SECTION FOUR

GENERAL THEORY AND METHODOLOGY

4.1 TIDAL OBSERVATION NETWORK

The main objective of the setting-up of tide gauge stations is to enable a continuous time series of sea level be determined. JUPEM is among the few agencies responsible for the overall coordination of the data acquisition, verification, storage and publication of sea level data. The sea level data obtained are used for a wide variety of purposes and some are summarised as follows:

- to establish a vertical datum that forms the basis for the definition of the national heighting system. The datum is defined by the average value taken from the 10-year tidal measurements carried out between 1984 and 1993 at Port Kelang.
- to assist in the design of land, engineering and harbour projects for flood control, navigation and irrigation;
- to demarcate coastal cadastral and jurisdictional boundaries, base point project being an obvious case in point; and
- to support research activities such as coastal erosion, crustal deformation, ocean current patterns, weather patterns etc.

4.1.1 Network Configuration

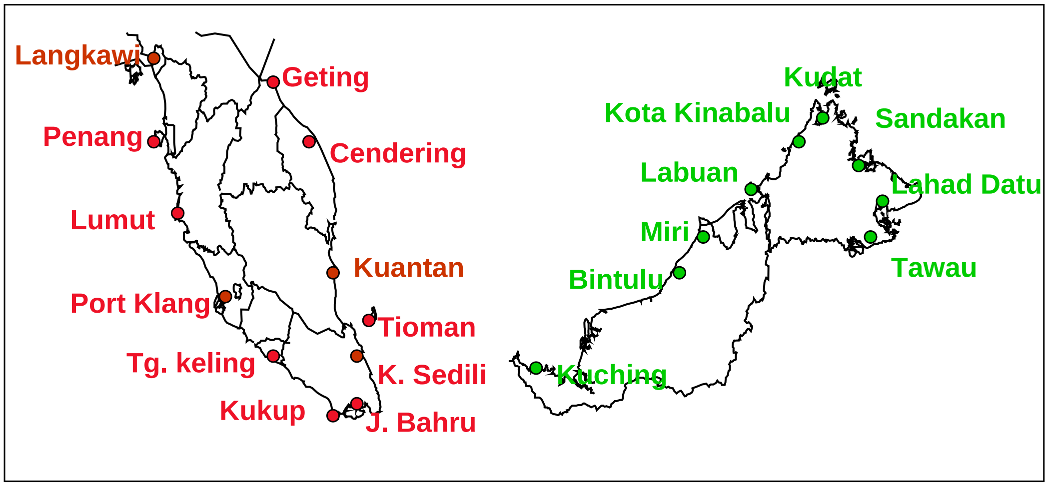


Figure 4.1 Tide gauge locations in Malaysia

JUPEM manages the Tidal Observation Network (TON) of 21 continuously operating sea level observation stations or tide gauge stations along the coastal areas of Malaysia. The distribution of these stations in Peninsular Malaysia is illustrated in Figure 4.1. The choice for the sites was so arranged such that they are evenly distributed along the coastline. The main objective of the establishment of the

network is to enable a continuous time series of sea level heights be obtained for the purpose of establishing a vertical datum for the nation.
According to records, attempts have been made as early as in the 1960's to establish a network of tide observing stations in Peninsular Malaysia. According to Daud (1969), a directive was issued at the 14th Meeting of the National Mapping Committee on March 19, 1968 to carry out preliminary investigations and observations for establishing one tide gauge station each for the east and the west coast of Peninsular Malaysia. However, due to the lack of know-hows, the project did not materialised.

It was not until 1981, under the Colombo Plan, that the project was re-initiated with the assistance from the Japanese International Cooperation Agency (JICA) in the form of technical aids, experts and advice. Following the successful collaboration between Government-to-Government (G2G), the first installation of Kyowa Shoko LTT-3AD float tide gauge was done at Port Kelang in December 1983. This was followed in a progressive manner by the establishment of the remaining stations in Malaysia. Currently, all the tide gauges were replaced by Kyowa Shoko DFT-1 that incorporate digital recorders. These new set of equipment have a reported measuring range of 0 to 7 meters and accuracies of ±0.1% of the range.

JUPEM is also involved in the ASEAN-Australia Tides and Tidal Phenomena Project (AATTP) which was implemented in 1985 for the purpose of improving regional cooperation in marine science. The project aimed to obtain simultaneous observations of sea level time series in the ASEAN region and to centralize all modern sea level data into a certified database. Two stations (Lumut and Chendering) have been selected to form part of the GLOSS (Global Sea Level Observing System), a network of some 300 sea level stations initiated by the Intergovernmental Oceanographic Commission (IOC).

4.1.2 Tide Gauge Station, Data Processing and Station Maintenance

A tide gauge station in Malaysia consists of a tide gauge protective house, stilling or tide well, tide staff and several reference bench marks, one of which is referred to as the tide gauge bench mark. The tide gauge measures water-level heights with respect to the zero mark on a tide staff. Seawater enters the well through a small inlet hole in the bottom of the well. The gauge is activated in analog form by a float hanging from the gauge in the stilling well. A quartz crystal clock controls the recoding mechanism. The well and float gauge is the standard instrument at all tide gauge stations in Malaysia. Aluminium tide poles were also installed at all the stations for comparative observations.

Presently the sampling interval of the tide gauge is set at 10 seconds, whilst the averaging is performed every 50 seconds. The averaged data is then transferred from the internal memory of the tide gauge and stored onto the IC memory cassette after 100 minutes. The tidal readings are stored in blocks with each block containing 120 tidal data (256 bytes). The DFT1 model can store digital data continuously for a period of more than nine months. It runs on a DC12V-15 Ah battery that needs recharging every 40 days. At present, the tide gauges do not have any data transmission facilities. Instead, the DSMM staff collects the data on a regular basis.

The sea level data processing at the Geodesy Section is a fully computerised operation and commences once the collected data on the IC memory cassette are transferred to the computer via the GPIB interface board. The whole procedure is performed on the recently acquired NEC PC9821 Ra43 microprocessor connected to a Graphtec Plotwriter WX 4731. The process can be split into three stages: observation data processing, data analysis and tidal prediction. The output from each tide gauge station are as follows:

- Hourly heights of sea level;
- Daily, monthly and yearly mean sea level values;
- Time and heights of high water and low water;
- Tidal marigram; and
- 29-day tidal analysis.

Figure 4.2 A typical tide gauge station (Kukup, Johor)

It should be noted that certain conditions needed to be fulfilled when computing these mean sea level values. Yearly MSL is not computed if gaps in tidal data are greater than three consecutive months. Similarly, should there be no data for a period of ten days or more for the daily means, the mean sea level for that month is not computed. On the other hand, missing hourly sea level data are only interpolated if the time gap of this occurring is less than 24 hours. This is done using the available data from the previous and the following day.

JUPEM produces two annual publications for all tide gauge stations:

- Record of Tidal Observations for previous year; and
- Tidal Prediction Tables for the following year.

The Geodesy Section carry out regular visits on a monthly basis to all the tide gauge stations to:

- collect the sea level data;
- change the batteries and the IC memory cassettes;
- check the Established Value (EV);
- compare readings at tide gauge and tide pole; and
- do general cleaning of tide gauge and its accessories to ensure its smooth functioning.

Within the vicinity of all tide gauge stations, there exist at least four tide gauge bench marks (TGBMs). One of these TGBMs is of particular importance as it is the tidal or datum bench mark whereby the zero of the tide gauge and the computed MSL are referred. Precise levelling is carried out twice a year between the base point of the tide gauge, standard marks, tide pole and bench marks. This is to guard against the possibility of unexpected land movements within the tide gauge area.

