SECTION FIVE

GEODYNAMICS

5.1 GEODYSSEA

In the international scene, DSMM has participated in the EC-ASEAN Geodynamic project known as the GEODYSSEA Project. This project that was initiated in 1994 and completed in 1997 aimed to study the plate motion and crustal deformation in the region of South and South East Asia. GPS campaigns were carried out in December 1994 and April 1996 to study such motion. This was followed by a GEODYSSEA seminar in April 1997 in which the results of the campaign were tabled and discussed.

Even though the GEODYSSEA project was officially ended in 1997 the geodynamics study is still on going with a GPS campaign carried out in September 1998 to further gauge and confirm the plate movement in the region as initiated by the GEODYSSEA project. With the availability of such data, a time series dynamics of the region could be collected and studied. From the 2 GPS campaigns of 1994 and 1997, a zero order network had been set-up in Malaysia with coordinates referring to ITRF94 and ITRF96 and with an absolute accuracy of better than ±3cm.

The two Malaysian stations involved in both GEODYSSEA campaigns are Bkt. Pak Apil, Kuala Terengganu (KUAL) and Tinagat, Tawau, Sabah (TAWA). From the GEODYSSEA 94/96 combined solution, their computed velocities related to ITRF 94 & 96 are shown in Table 5.1 and Table 5.2 below.

Table 5.1 GEODYSSEA 94/96 – combined Solution Velocity Estimates W.R.T. ITRF94

Station	North (mm/yr)	East (mm/yr)	Up (mm/yr)	Std.N (mm/yr)	Std.E (mm/yr)	Std.U (mm/yr)
KUAL (K.Terengganu)	3.477	43.015	15.463	2.147	2.543	4.090
TAWA (Tawau)	-10.168	27.364	20.114	2.058	2.241	4.034

Table 5.2 GEODYSSEA 94/96 – combined Solution Velocity Estimates W.R.T. ITRF96

Station	North (mm/yr)	East (mm/yr)	Up (mm/yr)	Std.N (mm/yr)	Std.E (mm/yr)	Std.U (mm/yr)
KUAL (K.Terengganu)	7.702	38.638	19.728	1.954	2.450	4.065
TAWA (Tawau)	- 5.859	23.759	23.408	1.890	2.112	3.919

5.2. ASIA AND PACIFIC REGIONAL GEODETIC PROJECT (APRGP) UNDER THE PERMANENT COMMITTEE FOR GIS INFRASTRUCTURE FOR ASIA AND THE PACIFIC (PCGIAP)

5.2.1 Introduction

The primary role of ASIA AND PACIFIC REGIONAL GEODETIC PROJECT (APRGP) is to facilitate a single regional datum through a network of compatible geodetic datums. Through this project, it is hoped to:

- Establish a reference regional datum
- Determine the transformation values between the regional datum and the local geodetic datums of the individual countries

The first ASIA AND PACIFIC REGIONAL GEODETIC PROJECT 1997 (APRG97) campaign was organized by AUSLIG to establish a geodetic infrastructure to support GIS in the Asia and the Pacific region. The second campaign or APRG98 also coincided with GEODYSSEA and was made in September 1998. The APRG97 results had been discussed in Canberra, Australia from 2 to 4 July 1998. The matters discussed are as follows:

- GPS data Analysis
- Satellite Laser Ranging Solutions
- VLBI Solutions
- Geodetic Datums of Malaysia, Japan, Philippines, Vietnam, Australia, New Zealand,
- GEODYSSEA results
- Regional Geodetic Datums
- Transformation from Local to Regional Datum
- ITRF Densification for Asia and the Pacific
- Unification of Vertical Datum
- Linking National Vertical Datums
- Cartesian 3-D Datum

5.2.2 APRGP2000 Campaign

GPS observation campaign was carried out from 8 to 14 October 2000. 24 hours of continuous GPS measurements were collected at 96 participating stations. GPS data from 26 IGS stations were also used (Figure 5.1).

The processing was divided into 5 blocks where each block consists of between 14 to 36 stations. At least 7 IGS stations were included in each block. It was also decided that the common number of IGS stations between blocks to be between 6 to 10 stations. It was divided as follows:

- Block I : Malaysian Network
- Block II : Middle East (Iran)
- Block III : East Asia
- Block IV : Pacific
- Block V : South East Asia

