Usage of Mesh Networking in a Continuous-Global Positioning System Array for Tectonic Monitoring

Hoang-Ha Tran and Kai-Juan Wong
Nanyang Technological University
Singapore

1. Introduction

In recent years, tectonic plate movements have caused huge natural disasters, such as the Great Sumatra-Andaman earthquake and the resulting Asian tsunami, which led to significant loss of human lives and properties (Ammon et al., 2005; Lay et al., 2005). Scientific evidences proved it was the beginning of a new earthquake supper-cycle in this active area (Sieh et al., 2008). In order for scientists to further study such disasters and provide early warning of imminent seismic events, many continuous-Global Positioning System (cGPS) arrays were developed and deployed to monitor the active tectonic plates around the world such as "SuGAr" along the Sumatran fault, "GEONET" covering all Japan islands, and "SCIGN" covering most of southern California. Each of these cGPS arrays contains tens to hundreds of GPS stations. Using precise GPS receivers, antennas and scientific-grade GPS processing software, measurements from each GPS station are able to provide location information with sub-millimeter accuracy. These location data produced by the GPS stations, which are located in the vicinity of active tectonic plates, provided accurate measurements of tectonic movements during the short period of a co-seismic event as well as for the long period observation of post-seismic displacement.

The GPS applications in earthquake studies (Segall & Davis, 1997) include monitoring of co-seismic deformation, post seismic and inter-seismic processes. Post seismic (except aftershocks) and inter-seismic deformations are much smaller than co-seismic events, where there is little or no supporting information from seismic measurements. In this instance, GPS can be used to detect the long time inter-seismic strain accumulation which leads to indentify the location of future earthquake (Konca et al., 2008).

In cGPS arrays utilizing satellite communications such as the Sumatran cGPS Array (SuGAr), each GPS station in the cGPS array will periodically measure the tectonic and/or meteorological data which will be stored locally. A collection of these observed GPS data will then be sent to a data server through a dedicated satellite link from each station either in real-time or at update intervals ranging from hours to months. At the server, the collected data from the GPS stations will be processed by using closely correlated data from each station to reduce errors in the location measurements. Since the amount of data transmitted from each station could be relatively large, the communication bandwidth and the number of uplinks are the most important factors in terms of operational expenditure. Each satellite

link requires costly subscription and data transmission across these links are usually charged based on the connection time or the amount of data transmitted/received. Therefore, in order to reduce the operational cost of a cGPS array, it is paramount that the number of satellite links as well as the data sent on these links be kept to a minimum. The rest of this chapter is organized as follows. Commonly used data formats for GPS processing is introduced in section 2. Introduction of cGPS arrays including SuGAr are presented in section 3. Proposed modifications of SuGAr network and parallel GPS processing which make use of mesh network are evaluated in section 4. Lastly, the chapter will end with a brief conclusion.

2. Common data formats used for cGPS systems

Scientific-grade GPS receivers store their measured signals in binary format that prolong logging time of those devices. Some of the most commonly used property binary formats for GPS receivers are R00/T00/T01/T02 and B-file/E-file used by Trimble and Ashtech receivers respectively. Another widely adopted binary format proposed by UNAVCO is the "BINary EXchange" (BINEX) format, which is used for research purposes. It has been designed to encapsulate most of the information currently acceptable for GPS data. Binary files were converted to text file for easy handling and processing. For GPS data storage and transmission, the most generally used GPS exchange data type is the RINEX format (Gurtner & Mader, 1990). It contains processed data collected by the GPS stations. This format defined four file types for observation data, navigation message, meteorological message and GLONASS navigation message. As correlation exists between the consecutive GPS measurement data, CRINEX (Hatanaka, 1996), a compressed RINEX format, proposed based on the idea that observation information between each measurement was related and changed at a small pace. The use of CRINEX reduces the storage space and transmission bandwidth requirements as only the difference between the current observation data and the first occurrence of it is stored.

3. Sumatran cGPS array - introduction and configuration

Many cGPS arrays were deployed to monitor some of the active tectonic plates around the world. Each of these cGPS arrays contains tens to hundreds of GPS stations, spanning from hundreds to thousands kilometers and varying methods are used for monitoring and harvesting the data from those stations. In this section, some of those arrays are described.

The GPS Observation Network system (GEONET) (Yamagiwa et al., 2006) is one of the most dense cGPS network comprising of over 1200 GPS stations nationwide. It was used to support real-time crustal deformation monitoring and location-based services. GEONET provides real-time 1Hz data through a dedicated IP-VPN (Internet Protocol Virtual Private Network).

The Southern California Integrated GPS Network (SCIGN) (Hudnut et al., 2001) contain more than 250 stations covering most of southern California which provide near real-time GPS data. SCIGN is used for fault interaction and post-seismic deformation in the eastern California shear zone.

The New Zealand GeoNet (Patterson et al., 2007) is a nation-wide network of broadband and strong ground motion seismometers complimented by regional short period seismometers and cGPS stations, volcano-chemical analyzers and remote monitoring

capabilities. It comprises of more than 150 cGPS stations across New Zealand. All seismic and GPS data are transmitted continuously to two data centers using radio, land-based or VSAT systems employing Internet Protocol data transfer techniques.

The Sumatran continuous-Global Positioning System Array (SuGAr) is located along Sumatra, Indonesia. As at the end of 2009, it consists of 32 operational GPS stations spanning 1400 km from north to south of Sumatra (Fig. 1). Stations are located either in remote islands or in rural areas near the tectonic place boundary which is one of the most active plates in the world. Due to the lack of local data communication network infrastructure, satellite telemetry is the only means of communicating with the GPS stations. All of the stations are equipped with a scientific-grade GPS receiver, a GPS antenna, a satellite modem, solar panels and batteries.
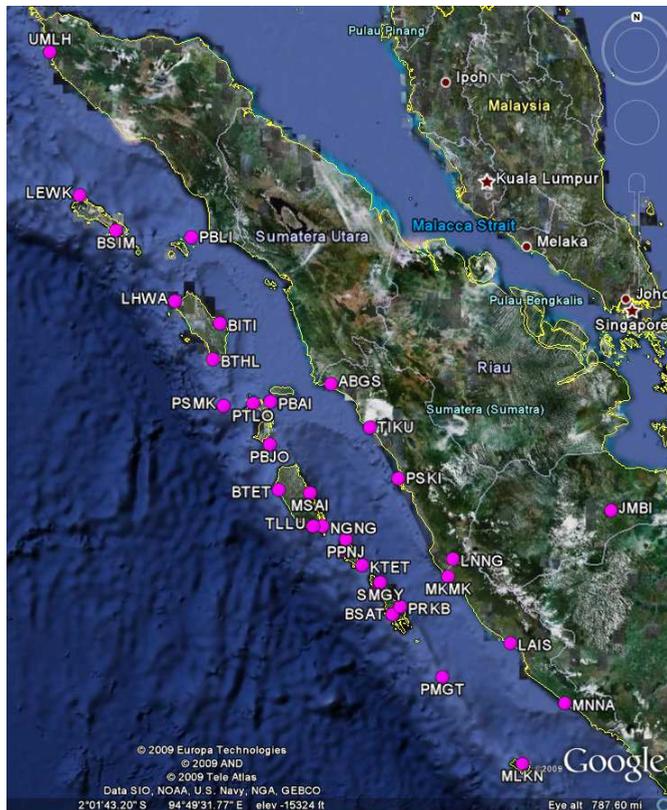
Fig. 1. Geographical distribution of the SuGAr stations

