The Deformation Study of High Building Using RTK-GPS: A First Experience in Malaysia

WAN AZIZ W.A, ZULKARNAINI M.A. and SHU K. K., Malaysia

Key words: RTK, Deformation, High Rise Building, Structural Monitoring.

SUMMARY

Deformation of large engineering structures is often measured in order to ensure that the structures are exhibiting safe deformation behaviour. Nowadays, there are much more high buildings than in the past. From the structural point of view, the dynamic behaviour of high building under loads is apparently the most important aspect at the designing stage. The design of buildings should follow the structural requirements under primary loading and for this reason they are designed according to standards. For many years, deformation monitoring of this engineering structure relies on geodetic surveys (e.g. theodolite-EDM, Close Range Photogrammetry) and geotechnical measurements (e.g. accelerometer). However, for the past few years, the use of GPS for deformation studies has evolved rapidly since the onset of processing and instrumentation improvement of the technology. There are two system architectures for structural monitoring using GPS, one based on a fixed network of sensors and the other based on mobile sensors. In both system, the GPS technology can measure directly the position's coordinates and relative displacements of the structure at rates of 10Hz or higher (rapid assessments). Here, a Real Time Kinematic (RTK) technique represents a smart solution to the problem of obtaining high productivity without sacrificing much in terms of accuracy and reliability. This technique has been considered as a cost-effective tool to monitor safety and performance of engineering structures, including high buildings. The RTK-GPS is a carrier phase observation, processed (corrected) in real-time to give the position's coordinates whereas the kinematic parameters of deformation can be computed in order to predict failure events. Therefore, this paper highlights the concept and methodology of the RTK-GPS and its potential application for high building monitoring surveys. The understandings and experiences gained from the test are proven to be invaluable in choosing a right GPS measurement and processing strategy for a building monitoring. The data collected through these preliminary tests will serve as a benchmark for the future implementation.

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1. INTRODUCTION

The need for deformation surveys often arises from concerns associated with environmental protection, property damage and public safety. Deformation refers to the changes a deformable body undergoes in its shape, dimension, and position. Sensors systems such as accelerometers, strain gauges and total stations are familiar tools to many professionals who involved with structural monitoring. But, nowadays, the GPS is the most important technological innovation in the field of geo-sciences including deformation studies in this century. Thus, the challenge of monitoring the large engineering structure using GPS technology has received growing attention during the last few years. Nowadays, there are more large and tall engineering structures such as long span bridge, dams and high rise buildings than in the past. These structures are being designed to be much more flexible and to resist extensive damage from changes in temperature, severe wind gusts and earthquakes. Structural engineers require precise, reliable instruments to resolve their concerns about angular movements, displacements and structural vibrations. Thus, deformation survey of this engineering structure has to be carried out in order to ensure that the structure is in a safe condition.

The use of GPS for high rise building monitoring has evolved rapidly since the onset of processing and instrumentation improvement of the technology. There are two system architectures for structural monitoring with GPS, one based on a fixed network of sensors and the other based on mobile sensors. In both systems, the GPS technology can measure the position's coordinates directly and relative displacements of the structure at rates of 10Hz or higher (rapid assessments). This information can be of vital importance to structural engineers in the evaluation of structural integrity, and the continuous RTK-GPS is a valuable tool for such monitoring. Thus, one is easily provided with dense and extensive time series of code and phase observations to all GPS satellites in view, on both the L1 and L2 frequency. Using the continuous RTK mode in deformation studies, we require the highest accuracy, maximum sensor reliability, automatic operation, built-in redundancy and highly flexible computational tools. This paper therefore highlights the continuous RTK-GPS application as a monitoring strategy for a high rise building, Menara Sarawak in Malaysia. Some preliminary results are presented.