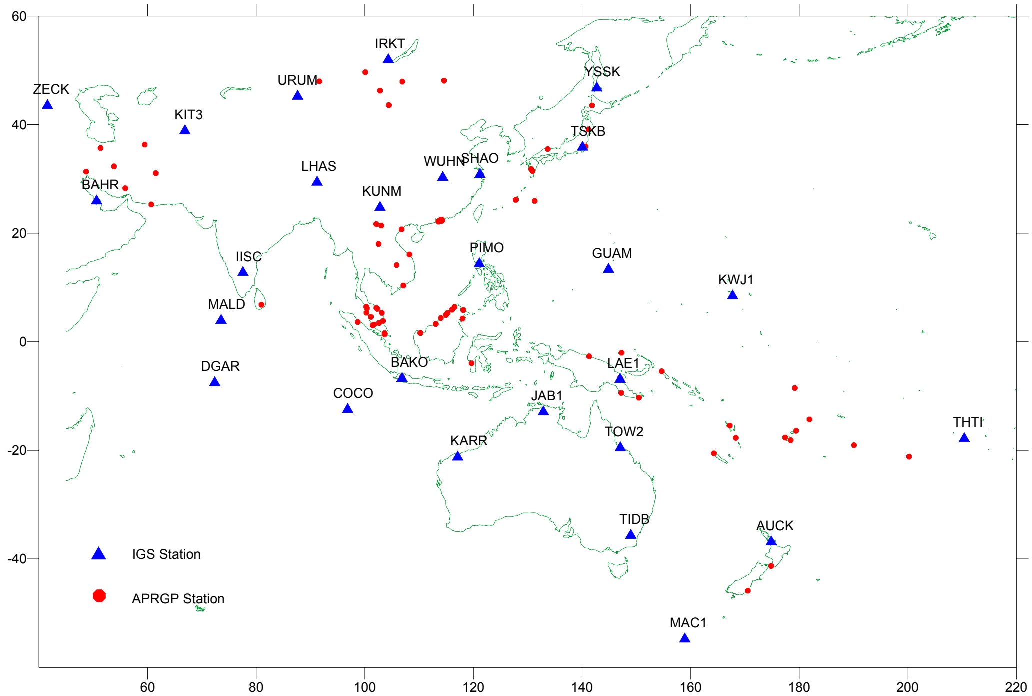

Figure 5.1 APRGP stations distribution

GPS data processing was performed using the Bernese Post Processing Software version 4.2. Automation was achieved using the Bernese Processing Engine (BPE). Results show that the following have been achieved:

- Daily Repeatability
  - Horizontal - 3.3 to 10.8 mm
  - Height - 10.6 to 14.5 mm
- RMS of Multi-Day Average
  - North - 3.9 mm
  - East - 7.5 mm
  - Height - 12.5 mm
- RMS of IGS Stations
  - North - 7.9 mm
  - East - 7.8 mm
  - Height - 6.0 mm
- Network Accuracy wrt ITRF2000 Epoch 101000
  - North - 11.8 mm
  - East - 15.3 mm
  - Height - 18.5 mm

5.3 ITRF2000 REALISATION OF MASS NETWORK

The MASS network is a homogeneous and coherent network that covers the whole of Malaysia. The data from fifteen MASS stations, excluding Segamat and Sibu, between January 1999 and December 2000 have been processed along with those from eleven IGS stations as part of the realisation of the Zero Order Geodetic Network for Malaysia (DSMM, 2002). The long-term objective is to integrate the network into the International Terrestrial Reference Frame (ITRF) based on the International Terrestrial Reference System (ITRS), (Abu & Mohamed, 1997; Abu & Mohamed, 1998).

ITRF is realised through a set of station coordinates of global terrestrial fiducial points. The coordinates of the points are published by the International Earth Rotation Service (IERS) in its annual reports. At the time of writing, the coordinates of the IGS stations were available in the ITRF2000, released in March of 2001. This is the latest realisation of the ITRF and thus the most accurate to date. It has the reference epoch on 1997 January 1 0h UTC. This means that the station coordinates are based on data recorded up to the year 2000 but mapped using a plate motion or velocity field to their coordinates at a time of 1997.0.

The 2000 realisation of the ITRF is based on fifty-four sites and it combines solutions from a number of space techniques including GPS, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography by Radio-positioning Integrated on Satellite (DORIS). The present estimated accuracy of the ITRF2000 coordinates is about 2 to 5mm in position and 1 to 2mm/yr in velocity. The stability of the frame over 10 years is reported to be accurate to better than 0.5 ppb in scale or equivalent to a shift of about 3mm in station height and 4mm in origin.

5.3.1 Transformation Between Various Frames

Due to the availability of numerous reference frames, there is a need to carry out transformations between them. To transform any station coordinates from one terrestrial reference frame to another at the same epoch, a Helmert similarity transform is used:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_E^{yyyy} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \begin{bmatrix} 1+\Delta s & -R_z & R_y \\ R_z & 1+\Delta s & -R_x \\ -R_y & R_x & 1+\Delta s \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_E^{YYYY} \qquad (5.1)$$

where (Δx Δy Δz) are the transformation parameters, (x y z) and (X Y Z) are the derived and station coordinates, E and $YYYY$ are the epoch and year of the ITRF realisation, Δs is the scale change, $yyyy$ is the desired year of the ITRF realisation and (R_x R_y R_z) are the rotations in the three axes.

Table 5.3 shows the transformation parameters that can be used to convert coordinates between various coordinate frames. Each new version of the reference frame, currently being prepared approximately every two years, incorporated more data and used better computational techniques. Hence a better solution is expected to be obtained with every new realisation. In some frames, it is assumed that there are no rotations in all of the three axes. It can be seen that the solutions from each realisation of the ITRF coordinates are slightly offset from previous solutions. For example, a transformation from ITRF1997 Epoch 1997.0 to ITRF2000 Epoch 1997.0 will result in offsets of about 2.1cm difference in the station coordinates.