4. Utilisation of mesh networking

Mesh networking is proposed in this chapter to reduce the number of satellite links and bandwidth requirement for transmission of GPS data. To analyze the optimization achieved by the use of mesh networking on the SuGAr network, evaluation was performed using the archived SuGAr observation data from the last two months (61 days) of 2007. Only 24 stations were taken into account in this case study, as only 24 GPS stations were able to provide the complete GPS dataset for this entire period. This experiment data set can be accessed from the SOPAC website (http://sopac.ucsd.edu/).

Several assumptions were made for the evaluations presented in this study as follows:

- All GPS stations have enough energy to deal with the overheads cause by the additional communication equipments and data computation required. This assumption can be satisfied by adding more batteries and solar panels to the existing nodes.
- To simplify the analysis, the terrain information between the GPS stations was not taken into consideration in this analysis. In practice, construction of tall antenna towers as well as the use of multi-hop relays/repeaters can be used to overcome obstructions if required.
- The transmission overheads for the long range radios, such as packet formatting and control protocols, were not included in the evaluation as they will not have an impact on the analysis presented in this study.

The two main performance attributes of interest in this study are the reduction of the number of satellite links as well as the total amount of data transmitted via these links.

4.1 Removal of co-related data and reduction of uplink requirements

Mesh networking and clustering can be used to reduce the number of satellite links required for data telemetry between the GPS stations and the remote server. Wireless mesh networks can be established using long-range radios such as those developed by companies like FreeWave or Intuicom. These radios provide a point-to-point line-of-sight (LoS) wireless communication link with a maximum range of more than 96 kilometres (60 miles) and a maximum over-the-air throughput of 154 Kbps. For communication links over a longer distance, multi-hop communications can be utilized by deploying relay stations. The use of relay stations may also overcome LoS obstructions between GPS stations as well as provide for extended mesh networking capabilities such as redundancy. Depending on the cost, geographical, power or latency considerations, the number of hops and the radio range supported may be limited. In this case, clusters of GPS stations will be formed and a cluster-head would be selected for each cluster. Each cluster-head will have satellite communication capabilities and will be responsible for collecting all the observation data from the GPS stations within the cluster and transmitting them to the remote centralized data server. This greatly reduces the number of satellite links needed, as each cluster requires a minimum of only one satellite link. The various possible mesh network setups using the current geographical locations of the GPS station in the SuGAr array will also be presented.

In this study, each GPS station can be equipped with one or more long-range radios such as the FreeWave FGR-115RE. These radios specify a maximum range of over 90 km and can be used to form peer-to-peer wireless mesh networks between GPS stations. Assuming the maximum range of 90 km, the absence of relay stations or repeaters and the geographical locations of the 24 GPS stations, Fig.2 shows the network topology of GPS stations that will be formed using the FreeWave radios. It will contain one cluster with eight nodes, one

cluster with three nodes, two clusters with two nodes, and nine clusters with one node. Assuming that only one satellite uplink is required for each cluster, 13 satellite links will have to be maintained.
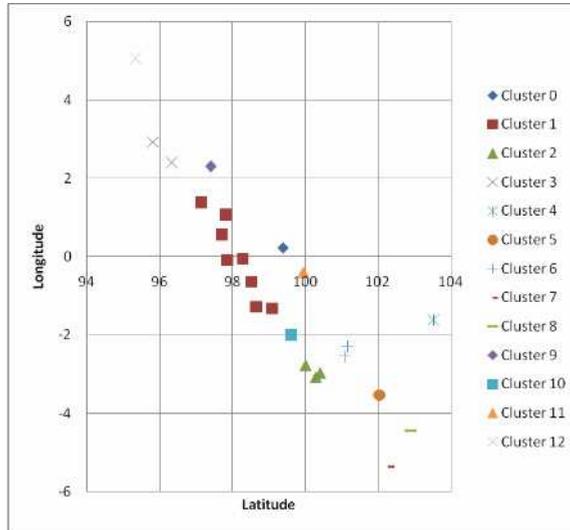

Fig. 2. Clusters of GPS station using 90 kilometer radio range

The range of the radio can be extended through the use of relay stations or repeaters. Thus, using the geographical locations of the 24 GPS stations, the minimum number of uplinks required and cluster size across various radio ranges can be determined. Fig. 3 shows the number of uplinks required for the various ranges. From the figure, it can be seen that given a maximum radio range of 20 km, only two GPS stations can be linked together and all other GPS stations were out of range from each other. Therefore, 23 satellite uplinks were required in this case. However, given a maximum radio range of 250 km, all GPS stations were grouped into one cluster using only one uplink.
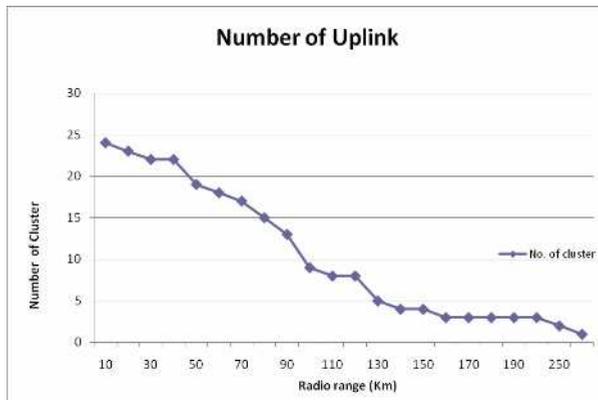

Fig. 3. Number of satellite uplinks required across various radio ranges

Fig. 4 provides the graph showing the average and the maximum number of GPS stations in a cluster across a radio range from 10 km to 250 km. As the number of GPS stations in a cluster increases, the data aggregated at the cluster-head will also increase in size. This will lead to better compression ratio at the cluster-heads and this phenomenal will be presented in more detail in the later part of this secion.
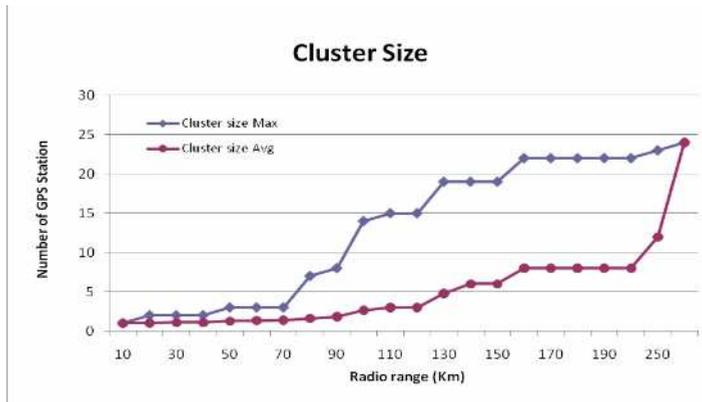

