Monitoring of High Rise Building using Real-Time Differential GPS

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Key words: Global Positioning System (GPS), Differential GPS (DGPS), Structural Monitoring, Real-Time Kinematic (RTK), GNSS, CORS, VRS

SUMMARY

High rise buildings and structures in Singapore are often affected by the earthquakes tremors from the Indonesia islands of Sumatra and Java. Currently, there is no real-time monitoring scheme to assist the authorities in decision making during and after tremors. In the damage assessment, the authority only carries out visual inspection after the tremors. The magnitude of the building/structure's deflection (harmonic movement) has not been able to be determined.

The Singapore Satellite Positioning Reference Network, SiReNT system was implemented by Singapore Land Authority (SLA) in September, 2006. This CORS system has been in operation for almost 3 years and has gained much recognition as the authoritative Differential GPS (DGPS) infrastructure in Singapore. SiReNT with nation-wide coverage is ideal and cost effective to provide reference for high precision positioning and monitoring. The user base has grow to more then one hundred for applications such as land surveying, mapping, GIS data acquisition and engineering positioning.

A Proof-of-Concept (POC) was proposed to showcase the capability of VRS-RTK (Virtual Reference Station - Real-Time Kinematic) service, supported by SiReNT, in detecting (monitoring) the deflection during tremors. The study was made on one of the 3 tallest buildings in Singapore, and the objective is to implement a reliable and robust Differential GPS (DGPS) Monitoring System that will give accurate, real-time structural stability information of the monitored building. The magnitude (displacement) of the building will be measured and the information will help the building owner (or building manager) to make fast and accurate decision in real-time.

The study is conducted in collaboration with the Nanyang Technological University (NTU) and GPS Lands Pte Ltd.

This paper will highlight the architecture, the design of the real-time system and the results.

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1. INTRODUCTION

Until recently, the monitoring of dynamic behaviour of large scale engineering structures and geotechnical features have relied on measurements made by conventional techniques such as the precise levelling, close range photogrammetry, automatic 3-D displacement monitoring systems etc. Sensors such as the robotic total station, accelerometers, strain gauge, tilt metres etc. are utilised. The technique and equipment chosen in a monitoring scheme depends on the period of monitoring, range from control points to the object, precision and parameters observed. The displacement values derived by such instruments generally require double integration of data recorded. Monitoring the response of structural systems for the purpose of assessing and mitigating effects of earthquakes has widely relied on accelerometers installed in several places on the structure of interest (Celebi, 1998).

GPS technology with high sampling rates (1 Hz or higher) is now economically feasible to provide direct relative displacement measurement. Since 1980s, deformation monitoring with Differential Global Positioning System (DGPS) has been deployed successfully in many parts of the world. In all the cases, the differential carrier-phase GPS measurement is adopted. The differential carrier-phase GPS measurement technique is known as Real-time Kinematic (RTK) when deployed in real time. The advancements in GPS technology and wireless communication link, as well as real-time DGPS data processing algorithm have made GPS technology a cost-effective and feasible tool for deformation monitoring. The phase measurement of GPS has a standard deviation of a few millimetres and other receiver related noise is even smaller.

High rise buildings and structures in Singapore are often affected by the earthquakes tremors from the Indonesia islands of Sumatra and Java. Currently, there is no real-time monitoring scheme to assist the authorities in decision making during and after tremors. In the damage assessment, the authority and building management only carry out visual inspection after the tremors. The magnitude of the building/structure’s deflection (harmonic movement) has not been able to be determined. There is a great need for better and more extensive monitoring of tall buildings.

This paper describes the proof-of-concept and presents the initial results of using Virtual Reference Station RTK (VRS-RTK) approach within the SiReNT network for the real-time application of deformation monitoring. The objective of this POC is to access the reliability and precision of VRS-RTK technique for long term observation.

1.1 Deformation Monitoring with GPS

Deformation of large engineering structures and geotechnical features such as long span bridges, high rise buildings, dams, slopes, volcanoes etc. are often measured in order to ensure that these structures or features are exhibiting safe deformation behaviour. In many monitoring applications, the DGPS technique offers significant advantages over other measurement techniques. GPS allows a high rate of measurement, over long distances between the control and monitoring points and does not require line of sight to the control points.

The advantages of GPS sensors compared to conventional deformation monitoring sensors are:

1. GPS requires no line-of-sight between the stations;
2. automated operation with high observation rate;
3. real-time data updates; and
4. operates under all weather condition.

However, the attainable accuracy of a GPS based system is limited by the satellite geometry and by systematic errors such as multipath, weak satellite geometry, etc. The concept of Network-DGPS was introduced to overcome the constraint of the short baseline limitation of conventional RTK technique. The Network-DGPS also will expand coverage area of GPS reference station infrastructure. The Network-DGPS technique based on the VRS-RTK will be deployed in this project.