Table 5.3 Transformation Parameters from ITRF2000 Epoch 1997 to previous frames

Coordinate Frame	Δx (cm)	Δy (cm)	Δz (cm)	Δs (ppb)	Rx (.001")	Ry (.001")	Rz (.001")
ITRF1997 Epoch 1997	0.67	0.61	-1.85	1.55	0.00	0.00	0.00
ITRF1996 Epoch 1997	0.67	0.61	-1.85	1.55	0.00	0.00	0.00
ITRF1994 Epoch 1997	0.67	0.61	-1.85	1.55	0.00	0.00	0.00
ITRF1993 Epoch 1988	1.27	0.65	-2.09	1.95	-0.39	0.80	-1.14
ITRF1992 Epoch 1988	1.47	1.35	-1.39	0.75	0.00	0.00	-0.18
ITRF1991 Epoch 1988	2.67	2.75	-1.99	2.15	0.00	0.00	-0.18

5.3.2 Data Acquisition

The data from 15 MASS stations and 11 IGS stations for 1999 and 2000 have been used in the data processing. However, only 8 stations in Peninsular Malaysia with 11 IGS station were used in the processing to establish the Zero Order Geodetic Network.

Eleven permanent GPS tracking stations of the International GPS Service (IGS) world-wide network in ITRF2000 Epoch 1997 were used as fiducial points in the processing to obtain the MASS set of station coordinates with two years (1999 to 2000) of continuous GPS data. These IGS stations are illustrated in Figure 5.2. Processing was done in a Digital-Unix environment using the Bernese Post Processing Software version 4.2.

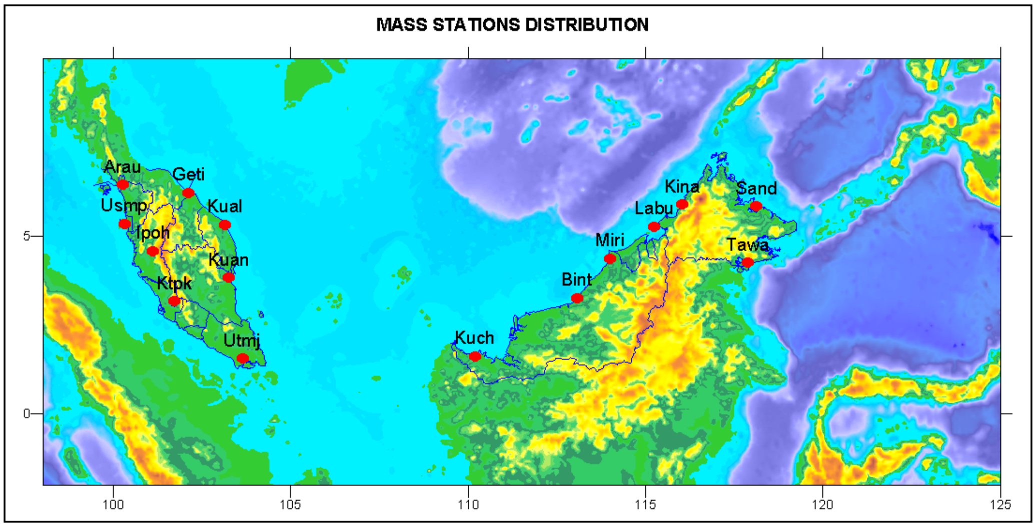

Figure 5.2 MASS stations distribution in Peninsular Malaysia

5.3.3 GPS Processing Strategy

Bernese is a scientific software written by a team of geodetic scientists at the Astronomical Institute University of Berne (AUIB) in Switzerland. The software is the latest offering and a revised version of its predecessor developed by the geodetic team at the University of Berne. It combines specialised surveying knowledge with advanced software techniques. Data input and output is achieved via keyboard interface within Unix environment, allowing one to select commands and performs tasks with relative ease. The main features of the software are as follows:

- All GPS observables (code and phase) on L1 and L2 carrier frequencies and their different linear combinations may be used;
- All mathematical correlations and the combinations among the observables may be modeled;
- Baseline, session and network processing can be performed.

The Bernese software consists of a collection of batch and interactive programs that are executed for the following operations:

Transfer	-	to decode GPS observational data and satellite navigation data in RINEX into the Bernese format
Orbit	-	to create, improve and update satellite orbits
Pre-Processing	-	to perform single point station positioning and correct cycle slips
Processing	-	to estimate parameters in baseline or network modes