2. REVIEW ON RTK GPS AND HIGH RISE BUILDING

The RTK technique represents a technological solution to the problem of obtaining high productivity, i.e. measure baseline in real time mode without sacrificing much in terms of accuracy and reliability. Here, the real time technique makes it possible to know exactly when ambiguities are solved, and details of the ambiguity resolution can be found in [2] and [5]. This approach is a differential positioning technique that uses known coordinates of a reference station occupied by one receiver to determine coordinates of unknown points visited by a rover receiver. The technique employs carrier phase measurements, and processing is carried out in real time, giving computed coordinates at the cm level of the visited point. To process the data in real time, the reference station coordinates and measurements are transmitted to the rover via data links. The data-link requirements are a function of: amount of data to be transmitted (number of satellites, data type and format), reliability and integrity requirements, operating conditions, and distance between the reference and remote stations. UHF, VHF or spread spectrum radios are currently the most used types of data links. UHF radios are usually used for distances less than 15 km. It should be noted here that the key feature enabling the accuracies afforded by RTK operation is the ability to determine the carrier phase integer ambiguities while rovers in motion. The RTK architecture system is shown in Figure 1.

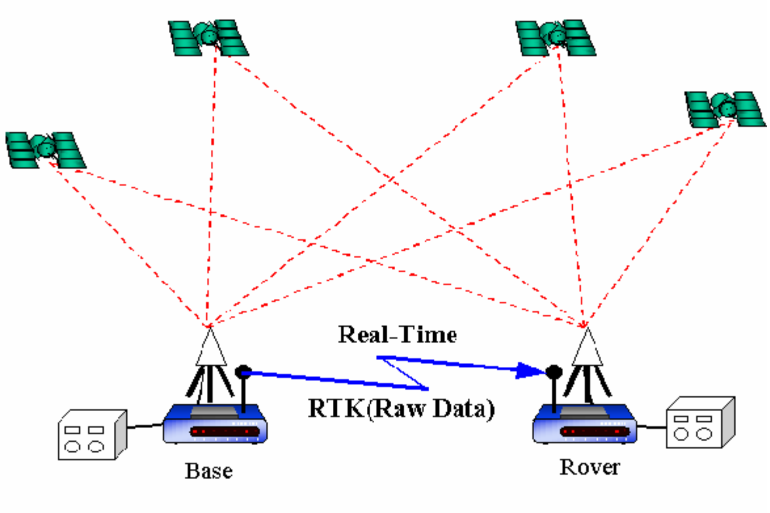


Figure 1: The RTK-GPS Architecture

A high-rise building is defined as a building 35 meters or greater in height, which is divided at regular intervals into occupy-able levels. To be considered a high-rise building an edifice must be based on solid ground, and fabricated along its full height through deliberate processes (as opposed to naturally-occurring formations). A high-rise building is distinguished from other tall man-made structures by the following guidelines (Emporis, 2004):

i. It must be divided into multiple levels of at least 2 meters height;
ii. If it has fewer than 12 such internal levels, then the highest undivided portion must not exceed 50% of the total height;
iii. Indistinct divisions of levels such as stairways shall not be considered floors for purposes of eligibility in this definition.

High rise building research is done at Sarawak Business Tower which is strategically located on Stulang Laut, Johor Bahru, Malaysia. The building's structure is consisted of 30 storey tower and most of them houses commercial offices.

