF sites occupied during three or more campaigns.
Second Order	TAMDEF sites occupied at least once
Third Order	LINZ sites occupied during the Antarctic Datum Unification Project (Campaign 1996-1997)

The site geodetic coordinates and precision estimates are given in Sections 0 - 0 for the 10° elevation mask solution. The cartesian and geodetic coordinates are also given in Appendix B and Appendix C.

4.2.1 Zero Order Sites

Coordinate Frame : ITRF96
Ellipsoid : GRS80
Velocity Field : Estimated
Epoch : 2000.000

	Cartesian Coordinates		**Geodetic Coordinates**		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) φ (° ′ ″) H (m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
CAS1 66011M001	-901776.153	0.1	110° 31' 10."9403	0.1	-87
	2409383.396	0.1	-66° 17' 00."0925	0.1	
	-5816748.437	0.1	22.459	0.1	
CHAT 50207M001	-4590670.985	0.1	-176° 33' 57."0221	0.1	80
	-275482.892	0.1	-43° 57' 20."8324	0.1	
	-4404596.710	0.1	57.989	0.1	
DAV1 66010M001	486854.560	0.1	77° 58' 21."4078	0.1	-74
	2285099.272	0.1	-68° 34' 38."3627	0.1	
	-5914955.713	0.1	44.421	0.1	
EISL 41703M003	-1884951.555	0.1	-109° 22' 59."8540	0.1	-82
	-5357595.960	0.1	-27° 08' 53."5530	0.1	
	-2892890.545	0.1	114.573	0.1	
HOB2 50116M004	-3950071.488	0.1	147° 26' 19."4412	0.1	90
	2522415.201	0.1	-42° 48' 16."9749	0.1	
	-4311638.242	0.1	41.069	0.1	
KERG 91201M002	1406337.337	0.1	70° 15' 19."8772	0.1	-76
	3918161.100	0.1	-49° 21' 05."2809	0.1	
	-4816167.398	0.1	73.054	0.1	
MCM4 66001M003	-1311703.239	0.1	166° 40' 09."5707	0.1	55
	310815.098	0.1	-77° 50' 18."0553	0.1	
	-6213255.171	0.1	98.052	0.1	
OHIG 66008M001	1525872.531	0.1	-57° 54' 01."2237	0.1	50
	-2432481.297	0.1	-63° 19' 14."6040	0.1	
	-5676146.088	0.1	30.682	0.1	
PERT 50133M001	-2368687.126	0.1	115° 53' 06."8962	0.1	89
	4881316.543	0.1	-31° 48' 07."0868	0.1	
	-3341796.028	0.1	12.766	0.1	
SANT 41705M003	1769693.405	0.1	-70° 40' 06."7989	0.1	84
	-5044574.168	0.1	-33° 09' 01."0411	0.1	
	-3468321.041	0.1	723.084	0.1	

Table 12 : Zero order station coordinates, 10° elevation mask solution, estimated velocity field

4.2.2 First Order Sites

Coordinate Frame : ITRF96
Ellipsoid GRS80
Velocity Field : Estimated
Epoch 2000.000

	Cartesian Coordinates		Geodetic Coordinates		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) φ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
ALN0	-1378322.888	1.4	159° 31' 42".5422	1.3	-87
	514552.952	1.4	-76° 42' 38".9697	1.5	
	-6187340.779	4.2	1961.300	4.7	
ANT0	-1181041.786	1.4	161° 27' 19".0289	1.2	-80
	396196.206	1.4	-78° 46' 32".6460	1.3	
	-6235401.154	4.2	1051.697	4.3	
ARR0	-1311719.480	1.4	166° 39' 50".6294	1.0	-86
	310946.167	1.3	-77° 50' 16".5177	1.3	
	-6213242.407	4.1	95.272	4.2	
BIR0	-1369580.037	2.2	166° 23' 42".4361	1.7	-78
	331459.733	2.0	-77° 16' 40".7302	2.0	
	-6199783.895	5.9	105.647	6.1	
BRA0	-1287577.117	1.6	165° 32' 52".0366	1.3	-83
	331844.591	1.5	-78° 00' 23".4557	1.4	
	-6217122.692	4.8	35.774	4.9	
BRM0	-1460472.954	2.0	158° 28' 07".6338	1.6	86
	576214.863	1.9	-75° 48' 00".9062	1.8	
	-6163302.194	5.1	2084.250	5.2	
CRZ0	-1359653.376	1.4	169° 19' 58".9288	1.1	-84
	256097.319	1.3	-77° 30' 46".6726	1.2	
	-6205712.158	3.8	314.028	3.9	
DWT0	-1329538.077	2.1	159° 51' 14".9590	1.6	-85
	487748.481	1.9	-77° 13' 01".8020	1.8	
	-6200229.880	6.3	2099.705	6.5	
ESH0	-1286232.721	1.8	164° 04' 50".7803	1.4	-71
	366859.741	1.7	-77° 56' 11".7151	1.6	
	-6216616.974	5.2	1182.365	5.4	
FLM0	-1300578.617	2.6	160° 16' 21".0982	2.0	-87
	466378.247	2.5	-77° 32' 00".2092	2.4	
	-6207722.331	7.6	1868.135	7.8	
PALM	1192671.812	0.7	-64° 03' 04".0461	0.4	-86
	-2450887.564	0.8	-64° 46' 30".3282	0.7	
	-5747096.100	1.4	31.075	1.6	
ROB0	-1374034.866	0.9	163° 10' 41".5512	0.7	87
	415415.873	0.8	-77° 02' 08".3658	0.8	
	-6193614.793	2.5	-54.100	2.6	
ROY0	-1339296.876	1.3	166° 10' 14".2452	1.0	-88
	329691.060	1.2	-77° 33' 05".6469	1.2	
	-6206308.556	3.8	-28.104	3.9	

	Coordinate Frame :	ITRF96			
	Ellipsoid	GRS80			
	Velocity Field :	Estimated			
	Epoch	2000.000			
	Cartesian Coordinates		Geodetic Coordinates		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) ϕ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
RYN0	-1533253.638	1.6	162° 34' 17".0987	1.2	-88
	481332.725	1.6	-75° 27' 13".6245	1.5	
	-6151854.910	4.5	179.231	4.6	
WAL0	-1337123.002	1.7	163° 49' 15".0056	1.3	89
	387942.930	1.5	-77° 25' 56".8284	1.5	
	-6203434.230	4.8	-22.222	5.0	
WRN0	-1194130.117	2.6	158° 17' 45".9855	2.0	-85
	475296.074	2.5	-78° 25' 02".3775	2.4	
	-6228886.362	7.8	2479.129	8.0	
WTE0	-1278644.172	1.5	167° 29' 45".2760	1.1	-81
	283564.351	1.4	-78° 11' 23".0878	1.4	
	-6221698.676	4.4	400.480	4.5	

Table 13 : First order station coordinates, 10° elevation mask solution, estimated velocity field

4.2.3 Second Order Sites

The second order stations include sites that have not been occupied three or more times during the four campaigns. For these sites, the station coordinates have been computed using the NUVEL1A velocity field.

Coordinate Frame : ITRF96
Ellipsoid GRS80
Velocity Field : NUVEL1A
Epoch 2000.000

	Cartesian Coordinates		**Geodetic Coordinates**		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) φ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
ARR1	-1311702.781	0.7	166° 39' 37".5997	0.5	14
	311029.726	0.6	-77° 50' 16".3754	0.6	
	-6213235.516	2.0	89.174	2.0	
ARR6	-1310837.784	0.7	166° 38' 30".1180	0.5	14
	311277.621	0.6	-77° 50' 41".3846	0.6	
	-6213277.273	2.0	-35.214	2.0	
BFT0	-1407868.254	1.9	166° 58' 47".4981	0.8	2
	325553.280	1.0	-76° 56' 55".8601	0.9	
	-6191939.756	3.1	465.515	3.1	
BTL0	-1298767.926	1.2	163° 31' 43".2888	1.4	-76
	384005.258	1.7	-77° 46' 58".4598	1.7	
	-6213206.502	5.3	1385.514	5.4	
CRN0	-1259954.721	11.9	159° 31' 51".9304	0.9	-82
	470298.629	1.1	-77° 52' 19".7454	1.1	
	-6216521.412	3.7	2626.761	3.8	
CRZ1	-1357293.913	1.1	169° 04' 39".2133	8.8	89
	261924.970	10.7	-77° 31' 31".7067	10.4	
	-6206635.009	36.8	950.063	37.7	
DOO1	-1338562.701	1.2	163° 01' 27".8103	0.9	174
	408616.655	1.1	-77° 21' 59".8221	1.1	
	-6202302.252	3.4	460.868	3.4	
DOO2	-1334185.017	1.1	162° 45' 30".4761	0.8	164
	414059.334	0.9	-77° 23' 30".1164	0.9	
	-6203584.006	2.8	1147.308	2.9	
ERE0	-1349766.234	0.9	167° 09' 12".4735	0.6	176
	307812.432	0.8	-77° 30' 40".0755	0.8	
	-6208638.671	2.8	3356.780	2.9	
FRK0	-1498791.241	2.5	168° 22' 54".1848	2.0	-79
	308156.077	2.5	-76° 09' 51".4201	2.5	
	-6171311.416	6.5	192.442	6.7	
FTP0	-1172500.925	1.4	162° 33' 51".7880	1.1	-71
	368240.063	1.3	-78° 55' 38".2049	1.3	
	-6237882.039	4.0	245.481	4.1	