4.1.3 Mean Sea Level and Local Vertical Datum

As mentioned, one of the main objectives of the setting-up of tide gauge stations is to enable a continuous time series of sea level be determined for the purpose of establishing a national vertical datum. In Peninsular Malaysia, this datum, known as the Peninsular Malaysia Geodetic Vertical Datum (PMGVD) is defined by the average value taken from the 10-year tidal measurements carried out between 1984 and 1993 at Port Kelang. The Port Kelang tide gauge station has been in operation since December 1983 and has over 17 years of hourly sea level data. The yearly MSL at Port Kelang is shown in Figure 4.3.

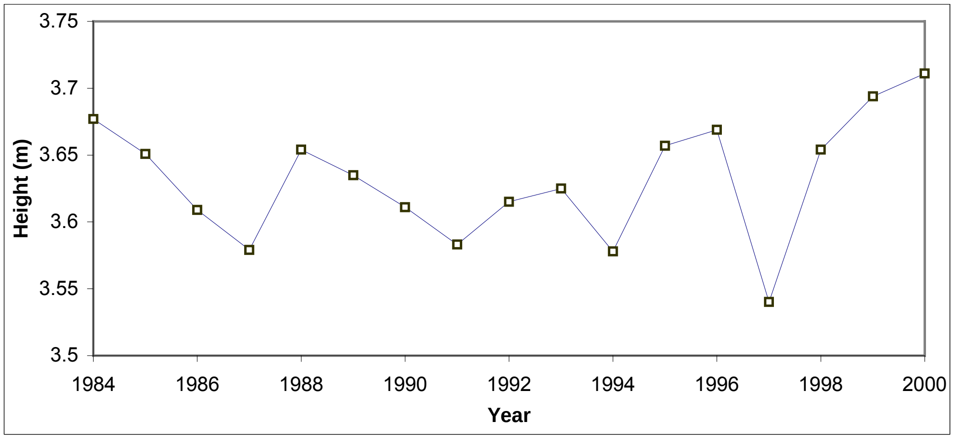


Figure 4.3 Yearly mean sea levels for Port Kelang

Figure 4.4 illustrates the geometrical relationships of various surfaces at Port Kelang Tide Gauge Station. As noted previously, the MSL at this tide station defines the vertical datum for Peninsular Malaysia, which was based upon the mean value of 10-year tidal observational data (1984-93). This is denoted by MSL_{PMGVD} and it exhibits a positive offset of 0.058m from the old vertical datum, MSL_{LSD12}. BM0169 is the reference bench mark that represents the origin of the present Precise Levelling Network (PLN). It is 3.863 m above the MSL_{PMGVD}.

Another surface of interest, 2.335 m below the MSL_{PMGVD} is the Datum Level, which is adopted from the Indian Spring Low Water. The adopted Established Value (EV) is the vertical distance from the tidal observation datum (Zero of Tide Gauge) to the tide gauge Base Point. It is given by the sum of *H* and *D*, where *H* is the tidal level or the sea surface height from the Zero of Tide Gauge and *D* is the vertical distance from the tide gauge base point to the sea surface.

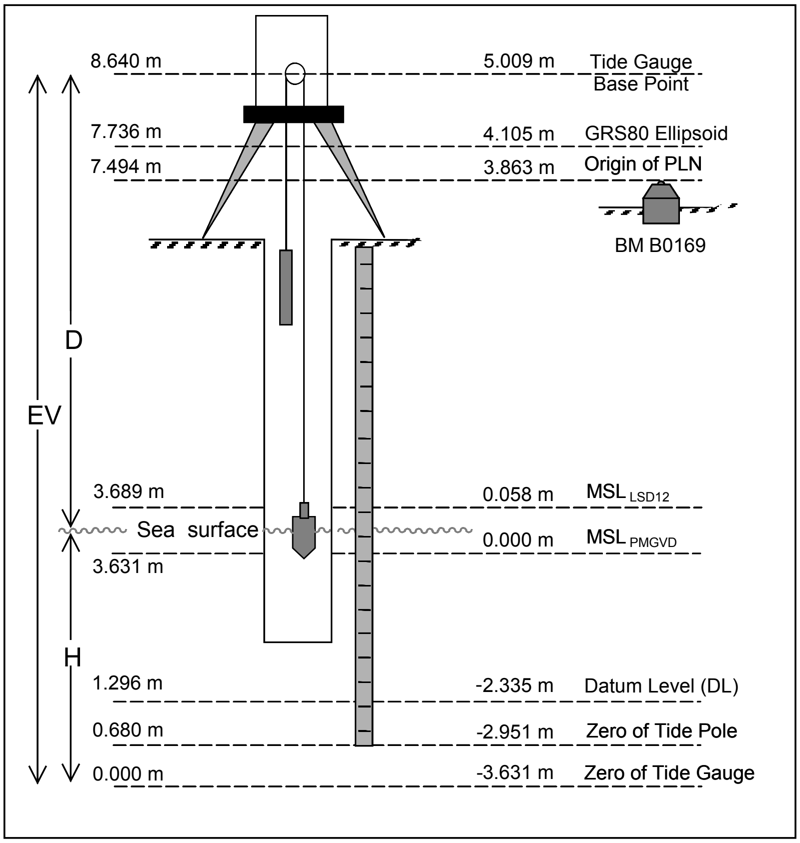


Figure 4.4 Geometrical relationship of various surfaces at Port Kelang Tide Gauge Station.

4.1.4 El Nino and La Nina

El Nino is a natural weather phenomenon that disrupts the climate. The tropical trade wind, which normally blows from South America to Asia across the Pacific, reverses its direction during this event. It causes a large body of warm water to flow from the coasts of Asia across the Pacific to the coasts of South America, forming rain clouds. This interannual see-saw or commonly referred to as the southern oscillation in the tropical sea level pressure between the eastern and western hemisphere has the centre action located in Indonesia and the tropical South Pacific Ocean. This phenomenon brings heavy rainfalls in the southern United States of America and Peru and droughts in much of Asia. This striking feature can be seen in the residual plots of Figure 4.5 during the El Nino event which occurred during the 1997-98 period, causing the sea levels at their lowest.

After the El Nino events which can lasts several seasons, La Nina occurred in the following years (between 1999 and 2000) where the warm tropical waters were driven westward by the trade winds and piled up in the western Pacific Ocean. Thus, in Peninsular Malaysia there were apparent rises in the sea level in the west coast as well as on the east coast.

The 1997-98 El Nino lowered sea levels along the coast of Peninsular Malaysia, especially at stations on the west coast. Figure 4.5 illustrate the full impact of El Nino and La Nina at Port Kelang tide gauge station. Sea level, that was under 4 cm above normal in 1996, was nearly 10 cm below normal in 1997. Thus it is clear that the annual sea levels between 1997 and 2000 might not be indicating a eustatic rise or fall, but simply reflecting the regional consequences of strong weather patterns.