Fig. 4. Cluster sizes characteristics based on the various radio ranges

4.2 Collaborative compression of data

Cluster-based compression at the cluster-heads will be introduced where each cluster-head will compress the observation data from all GPS stations within the cluster using the LZMA (Ziv & Lempel, 1977) algorithm prior to transmission via the satellite link. Compared to the existing SuGAr deployment where each GPS station transmits the observation data independently, the use of mesh networking allows larger datasets to be formed through the aggregation of observation data from each GPS station within the cluster. Given that the compression ratio generally increases in proportion to the size of the dataset to be compressed, the number of bytes transmitted via the satellite will be significantly reduced.

Currently, the SuGAr sends collected data daily through dedicated satellite links from each GPS station. For this analysis, the GPS measurements will be converted locally to CRINEX format at each GPS station. Fig. 5 shows the total number of data bytes transmitted via all the satellite links using three different setups as follows:

- **Setup 1**: For the first setup, CRINEX data was uploaded via dedicated satellite links from each GPS stations without further compression.
- **Setup 2**: For the second setup, the CRINEX data was compressed using the LZMA algorithm prior to transmitting via dedicated satellite links at each GPS station.
- **Setup 3**: For the third and final setup, clusters of GPS stations were formed using long range radios with various maximum transmission ranges. In each cluster, one GPS station will be designated as the cluster-head and all other stations will forward their CRINEX data to the cluster-head. The cluster-head will perform further compression using LZMA algorithm on the aggregated data as a whole prior to transmitting the compressed data to the data server via a satellite link.

From Fig. 5, it can be seen that for Setup 2, the total number of bytes transmitted via all the satellite links over a 61 days period were reduced by about 67% when compared to Setup 1.

This demonstrates the effectiveness of the LZMA compression algorithm. Further reduction was demonstrated by the use of the cluster-based approach in Setup 3. In this setup, as a larger dataset was compressed, the compression ratios achieved by the LZMA algorithm at the cluster-head were more significant than in the case where compression was performed at individual GPS stations separately. Thus, this method reduced the total number of bytes transmitted by about 2% and 9% when compared to Setup 2 for a maximum radio range of 90 km and 250 km respectively.
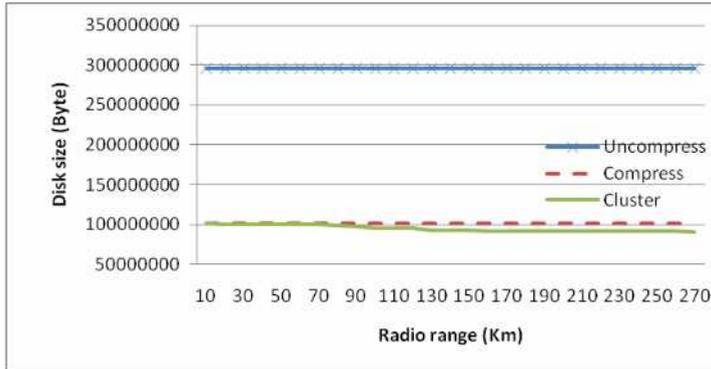
Fig. 5. Total size of transmitted data based on daily updates across two months (61 days) for various radio ranges

The analysis performed in Fig. 5 was based on daily updates from the GPS stations. However, more frequent updates might be useful for early warning systems and near real-time assessment of tectonic plate movements. Thus, further analysis was performed to evaluate the performance of the three setups across three different update intervals: daily, hourly and two minutely. Table 1 shows the comparison of Setup 1 (uncompressed data) and Setup 2 (un-clustered compressed data) with various update frequency. It can be seen from the results that as the update intervals get more regular, the performance of the LZMA algorithm suffers as smaller datasets were being compressed. For example, when daily updates were performed with the GPS station sampling once every 2 seconds, dataset consisting of a total of (24hrs * 60min * 60 sec /2) = 43200 measurements (epochs) was compressed whereas in the case where hourly updates were performed, each dataset consist of only (60 min * 60 sec /2) = 1800 measurements (epochs). However, from the results, it can be seen that even when updates were performed every two minutes, the use of the LZMA compression in Setup 2 still enables less data to be transmitted via the satellite when compared to Setup 1.

Update Frequency	Total Transmitted Data		
	Uncompress	Compress	Percentage[a]
Daily	325,099,037 byte	112,188,360 byte	35%
Hourly	402,298,012 byte	158,994,711 byte	40%
2Minutely	2,245,193,111 byte	979,810,017 byte	44%

a. Percentage of compress data when compare with uncompress data

Table 1. Compare Uncompressed and Compressed Data

Fig. 6 shows the total transmitted data size in Setup 3 as a percentage to the total transmitted data size in Setup 2 across various radio ranges. From the results, it can be seen that the use of long range radios to form mesh networks and clusters in Setup 3 significantly reduces the amount of data to be transferred via the satellite links when compared to Setup 2. This reduction is more significant when the update frequency increases. This is due to the use of data aggregation within the cluster to enable larger datasets to be compressed. For example, when a maximum radio range of 250 km is used, data from all 24 GPS stations will aggregated prior to compressing using the LZMA algorithm. Assuming hourly update intervals, each dataset consisting of ((60min * 60 sec /2) * 24 nodes) = 43200 measurements (epochs) was compressed in Setup 3 as compared to the 1800 measurements in Setup 2. Because of this, Setup 3 managed to reduce the total data transmission across the 61 days by about 70% when compared to Setup 2.
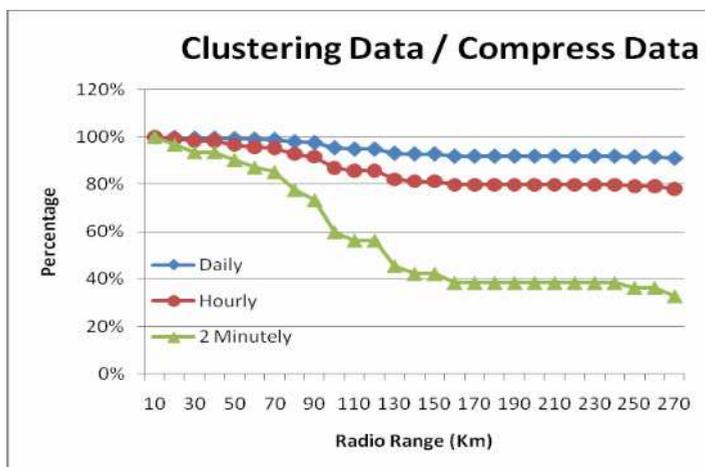

Fig. 6. Compare the improvement between compress observation data and use of clusters over different update intervals and radio range.