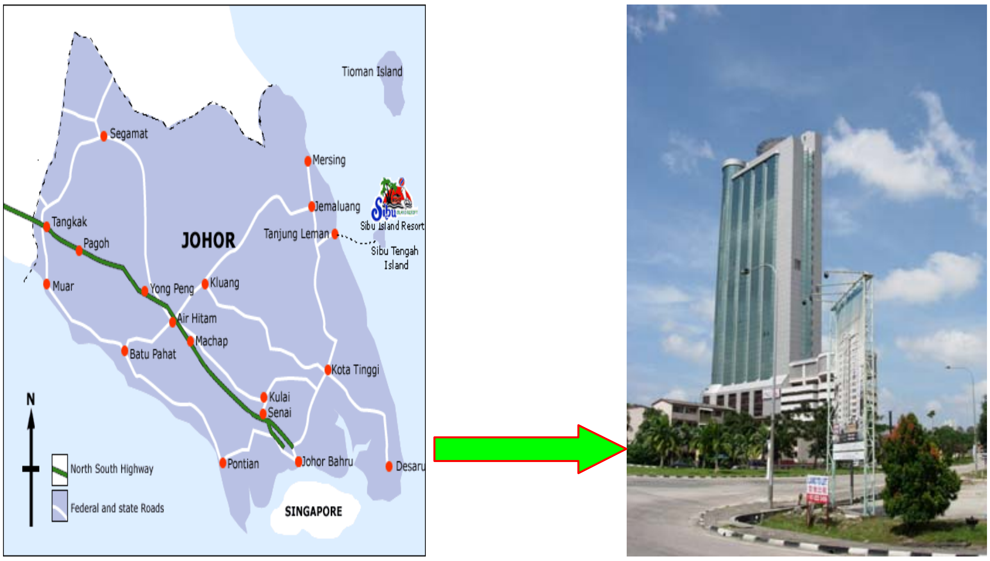


Figure 2 : Sarawak Business Tower, Johore, Malaysia

3. GPS MEASUREMENT MODEL

The RTK algorithm includes the following steps : extrapolation of the reference station observables; a recurrent procedure of averaging float ambiguities; cycle slip detection and correction; ambiguity resolution; and finally, calculation of the baseline. To achieve the best results, it is desirable to do all five tasks at the same update rate, and for kinematics this rate must be high enough. This section will highlights some important algorithms in kinematics application.- details can be found in [3], [4] and [5].

In the RTK operations, the object geometry (coordinates of moving stations) is determined by real time relative measurements of the 'vector observation' with respect to a reference system. We can express the carrier ambiguities in terms of double difference ambiguities, since these can be solved to their integer values (not with the single difference ambiguities). Assuming two receivers are tracking satellites s and r, and assuming satellite r is the reference satellite, we may write for a single differenced carrier observation at time t_k as :

$$\phi^s(t) = \rho^s(t_k) + \delta_\phi(t_k) + \Delta T^s(t_k) + \lambda N^{rs} + n_\phi^s(t_k) \qquad (1)$$

where $\rho^s(t_k)$ is the unknown satellite-receiver single differenced range, N^{rs} is the double difference carrier ambiguity., ΔT^s the tropospheric effect, λ is the carrier wavelength, n_ϕ^s is the single differenced measurement noise of carrier. For kinematics applications we introduce a new baseline for each observation epoch. For a single satellite the linearised first order expression for the single-differenced $\rho(tk)$ is given by :

$$\Delta\rho(t_k) = \rho(t_k) - (\rho(t_k))_o = [\frac{\partial\rho(t_k)}{\partial x} \frac{\partial\rho(t_k)}{\partial y} \frac{\partial\rho(t_k)}{\partial z}]_0 \begin{bmatrix} \Delta x(t_k) \\ \Delta y(t_k) \\ \Delta z(t_k) \end{bmatrix}$$

$$= u(t_k)^T \Delta b\ (t_k) \qquad (2)$$

By $\Delta b\ (t_k)$ we denote the corrections to the initial baseline vector $b\ (t_k)_0$ at epoch t_k and $u\ (t_k)$ is a 3-vector containing the partial derivatives of ρ with respect to the unknown coordinates and the subscript $_0$ indicates the single differenced range was computed at some initial value. Defining the computed single differences $r^s{}_i\,(t_k)_0$ and $\phi_i^s\,(t_k)$ as:

$$(\phi_i^s)(\ t_k))_0 = (ws(t_k) + \delta_{\phi i}(t_k) + \lambda_i N_i^{rs})_0 \qquad (3)$$

and substituting (3) into (1) yields

$$(\phi_i^s)(\ t_k)) - (\phi_i^s)(\ t_k))_0 = u^s(t_k))\Delta b(t_k)) + \Delta\delta_{\phi i}(t_k)) + \lambda i \Delta N_i^{rs} + n\phi_i^s\ (t_k)) \qquad (4)$$