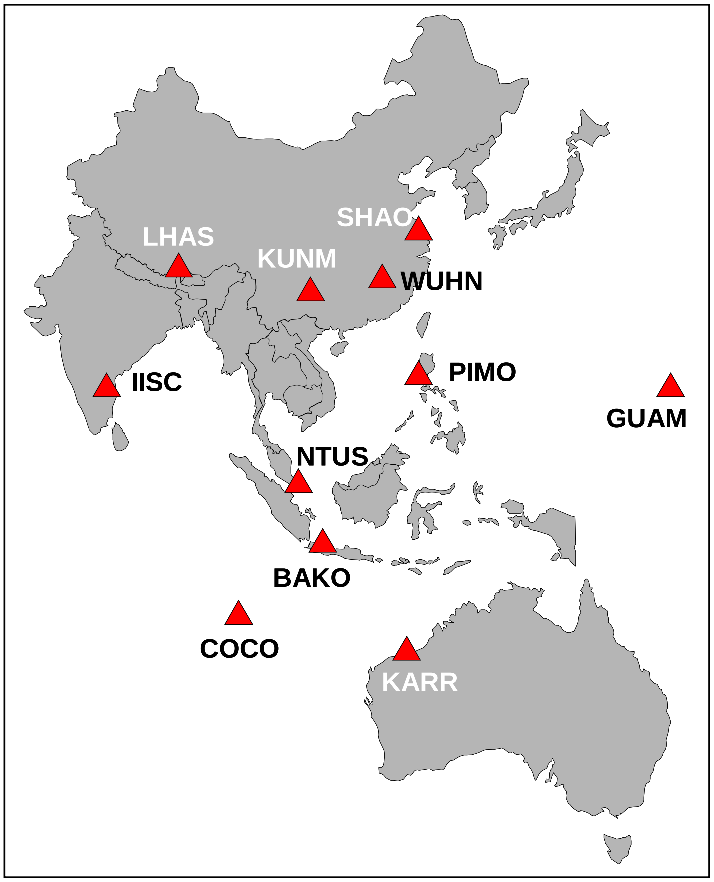

Figure 5.3 IGS stations used to derive MASS coordinates in ITRF2000

Automation in the routine GPS processing in order to obtain the MASS set of station coordinates was achieved using the Bernese Processing Engine (BPE) that runs on Red Hat Linux version 6.2. Following are the main highlights of the GPS processing (DSMM, 2002):

a) Pre-processing

The general strategy used for daily pre-processing is as follows:

- Use of IGS Final orbit referred to ITRF97 and C04 earth rotation parameter (ERP) series.
- The apriori coordinates of IGS stations (Official IERS release version) and MASS stations (APRGP Campaign).
- Antenna phase center offset - Phas_IGS.01 table.
- Rinex to Bernese Conversion : 30 second data sampling.
- Conversion: IGS SP3 ephemeris - tabular format - Bernese format. Ocean tides correction - OT-SCRC model is introduced with development planetary ephemeris (DE200).

- Single Point Positioning using the L3 code pseudo-range measurement - estimate the receiver clock correction.

- Satellite clock biases - eliminated by forming double-difference observations.

- Forming single difference observation by using “shortest” method.

- Phase check using triple difference for data screening - to fix the cycle-slips and to mark the short data interval, gaps, unpaired observations and ambiguity setup.

b) Daily Adjustment

The computation of baseline and daily solutions is as follows:

- Adjustment of double difference carrier phase and ionosphere effect eliminated by the L3 linear combination.

- Zenith delay parameters were estimated once per 2-hours interval relative to Saastamoinen model with apriori constraint of 5.0/5.0 m absolute/relative sigma.

- Ambiguity resolution : QIF (Quasi Ionosphere Free) [Mervart, 1995] ambiguity fixing strategy in baseline-by-baseline mode. Ionosphere for baseline specific model was used for baseline longer than 500 km.

- About 85 % of the ambiguities were fixed using the above strategy.

- The daily solutions (session) of the independent baselines were loosely constrained with 1 m apriori sigma and no coordinates in the network adjustment were fixed.

C) Weekly Solution

The weekly solution was carried out as follows:

- Weekly solution: Combination of seven (7) normal equations of the daily solution.

- 11 IGS stations were held fixed with the coordinates transformed to an epoch of the middle of the week.

- Two strategies had been applied for the weekly solution adjustment and the strategies:

    - Free Network adjustment with the introduction of Helmert Transformation
    - Heavily constrained

- Both results were analysed statistically for coordinate repeatability and RMS of residuals.

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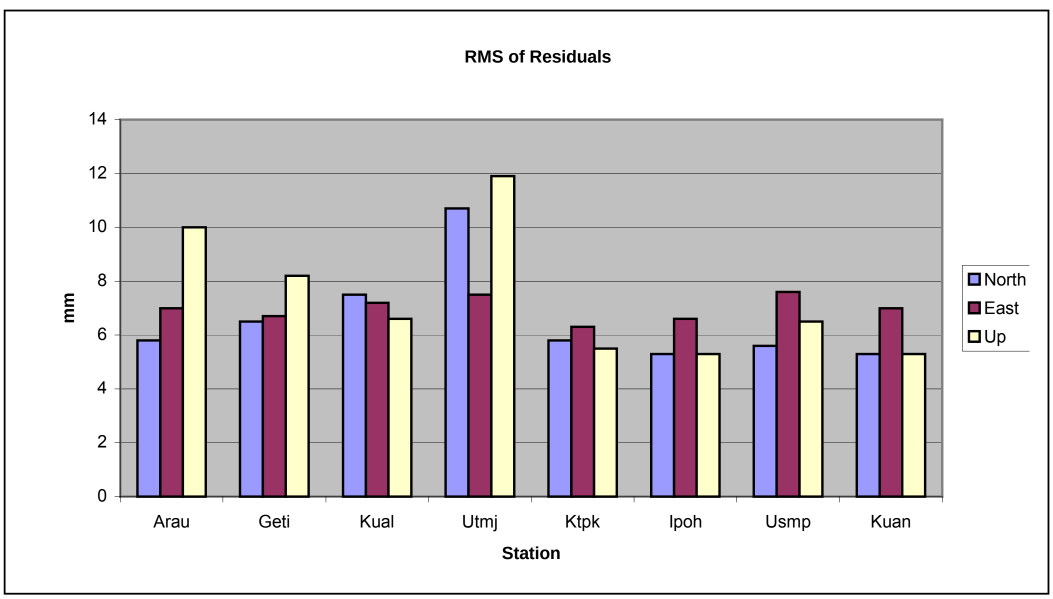

RMS of Residuals
14
12
10
8
6
4
2
0
mm
Arau
Geti
Kual
Utmj
Ktpk
Ipoh
Usmp
Kuan
Station
North
East
Up

From Figure 5.4, it shows that MASS station UTMJ has a slightly bigger RMS value in the northing and height components but the value is not significant. It can be concluded that the internal accuracy of the MASS stations from the free network adjustment is 5 to 11 mm in the horizontal component and 5 to 12 mm in the height component.