Update Frequency	Total Transmitted Data		
	Uncompress	Compress	Percentage[b]
Daily	322,554,780 byte	111,317,030 byte	35%
Hourly	341,813,991 byte	137,613,065 byte	40%
2 Minutely	710,381,007 byte	417,818,057 byte	59%

b. Percentage of compress data when compare with uncompress data without header

Table 2. Compare Uncompress and Compress Data without Header

To further reduce the size of the transmitted data, the observation headers sent with every update from the GPS stations were removed whenever possible. This significantly reduced the size of the uncompressed data in Setup 1 as shown in Table 2. Moderate reductions in Setup 2 were also observed when the observation headers were removed.

To conclude the evaluations, the use of Setup 3 (the use of wireless mesh networks) without observation headers was compared to Setup 2 (use of dedicated satellite links). The result of this comparison is shown in Fig. 7. From the figure, it can be seen that the use of mesh

networking, cluster-based compression and removal of the observation header significantly reduces the amount of data transmitted via the satellite links.
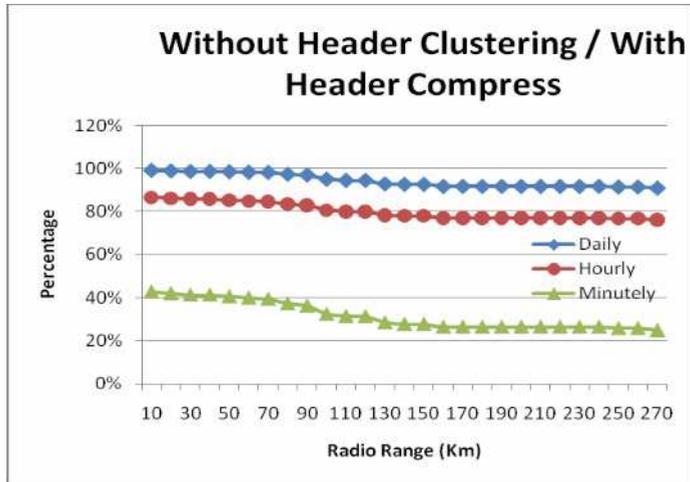

Fig. 7. Compare the improvement between compress observation data (with header) and use of cluster-based compression (without headers) over different update intervals and radio range.

4.3 Parallel and distributed in-situ processing for GPS corrections

In-situ parallel and distributed processing of GPS corrections can be made possible using mesh networking. The observation data from adjacent GPS stations can be grouped together and processed in a hierarchy fashion. Compared to the conventional method of sequential processing, the computational complexity and computation time of parallel and distributed GPS processing with various schemes decreases significantly. By sharing data within the mesh network, it is possible for in-network processing to be performed for GPS corrections using the embedded processing capability at each GPS station. This allows early-warning applications to be developed without the need for costly data transmission to a remote centralised server. The remaining of this section is organized as follow. Firstly, GPS measurement and parameters estimation process is briefly presented. Secondly, the computational complexity of parallel processing is evaluated using one layer and multiple layers approach. Finally, two empirical studies with various settings are studied.

Assuming that all receivers can receive signals from both frequencies L1 and L2, the ionosphere-free linear combination can be calculated. The distance between satellites and receivers are given by carrier phase and pseudo-range measurements. In phase measurement, at time t, the distance between receiver r and the satellite x models is derived as

$$L_{rxt} = \rho_{rxt} + b_{rxt} + z_{rt}m(\theta_{rxt}) + \omega_{rxt} + C_{rt} + c_{xt} + v_{rxt} \tag{1}$$

and the pseudo-range measurement is derived as

$$P_{rxt} = \rho_{rxt} + z_{rt}m(\theta_{rxt}) + C_{rt} + c_{xt} + \eta_{rxt} \tag{2}$$

in which, ρ_{rxt} is the true range, b_{rxt} is the phase bias or ambiguity, z_{rt} is the zenith troposphere delay, $m(\theta_{rxt})$ is the map function of elevation angle between transmitter and receiver. Receiver and transmitter correction are C_{rt} and c_{xt} respectively. The noise of the measurement is represented by v_{rxt} for phase and η_{rxt} for pseudo-range measurement.

Data is considered from R receiver and X transmitters spanning across Δ time with the data collection frequency σ. The median probability that a satellite signal is detected by a receiver above an elevation cutoff is given by $\Omega/4\pi$ (≈ 0.25 for a 15° cutoff). Thus, the number of measurement is given by

$$m = RX \, (\Omega/4\pi) \, (\Delta/\delta) \, d \tag{3}$$

in which d is the number of data types, typically including two types; ionosphere-free phase and pseudo-range. The number of parameters from those receivers and transmitters will be estimated and consist of receivers, transmitters and polar motion parameters. It is given by

$$n = aR + bX + c \tag{4}$$

The parameters related to the receiver include three Cartesian coordinates, tropospheric delay, receiver clock bias and phase bias parameter for each transmitter in the view of that receiver, so a = 5 + X. The transmitter parameters include epoch state position, velocity, two solar radiation parameters, Y bias parameter and clock bias, b = 10. Polar motion and rates are estimated in one day time given by c = 5.

The computation complexities of the parameter evaluation process using least square estimate method of n parameters with m measurement requires the number of arithmetic operations B in equation (5). This is also known as the computation burden. The detail analysis was presented in Zumberge, et al (1997).

$$B \propto n^2 m \tag{5}$$

One approach to reduce the computation complexity is to divide the data into groups and layers, which could then be processed in a parallel fashion. In addition, it makes use of common parameters and receivers between groups in the same layer. The detail of this processing approach will be presented in the next sub-sections.