Now, without further derivation, we can write the measurement model for a fixed solution as:

$$\begin{bmatrix} \phi_i - & \phi_{1,0} - \lambda_1 EN_1 \\ \phi_2 - & \phi_{1,0} - \lambda_1 EN_2 \end{bmatrix}_k = \begin{bmatrix} U \\ U \end{bmatrix} \Delta b_k + \begin{bmatrix} e_m & \\ & e_m \end{bmatrix} \begin{bmatrix} \Delta\delta_{\phi 1} \\ \Delta\delta_{\phi 2} \end{bmatrix}_k + \begin{bmatrix} n_{\phi 1} \\ n_{\phi 2} \end{bmatrix}_k \qquad (5)$$

where e_m in an *m*-vector having all ones as its components, E an *m* by *m-1* matrix, defined as $E = [I_{m-1}\ \ 0^T]^T$, U is defined as $U = [u^1 \ldots u^m]T$. Note that m is the tracking satellites.

4. THE EXPERIMENT

The 3 days RTK-GPS monitoring campaign has been carried out for Sarawak Business Tower on 21 December 2004 until 23 December 2004. The ultimate goals are (i) to determine and to classify the stability conditions of high rise building, and (ii) to demonstrate that GPS is well suitable to monitor selected points at the building. One GPS control station (situated on the solid ground and it is known as B1) for RTK measurements has been established from two GPS reference points, namely J416 and JHJY – see Figure 3. One monitoring point (R1) have been identified and surveyed. The monitoring point was placed (marked) at the top on the building. The location of this monitoring point is illustrated in Figure: 4. In our experiments, we had used two dual frequency GPS receivers Leica System 500 with RTK facilities.

Figure 3 The control point, B1.

Figure 4: The monitoring station, R1

5. RESULTS AND ANALYSIS

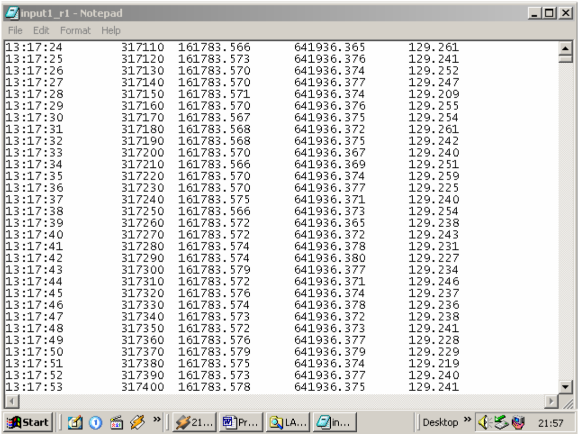
Some results of the Sarawak Business Tower experiment will be highlighted in this section. Table 1 shows the result adjustment of the data observation GPS for coordinate transfer from geodetic reference stations to control station. The geodetic reference stations are J416 (GPS station DSMM) and JHJY (Virtual Reference System station).

Table 1: Coordinates of the Geodetic Reference and Control Stations.

Point Name	Latitude	N error	Longitude	E error	Height	h error
B1	1°27'45.14692"N	0.004m	103°46'26.01444"E	0.007m	11.261m	0.011m
J416	1°27'42.54339"N	0.000m	103°46'24.05429"E	0.000m	11.297m	0.000m
JHJY	1°32'12.55948"N	0.000m	103°47'47.47728"E	0.000m	38.560m	0.000m

Figure 5 shows the data observation of continuous RTK for Base 1 (B1) and Rover 1 (R1) using Leica System 500 with 1 second sampling rate with AT502 (Normal) Antenna. Figures

6a, b, and c illustrates the time series results for monitoring point R1 in North, East (Coordinate RSO), and ellipsoid height, h components for this point, respectively.