Comparison of IGS stations coordinates has been made in order to determine the accuracy of the network with respect to the IGS stations. With the final combined coordinate from the network adjustment projected to 2 January 2000 (IGS and MASS stations), the reference coordinates (ITRF2000 Epoch 1997.0) for the IGS stations were transformed on the same epoch as the adjusted coordinates.

It can be concluded that the accuracy for MASS stations with respect to the ITRF2000 reference frame with free network strategy is 9 to 15 mm in the horizontal component and 12 to 19 mm in height.

5.3.4.2 Heavily Constrained Adjustment

The heavily constrained adjustment was to adopt the specific reference frame in ITRF2000. RMS of coordinates repeatability is shown in Figure 5.5.

From the figure, it shows that the RMS in easting component is larger than the northing and height components. This is a normal scenario due to the MASS station location in the equatorial belt and the development of velocity in IGS stations. The figures also show that the accuracy of station coordinates is between 3 to 16 mm in horizontal component and 8 to 13 mm for the height.

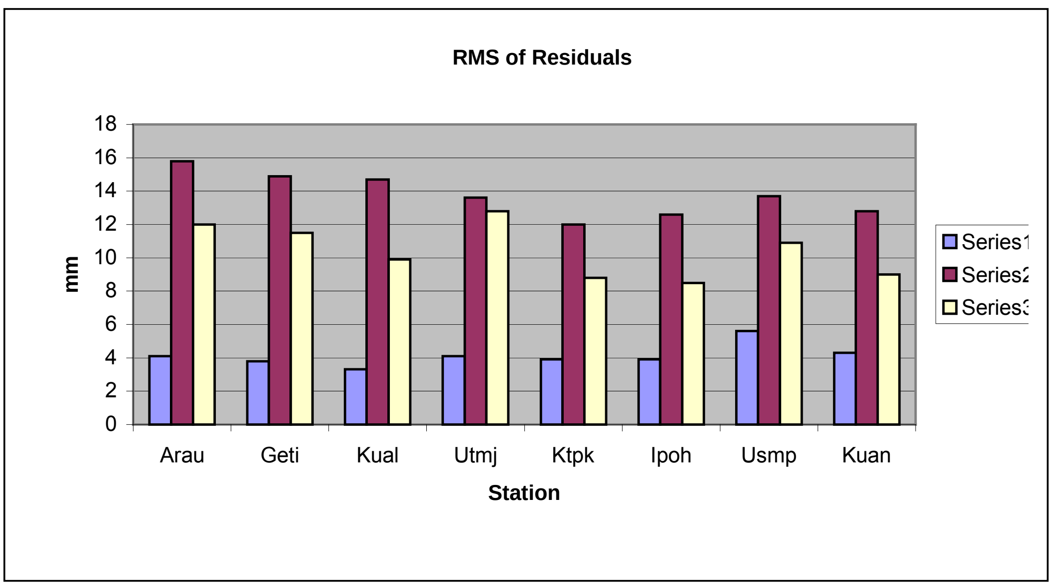

Figure 5.5 RMS of Residuals

Comparison between coordinates from free network adjustment and heavily constrained adjustment is also made. The RMS of residuals are 2.0, 1.7 and 4.4 mm for the northing, easting and height component respectively.

The translations component shows that the coordinates between two strategies were almost identical. With the above statistic, the coordinates of the heavily constrained adjustment was adopted as the final coordinates (Epoch 02.01.2000).

5.4 Continuous Monitoring of Tide Gauge Station Using GPS

Sea level and its changes are of prime importance to humanity. The global sea level used to be at more than 100 m below the current level and it has risen by 10-20 cm over the past century. A significant component of this rise is due to increasing global temperatures. Rises of sea level by any amount can lead to potential environment, economic and social consequences for coastal areas. Over the last two decades, there has been awareness among scientific and civilian communities to investigate trends and patterns in the world's climate and sea level. The most direct evidence for sea level changes can be derived from measurements using tide gauges. However, one of the main difficulties is the separation of sea level changes from the local changes of land level.

The mean sea level is determined at the tide gauge and the height is then transferred to a tide gauge bench mark (TGBM) by spirit levelling. TGBMs, on the other hand, are attached to solid earth. As a result, sea level measurements from tide gauge are considered ambiguous. The records do not only reflect sea level change but also vertical land movements due to crustal movements also contaminate the data. For example, if the ground is rising, a tide gauge would observe a fall in relative sea level, whereas absolute sea level may have remained constant. There are many reasons for the Earth crust to subside or uplift, including post-glacial rebound (PGR), sediment loading, tectonic activity and compaction caused by fluid extraction.