4.3.1 Parallel GPS processing

In this part, parallel parameters estimation is studied with the objective of reducing the computation complexity and processing time when compared to the centralize processing method that is mentioned previously. It deals with estimating n unknown parameters of m measurements from R receivers and X transmitters. Moreover, receivers are divided into groups based on some criteria such as antenna type (Miyazaki, 1999), geography (Serpelloni et al., 2006), and/or the availability of data. Groups may share some common reference stations/receivers. One layer and multilayer parallel processing approach will be presented in the remaining of this section. All used notations are listed at the end of this chapter.

a.   One layer parallelism

In one layer method, receivers are divided into J computation groups (Fig. 8) instead of estimating all parameters within one group. Suppose that the number of common parameters between all groups is κn and the remaining parameters equally divided for each group is $(1-\kappa)n/J$. In addition, the number of common reference receivers between all
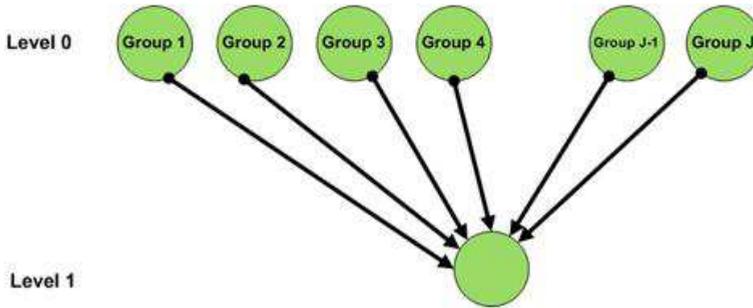
Fig. 8. One level parallel processing

groups is ζR. For simplicity, suppose the number of common measurement proportional to ζ is given by ζm and the remaining measurements are equally divided between groups, (1-ζ)m/J, for each group. The number of parameters and measurements at level zero for each group is thus derived as

$$n_{0,i} = \kappa n + \frac{(1-\kappa)n}{J} \; and \; m_{0,i} = \zeta m + \frac{(1-\zeta)m}{J} \tag{6}$$

Arithmetic operations required are proportional to $n_{0,i}^2 m_{0,i}$, thus from equation (5)

$$B_{0,i} \propto \left(\frac{(1+(J-1)\kappa)n}{J} \right)^2 \frac{(1+(J-1)\zeta)m}{J} \tag{7}$$

in which $B_{0,i}$ is the number of arithmetic operations required at any group i (1≤i≤J) at level zero. There are J groups in this level with the same number of arithmetic operations so the total number of operations is equal to J multiplied by the number of operation of one representative group $B_{0,1}$. Hence, the total number of arithmetic operations at level zero is equal to

$$B_0 = \sum_{i=1}^{J} B_{0,i} = J * B_{0,1} \tag{8}$$

Finally, the parameter estimation processing at level 1 is the refinement of J group at level zero. It includes n parameters and the number of measurement equaling to the total number of estimated parameter of J groups at level zero. Using equation (5), the computation burden is derived as

$$B_1 \propto n^2 \sum_{i=1}^{J} n_{0,i} = n^2 \left(1 + (J-1)\kappa \right) n \tag{9}$$

Thus, the total number of operations B is equal to the sum of all computation burdens at level zero and level one as follows,

$$B = B_0 + B_1 \propto n^2 (1+(J-1)\kappa)(\frac{(1+(J-1)\kappa)(1+(J-1)\zeta)m}{J^2} + n) \tag{10}$$

The computation reduction percentage χ is equal to number of operations divide by the number of operation n²m required for simultaneous parameter evaluation.

$$\chi = \frac{B}{n^2 m} \; \propto \; (1+(J-1)\kappa)(\frac{(1+(J-1)\kappa)(1+(J-1)\zeta)}{J^2} + \frac{n}{m}) \tag{11}$$

The value of χ approaches unity when ζ and κ approaches 1 assuming n/m is small. Therefore, if all the parameters and receivers are common between groups, parallel processing is ineffective.

This method is applied for the Sumatra continuous GPS (cGPS) array (Tran & Wong, 2009) and the results are evaluated for two different configurations using the parameters X = 24, Ω/4π = 0.25, Δ = 24h, σ = 2 min, d = 2, a = 29, b = 10, c = 5. For the first configuration, the number of receivers R equal to 40 which include 32 GPS stations of Sumatra cGPS array and 8 International GNSS Service (IGS) reference stations. In the second configuration, only 32 Sumatra cGPS stations were used without reference stations.

In the first configuration, we have ζ equal to the number of reference stations divide by the total number of stations, thus, ζ=8/40=0.2. The number of common parameters equal to the sum of the parameters of the common reference stations, the transmitter parameters and the polar motion. This can be calculated using equation (12), so κ ≈ 0.34.

$$\kappa n = a\zeta R + bX + c \tag{12}$$

In the second configuration, the number of common reference stations, ζ, is equal to zero and so, using equation (12), κ ≈ 0.17.

The computation reduction with respect to the different groups is presented in Fig. 9. In the case where reference stations were utilized, the maximum reduction reached 57% when receivers were divided into 5 groups. It decreases when the number of group increased due to the overheads of the reference station when using more groups. In the case where no reference stations were used, the maximum reduction reaches 91.6% when receivers where divided into 16 groups with 2 receivers per groups.
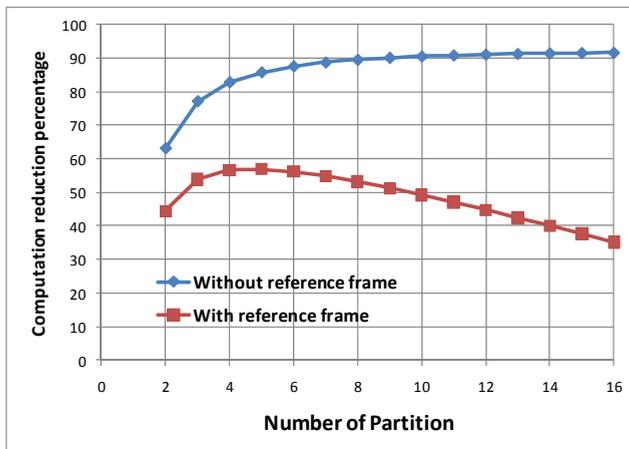

Fig. 9. Computation reduction for the Sumatra cGPS array using one level parallel processing

b.   Multilayer parallelism

For generalization, the multilayer parallel is studied with L layer and each layer includes power of p groups. It denotes that there are p power of L groups at level zero and each group at level j (1≤j≤L) receives data from p groups at the adjacent predecessor level j-1. For instance, p equals to two in Fig. 10.
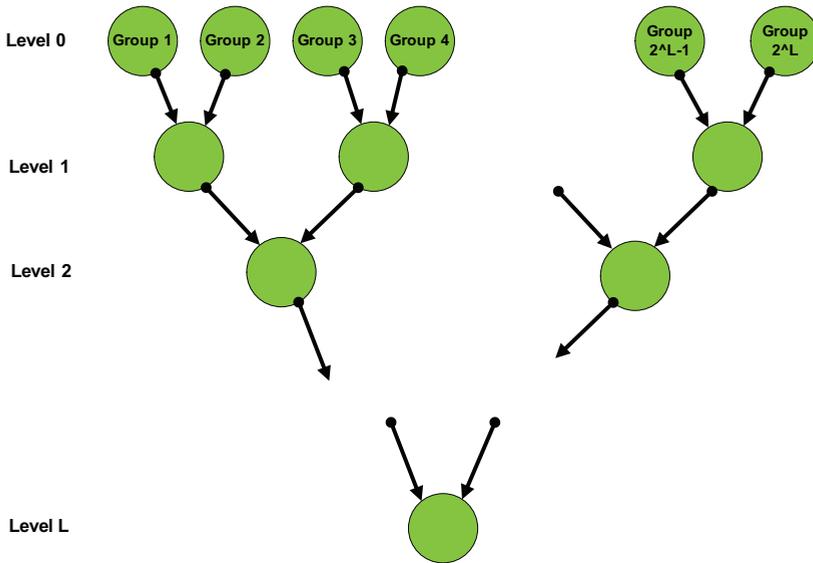

Fig. 10. Multilayer parallel processing with L layer with power of 2 groups. The processing tree will contain 2^L groups at level 0 and each group at level j (0<j≤L) is the combination of 2 node at level j – 1.