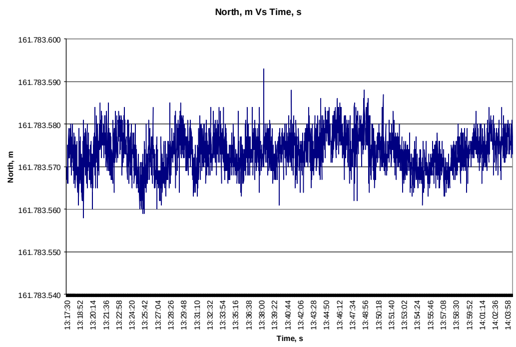
input1_r1 - Notepad

File Edit Format Help

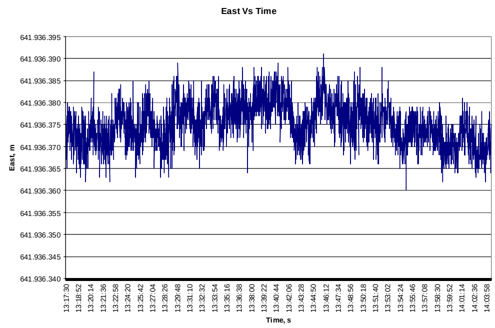
13:17:24	317110	161783.566	641936.365	129.261
13:17:25	317120	161783.573	641936.376	129.241
13:17:26	317130	161783.570	641936.374	129.252
13:17:27	317140	161783.570	641936.377	129.247
13:17:28	317150	161783.571	641936.374	129.209
13:17:29	317160	161783.570	641936.376	129.255
13:17:30	317170	161783.567	641936.375	129.254
13:17:31	317180	161783.568	641936.372	129.261
13:17:32	317190	161783.568	641936.375	129.242
13:17:33	317200	161783.570	641936.367	129.240
13:17:34	317210	161783.566	641936.369	129.251
13:17:35	317220	161783.570	641936.374	129.259
13:17:36	317230	161783.570	641936.377	129.225
13:17:37	317240	161783.575	641936.371	129.240
13:17:38	317250	161783.566	641936.373	129.254
13:17:39	317260	161783.572	641936.365	129.238
13:17:40	317270	161783.572	641936.372	129.243
13:17:41	317280	161783.574	641936.378	129.231
13:17:42	317290	161783.574	641936.380	129.227
13:17:43	317300	161783.579	641936.377	129.234
13:17:44	317310	161783.572	641936.371	129.246
13:17:45	317320	161783.576	641936.374	129.237
13:17:46	317330	161783.574	641936.378	129.236
13:17:47	317340	161783.573	641936.372	129.238
13:17:48	317350	161783.572	641936.373	129.241
13:17:49	317360	161783.576	641936.377	129.228
13:17:50	317370	161783.579	641936.379	129.229
13:17:51	317380	161783.575	641936.374	129.219
13:17:52	317390	161783.573	641936.377	129.240
13:17:53	317400	161783.578	641936.375	129.241

Start 21... Pr... LA... in... Desktop 21:57

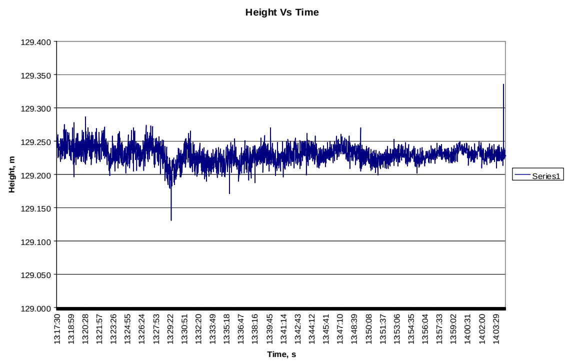
Figure 5 : Continuous RTK-GPS Observations



(a)



(
b)



(c)

Figure 6: The Dynamic variation for monitoring point R1.

