HIGH PRECISION GLOBAL POSITIONING SYSTEM DATA PROCESSING-VELOCITY VECTOR DETERMINATION FOR GEODYNAMIC APPLICATION

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To my lovely family and my beloved husband.

"Scientists still do not appear to understand sufficiently that all earth sciences must contribute evidence toward unveiling the state of our planet in earlier times, and that the truth of the matter can only be reached by combing all this evidence. . . It is only by combing the information furnished by all the earth sciences that we can hope to determine 'truth' here, that is to say, to find the picture that sets out all the known facts in the best arrangement and that therefore has the highest degree of probability. Further, we have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw."

Alfred Wegener. The Origins of Continents and Oceans (4th edition)

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ABSTRACT

Geodynamic studies involving Malaysia have been ventured upon in the South-East Asia region since the first GeodySEA project was carried out in 1996. For the fact that both East and West Malaysia lies on the same plate, we can assume that there will be no linear distortion for any two points joined relative to one another. In other words, for GPS observations over MASS stations, the baselines formed relative to any other MASS station can be roughly assumed to be constant without any significant changes. Though presumably Malaysia is out danger, but we take it for granted that it lies within the buffer of the 'Ring of Fire'. We are situated near several active faults lines. This study will only look upon three years of MASS data from which most of the data were available simultaneously processed with 3 consecutive years of selected IGS. Since this movement is not evident for short observation or even observation of 1-year time span, therefore, a longer period of observation is needed to identify this movement. In this research the author will output the relative MASS stations coordinates and velocity estimates in ITRF2000. At present the measures of quality for GPS derived coordinates given by commercial software packages tend to be unrealistic because unmodelled errors remain unaccounted for (Brown et al., 2002). In addition, commercial software packages are either over-optimistic, or conversely, are overly conservative and therefore have low fidelity (Keenan and Cross, 2001, Barnes et. al., 1998, Wang, 1999). However, in this study Bernese high precision GPS processing software version 4.2 is utilised to determine the final solution for the relative MASS station coordinates. Screening cycle slips, using linear combination of phase observables to estimate the site specific atmospheric parameters, and resolving ambiguities give a reliable coordinate of lesser than 10mm in horizontal and 15mm in vertical in predefined ITRF2000 frame.

ABSTRAK

Kajian tentang pergerakkan kerak bumi melibatkan Malaysia telah diterokai di rantau Asia Tenggara bermula dengan GeodySEA pada tahun 1996. Timur dan Barat Malaysia terletak di atas kerak bumi yang sama maka, boleh dianggap bahawa tiada herotan garis dasar antara dua stesen cerapan yang relatif antara satu sama lain. Walaupun Malaysia tidak berada di dalam bahaya yang nyata, namun, ia berada di sekitar lingkungan Gegelang Api ("Ring of Fire") dan berhampiran kawasan gempa. Maka, pergerakkan kerak bumi haruslah sentiasa diawasi agar perubahan ini dapat dijangka. Dalam kajian ini, data MASS sepanjang 3 tahun bermula dari tahun 2000 hinggalah ke 2002 telah diproses bersama dengan 3 tahun data dari 15 stesen IGS pada jangka masa yang sama. Disebabkan perubahan pada kerak bumi tidak ketara untuk cerapan jangka masa pendek walaupun data dalam setahun lamanya, maka, data jangka masa yang lebih panjang diperlukan untuk mengenalpasti perubahan ini. Pada masa ini, hasil kordinat dari GPS yang diproses menggunakan perisian komersil tidak memuaskan kerana banyak ralat yang tidak dapat dikenalpasti (Brown et al., 2002). Tambahan lagi, perisian komersil terlalu optimistik atau terlalu kurang optimistik maka tidak dapat dipercayai. (Keenan dan Cross, 2001, Barnes et. al., 1998, Wang, 1999). Dalam kajian ini perisian berkejituan tinggi Bernese versi 4.2 dipasangkan pada komputer Linux untuk pemprosesan data. Data ini kemudiannya diskrin, parameter atmosfera dianggarkan dengan *linear combination* dan peleraian ambiguity menghasilkan koordinat yang boleh dipercayai dengan rms *horizontal* kurang dari 10mm dan rms *vertical* kurang dari 15mm dalam ruang ITRF2000. Dalam kajian ini penulis dapat menghasilkan koordinat terakhir untuk pemprosesan data MASS kepada "*a posteriori unit weight*" 0.0023m dan anggaran halaju pergerakkan kerak bumi kepada 2cm setahun pada ITRF2000.