With the same assumption of common parameters and measurements with the one layer parallel method mentioned previously, the number of parameters is equal to the sum of the common parameters and private parameters of each group of receivers and number of measurements are equal to sum of the common measurements from common receivers and private measurements from the private receivers.

$$ n_{0,i} \; = \; \kappa n \; + \; \frac{(1-\kappa)n}{p^L} \; and \; m_{0,i} = \zeta m \; + \; \frac{(1-\zeta)m}{p^L} \tag{13} $$

Therefore, the number of arithmetic operations of group i at level zero is

$$ B_{0,i} \propto \; n_{0,i}^2 m_{0,i} = (\kappa n + \frac{(1-\kappa)n}{p^L})^2 (\zeta m + \frac{(1-\zeta)m}{p^L}) \tag{14} $$

So, the total computation burden for level zero which include p^L group equals to

$$ B_0 \; = \sum_{i=1}^{p^L} B_{0,i} \tag{15} $$

Furthermore, the computation burden for each group i at level j ($1 \leq j \leq L$) is proportional to $n_{j,i}^2 m_{j,i}$, in which the number of parameter $n_{j,i}$ is equal to the sum of common parameters κn and the private parameters of p ancestor group at level j–1, each of which comprise of $\left((1 - \kappa)n * p^{j-1}\right) / p^L$ private parameters. Therefore,

$$n_{j,i} \ = \ \kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^j \tag{16}$$

In addition, the number of measurements at level j is equal to the summation of all estimated parameters of p ancestor at level j–1,

$$m_{j,i} \ = \ p(\kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^{j-1}) = p\kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^i \tag{17}$$

Therefore, the computation burden of each group i at level j equals to

$$B_{j,i} \ \propto \ (\kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^j)^2 (p\kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^j) \tag{18}$$

The total computation burden for level j which include p^{L-j} groups is then derived as

$$B_j \ = \ \sum_{i=1}^{p^{L-j}} B_{j,i} \ \propto \ (\kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^j)^2 (p\kappa n \ + \ \frac{(1 - \kappa)n}{p^L} p^j) p^{L-j} \tag{19}$$

The total computation burden of multiple parallel processing is equal to summation of computation of all level from level 0 to L as follows:

$$\begin{aligned} B = \sum_{j=1}^{L} B_j + B_0 \ \propto \ & \sum_{j=1}^{L} (\kappa n \ + \frac{(1 - \kappa)n}{p^L} p^j)^2 (p\kappa n \ + \frac{(1 - \kappa)n}{p^L} p^j) p^{L-j} \ + \\ & (\frac{(1 - \kappa)n}{p^L} + \kappa n)^2 (1 + (p^L - 1)\zeta)m \end{aligned} \tag{20}$$

c.   Computation time

Assuming that the computation time is the dominant latency between processing groups at adjacent layer, the processing time of parallel GPS processing, in the worst case, is calculated by the summation of the maximum computation time at each layer at the critical computation path. The critical path for one layer and multilayer parallel processes is given in Fig. 11 and Fig. 12 respectively.

The computation time C is equal to number of arithmetic operation multiply by c, the computation time for each arithmetic operation. The equation for one layer and multilayer are therefore derived as follow:

$$C_{onelayer} = \left(n^2 \left(1 + (J-1)\kappa\right)n + \left(\frac{(1 + (J-1)\kappa)n}{J}\right)^2 \frac{(1 + (J-1)\zeta)m}{J} \right) * c \tag{21}$$

$$C_{multilayer} = (\sum_{j=1}^{L} (\kappa n + \frac{(1-\kappa)n}{p^L} p^j)^2 (p\kappa n + \frac{(1-\kappa)n}{p^L} p^j) +$$
$$(\frac{(1-\kappa)n}{p^L} + \kappa n)^2 (1 + (p^L - 1)\zeta) \frac{m}{p^L}) * c \qquad (21)$$
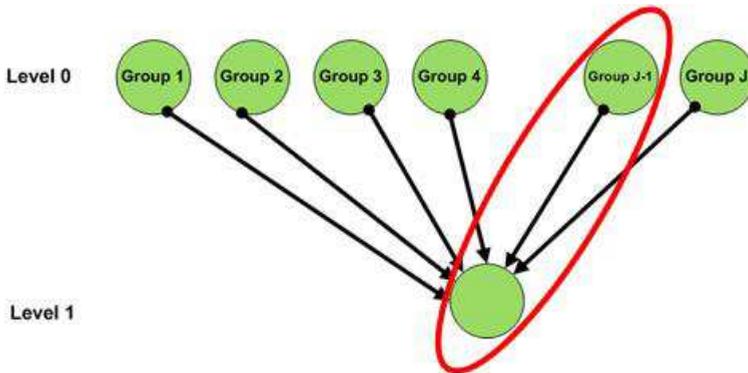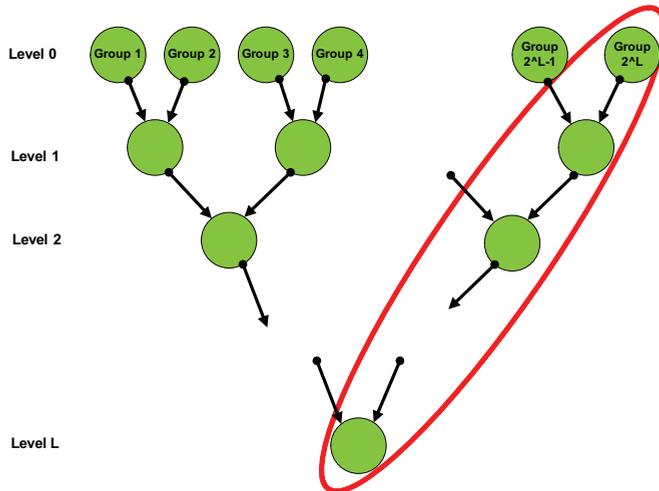

Fig. 11. One layer critical path

Fig. 12. Multilayer critical path

4.3.2 Empirical study

To compare the reduction in computation burden and computation time of one layer and multilayer parallel parameter estimation for GPS processing, two experimental setups were studied as following.