5.4.1 GPS Installation at Geting Tide Gauge Station

Of the 18 stations that comprise the MASS network, only the ones at Geting (Peninsular Malaysia) and Bintulu (East Malaysia) that the GPS are collocated within the same facility as the tide gauge. Geting station is situated beside the South China Sea and like most other tide gauge stations, it is in a well-protected area of a river channel, at latitude 06° 13′ 35″ N and longitude 102° 06′ 24″ E. Figures 5.6 and 5.7 depicts the functional configuration of the major elements that make up the Getting MASS Tide Gauge Station.

The installation of a permanent and continuous GPS at any site requires careful consideration. This includes sky clearance, station security, easy access, proper monumentation and the availability of power and communication. All these factors were taken into account during the setting up of Geting MASS Tide Gauge Station.

The GPS geodetic antenna is mounted through forced centering on a stainless steel plate via a 5/8" screw thread and is embedded onto the concrete rooftop of the tide gauge station. The station itself is located at the end of a 15 metre long steel and wooden pier. It is constructed with piled foundations on an outcrop of solid bedrock. This set-up ensures that sub-surface displacements that could change the level of the tide gauge and the GPS antenna is kept to a minimum. The station has a sky clearance of between 10 to 90 degrees all around. There is also no presence of radio interferences at the site that might affect GPS signals. The effects of multipath are reduced by attaching a ground plane to the antenna.

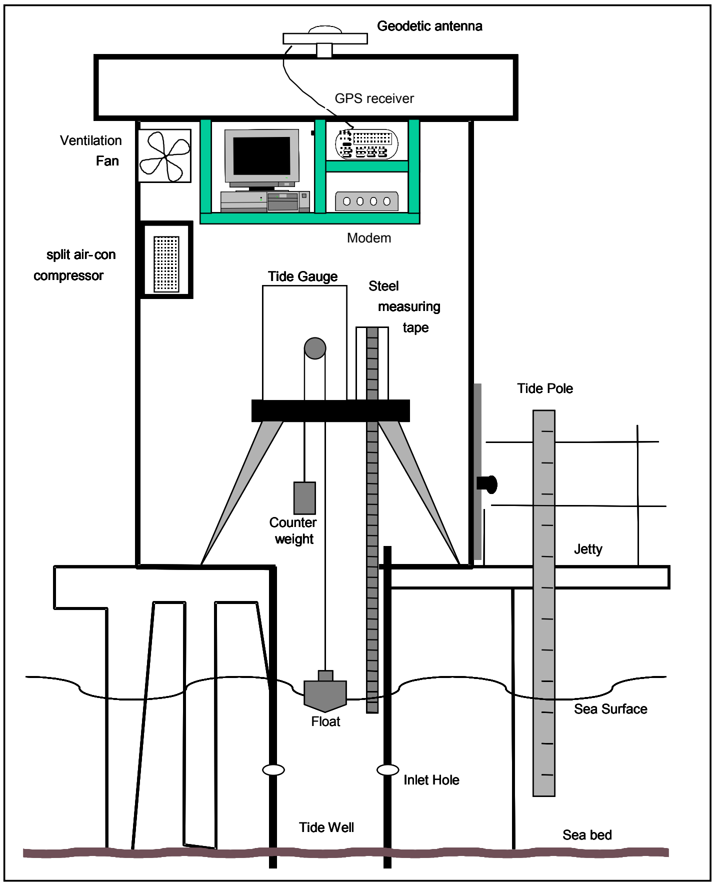

Figure 5.6 The configuration of Geting MASS Tide Gauge Station

5.4.2 Estimation of Relative Vertical Movements

Continuous GPS data from 1999 to 2000, collected at Geting tide gauge have been processed for the ITRF2000 realisation of the MASS network. The results from this processing are the estimates from the 104 weekly solutions and the combined solution. These weekly estimates of GETI station are then compared with its two-year combined solution.

Figure 5.8 represents the graphs of weekly residual time series as derived for the northing, easting and vertical components of Geting station coordinates. The residuals for the vertical component are the main concern in this study. The northing and easting residuals show similar level of consistencies at mm level. The ground tracks of GPS satellites are predominantly north-south direction. As such, the north component of the GETI coordinate residuals has good repeatability, ranging from –4.9mm to 16.6mm and a standard deviation of 3.2mm, as compared to the easting residuals.