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AIUB	-	Astronomical Institute of the University of Bern
AR	-	Ambiguity Resolution
ARP	-	Antenna Reference Point
AS	-	Anti-Spoofing
BKG	-	Federal Agency of Cartography and Geodesy
CBIS	-	Centre Bureau Information System
CGGS	-	Centre for Geodynamics and Geodetic Study
CIO	-	Conventional International Origin
CODE	-	Centre for Orbit Determination in Europe
CPC	-	Central Processing Center
DS	-	Data Screening
DSMM	-	Department of Survey and Mapping, Malaysian
ERP	-	Earth Rotation Parameter
EUREF	-	European Reference Frame
GDPC	-	Geodesy Data Processing Center
GIPSY	-	GPS-Inferred Positioning System
GLOSS	-	Global Sea Level Observing System
GMT	-	Graphical Mapping Tools
GPS	-	Global Positioning System
GPSEST	-	Program used in Bernese for Parameter Estimation
IAG	-	International Association of Geodesy
IAU	-	International Astronomical Union
IERS	-	International Earth Rotation Service
IGN	-	Institute Geographical National
IGS	-	International GPS Service
ITRF	-	International Terrestrial Reference Frame
ITRS	-	International Terrestrial Reference System

IUGG	-	International Union of Geodesy and Geophysics
JPL	-	Jet Propulsion Laboratory
JUPEM	-	Malaysia Language for DSMM
LLR		Long Laser Ranging
LOD	-	Length Of Day
MASS	-	Malaysian Active GPS System
MAUPRP	-	Program used in Bernese for Phase Check
MSRF	-	Malaysian Spatial Reference Frame
N	-	Number for independent baseline
NASA	-	National Aeronautic and Space Administration
NAVSTAR GPS	-	NAVigation Satellite Timing and Ranging GPS
NGS	-	National Geodetic Survey
PRN	-	Pseudo-Range Number
RINEX	-	Receiver Independent Exchange
RTK	-	Real Time Kinematic
RMS	-	Root Mean Square
SA	-	Selective Availability
SINEX	-	Solution Independent Exchange
SIO	-	Scripps Institution of Oceanography
SLR	-	Satellite Laser Ranging
SNGDIF	-	Program used in Bernese for Single Differences
SVN	-	Satellite Vehicle Number
UTM	-	Universiti Teknologi Malaysia
VLBI	-	Very Long Baseline Interferometry

CHAPTER 1

INTRODUCTION

1.1 General Background

Sun, Moon and Planets are continuously in motion, each on its own orbit in a continuous manner, of which, theoretically started from the birth of the universe between 10 to 20 billion years ago during the primeval fireball also known as the Big Bang (Hawkings, 1993). They influence each other through their very existence, exerting gravitational forces between two bodies according to Newton's law of gravitation. Focusing on the moving bodies that co-exist on earth such as; the ocean tides, earth tides, plate tectonics, and dynamics of the earth mantle are some of the movements that we take for granted in our daily lives until nature takes it toll.

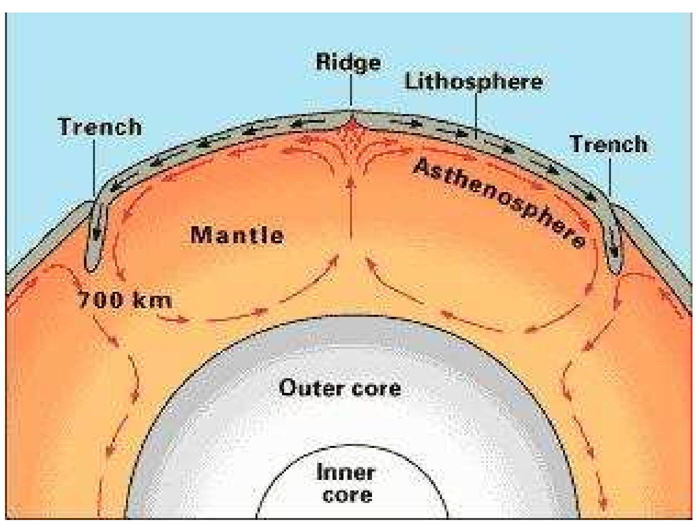

Figure 1.1: Earth's Core

According to the theory of plate tectonics derived during the 1960's evolved from the theory of continental drift by Alfred Wegener in 1912, said that the Earth's outer layer, or crust, consists of a series of plates made up of lithospheric material, which floats on the denser upper fluid asthenosphere mantle within the Earth's interior. These movements may cause the plates to convergent, divergent forming trenches and ridges or even having lateral movements that cause an earthquake. The earth consists of 12 major plates, the Eurasian plate, Indian plate, Philippine plate, Pacific plate, Nazca plate, Caribbean plate, North American plate, South American plate, African plate, Arabian plate, Australian plate and the Antarctic plate. The edges of these plates form the (plate margin) fault lines to where the occurrences of earthquakes and volcanic activities are profound.