			Coordinate Frame : ITRF96		
			Ellipsoid GRS80		
			Velocity Field : NUVEL1A		
			Epoch 2000.000		
	Cartesian Coordinates		**Geodetic Coordinates**		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) ϕ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
HDV0	-1259948.078	6.1	163° 46' 44".6369	4.4	176
	366548.012	5.4	-78° 10' 04".0889	5.3	
	-6221559.351	20.1	770.960	20.6	
MAS0	-1224210.682	1.2	164° 24' 59".4879	1.0	-78
	341425.202	1.1	-78° 32' 43".6449	1.1	
	-6230305.321	3.6	1011.119	3.6	
MBF0	-1228267.122	5.5	167° 09' 27".8324	0.5	164
	280008.504	4.9	-78° 38' 48".5670	0.5	
	-6232272.959	18.1	735.245	2.1	
MIE0	-1267383.930	0.7	163° 47' 12".2906	4.1	-84
	368526.982	0.5	-78° 05' 46".1977	4.9	
	-6219272.696	2.1	115.243	18.5	
ROS0	-1404642.694	15.9	163° 00' 57".3316	11.7	78
	429015.488	15.2	-76° 43' 47".9496	15.1	
	-6185898.205	43.0	-25.825	44.3	
VAN0	-1312482.831	0.5	161° 41' 23".5593	0.3	168
	434319.448	0.4	-77° 31' 20".5330	0.4	
	-6205673.510	1.5	41.985	1.5	

Table 14 : Second order station coordinates, 10° elevation mask solution, NUVEL1A velocity field

4.2.4 Third Order Sites

Coordinate Frame : ITRF96
Ellipsoid GRS80
Velocity Field : NUVEL1A
Epoch 2000.000

	Cartesian Coordinates		Geodetic Coordinates		
	X (m) Y (m) Z (m)	σX (mm) σY (mm) σZ (mm)	λ (° ′ ″) ϕ (° ′ ″) H(m)	b (mm) a (mm) σH (mm)	Azimuth of Major Axis (°)
B935	-1288278.542 430607.286 -6212491.715	0.8 0.7 2.7	161° 31' 04".0362 -77° 44' 47".8391 1532.738	0.6 0.7 2.8	170
B93D	-1312292.341 448939.730 -6206680.767	1.3 1.0 3.6	161° 06' 50".4213 -77° 29' 06".4687 1995.245	0.9 1.1 3.7	151
B93P	-1349887.524 425366.567 -6199506.334	1.1 1.0 3.2	162° 30' 34".9334 -77° 13' 23".7021 1203.695	0.8 0.9 3.3	175
B93U	-1311982.222 309553.595 -6213410.323	1.3 1.1 3.8	166° 43' 27".2409 -77° 50' 19".7012 245.766	1.0 1.0 3.9	5
B947	-1345670.885 439327.323 -6199678.380	1.8 1.7 5.0	161° 55' 10".0427 -77° 13' 17".0922 1426.605	1.4 1.6 5.1	13
B94F	-1288181.132 414692.346 -6214012.570	1.1 0.9 3.6	162° 09' 19".9845 -77° 47' 37".4441 1948.525	0.8 0.9 3.7	2
B94K	-1348027.667 405491.665 -6200612.325	1.3 1.1 3.9	163° 15' 30".6735 -77° 17' 31".4207 600.195	0.9 1.1 4.0	171
B94Q	-1327083.394 390177.699 -6206181.427	1.3 1.2 4.1	163° 36' 57".8181 -77° 30' 59".6625 705.458	1.0 1.2 4.2	1
B94T	-1286227.882 366860.995 -6216617.884	1.1 0.9 3.0	164° 04' 50".3896 -77° 56' 11".8571 1182.354	0.8 0.9 3.1	159
B94W	-1268405.380 307635.569 -6223245.851	1.5 1.3 4.5	166° 22' 00".8009 -78° 13' 56".2789 989.322	1.2 1.3 4.6	36
B959	-1380767.852 443425.851 -6191481.847	1.2 1.0 3.8	162° 11' 45".1318 -76° 54' 09".0583 1196.819	0.8 1.0 3.9	166
B95D	-1273637.972 332153.591 -6220700.957	1.0 0.8 2.9	165° 22' 59".9856 -78° 07' 50".5174 763.207	0.7 0.8 2.9	163
B95K	-1321422.549 413641.920 -6206934.847	1.0 0.8 3.1	162° 37' 06".3557 -77° 30' 20".9251 1743.266	0.7 0.8 3.1	166

Coordinate Frame : ITRF96
Ellipsoid GRS80
Velocity Field : Estimated
Epoch 2000.000

	Cartesian Coordinates		Geodetic Coordinates		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) ϕ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
B95N	-1326367.184	1.0	166° 22' 49".0267	0.8	2
	321365.132	0.9	-77° 41' 06".2899	0.9	
	-6209609.492	3.0	79.223	3.1	
B968	-1355409.985	1.4	163° 29' 15".9438	1.0	167
	401805.653	1.2	-77° 14' 07".8106	1.2	
	-6198600.468	4.5	-35.204	4.6	
B96E	-1372648.094	1.1	162° 32' 52".5939	0.7	170
	431531.856	1.0	-77° 00' 15".1476	1.0	
	-6192836.313	3.4	-43.723	3.5	
B96G	-1391173.001	1.2	162° 52' 30".9259	0.8	168
	428638.413	1.0	-76° 50' 58".2053	1.0	
	-6188951.544	3.7	-21.365	3.8	
B96K	-1372144.640	1.3	162° 17' 20".5700	0.9	167
	438196.249	1.1	-76° 59' 26".2473	1.1	
	-6192735.818	4.0	203.305	4.1	
B96V	-1328864.005	1.7	163° 47' 55".0776	1.3	174
	386105.073	1.6	-77° 30' 36".1851	1.6	
	-6205372.232	5.6	37.901	5.8	
B972	-1283522.310	1.0	161° 10' 24".5913	0.7	179
	437609.244	0.9	-77° 46' 00".0224	0.8	
	-6212604.096	3.3	1161.868	3.4	
B976	-1282595.862	0.8	160° 39' 58".3027	0.6	168
	450008.401	0.7	-77° 44' 20".1390	0.7	
	-6212637.151	2.7	1868.246	2.8	
B97H	-1295875.940	1.0	162° 18' 53".4201	0.7	165
	413196.999	0.9	-77° 43' 37".7669	0.9	
	-6210622.958	3.4	92.748	3.5	
B98H	-1281639.979	1.8	164° 31' 16".2450	1.3	170
	354920.086	1.6	-78° 00' 15".5041	1.6	
	-6216986.710	5.6	-50.851	5.8	
B98J	-1267368.013	9.8	163° 47' 17".0041	7.7	18
	368490.944	13.1	-78° 05' 47".0440	12.7	
	-6219279.707	26.4	116.875	27.2	
B9A2	-1331639.705	1.1	166° 25' 11".3410	0.8	7
	321670.058	1.0	-77° 38' 13".9987	0.9	
	-6208361.325	3.2	-29.681	3.2	
B9A8	-1310955.648	1.4	166° 45' 46".3068	1.1	29
	308378.466	1.2	-77° 50' 59".5739	1.2	
	-6213392.833	4.2	-38.478	4.3	
B9B7	-1300860.321	1.8	162° 32' 36".6502	1.3	4
	409073.774	1.5	-77° 41' 41".6245	1.5	
	-6209800.328	6.0	35.427	6.1	