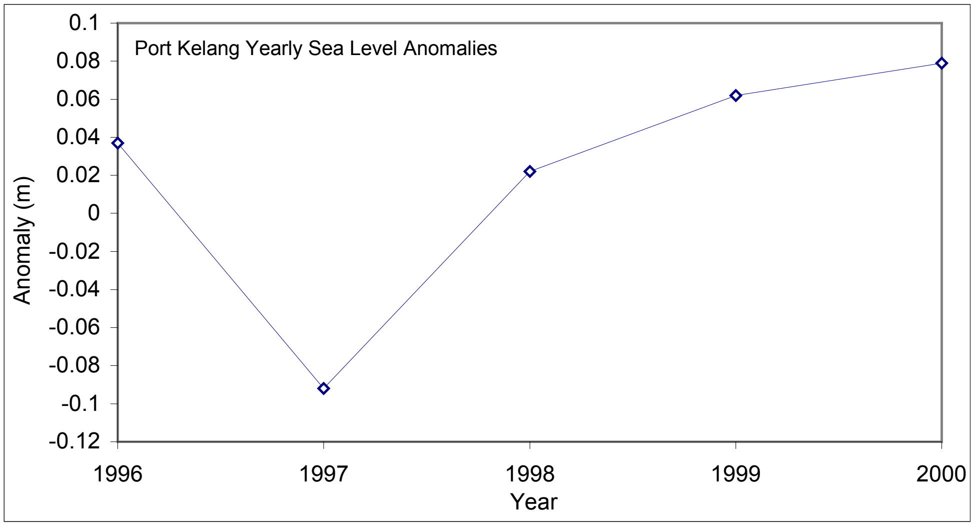


Figure 4.5 Residual plots of yearly sea level at Port Kelang

4.1.5 Sea Level Trends

The derivation of mean sea level trend is computed as the least squares linear regression to the distribution of the data value versus year. The trend rates are given in Table 4.1 and represented graphically in Figure 4.6. It shows that a trend in sea level around Peninsular Malaysia exists and varies quite significantly from one location to another. It can also be seen that the linear trends of the MSL variations are positive, indicating an overall rise in the sea level around the coast of Peninsular Malaysia. The rising trend ranges from 1.7 ± 6.0 mm/year at Tanjung Keling on the west coast to 3.4 ± 0.2 mm/year at Tanjung Gelang on the east coast. Taking the average of the group, the indication is that relative sea level trends in Peninsular Malaysia show 2.4 ± 0.5 mm/year.

As stated earlier, the study uses sea level data until 2000 (between 13 to 16 years), which would give a rather better characterisaton of sea level anomalies. Earlier study by Ses (1997) that used data up to 1994 showed that the linear trends of MSL at all locations are falling at an average rate of –0.2 cm/year. However, within the scientific community, there is a general consensus that overall world-wide rate of sea level rise during the past 100 years has been nearly 2 mm per year. Thus, the present results agree to some extent with other studies on global sea level, both in sign and magnitude at most tide gauge stations.

However, it must be noted that other factors such as local land or tide gauge subsidence, global sea level rise, coastal circulation or other meteorological influences are also reflected in the results. It is difficult to separate these effects from the observed trend in the local sea level. These local effects need to be averaged out geographically and suitably accounted for before any significance can be placed on the sea level rise.

Table 4.1 Computed linear trend estimate of mean sea level

	Tide Gauge Station								
	West Coast					East Coast			
	Lumut	**Port Kelang**	**Tanj. Keling**	**Kukup**	**Johor Bahru**	***Tanj. Sedili***	**Tanj. Gelang**	**Cendering**	**Geting**
Data Used	1985 to 2000	1984 to 2000	1985 to 2000	1986 to 2000	1985 to 2000	1987 to 2000	1987 to 2000	1985 to 2000	1987 to 2000
Mean	2.189	3.632	2.847	3.997	2.847	2.403	2.795	2.199	2.290
Linear Trend (cm/yr)	0.28	0.18	0.17	0.26	0.22	0.25	0.34	0.26	0.21
Std. Error (cm/yr)	± 0.04	± 0.05	± 0.60	± 0.03	± 0.02	± 0.02	± 0.02	± 0.62	± 0.02

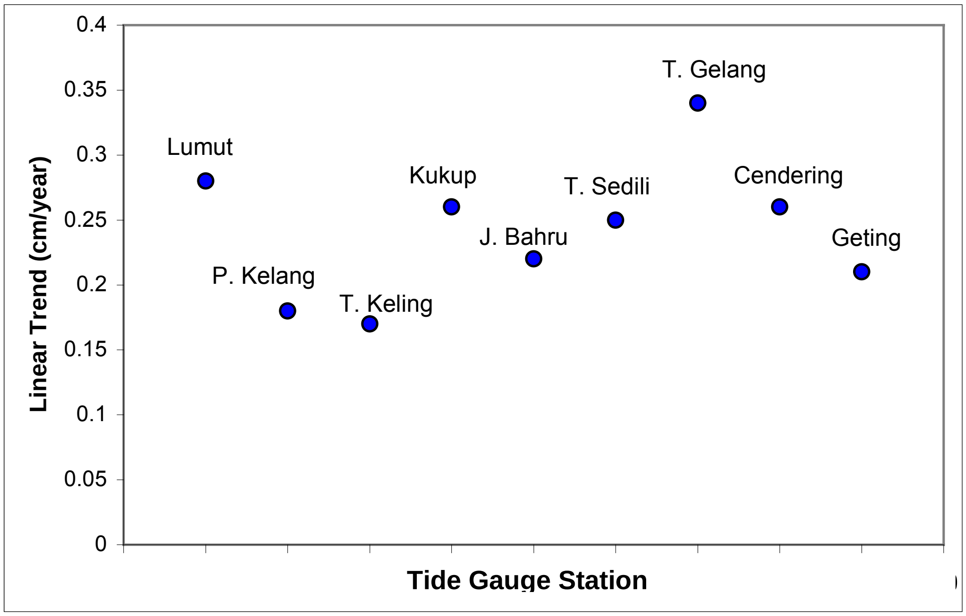
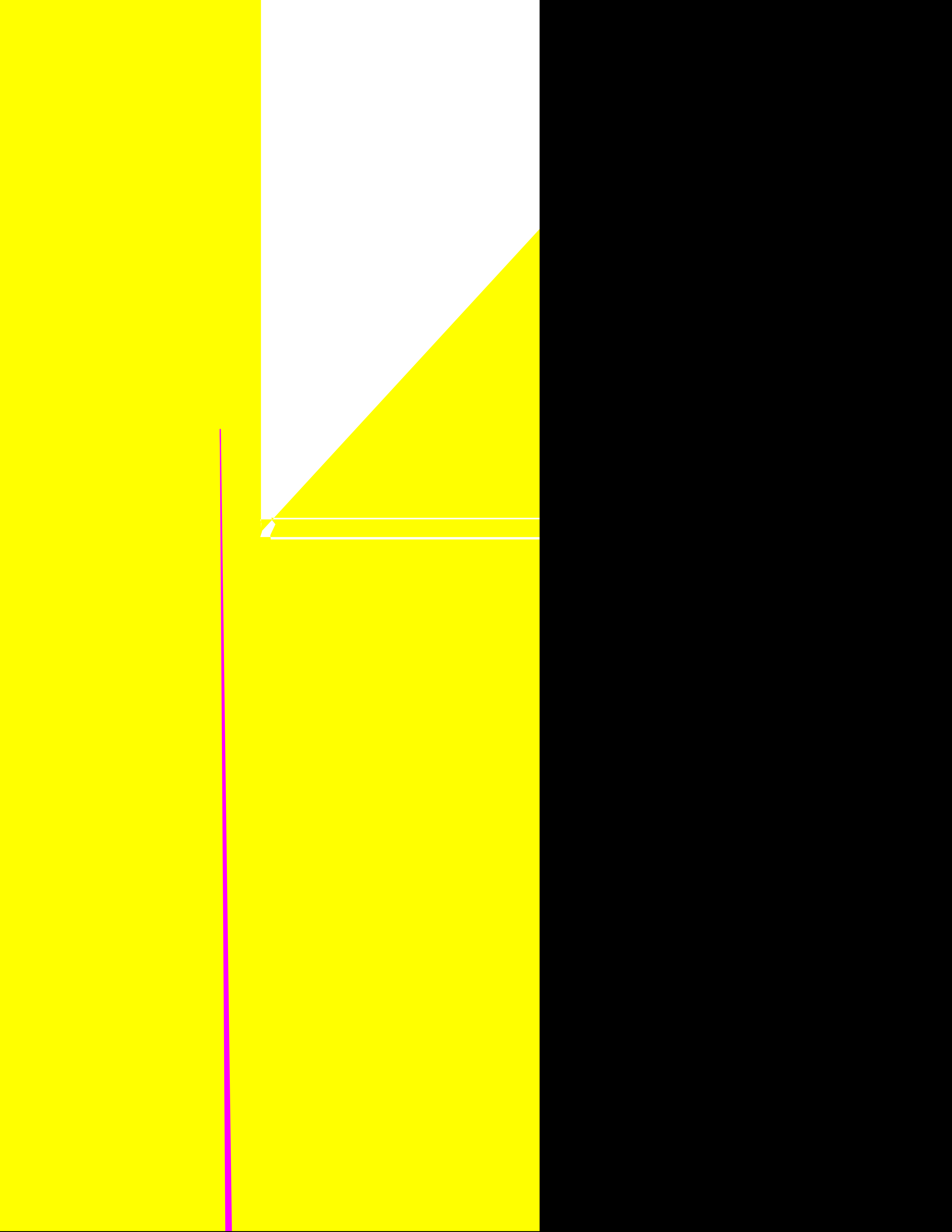