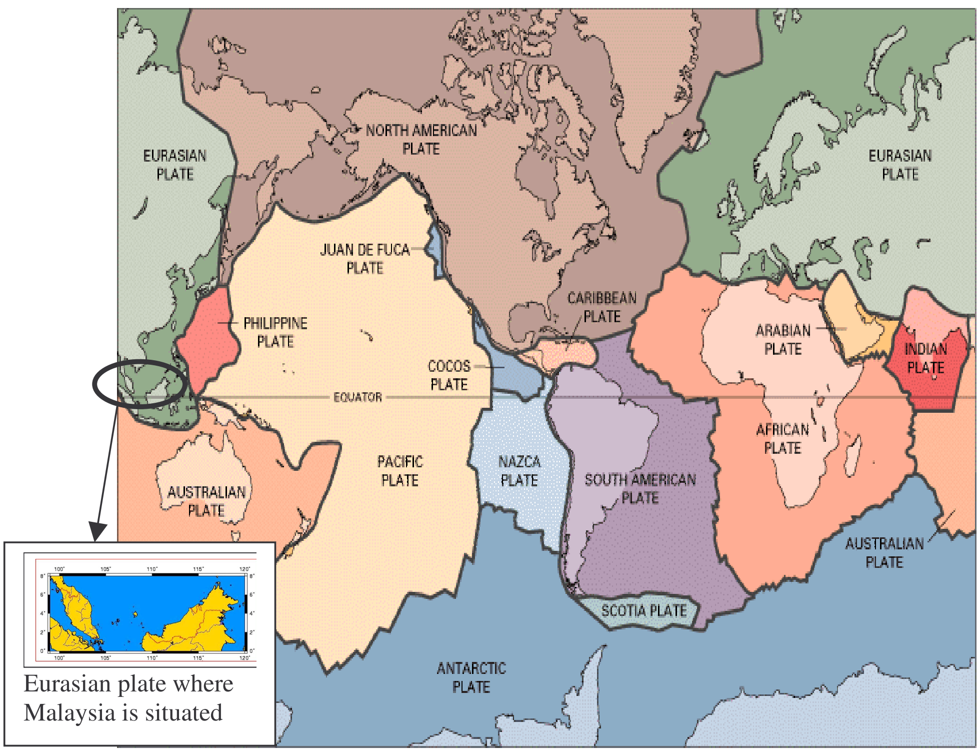

Figure 1.2: Continental Plates of the Earth

In Malaysia, these movements are taken for granted since geographically the peninsular is located on one command plate, the Eurasian plate. The fault lines however, meanders not very far from the edges of the peninsular and passes through the Indonesian Javanese Island. Krakatau is situated between Sumatra and Java in

Indonesia, and forms part of the volcanic arc of a subduction zone in the Indo-Australian Plate, moves towards the northeast (Forde, 1994).