Coordinate Frame : ITRF96

Ellipsoid GRS80
Velocity Field : NUVEL1A
Epoch 2000.000

	Cartesian Coordinates		Geodetic Coordinates		
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) ϕ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
B9BC	-1321113.484	0.8	166° 53' 51".4493	0.7	3
	307490.471	0.7	-77° 45' 41".6224	0.7	
	-6211543.142	2.5	200.013	2.6	
B9C4	-1310729.194	1.8	166° 38' 19".6461	1.3	12
	311322.133	1.6	-77° 50' 44".4831	1.6	
	-6213290.874	5.2	-41.998	5.3	
B9DD	-1304341.065	1.4	161° 10' 48".0020	0.8	171
	444542.031	1.2	-77° 33' 48".0981	1.2	
	-6206683.578	4.7	65.465	4.8	
B9DE	-1357151.147	1.0	161° 14' 57".1664	0.7	167
	460711.529	0.8	-77° 03' 32".8509	0.8	
	-6195562.194	2.9	1341.512	3.0	
B9DM	-1269279.786	0.6	162° 02' 34".2861	0.5	174
	411364.603	0.5	-77° 58' 05".4403	0.5	
	-6218281.603	2.0	2131.560	2.0	
BMWA	-1327762.278	1.4	162° 39' 25".5559	0.9	176
	414642.782	1.2	-77° 26' 40".2991	1.2	
	-6203962.799	4.5	218.925	4.6	
BOB1	-1310848.148	2.4	162° 54' 17".5683	1.6	164
	403147.334	1.9	-77° 37' 24".8016	2.0	
	-6208083.260	7.1	20.240	7.3	
CAMP	-1310856.334	1.4	166° 40' 36".8260	1.0	171
	310431.486	1.2	-77° 50' 47".4497	1.2	
	-6213347.926	4.4	-3.452	4.5	
GRAV	-1311155.729	1.3	166° 46' 06".4141	1.0	1
	308290.647	1.1	-77° 50' 53".8255	1.1	
	-6213357.110	4.0	-36.636	4.1	
HEIN	-1290607.073	1.0	167° 27' 02".5243	0.8	13
	287285.973	0.9	-78° 04' 33".6705	0.9	
	-6219365.536	3.2	684.721	3.2	
MCM1	-1310856.326	1.1	166° 40' 36".8236	0.8	177
	310431.500	0.9	-77° 50' 47".4498	0.9	
	-6213347.919	3.2	-3.459	3.3	
SCO1	-1311028.754	1.1	166° 45' 28".8513	0.9	163
	308512.752	0.9	-77° 50' 56".3459	0.9	
	-6213390.592	3.1	-19.217	3.2	
ST53	-1310844.378	13.8	166° 38' 30".6608	9.0	159
	311275.543	17.2	-77° 50' 41".1793	19.6	
	-6213274.605	22.9	-36.572	23.2	
VCE4	-1319905.080	1.6	163° 31' 05".5285	1.1	163
	390517.625	1.3	-77° 34' 38".4512	1.3	
	-6206905.351	5.1	-51.611	5.2	

		Coordinate Frame :	**ITRF96**			
		Ellipsoid	**GRS80**			
		Velocity Field :	**NUVEL1A**			
		Epoch	**2000.000**			
	Cartesian Coordinates		**Geodetic Coordinates**			
	X (m) Y (m) Z (m)	σ_X (mm) σ_Y (mm) σ_Z (mm)	λ (° ′ ″) ϕ (° ′ ″) H(m)	b (mm) a (mm) σ_H (mm)	Azimuth of Major Axis (°)
VIDA	-1328383.114 436325.153 -6202431.869	1.1 0.9 3.2	161° 48' 59".5588 -77° 22' 42".7562 295.400	0.8 0.9 3.3	162

Table 15 : Third order station coordinates, 10° elevation mask solution, NUVEL1A velocity field

4.2.5 Station Precision Estimates

The mean, standard deviation, maximum and minimum error ellipse parameters and vertical precision values for the 10° elevation mask solution are given in Table 16 and Table 17.

	Semi-axis Minor (mm)	Semiaxis Major (mm)	Height (mm)
Mean :	1.3	1.5	4.9
Standard Deviation :	0.4	0.5	1.6
Count :	17	17	17
Maximum :	2.0	2.4	8.0
Minimum :	0.4	0.7	1.6
Range :	1.6	1.7	6.5

Table 16 : Station precision estimates using the 10° elevation mask: Station coordinates derived from estimated velocities

	Semi-axis Minor (mm)	Semiaxis Major (mm)	Height (mm)
Mean :	1.6	2.2	6.5
Standard Deviation :	2.3	3.6	8.4
Count :	56	56	56
Maximum :	11.7	19.6	44.3
Minimum :	0.3	0.4	1.5
Range :	11.4	19.2	42.8

Table 17 : Station precision estimates using the 10° elevation mask: Station coordinates derived from NUVEL1A velocities

The mean one sigma horizontal precision is in the order of 2mm. However, the maximum error ellipse is less than 2.5mm for the sites where the velocities have been estimated and in the order of 20mm for the sites coordinates derived with the NUVEL1A model.

For the vertical component, the estimated velocity position and NUVEL1A positions give different results. The mean vertical precision derived from the single epoch solutions (NUVEL1A estimated positions) are about 30% larger than those derived from the multi-epoch solutions (estimated velocity positions). The maximum error is 5 times the size for the single epoch solutions compared to the multi-epoch solutions.

4.3 Station velocity estimates

Station velocities have been estimated for 25 TAMDEF sites. Both the geocentric and topocentric (horizontal and vertical) station velocities are given in Sections 0 - 0. Listings of both the geocentric and topocentric velocity estimates are also given in Appendix D and Appendix E respectively.

4.3.1 Zero Order Stations

Coordinate Frame : ITRF96
Epoch : 2000.000

Station	Geocentric Velocities: NUVEL1A v_X (mm/yr) v_Y (mm/yr) v_Z (mm/yr)	Geocentric Velocities: Estimated v_X (mm/yr) v_Y (mm/yr) v_Z (mm/yr)	σ_{vX} (mm/yr) σ_{vY} (mm/yr) σ_{vZ} (mm/yr)	Topocentric Velocities: NUVEL1A v_E (mm/yr) v_N (mm/yr)	Tectonic Plate	Estimated v_E (mm/yr) v_N (mm/yr) v_H (mm/yr)	σ_{vE} (mm/yr) σ_{vN} (mm/yr)	Azimuth of major axis (°)
CAS1 66011M001	1.0	-0.4	0.3	1.9	ANTA	3.0	0.2	-87
	-8.1	-7.4	0.2	-8.7		-12.0	0.3	
	-3.5	-14.4	0.3			10.5	0.3	
CHAT 50207M001	-24.5	-24.2	0.3	-39.5	PCFC	-39.0	0.3	80
	38.1	37.6	0.3	30.8		30.4	0.3	
	21.4	21.2	0.3			1.1	0.3	
DAV1 66010M001	1.6	0.8	0.3	-2.2	ANTA	-1.7	0.2	-74
	-3.1	-4.6	0.2	-2.9		-6.9	0.3	
	-1.1	-7.8	0.3			5.6	0.3	
EISL 41703M003	67.4	66.2	0.3	74.6	NAZC	73.2	0.3	-82
	-33.1	-32.5	0.3	-8.8		-8.7	0.3	
	-14.4	-14.2	0.3			14.2	0.3	
HOB2 50116M004	-39.6	-39.1	0.3	15.4	AUST	15.2	0.3	90
	7.0	6.9	0.3	53.0		52.4	0.3	
	37.9	37.4	0.3			1.5	0.3	
KERG 91201M002	-5.6	-5.5	0.3	6.4	PCFC	6.3	0.3	-76
	3.2	3.2	0.3	-5.9		-5.7	0.3	
	-10.3	-10.1	0.3			8.4	0.3	
MCM4 66001M003	9.4	9.6	0.2	7.6	ANTA	12.4	0.2	55
	-10.0	-15.0	0.2	-11.7		-11.6	0.2	
	-2.5	4.1	0.3			-6.7	0.3	
OHIG 66008M001	18.6	20.1	0.3	16.3	ANTA	14.9	0.3	50
	1.0	-3.9	0.3	10.1		9.0	0.3	
	4.6	-7.7	0.3			13.1	0.3	
PERT 50133M001	-49.8	-50.7	0.3	40.0	PCFC	40.8	0.3	89
	10.9	11.1	0.3	55.5		56.5	0.3	
	45.7	46.6	0.3			2.8	0.3	
SANT 41705M003	21.6	21.2	0.3	18.0	PCFC	17.7	0.3	84
	-7.2	-7.1	0.3	13.4		13.2	0.3	
	6.9	6.8	0.3			7.8	0.3	

Table 18: Station velocity estimates using the 10° elevation mask:

Most of the estimated horizontal velocities agree to better than 2mm / year of the NUVEL1A plate model. The largest differences is the east-west velocity at MCM4 (4.8mm / year) and the north-south velocities at CAS1 and DAV1 (3.3 mm/year and 4.0 mm / year respectively).