Figure 4.6 Ordered plot of linear trend estimate of mean sea level



levels. The levelling operation commenced in 1985 and the network was completed in 1999. Figure 4.7 shows the final and main levelling frame of PLN.

PLN consists of 113 first order levelling lines with 5443 bench marks, involving a total distance of 5004 km. Twenty-two main loops make up the network that covers a geographical area of about 131, 598 km^2. There also exists within the network itself an array of second class levelling lines.

4.2.2 Precise Levelling Field Specifications and Procedures

In Peninsular Malaysia, there exist two classes of levelling being undertaken by DSMM. These are defined in accordance to the permissible discrepancy between the forward and return levellings as dictated in the Survey Regulations 1976 Appendix 1B. These are as follows:

Class of Levelling	Permissible Discrepancy
1st Order	$3\sqrt{K}$ mm
2nd Order	$12\sqrt{K}$ mm

where K is the distance in kilometers between two successive bench marks along a levelling line.

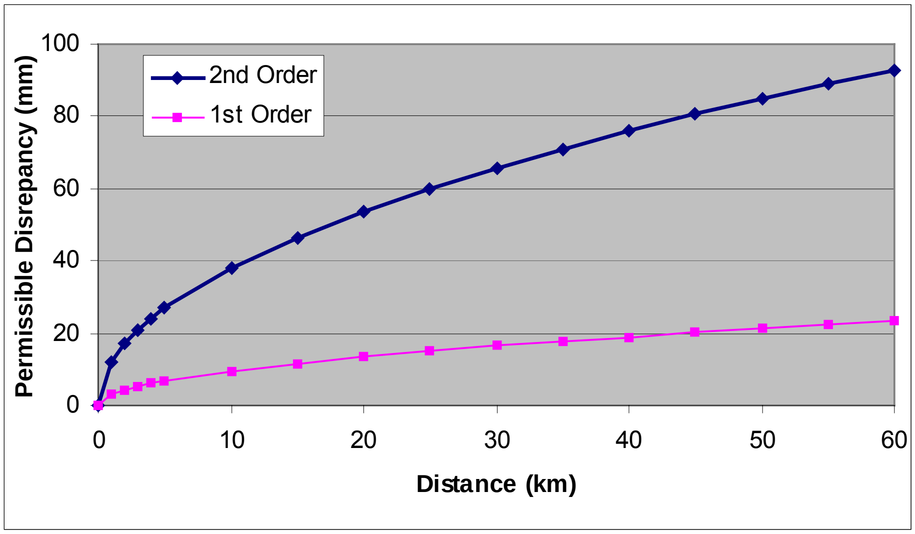


Figure 4.8 Permissible discrepancy curves in levelling

Figure 4.8 shows the error curves for the two orders of levelling over increasing distance as applied in Peninsular Malaysia. The average distance between SBMs is normally about 5 km and this equates to a permissible misclosure of 6.71 mm in first order levelling work.

DSMM dictates that the precise levelling survey should start from an established permanent bench mark and incorporate at least two old bench marks. Overall, the general characteristics of field specifications for precise levelling as practiced in Peninsular Malaysia are summarised as follows:

Technique : Double-run levelling in sections

Height Discrepancy : 3 $\sqrt{(\text{distance in km})}$ mm

Instruments

- Level :
  - Tilting type and fitted with parallel plate micrometer
  - Automatic type with compensator
  - Automatic digital type with compensator
- Staff :
  - Two staves used
  - Precise type and fitted with an invar strip with 0.01 meter graduations
  - Supported on turning points using steel pickets/plates
  - Weekly checks using plumbline for verticality
  - Calibrate every 3 months against a standard or by using a laser comparator
  - Two-peg test performed before the start of any new survey

Field Procedures :

- Start and finish levelling line at SBM
- Double-run sections on different days and times
- Staff sight clearance at 30 cm, same staff read first, even number of set-ups and in leap-frog manner
- Shading of instruments from direct sun

Method of Reading :

- Read to the nearest 0.01 mm
- 3-wire method for conventional levelling technique
- 'red-trousers' method for motorised levelling technique
- BFBF method for digital levelling technique

Line of Sight

- Optimum length : 40 to 50 meters with equal forward and backward distances to within 1 meter.
- Time : Early morning and late afternoon.

The PLN was completed in 1999 with more than 5300 BMs planted. The mean sea level at Port Kelang, based upon a 10-year tidal observation (1984-93), was later being adopted as the new Peninsular Malaysia Geodetic Vertical Datum (PMGVD). Three different levelling techniques were used in the realisation of the PLN: conventional, motorised and digital barcode levelling techniques. All three methods differ in terms of equipment, specifications, field procedures and levelling data acquisition.

Conventional levelling is extremely tedious and time consuming, achieving a very slow progress at 2 km per day. Booking procedures and data retrieval were cumbersome and the sighting distance was limited to about 30 meters. On the other hand, higher line of sight in motorised levelling increases the rate of progress to 12 km per day, without significant loss of accuracy. Rapid advancement in the field of electronics provides an easier and faster mode of operation than the classical levels. Nowadays, the use of digital levels is becoming widespread within the DSMM due to the simplicity in operation and for its high accuracy. It also forces strict compliance with the regulations and procedures as outlined by the department.

4.2.3 Pre-Analyses of Levelling Data

The Precise Levelling Network (PLN) of Peninsular Malaysia comprises of 113 lines in 22 loops. Out of these, 7 lines were measured using conventional levelling technique, 46 using automatic digital barcode level and 60 using motorised levelling method. These three diversified primary sources of data were firstly verified and checked against any gross errors and applied for various corrections. Finally the data were transferred to a suitable format for further statistical analysis and processing.