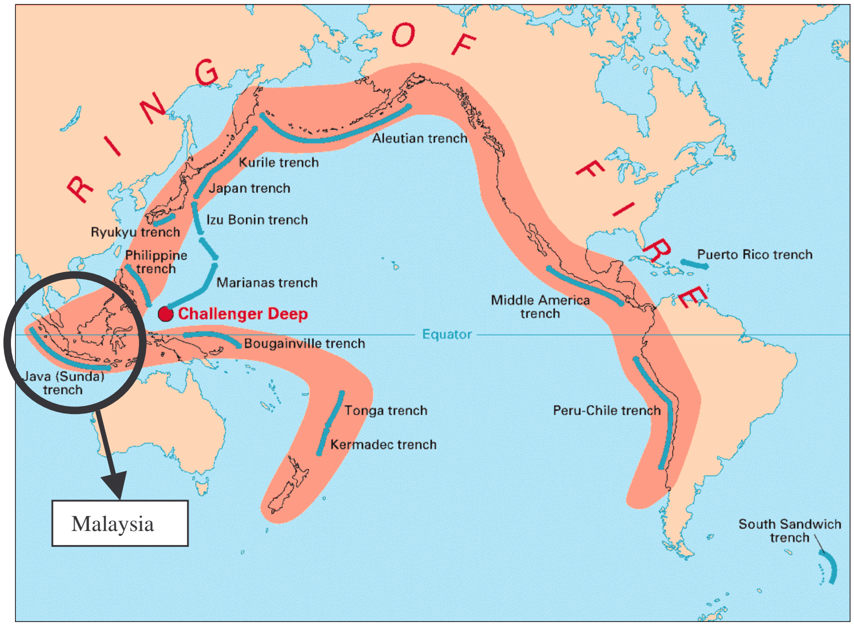

Figure 1.3: The Ring of Fire

The Sunda Islands allocated in the western part of Indonesia consists of Sumatra, Java, Kalimantan and Sulawesi. They also form a string of volcanic islands extending from the Bay of Bengal forming an arc facing the Indian Ocean toward Australia curving back to the north and west, constituting what is called an island arc in geology. The Philippine Plate is located on the northeast from the edge of the Eurasian plate. Another string of islands extends from the Mollucas to the north into the Philippine islands. This island arc, often called the Sunda arc, encloses to the north the Malay Peninsula, the great island of Kalimantan (Borneo) and four armed islands of Sulawesi (Celebes), with a string of small volcanic islands extending from the north eastern arm of Sulawesi to the Philippines. The above description all falls into an area also known as the "Ring of Fire" which is an arc stretching from New Zealand, along the eastern edge of Asia, north across the Aleutian Islands of Alaska, and south along the coast of North and South America. It is composed over 75% of the world's active and dormant volcanoes located at the borders of the Pacific Plate and other tectonic plates.

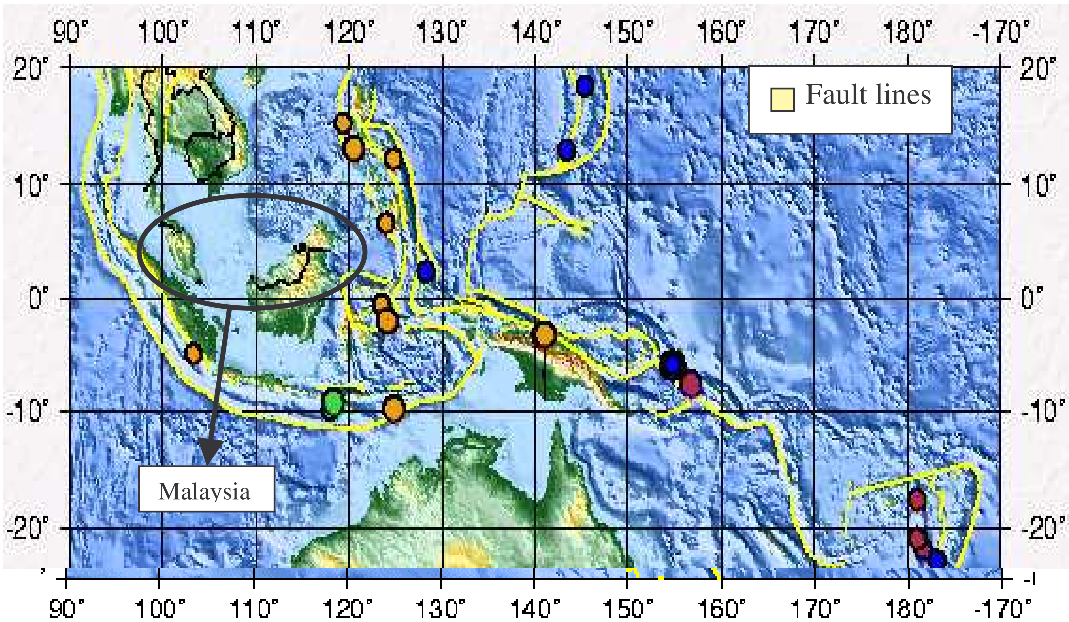

Figure 1.4: Fault lines in the South-East Asian Region.

Earthquakes occurrences along these lines do influences and disrupt the stability of buildings and structures in Malaysia. For instance, a powerful earthquake rocked the Indonesian island of Sumatra according to the United States Geological Survey (USGS) on the 4th of June 2000 recorded the quake at 7.9 on the Richter scale and it was felt throughout KL, though no massive destruction occurred. The latest occurrence is the oceanic earthquake on December 2004 carrying a magnitude of 8.9 on the Richter scale and brought with it the Tsunami one of the biggest in the century. The seawater displacement result from the plate subduction killed over hundreds of thousands across Asia.

1.2 GPS and Its Ability to Predict the Plate Deformation

A fiducial network incorporates VLBI, SLR, and GPS systems which are operated on a permanent, continuous basis, and which will provide reference geodetic data to which regional studies occupying many sites on a short-term, temporary basis can anchor. GPS, VLBI, SLR, and LLR technology can be integrated to monitor plate motion and deformation, to monitor Earth rotation, and to define and maintain a terrestrial reference frame. Permanent regional and local monitoring networks deployed across tectonically active regions to measure and analyze the motion and deformation over a broad range of spatial and temporal scales.

Figure1.5: IGS Sites selected to tie the MASS to ITRF

The DoD of America adopted global Positioning System (GPS) and had launched their first satellite for the purpose of military was on the 18th February 1978. To date, GPS is known to many civilian users for many different purposes, one of which mentioned above, for instance, scientist utilize it for monitoring plate motion. In general, static relative positioning GPS are able to provide users with high accuracy of ±1ppm or 1mm for 1km baseline with good sky view and over 10minute of observation (Wellenhof et al, 1994). If a GPS observation is done over a long session of over several hours continuously even for long baselines, it can promise accuracy of 1ppm with proper scientific software and reliable strategy, and this will be explained further in the other chapters.