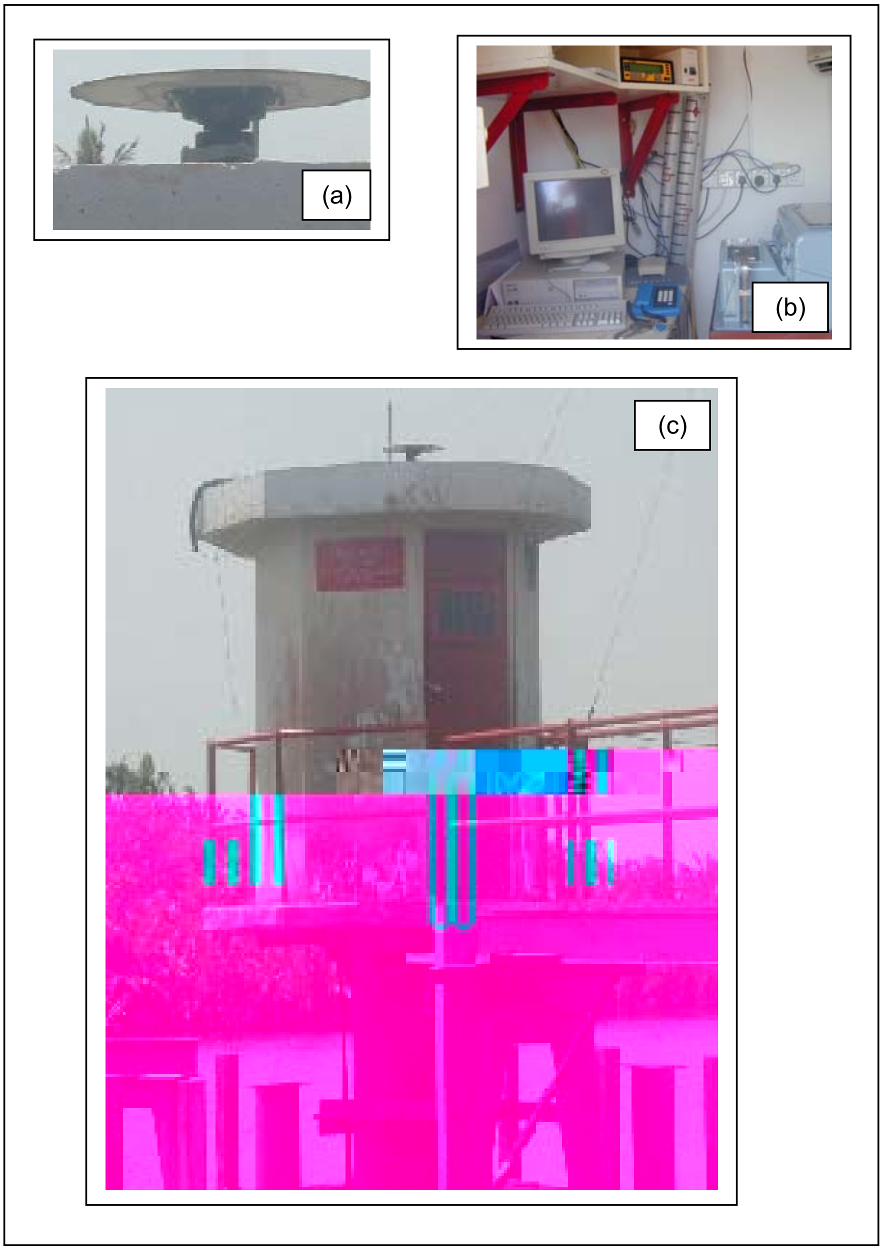

Figure 5.7 (a) The L1/L2 Geodetic GPS antenna with ground plane
(b) Inside the Geting MASS Tide Gauge Station, showing the GPS receiver, the PC and the tide gauge equipment
(c) Geting MASS Tide Gauge Station

The vertical component is the least constrained by GPS observations. The discrete vertical estimates for the height time series have a total spread of 61.2mm and a standard deviation of 11.7mm. It is the least precise component since measurements are made upward to the satellites. The vertical component is also most sensitive to tropospheric refraction. Its variation is random in nature and as shown in Figure 5.8 is at cm level. It demonstrates the fact that although GPS is essentially a 3-dimensional positioning system, the height component of GPS solutions tends to be weaker than the horizontal component.