The application of orthometric corrections based on observed and interpolated gravity seemed to not improve the loop closures in any significantly. The statistical analyses of the leveling data were undertaken to gain some insight into the quality of the data. The main quantities used are the distance between benchmarks, the number of sections, year of observation, heights discrepancies between the forward and return height differences and loop misclosures. Results indicate that a certain degree of skewness does exist in all three data sets with the motorised data set showing a negative skewness. Positive kurtosis is also observed in the three data sets with the digital barcode data portraying a greater steepness than a normal distribution with its highest kurtosis index. However, the deviation from normality is not significant in all three data sets, indicating that the levelling data are of a homogeneous data set.

Results from run and trend tests provide no evidence of a non-random behaviour of the data set. On the other hand, the results from the χ^2 test indicates a highly significant departure of the normalised height discrepancies from normality. This could be due to the effect of the rejection criteria $3\text{mm}\sqrt{K}$ used that causes most of the observations to concentrate much more around the mean, resulting in a truncated normal distribution. In general, one can say that the results from the tests are indicative of a trend on only a small fraction of the whole data set.

Based on the analysis of height discrepancies, it appears that post-1990 levelling data are more precise than the prior data. The introduction of digital barcode levelling technique also had improved the precision of levelling data. An examination of loop misclosures suggests that the levelling loops need to be reduced in size to improve the strength of the network, possibly under 400km in perimeter distance. Statistical analyses of the levelling height discrepancies and levelling loops indicate that the measurement accuracy of the PLN conformed to the IAG regulations of precise levelling.

4.2.4 Adjustment of PLN

A consistent and accurate set of adjusted heights of BMs has been achieved in the adjustment of the Precise Levelling Network of Peninsular Malaysia on a single defined datum. These adjusted heights are based on the Helmert orthometric height system. The height estimates for some 5300 bench marks are attained through the least square adjustment using observation equations. Mean line height differences were adjusted to derive a set of final height estimates. The network also connects to nine tide gauge stations, which are part of the Tidal Observation Network.

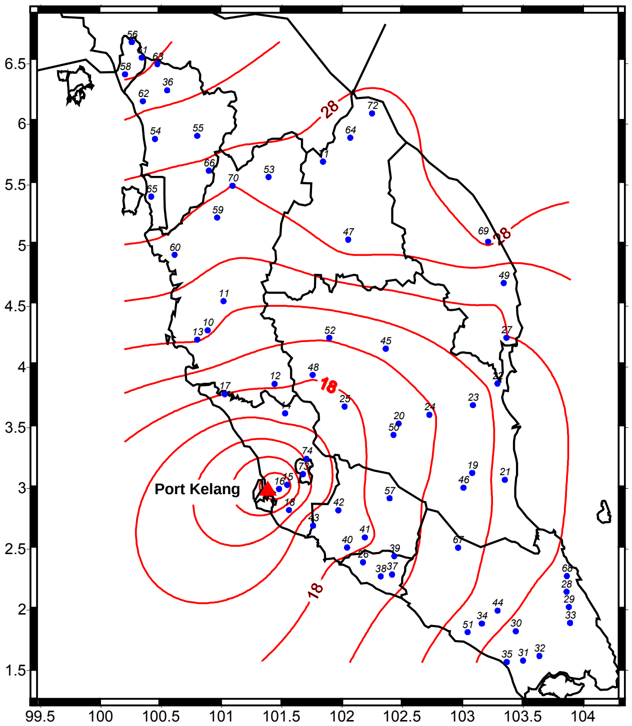


Figure 4.9 Contour plot of standard errors from minimal constraint network adjustment at Port Kelang Tide Gauge Station (contour interval is 20mm)

The adjustment of the PLN first followed the minimally constraint adjustment. By fixing Port Kelang, the precision of the PLN can be expressed as 1.14 mm $\sqrt{km}$. This implies that for any of the 5300 first-order levelling bench mark across the nation, a height value of better than 3 cm can be expected (see Figure 4.9). The least-squares estimates of the residuals has a normal distribution and that the statistic $r\,\sigma^2/\sigma_o$ has a χ^2 probability distribution with 28 degrees of freedom. Adjustment results indicate that the standardised residuals of the adjusted heights have a normal distribution and show an almost blunder-free network. The estimated variance factor is within the two-tailed 95% confidence region.

4.3 COMPARISON BETWEEN MSL AND LEVELLING HEIGHTS

Orthometric height of the tide gauge bench marks and the heights of mean sea level are compared. Here an assumption is made that the height differences between the local mean sea level values are zero. Figure 4.10 illustrates the various surfaces at a typical tide gauge station. Their relationship are given as:

$$H_{BM\_MSL} = H_{BP} - H_{MSL} - \Delta H \tag{4.1}$$

where H_{BM_MSL} is height of the TGBM above the mean sea level, H_{BP} is the height of the tide gauge base point above the zero of tide gauge, H_{MSL} is the height of the mean sea level at the tide gauge station from tidal records and ΔH is the height difference between the tide gauge base point and the tide gauge bench mark as derived from the periodic precise levelling.

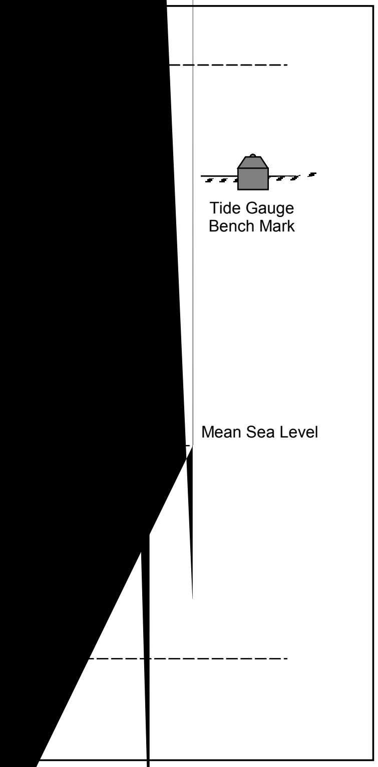

Tide Gauge
Bench Mark
Mean Sea Level

Table 4.2 Height discrepancies between precise levelled heights and MSL heights at tide gauge bench marks

Tide Gauge Station Name	TGBM	H_{BP}	H_{MSL}	ΔH	H_{BM_MSL}	H_{BM_PLN}	Discrepancy δ
Lumut	A0401	7.100	2.189	1.415	3.496	3.5141	0.0181
Tanjung Keling	M0331	7.500	2.847	1.073	3.580	3.6809	0.1009
Kukup	J1323	8.500	3.997	1.616	2.887	3.0346	0.1476
Johor Bahru	J0416	7.100	2.847	1.021	3.232	3.4450	0.2130
Tanjung Sedili	J0802	6.000	2.403	1.473	2.124	2.3418	0.2178
Tanjung Gelang	C0331	7.800	2.795	1.317	3.688	3.8602	0.1722
Cendering	S0148	6.800	2.199	1.737	3.691	2.9961	0.1321
Geting	D0353	7.300	2.290	1.319	2.864	3.8673	0.1763