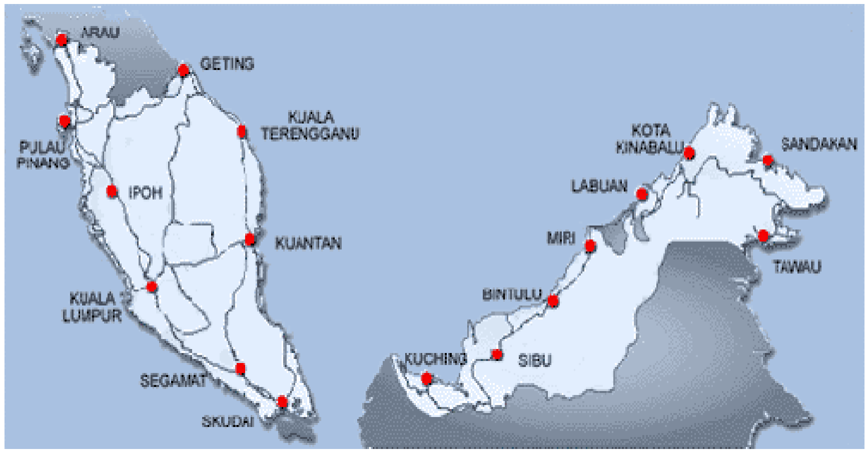

Figure1.6: MASS sites in East and West Malaysia

Currently, there are 18 permanent GPS stations around Malaysia as shown in figure 1.6, operating on a 24 hours basis called the MASS. The reconnaissances of the stations were carried out in the late 1997 as proposed after the GEODYSSEA second campaign by the DSSM (Majid et al., 1998). Moreover, with the realization of the ITRF, Malaysia can now be mapped onto the globe more accurately. Basically, the ITRF frame is a conventional frame created under international sponsorship in order to satisfy the accuracy requirements of various modern space techniques. Furthermore, the origin, coordinate axes orientation, and scale of the ITRF frame are implicitly defined by the coordinates adopted for the worldwide tracking GPS sites involved in each IERS yearly global solution (Soler et al., 1999). Thus, the IGS sites in ITRF frame will be very useful for those scientifically advancing countries to fix their region onto the same frame as the rest of the world.

1.3 Problem Statement

Since both East and West Malaysia lies on one plate, which is the Indo-Australian plate we can assume that there will be no linear distortion for any two points joined relatively to one another. In other words, for a GPS observation between MASS stations, the baselines formed from one MASS station to another, for example GETI, in Kelantan to BINT, in Bintulu, over a long period of time or between epochs of different time line can be roughly assumed to be relatively constant without any significant differences.

Presumably Malaysia is out danger, but we take it for granted though realizing that it lies within the buffer of the 'Ring of Fire'. It is fortunate, that Malaysia do not lie on a fault line, however, Malaysia is situated near several active faults lines. Therefore, monitoring of the plate motion is essential for predicting the changing plate motion.

The world changes in more then one way i.e. the eccentricity of the earth increases over time making the earth more elliptical (Pine, 1989). Monitoring the trend of the unpredictability might help us take some precautionary actions before the occurrence of natural disaster, to identify changing fault lines or new born faults. Moreover, since crustal movements but could be patterned if monitored over several of years. A long time series of measurements, of several years or more, are required in order to obtain accurate site velocity estimates (Mao et al. 1999).

Learning from the 2004 Tsunami that hit Aceh, India and reflected to a small area in the Upper West Coast of Malaysia proofs that geodynamic exploration should be escalated and this study is a form of realization to this vulnerability.

This study will only look upon three years of MASS data from which most of the data were available simultaneously processed with 3 consecutive years of selected IGS. Since this movement is not evident for short observation or even observation of 1-year time span, therefore, a longer period of observation is needed to identify this movement. In this research the author will output the relative MASS stations coordinates and velocity estimates in ITRF2000.

At present the measures of quality for GPS derived coordinates given by commercial software packages tend to be unrealistic because unmodelled errors remain unaccounted for (Brown et al., 2002). In addition, commercial software packages are either over-optimistic, or conversely, are overly conservative and therefore have low fidelity (Keenan and Cross, 2001, Barneset al., 1998, Wang, 1999).

However, in this study Bernese high precision GPS processing software version 4.2 was utilised to determine the final solution for the relative MASS station coordinates, hence to estimate the relative velocity of each station to the global velocity (NUVEL1A). Screening cycle slips, using linear combination of phase observables to estimate the site specific atmospheric parameters, and resolving ambiguities will give a reliable coordinate of lesser than 10mm in horizontal and 15mm in vertical in predefined ITRF2000 frame.