4.3.2 First Order Stations

Coordinate Frame : ITRF96
Epoch : 2000.000

Station	Geocentric Velocities NUVEL1A v_X (mm/yr) v_Y (mm/yr) v_Z (mm/yr)	Geocentric Velocities Estimated v_X (mm/yr) v_Y (mm/yr) v_Z (mm/yr)	σ_{vX} (mm/yr) σ_{vY} (mm/yr) σ_{vZ} (mm/yr)	Tectonic Plate	Topocentric Velocities NUVEL1A v_E (mm/yr) v_N (mm/yr)	Topocentric Velocities Estimated v_E (mm/yr) v_N (mm/yr) v_H (mm/yr)	b (mm/yr) a (mm/yr) σ_{vH} (mm/yr)	Azimuth of major axis (°)
ALN0	8.6	10.4	0.7	ANTA	6.5	8.0	2.0	89
	-10.2	-12.2	0.6		-12.0	-14.7	2.4	
	-2.8	-2.9	2.0			-1.0	7.5	
ANT0	9.1	9.2	0.6	ANTA	6.1	9.5	1.8	-84
	-9.5	-12.7	0.6		-11.9	-12.4	2.1	
	-2.3	1.3	1.8			-2.2	6.9	
ARR0	9.4	11.9	0.4	ANTA	7.6	9.1	1.2	-90
	-10.0	-12.1	0.4		-11.7	-12.8	1.4	
	-2.5	3.3	1.1			-6.6	4.8	
BIR0	9.3	10.4	0.7	ANTA	7.7	9.5	2.3	-83
	-10.2	-12.2	0.7		-11.7	-12.0	2.7	
	-2.6	1.0	2.1			-3.5	8.4	
BRA0	9.3	9.9	0.7	ANTA	7.3	8.9	2.2	86
	-9.9	-11.8	0.6		-11.7	-12.4	2.5	
	-2.5	-2.9	2.1			-0.1	8.8	
BRM0	8.3	8.4	0.8	ANTA	6.7	9.1	2.4	83
	-10.5	-13.2	0.7		-12.0	-13.8	2.8	
	-3.0	-5.3	2.1			3.0	8.4	
CRZ0	9.6	11.1	0.8	ANTA	8.1	10.5	2.0	-87
	-10.1	-12.5	0.8		-11.6	-11.2	2.3	
	-2.5	-0.1	2.4			-3.5	7.8	
DWT0	8.7	9.1	0.7	ANTA	6.4	9.0	2.1	-89
	-10.0	-13.2	0.6		-11.9	-13.4	2.4	
	-2.7	-3.6	2.0			0.2	8.5	
ESH0	9.2	10.2	1.8	ANTA	7.0	9.5	4.0	-80
	-9.9	-14.9	1.6		-11.8	-11.9	4.6	
	-2.5	6.3	5.3			-4.5	15.9	
FLM0	8.8	8.2	1.2	ANTA	6.3	11.0	3.7	88
	-9.9	-15.5	1.2		-11.9	-13.7	4.5	
	-2.6	-5.3	3.5			0.6	14.1	
PALM	18.8	18.1	1.6	ANTA	16.8	13.1	1.1	-90
	-0.3	-6.7	1.7		9.4	13.6	1.7	
	4.0	2.5	3.2			3.8	3.7	
ROB0	9.0	8.4	0.3	ANTA	7.2	9.9	1.0	85
	-10.2	-12.9	0.3		-11.9	-11.6	1.2	
	-2.7	-1.1	0.9			-1.9	3.7	
ROY0	9.3	10.7	0.5	ANTA	7.6	10.4	1.5	-90
	-10.1	-13.4	0.4		-11.7	-13.1	1.7	
	-2.5	-1.1	1.5			-2.2	6.0	

Coordinate Frame : ITRF96
Epoch : 2000.000

Station	Geocentric Velocities NUVEL1A v_X (mm/yr) v_Y (mm/yr) v_Z (mm/yr)	Estimated v_X (mm/yr) v_Y (mm/yr) v_Z (mm/yr)	σ_{vX} (mm/yr) σ_{vY} (mm/yr) σ_{vZ} (mm/yr)	Tectonic Plate	Topocentric Velocities NUVEL1A v_E (mm/yr) v_N (mm/yr)	Estimated v_E (mm/yr) v_N (mm/yr) v_H (mm/yr)	b (mm/yr) a (mm/yr) σ_{vH} (mm/yr)	Azimuth of major axis (°)
RYN0	8.7	9.0	0.6	ANTA	7.6	11.1	1.8	90
	-10.7	-14.1	0.6		-11.9	-13.2	2.3	
	-3.0	-3.1	1.8			-0.8	7.0	
WAL0	9.1	9.3	0.5	ANTA	7.2	10.9	1.6	87
	-10.1	-14.1	0.5		-11.8	-13.0	1.9	
	-2.6	-3.3	1.5			0.1	6.5	
WRN0	8.8	5.2	0.9	ANTA	5.7	6.0	2.9	-90
	-9.6	-8.9	0.9		-12.0	-8.3	3.5	
	-2.4	-1.4	2.8			-0.8	11.8	
WTE0	9.5	9.8	0.4	ANTA	7.6	9.9	1.4	-87
	-9.9	-12.6	0.4		-11.7	-11.5	1.7	
	-2.4	0.9	1.3			-3.1	5.5	

Table 19: Station velocity estimates using the 10° elevation mask:

The horizontal velocities are shown in Figure 7.

The horizontal velocities in the vicinity of the Ross Sea Region, are consistent with the NUVEL1A plate motion. Compared to the NUVEL1A velocities, the biggest difference is at the station PALM on the Antarctic Peninsular where the difference is in the order of 5mm / year. The station FLM0 also has a large difference between the predicted and estimated velocities.

Table 20 give the mean velocity, standard deviation and range in the velocity estimates. Note that PALM has been excluded since it is in a different region.

	v_E (mm)	v_N (mm)	v_H (mm)
Mean :	9.5	-12.4	-1.6
Standard Deviation :	1.3	1.5	2.3
Count :	16	16	16
Maximum :	11.1	-8.3	3.0
Minimum :	6.0	-14.7	-6.6
Range :	5.0	6.4	9.6

Table 20 : Velocity precision using the 10° elevation mask. Excluding station PALM.

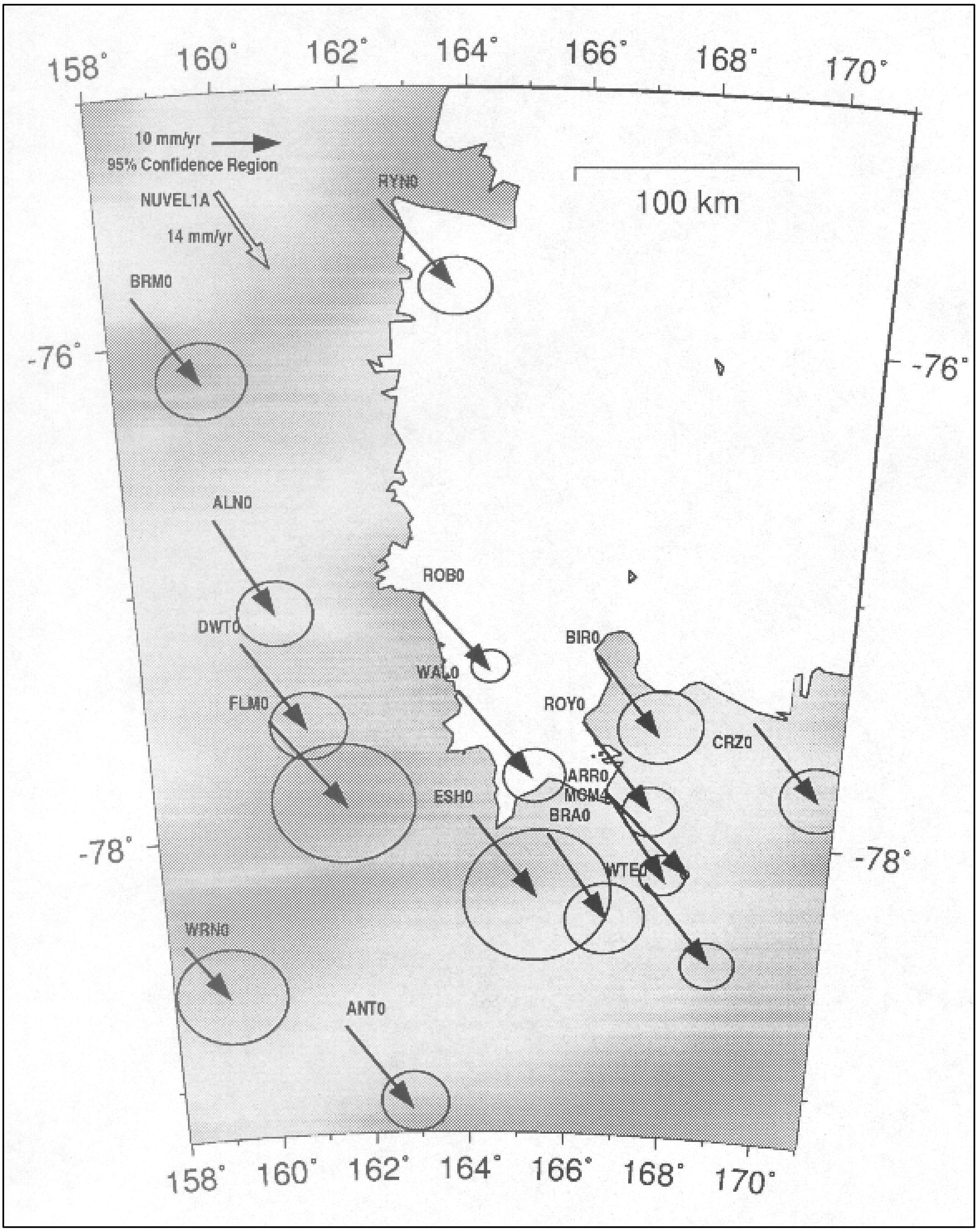

Figure 7: Estimated horizontal velocities

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Appendix A Coordinate Repeatability

The frequency distributions of the coordinate repeatability for each campaign network solution are given in the following four figures (Figures 8 to 11). The graphs combine all three components, namely; latitude, longitude and height. The bin size is 5mm. The frequency distributions for the 10° elevation mask solution only have been given.