All values are in metres

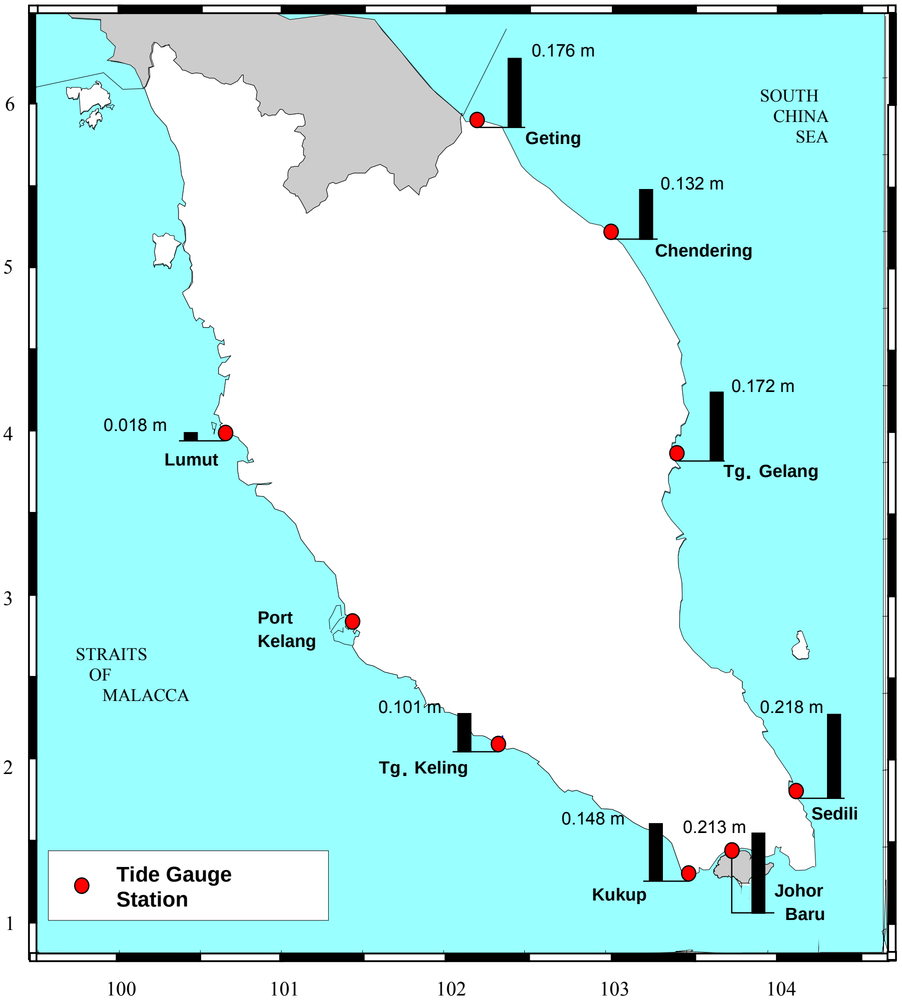


Figure 4.11 Geographical distributions of the height discrepancies between PLN heights and mean sea level heights at tide gauge bench marks, where the difference is assumed zero at Port Kelang.

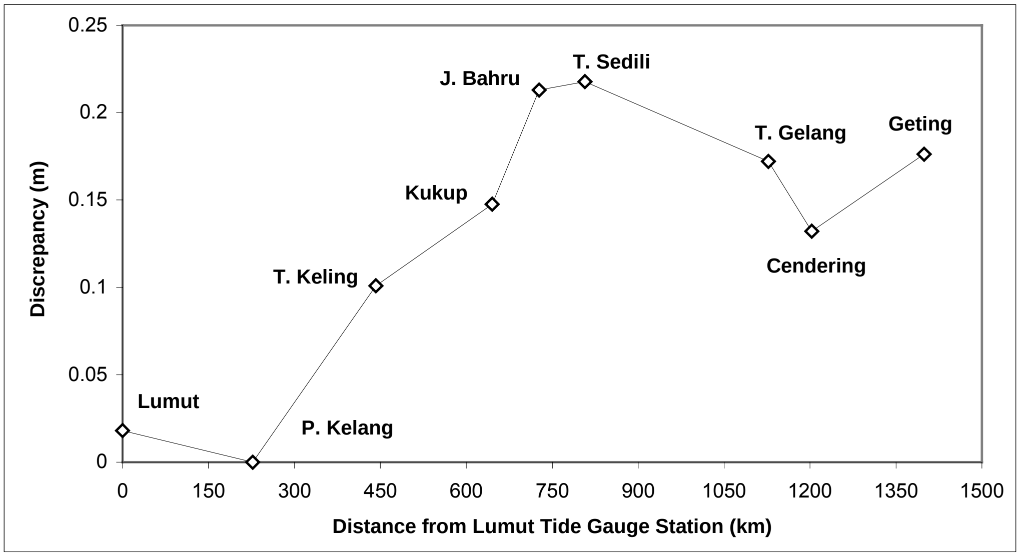


Figure 4.12 Discrepancy between mean sea level heights and precise levelled heights of TGBMs

Figure 4.12 shows the discrepancies as a function of the distance along the coastline from Lumut with respect to Port Kelang. Along the west coast of Peninsular Malaysia (Lumut to Kukup), an apparent tilt of 13cm in the sea surface over a distance of 646km is observed in the north-south direction. A slope having a positive sign indicates that the sea surface at the second terminal is raised. On the eastern side (Geting to Tg. Sedili), a smaller tilt of 4cm over 593km is obtained. However, one feature that is apparent at both sides of the coast is the north-south sea slope. It can be seen that the northern TGBMs (Lumut and Geting) are lower than their respective southern TGBMs (J. Bahru and Tg. Sedeli).

4.4 GPS SURVEY AT TIDE GAUGE STATIONS

Before the advent of GPS, the geodetic positions of the tide gauge stations were poorly defined. In this study, GPS is used to determine the difference in the height of mean sea level at selected tide gauge stations in Peninsular Malaysia. A project, TG2000 GPS Campaign, has been initiated to investigate the deviation of the MSL from the geoid. The project involved GPS observation at nine Tide Gauge Stations in Peninsular Malaysia by occupying suitable TGBMs within their vicinity. The reference stations used in this campaign were the continuous operating stations of the Malaysian Active GPS System (MASS) network. The height coordinate components are of particular interest, as they will define the base from which future surveys are referred.

4.4.1 Aims of TG2000 GPS Campaign

The aims of this single epoch TG2000 GPS Campaign were three-fold:

- to derive a first epoch set of coordinates in the ITRS for selected tide gauges in Peninsular Malaysia;
- to determine the separation of the MSL from the geoid at the tide gauges; and
- to investigate the presence of a sea surface topography.