1.4 Research Objectives

Referring to the applicability of GPS to geodetic and geodynamic studies the objectives of this study are as follows:

1. To produce a high precision GPS solution of the Malaysian Network.

2. To derive accurate position Time Series leading to accurate velocity determination.

3. To make a geodynamic interpretation from the GPS analysis using the derived velocity.

1.5 Research Scope

The continuous GPS data for over three years were acquired from DSMM for all the available 18 MASS stations with another 15 IGS stations so that the MASS will be tied to the global network. These data were processed via Highbred GPS Processing Software known as Bernese version 4.2. The processes were carried out on a day-by-day basis to form network solutions. Whilst after weekly solutions were formed comprising of 7 days of the GPS week for the available stations.

These weekly solutions were tied with reference to the mid of each respective week. Final coordinates for each MASS stations were acquired and their residuals plotted. These residual plots were over a period of three consecutive years, thus, resulting in a time series. From these time series, graphs plotted were analysed to determine the accuracy of the relative velocity of each station.

The weekly solutions were stacked together to produce the velocity estimation of each station. The mean from this stations velocity is the result of the overall movement of the peninsular and East Malaysia with respect to the Indo-Eurasian Plate. Thus, geodynamic interpretation can be analysed from the derived velocity.

1.6 Research Contribution

Generally, this study will be of benefit for DSMM towards a dissertation of handling of the Bernese GPS software version 4.2 and the processing strategy to achieve accurate MASS final coordinate. Conversely, generating relative velocity estimates for the MASS stations and give a geophysical study of the crustal motion achieved from the GPS measurements.

MASS station coordinates are refined which was previously computed with reference to ITRF 97 over a period of 1 and a half year are process over an even longer period to derive to an up to date coordinate with reference to the ITRF 2000 frame towards 1ppm in precision. 5mm level of accuracy within a 95% confidence interval for the horizontal components and vertical component of no more than three times the ratio to the horizontal component of the MASS absolute coordinate is to be achievable.

Data qualities of the MASS stations are analysed for the three years processing and one can identify the station that profoundly contributes to the biases and the errors due to low data quality.

Estimating the velocity of each MASS station and determine the accuracy of this velocity generated. These velocity can later be use to interpret geodynamic movements of the plates.

1.7 Research Methodology

There are 4 major phases in processing, before we can achieve the end products of both the estimated relative velocity and the time series of each MASS station coordinates. The 4 phases are as followings:

- Pre-processing
- Daily Adjustment
- Weekly Solutions
- Velocity Generation and Time Series Plotting

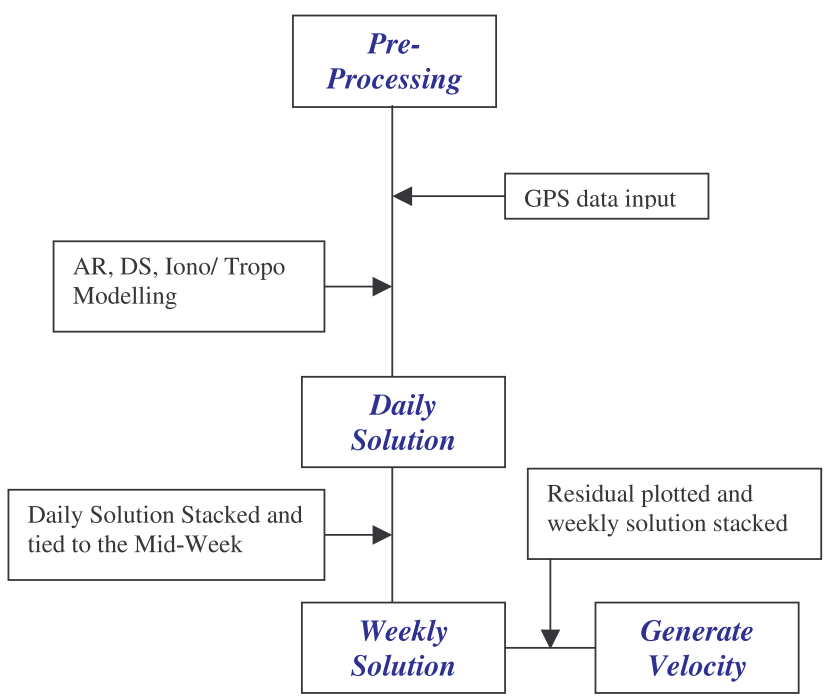

Figure 1.7: GPS Processing Diagram

Methodology of this study consist mainly preparation and processing before the final output can be achieved. Each of these steps are crucial and it is essential for them to be carried out well before proceeding to the next phase, since they are interrelated and the accuracy of the results very much depends on the reliability of the former stages. However, chapter four will explain this process in greater length.