Experiment set 1: for the network parameter estimation, reference receivers were not included. This experiment compares the number of processing groups, computation reduction and computation time between three system settings with different number of GPS receivers. Three system settings are

- One layer,
- Multilayer with power of 2,
- Multilayer with power of 3

The results of experiment set 1 is shown from Fig. 13 to Fig. 15. From the results, it can be seen that when the number of receivers is equal to 16 or 48, the number of computation process for multilayer with power of 3 is smaller than other two settings. As a result, the computer reduction is lower than other settings and the computation burden is larger than multilayer with power of 2. With other number of receivers bigger than 48, the computation reduction is almost analogous for all settings. Parallel GPS processing significantly reduces the computation complexity, especially when the number of receivers is bigger than 32. Furthermore, multilayer processing drastically reduces the computation time by about 50% when compared with the one layer approach. In most of cases, the number of computation
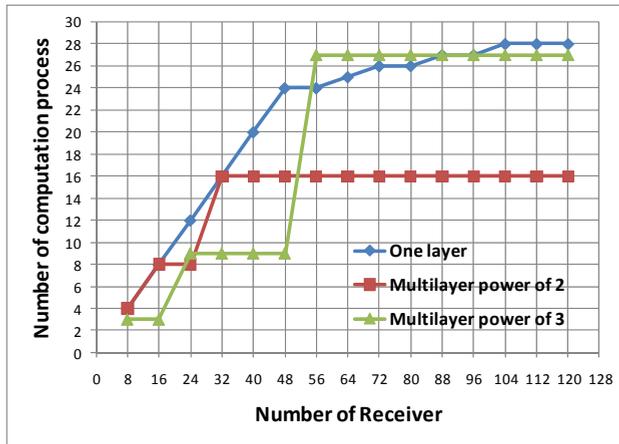
Fig. 13. Compare the number of computation processing groups with respect to number of receiver
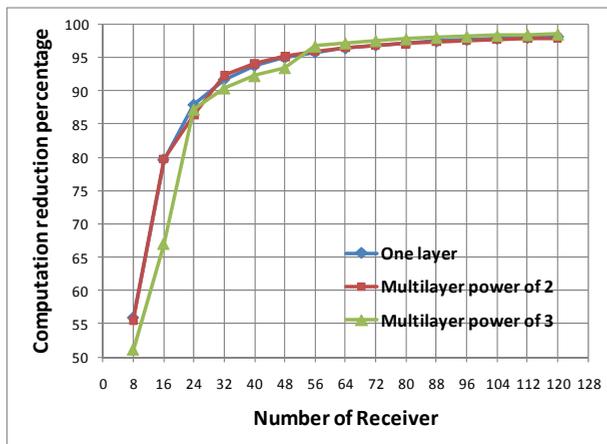

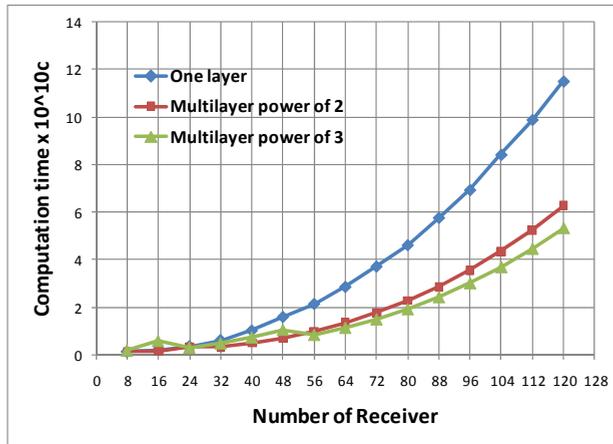Fig. 14. Compare the computation reduction with respect to number of receivers

Fig. 15. Computation time comparison. The computation time is product of c, the computation time for one arithmetic operation

processes of multilevel methods is lower than one level method. As a result, multilevel is the best selection for in-network parameter estimation processing as demonstrated in this experiment.

Experiment set 2: global parameter estimate with 8 reference receivers (all group will share the same 8 reference receivers) using the same three comparative setting with the first experiment:

- One layer,
- Multilayer with power of 2,
- Multilayer with power of 3

The experiment results are shown from Fig. 16 to Fig. 18 (reference receivers are not included in the number receivers in the x-axis of the graph).
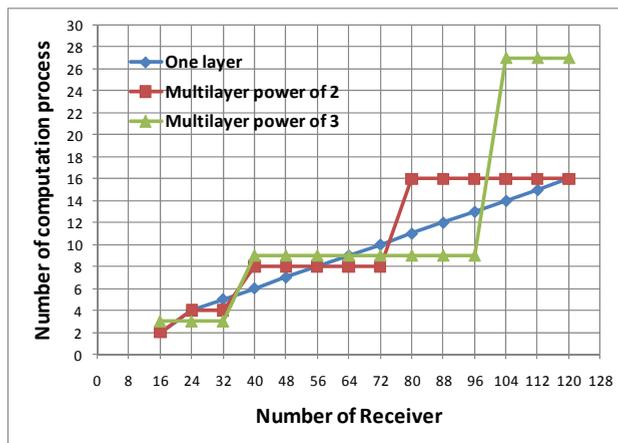

Fig. 16. Compare the number of computation processing groups with respect to number of receivers
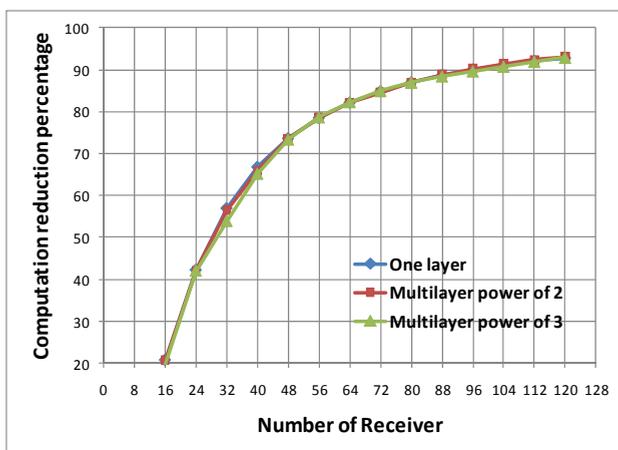
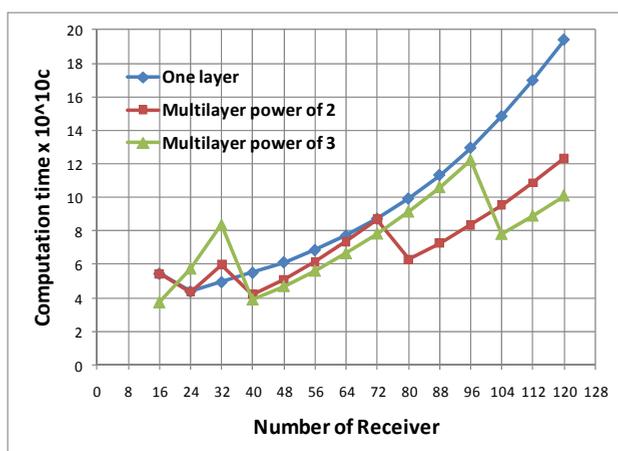Fig. 17. Compare the computation reduction with respect to number of receivers

Fig. 18. Computation time comparison. The computation time is product of c, the computation time for one arithmetic operation

From the results, it can be seen that when the number of receivers is equal to 32 or 96, the number of computation processes using the multilayer approach with a power setting of 3 is smaller when compared to the other settings. The computation reduction is also larger than the other settings in the case of 32 receivers and larger than multilayer with a power of 2 in the case of 96 receivers. Thus, it can be seen that parallel GPS processing significantly reduces the computation complexity, especially when the number of receivers is bigger than 32 and steadily increases when the number of receivers increases. Furthermore, the multilayer processing approach slightly decreases the computation time, as in most of the cases, the number of computational operations performed by the multilevel methods is lower than the one level method.