4.4.2 GPS Field Data Acquisition

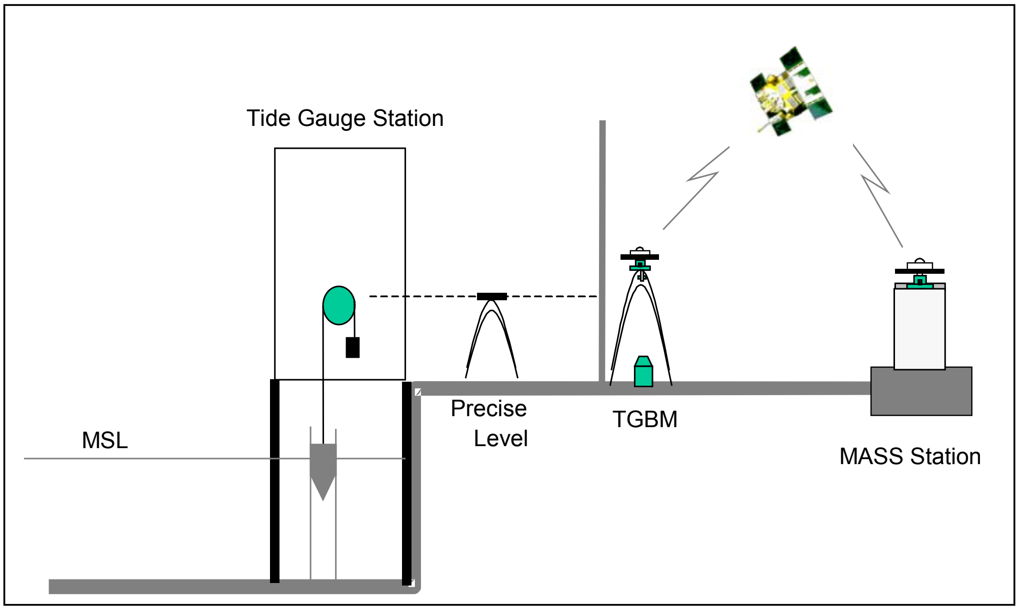


Figure 4.13 Scheme for the TG2000 GPS Campaign

Figure 4.13 shows a schematic diagram of the TG 2000 GPS campaign. It demonstrates typical measurements that were made at GPS and tide gauge stations. The actual GPS survey was carried out on selected days from June 23 to July 7, 2000. Three GPS receivers were utilised during the campaign. The observations were carried out by three teams on nine bench marks in the vicinity of the Tide Gauges.

Figure 4.14 shows the network description of the GPS campaign. The GPS sessions lasted between 5 to 7 hours for all sites. All field sites were occupied by the same type of receiver: Ashtech, a dual frequency receiver with 12 channels. The receivers were set to record both L-band frequencies broadcast by the GPS satellites to enable the reduction of ionospheric effect on the data during post processing. Data sampling at a rate of two epochs per minute was set to match with that of the base stations of the Malaysia Active GPS System or MASS.

4.4.3 GPS Processing Methodology

The required GPS data from the MASS stations that encompassed the period of TG2000 field survey were obtained through the Internet by accessing the Geodesy Section website at *http://www.geodesi.jupem.gov.my/mass.htm*. However, due to some technical problems, the KUAL MASS station was not operating during the campaign period and thus excluded in the processing.

All GPS data was processed in a PC-environment using the Bernese Post Processing software version 4.2 (Beutler *et al.*, 2001). In the processing of the project, a suitable methodology was devised to derive each daily session coordinates.

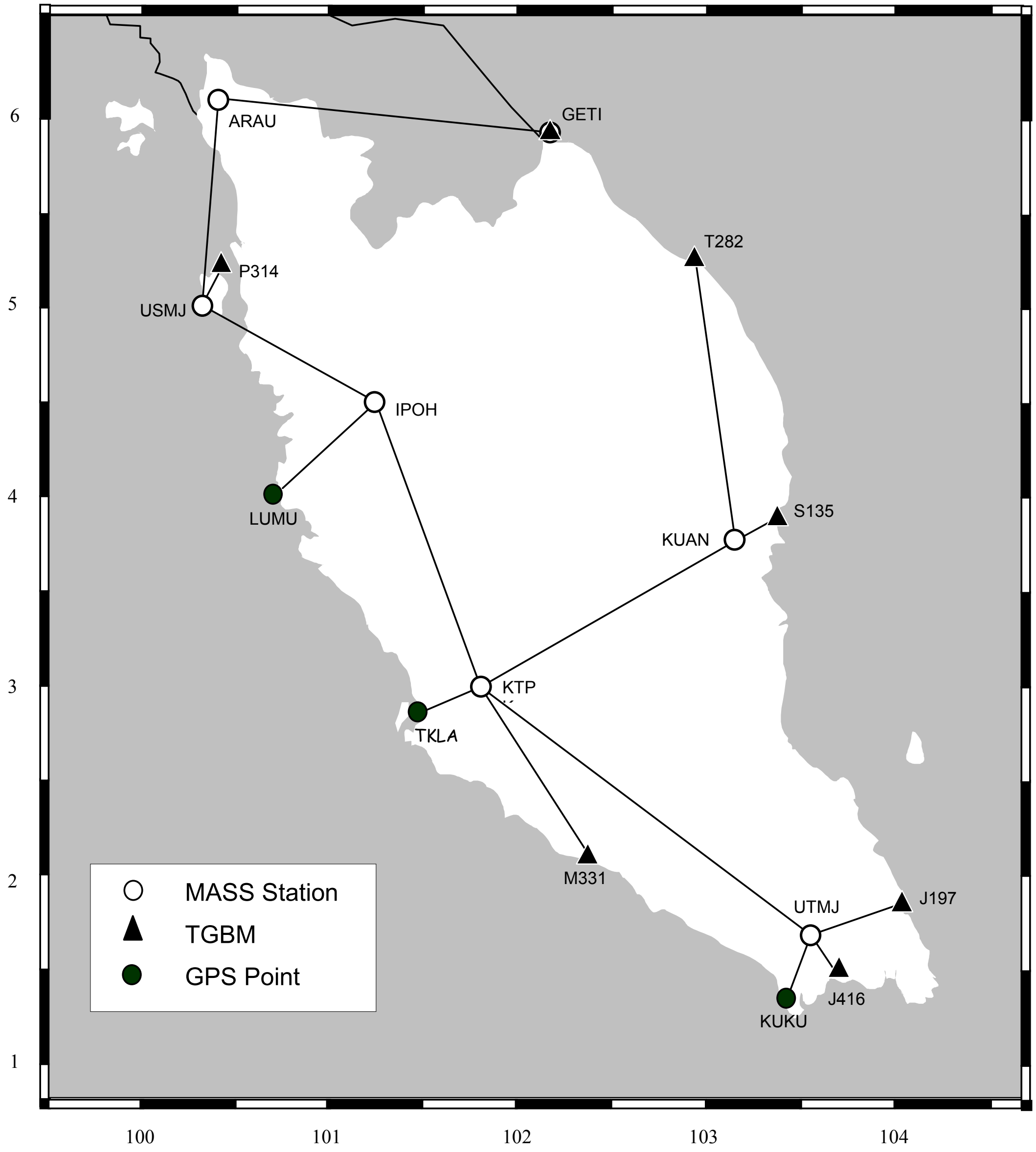


Figure 4.14 The network map of the TG2000 GPS Campaign

4.4.4 Results and Analyses

The processing methodology resulted in estimates of the baseline components between the stations and hence the first epoch set of field site coordinates. The quality of the field sites is indicated by the RMS errors of each point. All the estimated coordinates of the field sites in the TG2000 GPS campaign were based on the MASS stations in terms of ITRF2000 Epoch 2000.5. Figure 4.15 illustrates the RMS of the solutions in north, east and up components. The average RMS of the station coordinates is 0.6mm and 3.3mm in the northing and easting components respectively and is of the order of 3.9mm in the vertical component. Results also suggest that the precision is uniform throughout the network.

The results obtained from the GPS campaign are very encouraging. The results indicate that the use of accurate fixed station coordinates, precise orbits and proper modeling of the troposphere, combined with a sophisticated GPS software are of paramount importance in order to achieve high accuracies.