1.7.1 Hardware and Software Set-up

GPS data will be processed using the Bernese version 4.2. Specification of the hardware compatible for mounting the Bernese environment and to manage the 3 years of data will be rather immense. A large hard disk space is recommended eg. the power station that is utilized in this study have two 80GByte hard disk one as the processing platform and the other for backing up the data and results. Anyway, a large space will be needed to store the GPS data.

Most importantly, a large space hard disk will make it possible to process the GPS data efficiently and at ease especially with the ability of the BPE. Then, even months of continuous data can be processed within a short time span compared to other lower graded workstation. However, minimal computer is not stated regardless utilizing 48MB of RAM and old Intel 386 processor the Bernese software is still capable to run. For safety purposes and maintenance of hardware a UPS system will be very useful and overnight processing.

Red Hat Linux 8.0 is mounted as the operating system since it complies well with the Bernese Processing Engine (BPE) and its virus free system is an advantage for the processing. Networking has to be set-up and user specified for ability to ftp to other computers and important download sites. An IP address and host name of the PC has to be stipulated for BPE to be able to communicate with the hardware and run each bernese program and script automatedly.

Only then can one set up the bernese environment on root later then on the main user home utilising bernese. More then one user in a group specified to use the bernese environment could use bernese simultaneously. However, it is preferable that only the main user has all the unrestricted access and managers all the files, folders of bernese as well as the RHL8.0 system. Fortran compiler G77 and source F77 are use for these and BPE demo will be install automatically then after editing the remote hosts and remote bash profile is needed for bernese to run properly. It is mandatory to recompile the software after installation for it to link the directories and folders.

For BPE to run the processing control script (PCS) are edited. Each program to be run for the GPS processing edited to the preference of the user. Strategy setting for GPS processing starts here. Then each program run tested. BPE is well suited to process data from permanent GPS arrays in a completely automatic and efficient way.

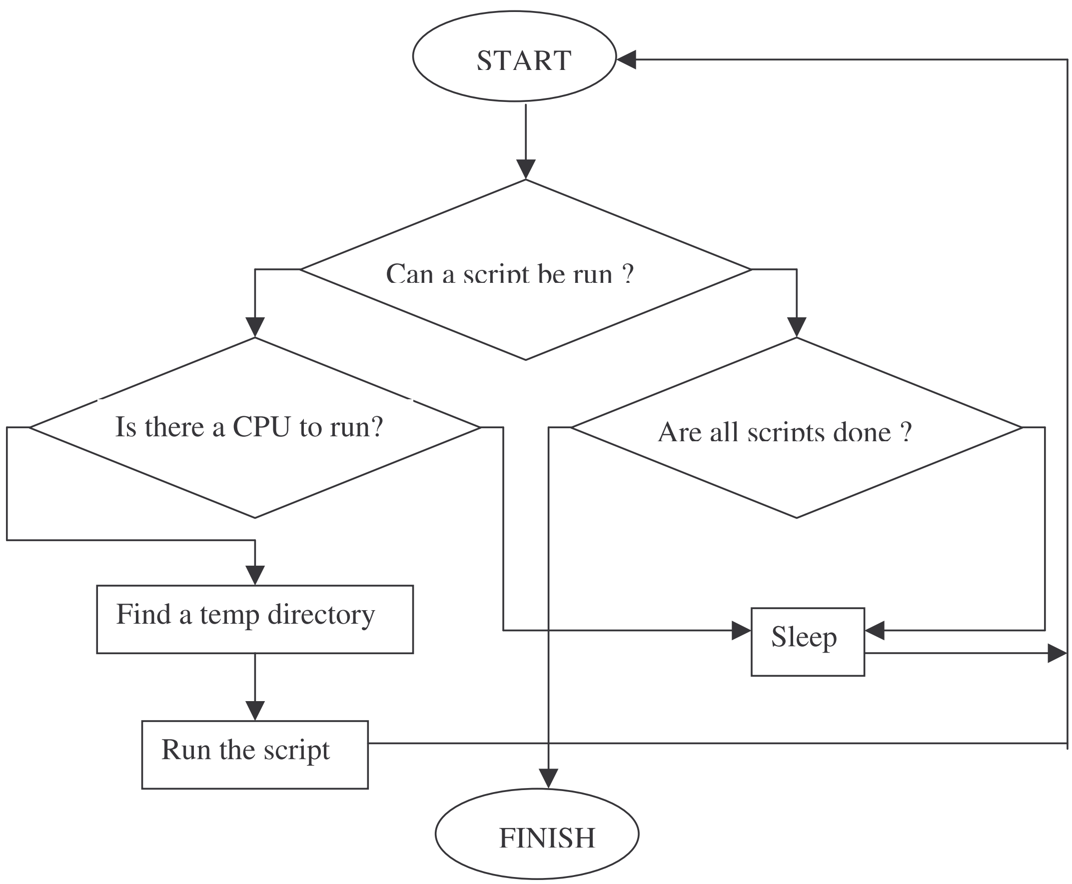

Figure 1.8: Process Control Script flow chart. Basically how the BPE works.