5. Conclusion

A study using mesh networking for tectonic monitoring was presented. Mesh networks can be established between the GPS stations by means of long-range radios and data aggregation was performed to enable cluster-based compression. Using the actual data captured from the Sumatran cGPS array (SuGAr) in the evaluation and analysis, it was concluded that the proposed use of mesh networking not only reduces the number of costly satellite uplinks required, it also significantly reduces the total amount of data transferred through these links. Moreover, by making use of mesh networks between the GPS stations, parallel, distributed and hierarchical GPS processing methods can be made possible. By reducing the computation complexity, this proposed computational model allows the possible use of the spare computational power within the cGPS network such as from the routers and station controllers using the wireless mesh network connections between stations to transmit GPS data and perform collaborative GPS processing in a real-time fashion.

6. References

Ammon, C. J., Ji, C., Thio, H.-K., Robinson, D., Ni, S., Hjorleifsdottir, V., et al. (2005). Rupture Process of the 2004 Sumatra-Andaman Earthquake. Science, 308(5725), 1133-1139. doi: 10.1126/science.1112260

Gurtner, W., & Mader, G. (1990). Receiver Independent Exchange Format Version 2. GPS Bulletin, 3(3), 1-8.

Hatanaka, Y. (1996, 17-20 September). A RINEX Compression Format and Tools. Paper presented at the Proceedings of ION GPS-96.

Hudnut, K. W., Bock, Y., Galetzka, J. E., Webb, F. H., & W. H. Young. (2001). The Southern California Integrated GPS Network (SCIGN). 10th International Symposium on Crustal Deformation Measurement, 129-148.

Konca, A. O., Avouac, J.-P., Sladen, A., Meltzner, A. J., Sieh, K., Fang, P., et al. (2008). Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence. [10.1038/nature07572]. Nature, 456(7222), 631-635. doi: http://www.nature.com/nature/journal/v456/n7222/suppinfo/nature07572_S1.html

Lay, T., Kanamori, H., Ammon, C. J., Nettles, M., Ward, S. N., Aster, R. C., et al. (2005). The Great Sumatra-Andaman Earthquake of 26 December 2004. Science, 308(5725), 1127-1133. doi: 10.1126/science.1112250

Miyazaki, S.-i. (1999). Construction of GSI's Nationwide GPS Array. Proceedings of the Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resources Panel on Wind and Seismic Effects, 31, 518-528.

Patterson, N., Gledhill, K., & Chadwick, M. (2007). New Zealand National Seismograph Network Report for the Federation of Digital Seismograph Networks Meeting, 2007. Perugia, Italy: 2007 FDSN Meeting.

Segall, P., & Davis, J. L. (1997). GPS applications for geodynamics and earthquake studies. Annual Review of Earth and Planetary Sciences, 25, 301-336. doi: 10.1146/annurev.earth.25.1.301

Serpelloni, E., Casula, G., Galvani, A., Anzidei, M., & Baldi, P. (2006). Data analysis of permanent GPS networks in Italy and surrounding regions: application of a distributed processing approach. [Article]. Annals of Geophysics, 49(4-5), 897-928.

Sieh, K., Natawidjaja, D. H., Meltzner, A. J., Shen, C.-C., Cheng, H., Li, K.-S., et al. (2008). Earthquake Supercycles Inferred from Sea-Level Changes Recorded in the Corals of West Sumatra. Science, 322(5908), 1674-1678. doi: 10.1126/science.1163589

Tran, H.-H., & Wong, K.-J. (2009). Mesh Networking for Seismic Monitoring - The Sumatran cGPS Array Case Study. Paper presented at the Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE.

Yamagiwa, A., Hatanaka, Y., Yutsudo, T., & Miyahara, B. (2006). Real-time capability of GEONET system and its application to crust monitoring. Bulletin of the Geographical Survey Institute, 53.

Ziv, J., & Lempel, A. (1977). A Universal Algorithm for Sequential Data Compression. IEEE Transactions on Information Theory, 23(3), 337 - 343.

Zumberge, J., Heflin, M., Jefferson, D., Watkins, M., & Webb, F. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. J. Geophys. Res., 102(B3), 5005-5017.

Notations

R	number of receiver (GPS station)
X	number of transmitter (satellite)
n	total number of parameter have to estimate
m	total number of measurement
κ	share parameters percentage between groups
ζ	share measurement percentage between groups
B	computation burden
J	number of computation group
L	number of processing level
p	in multiple level processing method, group at level i receive data from p group at level i-1
$n_{j,i}$	number of parameter at level j and group i have to estimate
$m_{j,i}$	number of measurement at level j and group i
$B_{j,i}$	computation burden at group i of level j
B_j	total computation burden at level j
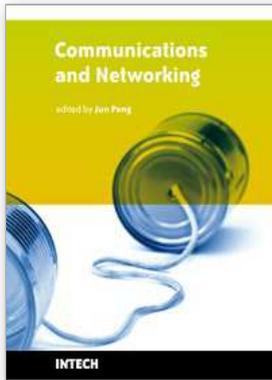
Communications and Networking

Edited by Jun Peng

ISBN 978-953-307-114-5

Hard cover, 434 pages

Publisher Sciyo

Published online 28, September, 2010

Published in print edition September, 2010

This book "Communications and Networking" focuses on the issues at the lowest two layers of communications and networking and provides recent research results on some of these issues. In particular, it first introduces recent research results on many important issues at the physical layer and data link layer of communications and networking and then briefly shows some results on some other important topics such as security and the application of wireless networks. In summary, this book covers a wide range of interesting topics of communications and networking. The introductions, data, and references in this book will help the readers know more abut this topic and help them explore this exciting and fast-evolving field.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Hoang-Ha Tran and Kai-Juan Wong (2010). Usage of Mesh Networking in a Continuous-Global Positioning System Array for Tectonic Monitoring, Communications and Networking, Jun Peng (Ed.), ISBN: 978-953-307-114-5, InTech, Available from: http://www.intechopen.com/books/communications-and-networking/usage-of-mesh-networking-in-a-continuous-global-positioning-system-array-for-tectonic-monitoring