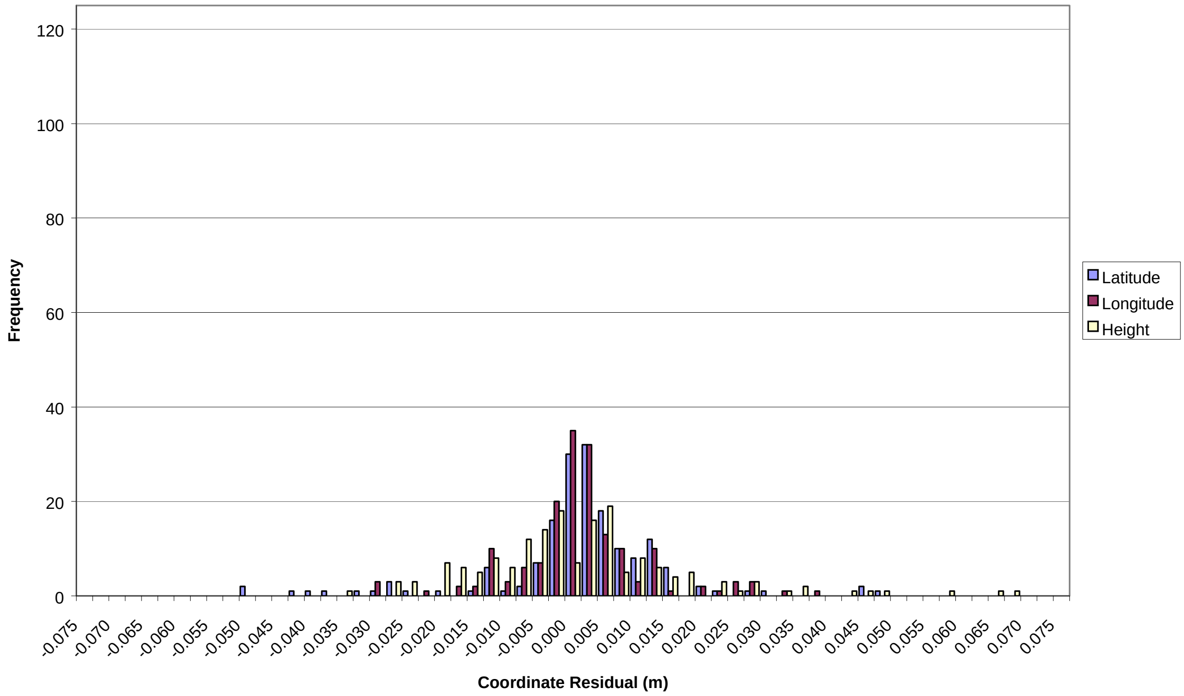

Figure 8 : Epoch 1996-1997, coordinate repeatability frequency distribution, 10° elevation mask solution

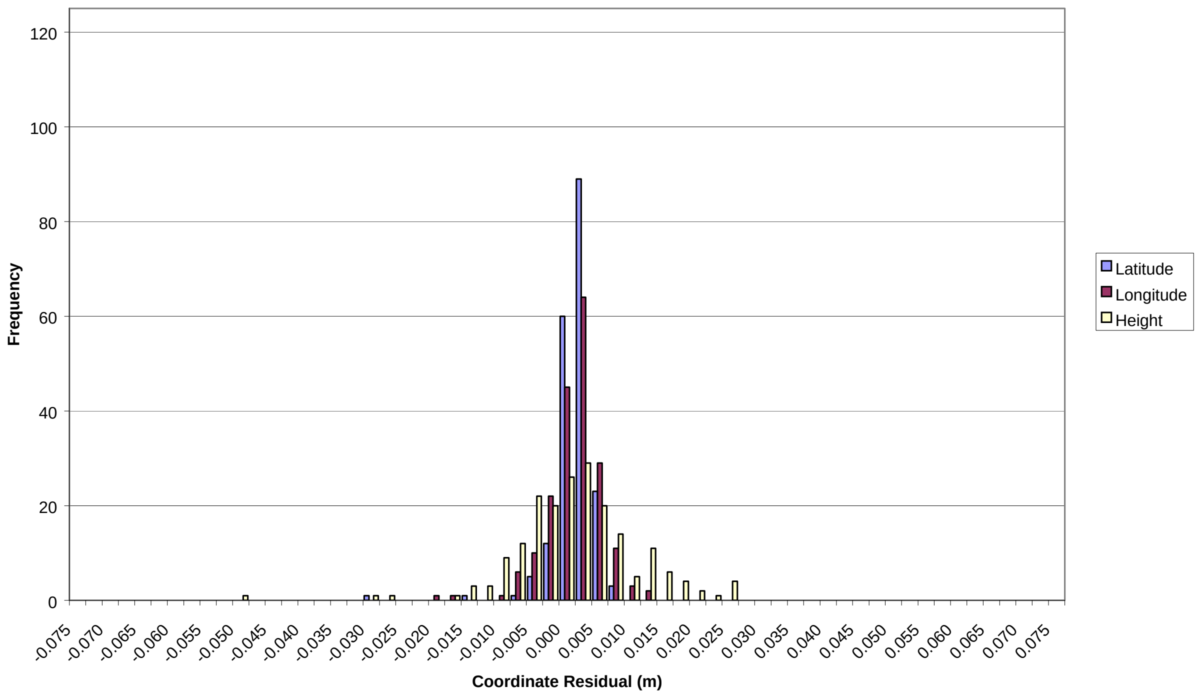

Figure 9 : Epoch 1997-1998, coordinate repeatability frequency distribution, 10° elevation mask solution

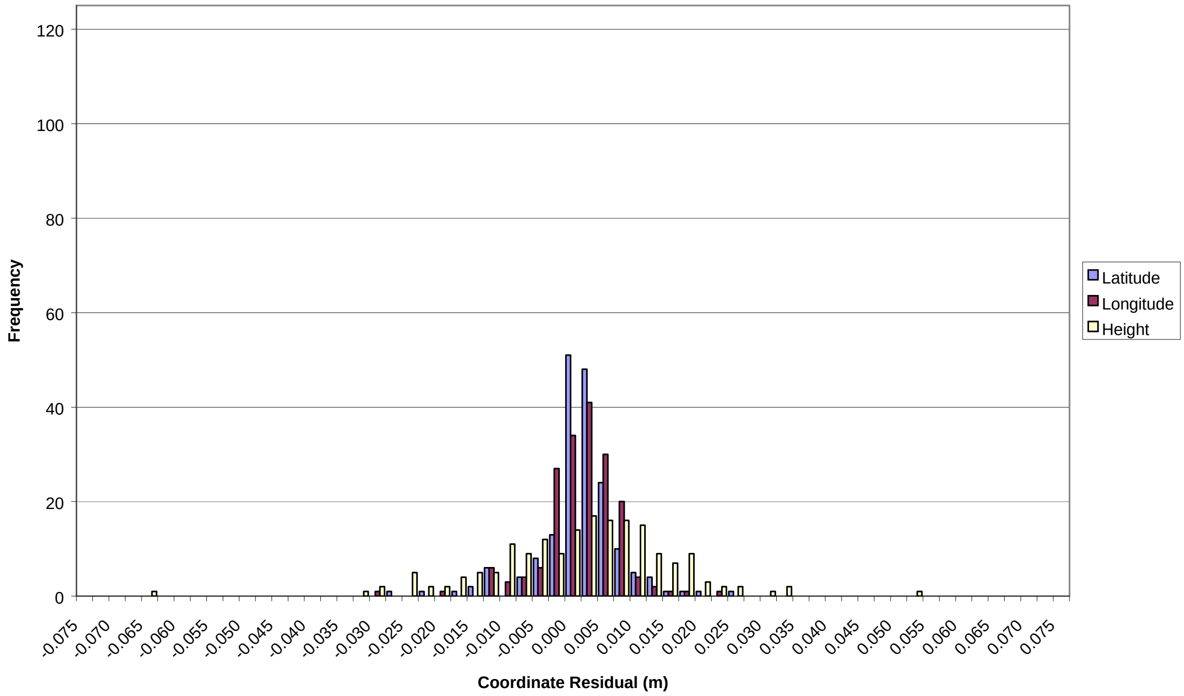

Figure 10 : Epoch 1998-1999, coordinate repeatability frequency distribution, 10° elevation mask solution