Bernese GPS software itself is created to cater for rapid processing of small-size single and dual frequency surveys and permanent network processing. It can resolve ambiguity on long baselines of up to 2000km using final orbits and taking into accounts of other parameters to be modelled or estimated.

1.7.2 Data Preparation

The hourly MASS data was acquired from DSMM headquarters for 1st January 2000 up to 31st December 2002. Most of the data was already archived in a 24hours daily compact rinex zip form. These data were then scanned through teqc for quality and checking for errors in the header. Essentially, the monument name, dome number, antenna and receiver pair type, and the antenna height. Data were decimated to 30seconds interval and kept in the RAW folder in the campaign directory. Data with too many missing observation can be predicted to cause inaccuracy in the processing later.

IGS stations scattered around the Malaysian parameters were selected to its availability and to the period of establishment of the station which will determine the stability of the data collected. These data are usually readily 'teqc'ed. However, this does not mean that they are free from causing problems to the results later on. Thus, the data quantity has to be checked before processing can even take place. Low quality and inadequate data quantity of lesser than 12 hours observation should be identified and listed out.

1.8 Literature Review

The Bernese GPS Software version 4.2 is a tool meeting highest accuracy standards. Users of this software are typically scientists for research purposes, academician for education, survey agencies responsible for high accuracy GPS surveys or to maintain arrays of permanent GPS receivers and commercial applications for demanding high accuracy, reliability and high productivity (Hugentobler et. al., 2001). It is also suitable for permanent GPS stations processing on long baseline (2000km) ambiguity resolution for post-processing (Beutler et al, 1996).

Ambiguity resolutions are recommended in baseline mode, whereby each baseline are processed separately then introducing the resolved ambiguities as known quantities into the subsequent session processing (Hugentobler et. al., 2001). Over long baselines of over thousands of kilometres the processing strategy (proposed are as follows:

- Use of IGS precise orbit and ERP parameters
- Processing using 24 hours sessions of 15/30 second data
- Elevation cut-off angle 15 degrees and with dependent satellite elevation-weighting COS Z.
- Phase center offset are referenced to antenna phase center variations (PCV) Phasigs-01. table
- Single difference using OBMAX / SHORTEST test for the better dependent on station location and data availability
- Zenith delay parameters at least once every two hours and residual markings.
- Estimated troposphere parameters
- L3 linear combination of ionosphere-free float solution
- Quasi-Ionosphere Free (QIF) ambiguity resolution strategy
- Daily solutions computed for normal equations and analysis of precision
- Weekly solutions formed by combining the daily normal equations (can skip this step if its a small campaign)

- Final solution staking of all (weekly/daily) normal equations and constrained to the fudicial stations final coordinates in the respective ITRF reference frame

Usually, the achievable precision for the final coordinates will fall within 2 to 8mm in horizontal position and 10 to 20 mm in vertical position, and about 1-2x10^{-8} (or 1 to 2 cm in thousand kilometer baseline). The absolute coordinate accuracy in the ITRF frame could be approximate or at least better than 3cm (Becker et al., 1998; Alves Costa et al., 2001; Li and Cheng et al., 2001; Rozsa, 2002)

According to Borkowski et al. (2002) the EPN time series analysis station are located more than 700km from the local LGN network. Few of the European network station selected to tie to the local network are located close to the research area thus possesses significantly worse quality parameters. Selections of the reference stations were made from the mean trend congruency analysis of the EPN stations coordinate time series. Relative velocities between selected EPN stations evaluated using different approaches (time series analysis, ITRF2000 velocities, NUVEL1A-NNR velocities)

In China, Fu et al. (2002) the regional crustal deformation was taken relative to ITRF97 kinematic plate model. Data of the ‘Investigation on Present Crustal Motion and Geodynamics in China’ (CMMN), which consist of four campaigns, with 1000km, average in baseline length and situated in each geological tectonic block in China. Horizontal velocity accuracy of site produced better than 1.5mm/year. Then China setup its fudicial network reconnaissance since mid of 1998, and was operational in 1999 known as the CMONC, ‘Crustal Movement Observation Network of China’. With that China produced its sub-plate Euler vector from incorporating the global ITRF97 velocity field plate model to the 45 regional GPS sites in the same ITRF frame.