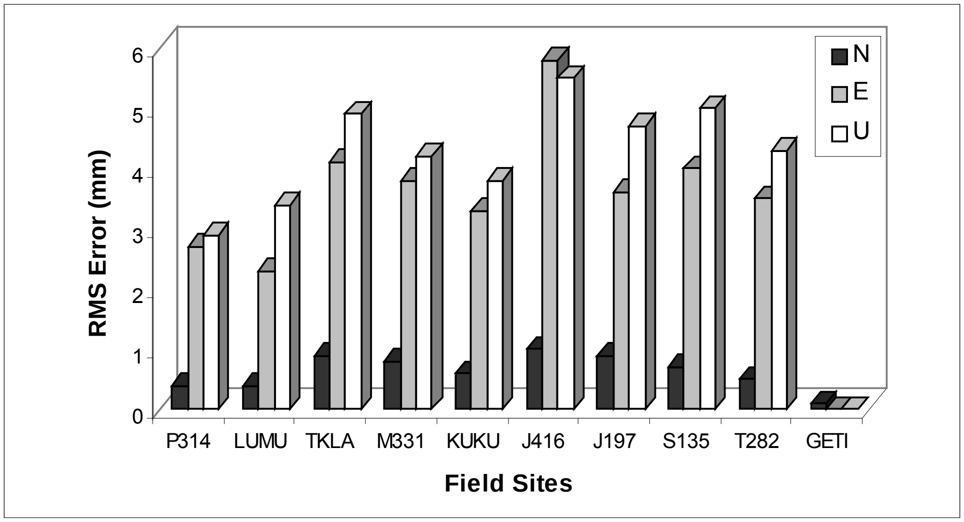


Figure 4.15 RMS error of the field site coordinates in the TG2000 GPS Campaign

4.4.5 Geodetic Investigation of Sea Surface Topography

Sea surface topography or SST refers to the physical separation between the geoid and the local MSL. It exists because the MSL as determined at a tide gauge station does not lie on the same equipotential surface as the geoid. It also varies from location to location. Numerous oceanographic phenomena are known to cause the presence of SST, which can reach up to 2m globally. These include ocean currents, water density, temperature, air pressure, seabed topography, river discharge and wind stress.

The MSL above GRS80 reference ellipsoid at the observing point is given by the following expression:

$$h_{MSL} = h_{GPS} - \Delta H_{Lev} + \Delta H_{MSL} \tag{4.3}$$

where h_{GPS} is the GPS-derived ellipsoidal height for the tide gauge bench mark, determined for the nine TGBMs following the TG2000 GPS campaign. ΔH_{Lev} is the height of tide gauge bench mark above the zero of tide gauge which is provided by DSMM. ΔH_{MSL} is the height of observed MSL above the zero of tide gauge, based on the mean yearly MSLs. Thus, by definition, the topography of the MSL or the sea surface topography (SST) is given by:

$$SST = h_{MSL} - N \tag{4.4}$$

where N is the gravimetric geoidal height at the tide gauge bench mark. The estimation of the gravimetric geoidal heights at each tide gauge bench mark was performed using a preliminary geoid model of Peninsular Malaysia, MYGeoid02.

Table 4.3 Computation of sea surface topography at tide gauge station (in metres)

Tide Gauge	TGBM	h_{GPS}	ΔH_{Lev}	ΔH_{MSL}	h_{MSL}	N	SST	SST w.r.t. Port Kelang
Lumut	A0401	-4.7621	5.685	2.189	-8.2581	-8.569	0.3109	-0.2072
Port Kelang	S0261	-0.2419	6.773	3.864	-3.1509	-3.669	0.5181	0
Tg. Keling	M0331	4.3477	6.427	2.847	0.7677	0.031	0.7367	0.2186
Kukup	J1323	10.3395	6.884	3.997	7.4525	6.185	1.2675	0.7494
Johor Bahru	J0416	12.0844	6.079	2.847	8.8524	7.515	1.3374	0.8193
Tg. Sedili	J0197	11.5634	4.787	2.403	9.1794	8.140	1.0394	0.5213
Tg. Gelang	S0135	7.2960	6.953	2.795	3.1380	1.678	1.4600	0.9419
Cendering	T0282	2.6616	5.252	2.199	-0.3914	-1.767	1.3756	0.8575
Geting	D0353	-3.1270	5.981	2.290	-6.8180	-8.184	1.3660	0.8479

Based on Equations 4.4 and 4.3, the values of SST at each tide gauge station can be computed. Table 4.3 presents the results in metres where the values of SST, represented by the differences between the ellipsoidal and geoidal heights of MSL, are shown on the second last column. The values of SST with respect to the Port Kelang are deduced in the last column. The results indicate that different SST values exist at different tide gauges. As such, if more than one TGBM is constrained in the levelling network adjustment, then one would expect significant distortions will result in the vertical control network.

The values of SSTs range from 31cm in the west coast to 1.5m on the east coast. These results agree to some extent with other studies on SSTs, which are reported to be generally less than 50cm but could be up to two meters. Closer inspection of Table 4.2 seems to show a gradual latitude dependent trend between the SST heights and the geoid along the west coast. At Lumut station, where the value of SST starts at 0.31m, the trend indicates that it does not follow the geoid, but runs at an inclination to it. This trend continues to the south and results in a separation of 1.27m at Kukup.

On the other hand, the trend along the east coast is not so obvious although the magnitudes of the SST are higher. However, the heights of SSTs from Tanjung Sedili to Johor Bahru and from Geting to Tanjung Gelang still exhibit a north-south tilt. It should be noted that a slope having a positive sign indicates that the SST at the second terminal is raised.

It is also noted that the computed trend on both sides of the coast of Peninsular Malaysia corresponds closely in magnitude to the oceanographic SST detected by Jet Propulsion Laboratory (JPL), USA. The average values of the SST were computed over the period of September 1992 to April 2000. This is illustrated in Figure 4.16. The colour scale starts at –2.0m and saturates at a value of 2.0m. The figure shows the values of SST range from 0.8 to 1.2m in the west coast and from 1.2 to 1.8m in the east coast of Peninsular Malaysia.

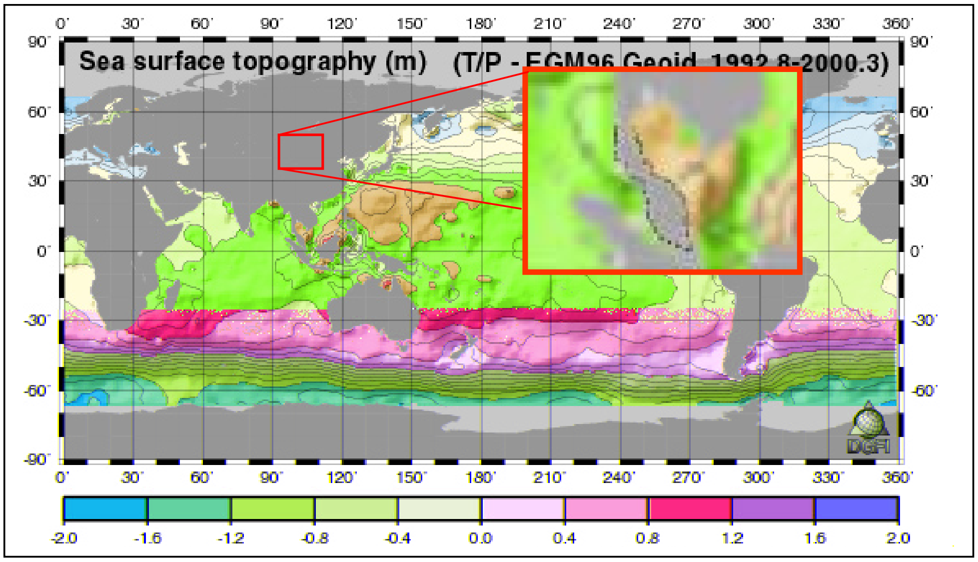


Figure 4.16 Sea surface topography as illustrated by JPL, with the inset showing that of Peninsular Malaysia region