The attainable precision of position for the monitoring point R1 is as shows in Figure 6, about 1.5cm. However, for certain epochs during the observation, this value will reach to almost 3cm. This may due to the loss of lock. This situation is similar to the attainable precision of vertical for the monitoring point. It reaches about 4 cm normally during the observation but it reached more than 5 cm at certain time that probably due to loss of lock. A program had been developed using Matlab version 6.1 for building structural monitoring analysis. Each filtering step in the program takes five observations into account to discard the irrelevant data (loss of lock). The structural monitoring analysis is performed in three dimensions: north, east, and height. The results are plotted in the figure 7.

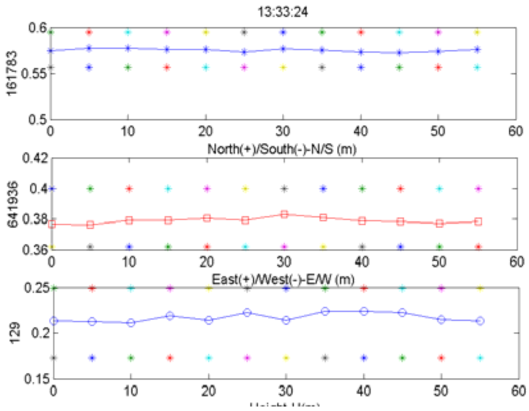


Figure 7: Structural Monitoring Analysis in Three Dimensions

Meanwhile, the program also generated an output file which contained single point test of three analysis components, which is north, east, and height. If all statistical test of all three components are smaller than t-table, then it can be considered as no deformation. If any of the three components has values larger than t-table, there are some displacements about the point (refer to figure 8).

```
------------Global Test ( 13:33:23 ) -------------
 0.00 (Tcalculate) < 1.000 (Table-F)
 Global Test Passess!

--------------Single Point Test-------------------
Difference   t-calculate   t-table   Result
  -0.002       0.20         1.96     Stable
   0.000       0.04         1.96     Stable
  -0.001       0.07         1.96     Stable
------------Global Test ( 13:33:28 ) -------------
 0.00 (Tcalculate) < 1.000 (Table-F)
 Global Test Passess!

--------------Single Point Test-------------------
Difference   t-calculate   t-table   Result
   0.002       0.18         1.96     Stable
   0.004       0.42         1.96     Stable
  -0.003       0.14         1.96     Stable
------------Global Test ( 13:33:33 ) -------------
 0.00 (Tcalculate) < 1.000 (Table-F)
 Global Test Passess!

--------------Single Point Test-------------------
Difference   t-calculate   t-table   Result
  -0.001       0.08         1.96     Stable
   0.005       0.48         1.96     Stable
  -0.002       0.10         1.96     Stable
```

```
------------Global Test ( 13:33:38 ) -------------
  0.00 (Tcalculate) < 1.000 (Table-F)
  Global Test Passess!

--------------Single Point Test-------------------
Difference    t-calculate    t-table    Result
   -0.001        0.08         1.96      Stable
    0.002        0.18         1.96      Stable
   -0.001        0.03         1.96      Stable
------------Global Test ( 13:33:43 ) -------------
  0.00 (Tcalculate) < 1.000 (Table-F)
  Global Test Passess!

--------------Single Point Test-------------------
Difference    t-calculate    t-table    Result
    0.000        0.02         1.96      Stable
    0.002        0.16         1.96      Stable
   -0.008        0.40         1.96      Stable
------------Global Test ( 13:33:48 ) -------------
  0.00 (Tcalculate) < 1.000 (Table-F)
  Global Test Passess!

--------------Single Point Test-------------------
Difference    t-calculate    t-table    Result
    0.001        0.06         1.96      Stable
    0.000        0.04         1.96      Stable
   -0.003        0.15         1.96      Stable
------------Global Test ( 13:33:53 ) -------------
  0.00 (Tcalculate) < 1.000 (Table-F)
  Global Test Passess!

--------------Single Point Test-------------------
Difference    t-calculate    t-table    Result
    0.003        0.32         1.96      Stable
    0.002        0.16         1.96      Stable
   -0.012        0.60         1.96      Stable
------------Global Test ( 13:33:58 ) -------------
  0.00 (Tcalculate) < 1.000 (Table-F)
  Global Test Passess!

--------------Single Point Test-------------------
Difference    t-calculate    t-table    Result
   -0.000        0.02         1.96      Stable
   -0.002        0.22         1.96      Stable
   -0.003        0.17         1.96      Stable
------------Global Test ( 13:34:03 ) -------------
  0.00 (Tcalculate) < 1.000 (Table-F)
  Global Test Passess!

--------------Single Point Test-------------------
Difference    t-calculate    t-table    Result
    0.001        0.12         1.96      Stable
   -0.000        0.00         1.96      Stable
   -0.013        0.66         1.96      Stable
```