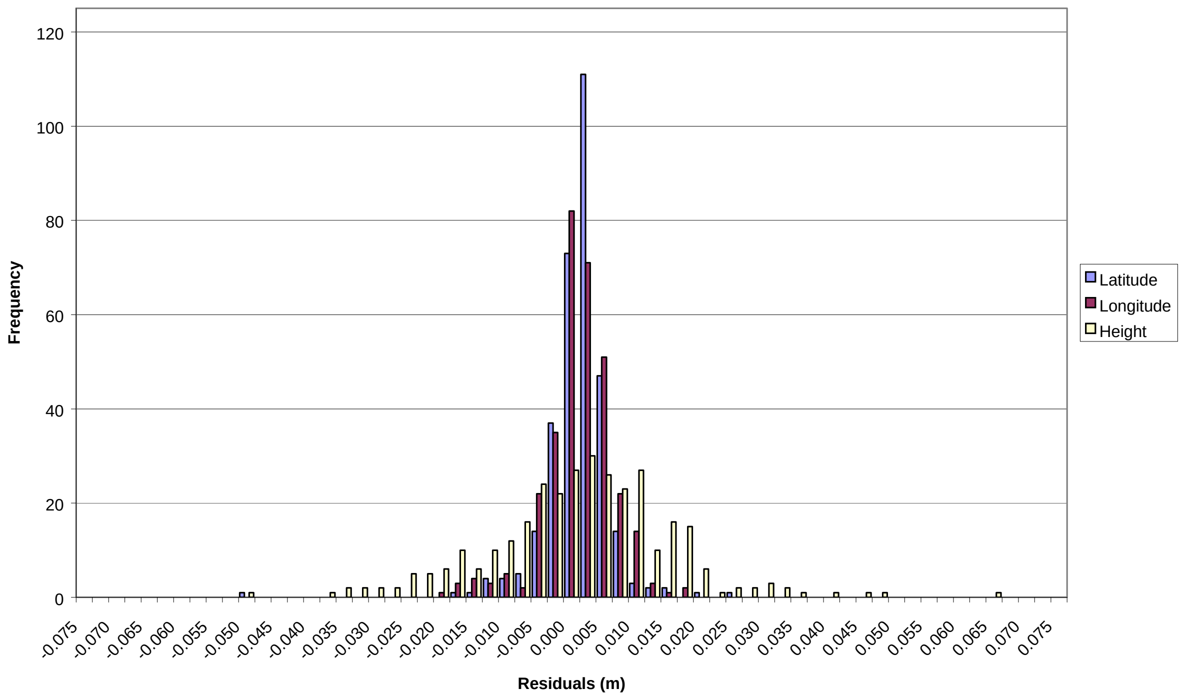

Figure 11 : Epoch 1999-2000, coordinate repeatability frequency distribution, 10° elevetion mask solution

Appendix B Cartesian Coordinates

Cartesian coordinates: 10° elevation mask

Coordinate Frame : ITRF96
Ellipsoid GRS80
Velocity Field : Estimated
Epoch 2000.000

	Cartesian Coordinates			Geocentric Standard Errors		
	X (m)	Y (m)	Z (m)	σ_X (m)	σ_Y (m)	σ_Z (m)
Zero Order Sites						
CAS1	-901776.153	2409383.396	-5816748.437	0.000	0.000	0.000
CHAT	-4590670.985	-275482.892	-4404596.710	0.000	0.000	0.000
DAV1	486854.560	2285099.272	-5914955.713	0.000	0.000	0.000
EISL	-1884951.555	-5357595.960	-2892890.545	0.000	0.000	0.000
HOB2	-3950071.488	2522415.201	-4311638.242	0.000	0.000	0.000
KERG	1406337.337	3918161.100	-4816167.398	0.000	0.000	0.000
MCM4	-1311703.239	310815.098	-6213255.171	0.000	0.000	0.000
OHIG	1525872.531	-2432481.297	-5676146.088	0.000	0.000	0.000
PERT	-2368687.126	4881316.543	-3341796.028	0.000	0.000	0.000
SANT	1769693.405	-5044574.168	-3468321.041	0.000	0.000	0.000
First Order Sites						
ALN0	-1378322.888	514552.952	-6187340.779	0.002	0.002	0.005
ANT0	-1181041.786	396196.206	-6235401.154	0.001	0.001	0.004
ARR0	-1311719.480	310946.167	-6213242.407	0.001	0.001	0.004
BIR0	-1369580.037	331459.733	-6199783.895	0.002	0.002	0.006
BRA0	-1287577.117	331844.591	-6217122.692	0.002	0.001	0.005
BRM0	-1460472.954	576214.863	-6163302.194	0.002	0.002	0.005
CRZ0	-1359653.376	256097.319	-6205712.158	0.001	0.001	0.004
DWT0	-1329538.077	487748.481	-6200229.880	0.002	0.002	0.006
ESH0	-1286232.721	366859.741	-6216616.974	0.002	0.002	0.005
FLM0	-1300578.617	466378.247	-6207722.331	0.003	0.002	0.008
PALM	1192671.812	-2450887.564	-5747096.100	0.001	0.001	0.001
ROB0	-1374034.866	415415.873	-6193614.793	0.001	0.001	0.002
ROY0	-1339296.876	329691.060	-6206308.556	0.001	0.001	0.004
RYN0	-1533253.638	481332.725	-6151854.910	0.002	0.002	0.004
WAL0	-1337123.002	387942.930	-6203434.230	0.002	0.002	0.005
WRN0	-1194130.117	475296.074	-6228886.362	0.003	0.003	0.008
WTE0	-1278644.172	283564.351	-6221698.676	0.001	0.001	0.004
Second Order Sites						
ARR1	-1311702.781	311029.726	-6213235.516	0.001	0.001	0.002
ARR6	-1310837.784	311277.621	-6213277.273	0.001	0.001	0.002
BFT0	-1407868.254	325553.280	-6191939.756	0.002	0.001	0.003
BTL0	-1298767.926	384005.258	-6213206.502	0.001	0.002	0.005

CRN0	-1259954.721	470298.629	-6216521.412	0.012	0.001	0.004
CRZ1	-1357293.913	261924.970	-6206635.009	0.001	0.011	0.037
DOO1	-1338562.701	408616.655	-6202302.252	0.001	0.001	0.003
DOO2	-1334185.017	414059.334	-6203584.006	0.001	0.001	0.003
ERE0	-1349766.234	307812.432	-6208638.671	0.001	0.001	0.003
FRK0	-1498791.241	308156.077	-6171311.416	0.003	0.002	0.007
FTP0	-1172500.925	368240.063	-6237882.039	0.001	0.001	0.004
HDV0	-1259948.078	366548.012	-6221559.351	0.006	0.005	0.020
MAS0	-1224210.682	341425.202	-6230305.321	0.001	0.001	0.004
MBF0	-1228267.122	280008.504	-6232272.959	0.006	0.005	0.018
MIE0	-1267383.930	368526.982	-6219272.696	0.001	0.001	0.002
ROS0	-1404642.694	429015.488	-6185898.205	0.016	0.015	0.043
VAN0	-1312482.831	434319.448	-6205673.510	0.001	0.000	0.002
Third Order Sites						
B935	-1288278.542	430607.286	-6212491.715	0.001	0.001	0.003
B93D	-1312292.341	448939.730	-6206680.767	0.001	0.001	0.004
B93P	-1349887.524	425366.567	-6199506.334	0.001	0.001	0.003
B93U	-1311982.222	309553.595	-6213410.323	0.001	0.001	0.004
B947	-1345670.885	439327.323	-6199678.380	0.002	0.002	0.005
B94F	-1288181.132	414692.346	-6214012.570	0.001	0.001	0.004
B94K	-1348027.667	405491.665	-6200612.325	0.001	0.001	0.004
B94Q	-1327083.394	390177.699	-6206181.427	0.001	0.001	0.004
B94T	-1286227.882	366860.995	-6216617.884	0.001	0.001	0.003
B94W	-1268405.380	307635.569	-6223245.851	0.002	0.001	0.005
B959	-1380767.852	443425.851	-6191481.847	0.001	0.001	0.004
B95D	-1273637.972	332153.591	-6220700.957	0.001	0.001	0.003
B95K	-1321422.549	413641.920	-6206934.847	0.001	0.001	0.003
B95N	-1326367.184	321365.132	-6209609.492	0.001	0.001	0.003
B968	-1355409.985	401805.653	-6198600.468	0.001	0.001	0.005
B96E	-1372648.094	431531.856	-6192836.313	0.001	0.001	0.003
B96G	-1391173.001	428638.413	-6188951.544	0.001	0.001	0.004
B96K	-1372144.640	438196.249	-6192735.818	0.001	0.001	0.004
B96V	-1328864.005	386105.073	-6205372.232	0.002	0.002	0.006
B972	-1283522.310	437609.244	-6212604.096	0.001	0.001	0.003
B976	-1282595.862	450008.401	-6212637.151	0.001	0.001	0.003
B97H	-1295875.940	413196.999	-6210622.958	0.001	0.001	0.003
B98H	-1281639.979	354920.086	-6216986.710	0.002	0.002	0.006
B98J	-1267368.013	368490.944	-6219279.707	0.010	0.013	0.026
B9A2	-1331639.705	321670.058	-6208361.325	0.001	0.001	0.003
B9A8	-1310955.648	308378.466	-6213392.833	0.001	0.001	0.004
B9B7	-1300860.321	409073.774	-6209800.328	0.002	0.002	0.006
B9BC	-1321113.484	307490.471	-6211543.142	0.001	0.001	0.003
B9C4	-1310729.194	311322.133	-6213290.874	0.002	0.002	0.005
B9DD	-1304341.065	444542.031	-6206683.578	0.001	0.001	0.005
B9DE	-1357151.147	460711.529	-6195562.194	0.001	0.001	0.003
B9DM	-1269279.786	411364.603	-6218281.603	0.001	0.001	0.002
BMWA	-1327762.278	414642.782	-6203962.799	0.001	0.001	0.005
BOB1	-1310848.148	403147.334	-6208083.260	0.002	0.002	0.007
CAMP	-1310856.334	310431.486	-6213347.926	0.001	0.001	0.004
GRAV	-1311155.729	308290.647	-6213357.110	0.001	0.001	0.004
HEIN	-1290607.073	287285.973	-6219365.536	0.001	0.001	0.003