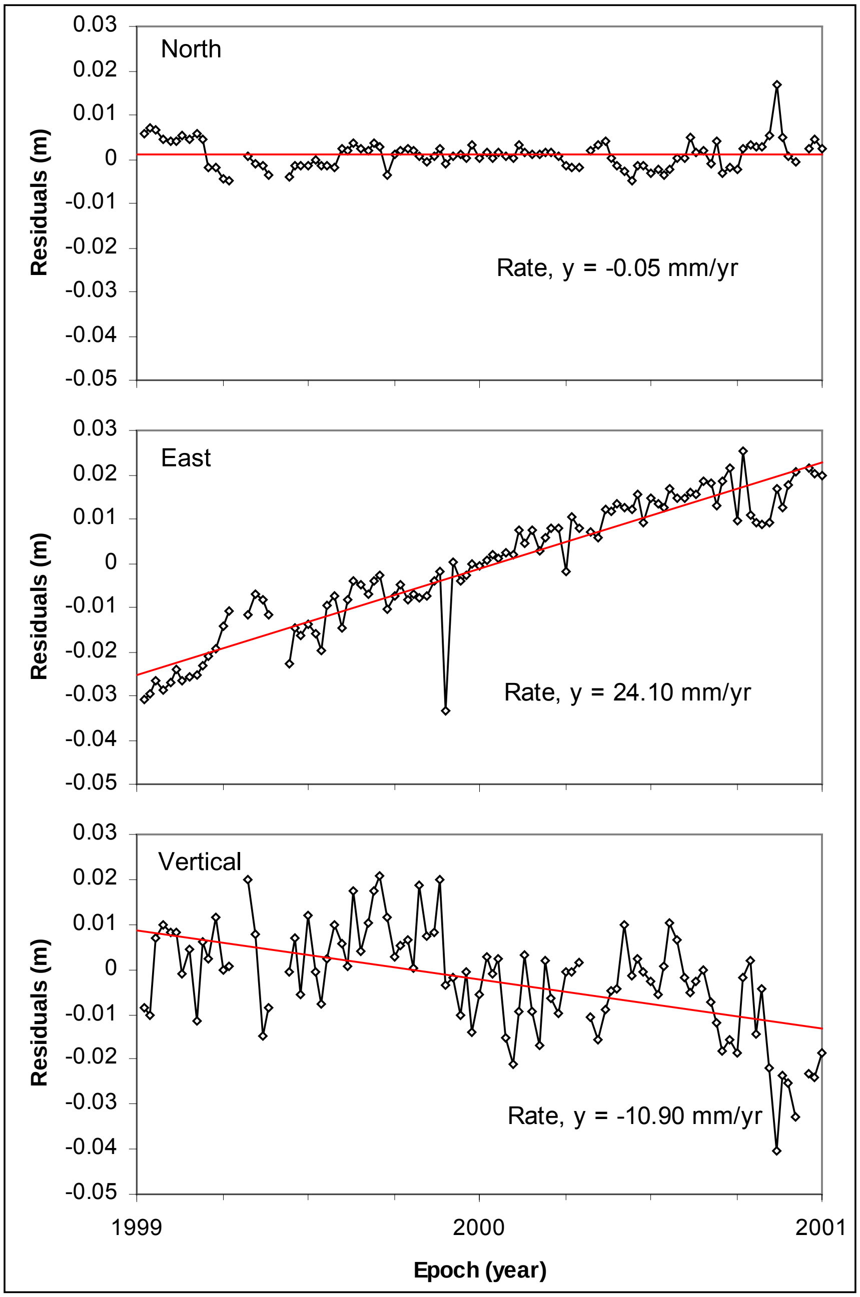

Figure 5.8 Residuals time series for the northing, easting and vertical residuals of co-located GPS and tide gauge at Getting MASS station

A linear trend in each components of GETI station is estimated. The linear trend are estimated as –0.05 and 24.10 mm/yr for the north and east components respectively. On the other hand, the vertical velocity estimate is –10.90 mm/yr. Closer inspection of Figure 5.8 reveals some evidence for a cycle in the height time series. It is also noticeable that the height time series undergoes periodic variations with varying amplitudes. This would not have been apparent in episodic GPS campaign-type such as the TG2000. The value for the vertical velocity estimate represents the first estimation of the vertical land movement at Geting tide gauge station. More reliable values are expected to be obtained if the period of observation is longer.

However, caution must be exercised when using station velocity estimates from short amount of data. Annual repeating signals in the time series are known to have been attributed to a number of effects. This includes atmospheric and ocean loading effects and reference frame effects due to the limitations in global network methodology.

5.4.3 Comparisons with Sea Level Data

A graph of the residual plots of the yearly sea level variation at Geting station for the years 1987 to 2000 is shown in Figure 5.9. It can be seen that large fluctuations due to weather conditions tend to balance through the years. It is also observed that the periodic seasonal changes are mostly eliminated. The range of the mean annual variation is about 8cm.

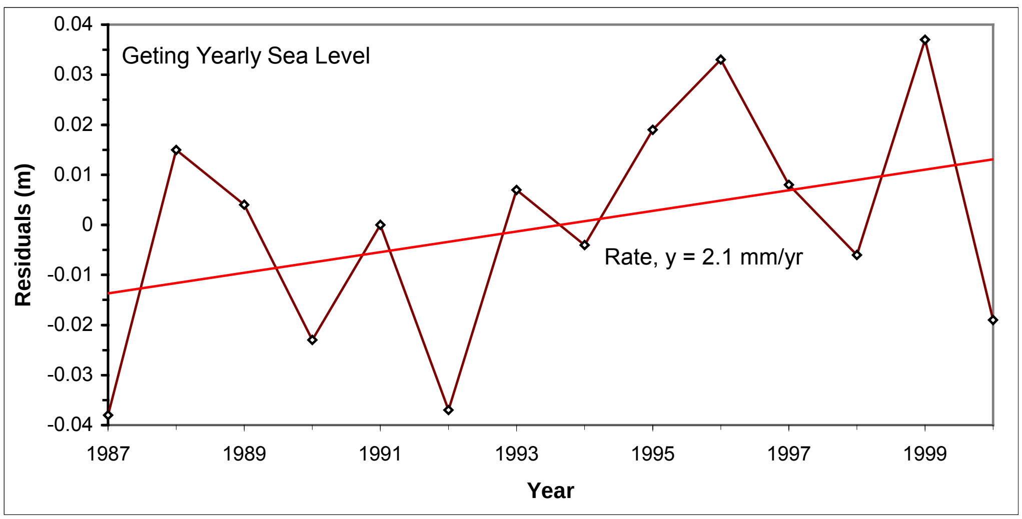

Figure 5.9 Residual plots of available yearly sea level at Geting Tide Gauge Station

The relative sea level trend for Geting tide gauge station is estimated as 2.1 mm/yr. The indication is that the trend is almost similar to the overall world-wide rate of sea level rise during the past 100 years, which is between 1- 2 mm/yr. Assuming that 1.5 mm/yr was due to the rise in global sea level, this suggests that Geting tide gauge station has, over a period of 14 years, experienced a subsidence of about 0.6 mm/yr. However, the height time series shows that the station has subsided by 10.9 mm/yr. It can be concluded that uncertainties still exist in both the sea level and ground level, thus, perhaps, suggesting the need for longer term data sets.