------------Global Test (13:34:08) -------------
0.00 (Tcalculate) < 1.000 (Table-F)
Global Test Passess!

--------------Single Point Test-------------------

Difference	t-calculate	t-table	Result
0.003	0.32	1.96	Stable
0.002	0.24	1.96	Stable
-0.013	0.65	1.96	Stable

------------Global Test (13:34:13) -------------
0.00 (Tcalculate) < 1.000 (Table-F)
Global Test Passess!

--------------Single Point Test-------------------

Difference	t-calculate	t-table	Result
0.004	0.38	1.96	Stable
0.003	0.26	1.96	Stable
-0.012	0.59	1.96	Stable

------------Global Test (13:34:18) -------------
0.00 (Tcalculate) < 1.000 (Table-F)
Global Test Passess!

--------------Single Point Test-------------------

Difference	t-calculate	t-table	Result
0.003	0.26	1.96	Stable
0.004	0.38	1.96	Stable
-0.004	0.20	1.96	Stable

------------Global Test (13:34:23) -------------
0.00 (Tcalculate) < 1.000 (Table-F)
Global Test Passess!

--------------Single Point Test-------------------

Difference	t-calculate	t-table	Result
0.000	0.04	1.96	Stable
0.003	0.26	1.96	Stable
-0.003	0.13	1.96	Stable

Figure 8: Deformation Report

Our experimental data demonstrate the real time capability of continuous RTK-GPS monitoring to determine the behavior of the building. We suggest using GPS as the basis of a building monitoring system which yields long term deformation information related to structural fatigue and thus safety of the building. We realize that develop a program for structural monitoring analyze by using continuous RTK-GPS is absolutely necessary.

6. CONCLUSION

The timely identification of deformation associated with geologic hazards or ground settlement can save lives, avert large financial liabilities and avoid severe environmental damage. Periodic surveys do not provide a real-time warning capability and automated sensors, also unable to provide continuous data; do not yield conclusive information about displacement vectors. However, nowadays relative displacements can be measured at rates of 10Hz or higher. Based on some preliminary results of our first continuous RTK experiment, one is easily provided with dense and extensive time series of phase observations to all GPS satellites in view, on both the L1 and L2 frequency. Real time kinematics monitoring of Sarawak Businee Tower may lead to the early detection of changes of the building's response to earthquake and wind load. It is thus an important step towards increasing safety and lifespan of the building.

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CONTACTS

Wan Aziz W. A.
Department of Geomatic Engineering
University Technology Malaysia,81300
UTM Skuda,i Johore, Malaysia
Email: waziz@fksg.utm.my