MCM1	-1310856.326	310431.500	-6213347.919	0.001	0.001	0.003
SCO1	-1311028.754	308512.752	-6213390.592	0.001	0.001	0.003
ST53	-1310844.378	311275.543	-6213274.605	0.014	0.017	0.023
VCE4	-1319905.080	390517.625	-6206905.351	0.002	0.001	0.005
VIDA	-1328383.114	436325.153	-6202431.869	0.001	0.001	0.003

Appendix C Geodetic Coordinates

Geodetic coordinates: 10° elevation mask solution

Coordinate Frame : ITRF96
Ellipsoid GRS80
Velocity Field : Estimated
Epoch 2000.000

	Geodetic Coordinates			**Topocentric Error Ellipse**			
	Latitude (° ′ ″)	Longitude (° ′ ″)	Height (m)	semi-axis minor b (m)	semi-axis major a (m)	Azimuth (°)	σ_H (m)
Zero Order Sites							
CAS1	-66° 17'00".0925	110° 31'10".9403	22.459	0.000	0.000	-87	0.000
CHAT	-43° 57'20".8324	-176° 33'57".0221	57.989	0.000	0.000	80	0.000
DAV1	-68° 34'38".3627	77° 58'21".4078	44.421	0.000	0.000	-74	0.000
EISL	-27° 08'53".5530	-109° 22'59".8540	114.573	0.000	0.000	-82	0.000
HOB2	-42° 48'16".9749	147° 26'19".4412	41.069	0.000	0.000	90	0.000
KERG	-49° 21'05".2809	70° 15'19".8772	73.054	0.000	0.000	-76	0.000
MCM4	-77° 50'18".0553	166° 40'09".5707	98.052	0.000	0.000	55	0.000
OHIG	-63° 19'14".6040	-57° 54'01".2237	30.682	0.000	0.000	50	0.000
PERT	-31° 48'07".0868	115° 53'06".8962	12.766	0.000	0.000	89	0.000
SANT	-33° 09'01".0411	-70° 40'06".7989	723.084	0.000	0.000	84	0.000
First Order Sites							
ALN0	-76° 42'38".9697	159° 31'42".5422	1961.300	0.001	0.002	-87	0.005
ANT0	-78° 46'32".6460	161° 27'19".0289	1051.697	0.001	0.001	-80	0.004
ARR0	-77° 50'16".5177	166° 39'50".6294	95.272	0.001	0.001	-86	0.004
BIR0	-77° 16'40".7302	166° 23'42".4361	105.647	0.002	0.002	-78	0.006
BRA0	-78° 00'23".4557	165° 32'52".0366	35.774	0.001	0.001	-83	0.005
BRM0	-75° 48'00".9062	158° 28'07".6338	2084.250	0.002	0.002	86	0.005
CRZ0	-77° 30'46".6726	169° 19'58".9288	314.028	0.001	0.001	-84	0.004
DWT0	-77° 13'01".8020	159° 51'14".9590	2099.705	0.002	0.002	-85	0.006
ESH0	-77° 56'11".7151	164° 04'50".7803	1182.365	0.001	0.002	-71	0.005
FLM0	-77° 32'00".2092	160° 16'21".0982	1868.135	0.002	0.002	-87	0.008
PALM	-64° 46'30".3282	-64° 03'04".0461	31.075	0.000	0.001	-86	0.002
ROB0	-77° 02'08".3658	163° 10'41".5512	-54.100	0.001	0.001	87	0.003
ROY0	-77° 33'05".6469	166° 10'14".2452	-28.104	0.001	0.001	-88	0.004
RYN0	-75° 27'13".6245	162° 34'17".0987	179.231	0.001	0.002	-88	0.005
WAL0	-77° 25'56".8284	163° 49'15".0056	-22.222	0.001	0.002	89	0.005
WRN0	-78° 25'02".3775	158° 17'45".9855	2479.129	0.002	0.002	-85	0.008
WTE0	-78° 11'23".0878	167° 29'45".2760	400.480	0.001	0.001	-81	0.004
Second Order Sites							
ARR1	-77° 50'16".3754	166° 39'37".5997	89.174	0.001	0.001	14	0.002
ARR6	-77° 50'41".3846	166° 38'30".1180	-35.214	0.001	0.001	14	0.002
BFT0	-76° 56'55".8601	166° 58'47".4981	465.515	0.001	0.001	2	0.003
BTL0	-77° 46'58".4598	163° 31'43".2888	1385.514	0.001	0.002	-76	0.005
CRN0	-77° 52'19".7454	159° 31'51".9304	2626.761	0.001	0.001	-82	0.004

CRZ1	-77° 31'31".7067	169° 04'39".2133	950.063	0.009	0.010	89	0.038
DOO1	-77° 21'59".8221	163° 01'27".8103	460.868	0.001	0.001	174	0.003
DOO2	-77° 23'30".1164	162° 45'30".4761	1147.308	0.001	0.001	164	0.003
ERE0	-77° 30'40".0755	167° 09'12".4735	3356.780	0.001	0.001	176	0.003
FRK0	-76° 09'51".4201	168° 22'54".1848	192.442	0.002	0.002	-79	0.007
FTP0	-78° 55'38".2049	162° 33'51".7880	245.481	0.001	0.001	-71	0.004
HDV0	-78° 10'04".0889	163° 46'44".6369	770.960	0.004	0.005	176	0.021
MAS0	-78° 32'43".6449	164° 24'59".4879	1011.119	0.001	0.001	-78	0.004
MBF0	-78° 38'48".5670	167° 09'27".8324	735.245	0.001	0.001	164	0.002
MIE0	-78° 05' 46".1977	163° 47' 12".2906	115.243	0.004	0.005	-84	0.018
ROS0	-76° 43'47".9496	163° 00'57".3316	-25.825	0.012	0.015	78	0.044
VAN0	-77° 31'20".5330	161° 41'23".5593	41.985	0.000	0.000	168	0.002

Third Order Sites

B935	-77° 44'47".8391	161° 31'04".0362	1532.738	0.001	0.001	170	0.003
B93D	-77° 29'06".4687	161° 06'50".4213	1995.245	0.001	0.001	151	0.004
B93P	-77° 13'23".7021	162° 30'34".9334	1203.695	0.001	0.001	175	0.003
B93U	-77° 50'19".7012	166° 43'27".2409	245.766	0.001	0.001	5	0.004
B947	-77° 13'17".0922	161° 55'10".0427	1426.605	0.001	0.002	13	0.005
B94F	-77° 47'37".4441	162° 09'19".9845	1948.525	0.001	0.001	2	0.004
B94K	-77° 17'31".4207	163° 15'30".6735	600.195	0.001	0.001	171	0.004
B94Q	-77° 30'59".6625	163° 36'57".8181	705.458	0.001	0.001	1	0.004
B94T	-77° 56'11".8571	164° 04'50".3896	1182.354	0.001	0.001	159	0.003
B94W	-78° 13'56".2789	166° 22'00".8009	989.322	0.001	0.001	36	0.005
B959	-76° 54'09".0583	162° 11'45".1318	1196.819	0.001	0.001	166	0.004
B95D	-78° 07'50".5174	165° 22'59".9856	763.207	0.001	0.001	163	0.003
B95K	-77° 30'20".9251	162° 37'06".3557	1743.266	0.001	0.001	166	0.003
B95N	-77° 41'06".2899	166° 22'49".0267	79.223	0.001	0.001	2	0.003
B968	-77° 14'07".8106	163° 29'15".9438	-35.204	0.001	0.001	167	0.005
B96E	-77° 00'15".1476	162° 32'52".5939	-43.723	0.001	0.001	170	0.004
B96G	-76° 50'58".2053	162° 52'30".9259	-21.365	0.001	0.001	168	0.004
B96K	-76° 59'26".2473	162° 17'20".5700	203.305	0.001	0.001	167	0.004
B96V	-77° 30'36".1851	163° 47'55".0776	37.901	0.001	0.002	174	0.006
B972	-77° 46'00".0224	161° 10'24".5913	1161.868	0.001	0.001	179	0.003
B976	-77° 44'20".1390	160° 39'58".3027	1868.246	0.001	0.001	168	0.003
B97H	-77° 43'37".7669	162° 18'53".4201	92.748	0.001	0.001	165	0.004
B98H	-78° 00'15".5041	164° 31'16".2450	-50.851	0.001	0.002	170	0.006
B98J	-78° 05'47".0440	163° 47'17".0041	116.875	0.008	0.013	18	0.027
B9A2	-77° 38'13".9987	166° 25'11".3410	-29.681	0.001	0.001	7	0.003
B9A8	-77° 50'59".5739	166° 45'46".3068	-38.478	0.001	0.001	29	0.004
B9B7	-77° 41'41".6245	162° 32'36".6502	35.427	0.001	0.002	4	0.006
B9BC	-77° 45'41".6224	166° 53'51".4493	200.013	0.001	0.001	3	0.003
B9C4	-77° 50'44".4831	166° 38'19".6461	-41.998	0.001	0.002	12	0.005
B9DD	-77° 33'48".0981	161° 10'48".0020	65.465	0.001	0.001	171	0.005
B9DE	-77° 03'32".8509	161° 14'57".1664	1341.512	0.001	0.001	167	0.003
B9DM	-77° 58'05".4403	162° 02'34".2861	2131.560	0.001	0.001	174	0.002
BMWA	-77° 26'40".2991	162° 39'25".5559	218.925	0.001	0.001	176	0.005
BOB1	-77° 37'24".8016	162° 54'17".5683	20.240	0.002	0.002	164	0.007
CAMP	-77° 50'47".4497	166° 40'36".8260	-3.452	0.001	0.001	171	0.005
GRAV	-77° 50'53".8255	166° 46'06".4141	-36.636	0.001	0.001	1	0.004
HEIN	-78° 04'33".6705	167° 27'02".5243	684.721	0.001	0.001	13	0.003
MCM1	-77° 50'47".4498	166° 40'36".8236	-3.459	0.001	0.001	177	0.003

SCO1	-77° 50'56".3459	166° 45'28".8513	-19.217	0.001	0.001	163	0.003
ST53	-77° 50'41".1793	166° 38'30".6608	-36.572	0.009	0.020	159	0.023
VCE4	-77° 34'38".4512	163° 31'05".5285	-51.611	0.001	0.001	163	0.005
VIDA	-77° 22'42".7562	161° 48'59".5588	295.400	0.001	0.001	162	0.003

Appendix D Geocentric velocity estimates

Geocentric velocity estimates: 10° elevation mask solution

Coordinate Frame : ITRF96 Epoch 2000.000									
	NUVEL1A			Estimated			Standard Deviations		
	v_X (m)	v_Y (m)	v_Z (m)	v_X (m)	v_Y (m)	v_Z (m)	σ_{vX} (m)	σ_{vY} (m)	σ_{vZ} (m)
Zero Order Sites									
CAS1 66011M001	0.001	-0.008	-0.004	0.000	-0.007	-0.014	0.000	0.000	0.000
CHAT 50207M001	-0.025	0.038	0.021	-0.024	0.038	0.021	0.000	0.000	0.000
DAV1 66010M001	0.002	-0.003	-0.001	0.001	-0.005	-0.008	0.000	0.000	0.000
EISL 41703M003	0.067	-0.033	-0.014	0.066	-0.032	-0.014	0.000	0.000	0.000
HOB2 50116M004	-0.040	0.007	0.038	-0.039	0.007	0.037	0.000	0.000	0.000
KERG 91201M002	-0.006	0.003	-0.010	-0.006	0.003	-0.010	0.000	0.000	0.000
MCM4 66001M003	0.009	-0.010	-0.003	0.010	-0.015	0.004	0.000	0.000	0.000
OHIG 66008M001	0.019	0.001	0.005	0.020	-0.004	-0.008	0.000	0.000	0.000
PERT 50133M001	-0.050	0.011	0.046	-0.051	0.011	0.047	0.000	0.000	0.000
SANT 41705M003	0.022	-0.007	0.007	0.021	-0.007	0.007	0.000	0.000	0.000
First Order Sites									
ALN0	0.009	-0.010	-0.003	0.010	-0.012	-0.003	0.001	0.001	0.002
ANT0	0.009	-0.010	-0.002	0.009	-0.013	0.001	0.001	0.001	0.002
ARR0	0.009	-0.010	-0.003	0.012	-0.012	0.003	0.000	0.000	0.001
BIR0	0.009	-0.010	-0.003	0.010	-0.012	0.001	0.001	0.001	0.002
BRA0	0.009	-0.010	-0.003	0.010	-0.012	-0.003	0.001	0.001	0.002
BRM0	0.008	-0.011	-0.003	0.008	-0.013	-0.005	0.001	0.001	0.002
CRZ0	0.010	-0.010	-0.003	0.011	-0.012	0.000	0.001	0.001	0.002
DWT0	0.009	-0.010	-0.003	0.009	-0.013	-0.004	0.001	0.001	0.002
ESH0	0.009	-0.010	-0.003	0.010	-0.015	0.006	0.002	0.002	0.005
FLM0	0.009	-0.010	-0.003	0.008	-0.016	-0.005	0.001	0.001	0.003
PALM	0.019	0.000	0.004	0.018	-0.007	0.003	0.002	0.002	0.003
ROB0	0.009	-0.010	-0.003	0.008	-0.013	-0.001	0.000	0.000	0.001
ROY0	0.009	-0.010	-0.003	0.011	-0.013	-0.001	0.001	0.000	0.001
RYN0	0.009	-0.011	-0.003	0.009	-0.014	-0.003	0.001	0.001	0.002
WAL0	0.009	-0.010	-0.003	0.009	-0.014	-0.003	0.001	0.000	0.002
WRN0	0.009	-0.010	-0.002	0.005	-0.009	-0.001	0.001	0.001	0.003
WTE0	0.010	-0.010	-0.002	0.010	-0.013	0.001	0.000	0.000	0.001

Appendix E Topocentric velocity estimates

Topocentric velocity estimates: 10° elevation mask solution

Coordinate Frame : ITRF96
Epoch 2000.000

	NUVEL1A		Estimated			Topocentric Error Ellipse			
	v_E (m)	v_N (m)	v_E (m)	v_N (m)	v_H (m)	semi-axis minor b (m)	semi-axis minor a (m)	Azimuth	σ_H (m)
Zero Order Sites									
CAS1 66011M001	0.002	-0.009	0.003	-0.012	0.010	0.000	0.000	-87	0.000
CHAT 50207M001	-0.040	0.031	-0.039	0.030	0.001	0.000	0.000	80	0.000
DAV1 66010M001	-0.002	-0.003	-0.002	-0.007	0.006	0.000	0.000	-74	0.000
EISL 41703M003	0.075	0.009	0.073	-0.009	0.014	0.000	0.000	-82	0.000
HOB2 50116M004	0.015	0.053	0.015	0.052	0.001	0.000	0.000	90	0.000
KERG 91201M002	0.006	-0.006	0.006	-0.006	0.008	0.000	0.000	-76	0.000
MCM4 66001M003	0.008	-0.012	0.012	-0.012	-0.007	0.000	0.000	55	0.000
OHIG 66008M001	0.016	0.010	0.015	0.009	0.013	0.000	0.000	50	0.000
PERT 50133M001	0.040	0.056	0.041	0.057	0.003	0.000	0.000	89	0.000
SANT 41705M003	0.018	0.013	-0.018	-0.013	0.008	0.000	0.000	84	0.000
First Order Sites									
ALN0	0.007	-0.012	0.008	-0.015	-0.001	0.002	0.002	89	0.007
ANT0	0.006	-0.012	0.009	-0.012	-0.002	0.002	0.002	-84	0.007
ARR0	0.008	-0.012	0.009	-0.013	-0.007	0.001	0.001	-90	0.005
BIR0	0.008	-0.012	0.009	-0.012	-0.003	0.002	0.003	-83	0.008
BRA0	0.007	-0.012	0.009	-0.012	0.000	0.002	0.002	86	0.009
BRM0	0.007	-0.012	0.009	-0.014	0.003	0.002	0.003	83	0.008
CRZ0	0.008	-0.012	0.011	-0.011	-0.004	0.002	0.002	-87	0.008
DWT0	0.006	-0.012	0.009	-0.013	0.000	0.002	0.002	-89	0.008
ESH0	0.007	-0.012	0.009	-0.012	-0.004	0.004	0.005	-80	0.016
FLM0	0.006	-0.012	0.011	-0.014	0.001	0.004	0.004	88	0.014
PALM	0.017	0.009	0.013	0.014	0.004	0.001	0.002	-90	0.004
ROB0	0.007	-0.012	0.010	-0.012	-0.002	0.001	0.001	85	0.004
ROY0	0.008	-0.012	0.010	-0.013	-0.002	0.001	0.002	-90	0.006
RYN0	0.008	-0.012	0.011	-0.013	-0.001	0.002	0.002	90	0.007
WAL0	0.007	-0.012	0.011	-0.013	0.000	0.002	0.002	87	0.007
WRN0	0.006	-0.012	0.006	-0.008	-0.001	0.003	0.003	-90	0.012
WTE0	0.008	-0.012	0.010	-0.012	-0.003	0.001	0.002	-87	0.005