1.2 Permanent GPS reference station network

Permanent GPS reference station infrastructures are being increasingly established by many countries all over the world. These permanent reference stations are developed in a network environment and operate continuously. They are mainly used to support two categories of applications - the geodetic and the differential GPS (DGPS) applications.

The Singapore Land Authority (SLA) implemented the permanent GPS reference station network infrastructure in September 2006. The infrastructure known as the Singapore Satellite Positioning Reference Network (or SiReNT in short), is a nation-wide DGPS infrastructure developed to support various DGPS positioning businesses and industries. The primary objective of SiReNT is to support the coordinated cadastral survey system in Singapore. Broadly, SiReNT system also ensures a homogeneous geographical reference frame for other land surveying, mapping and positioning activities in Singapore.

SiReNT offers 3 standard services to meet various positioning needs and accuracy requirements:

- Post-processing (PP) service;
- Real-time Kinematic (RTK) service (include both conventional single-base and VRS service);
- Code Differential GPS (DGPS) service.

Beside surveying and mapping applications, SiReNT is developed as an infrastructure with the fundamental design for the integration with applications that make use of DGPS technology. Applications such as vehicle tracking, navigation, deformation monitoring etc. can be developed to leverage on the SiReNT infrastructure.

Currently the reference network consists of 6 GPS reference stations connected to a Data Control Centre (DCC) adopts the leading-edge technology of Network-DGPS both for Real-Time Kinematic (RTK) and code-based DGPS techniques. It supports the Network-RTK technique known as the Virtual Reference Station (VRS). It uses the network software, GPSNet from Trimble Terrasat GmbH at the DCC for DGPS corrections generation. The GPSNet software performs continuous computation of the following parameters by analyzing double difference carrier observations:

- Ionospheric errors
- Tropospheric errors
- Ephemeris errors
- Carrier phase ambiguities for L1 and L2.

In VRS mode, using these parameters, GPSNet software will provide all GPS data and interpolate to match the position of the rover, which may be at any location within the reference station network. Matching the rover's position provides a very short baseline, which reduces systematic errors for RTK considerably. The VRS-RTK technique will be adopted in this project. See (Vollath, 2000) for more information about VRS. Figure 1 show the SiReNT network which consists of 6 permanent GPS reference stations.

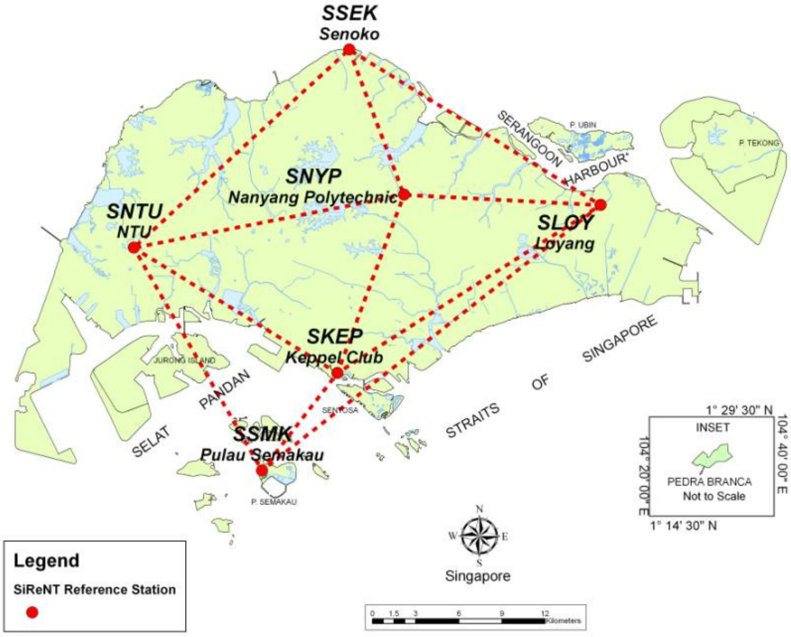


Figure 1: Singapore Satellite Positioning Reference Network, SiReNT

2. MONITORING SYSTEM IMPLEMENTATION

2.1 Monitoring Setup at Republic Plaza

Republic Plaza is located in the Central Business District (CBD) of Singapore, at approximately 1°17’00"N and 103° 51 '03"E. This building is 280 meters tall (66 storeys and 1 basement) and is one of the tallest building in Singapore. It has central core wall frame structural system and is sitting on the Kallang formation.

It is its height that it was selected for the monitoring project in addition to the fact that there were already building monitoring works being carried out on this building using accelerometers since the mid-90s. The management of Republic Plaza is also very forthcoming and welcomed the prospect of using their building as the focal point in the project.

A real-time monitoring scheme based on GPS RTK (Real-Time Kinematics) was installed on the roof-top of Republic Plaza with dedicated internet connection to a monitoring control centre located off-site. The setup on Republic Plaza consisted of 3 high-precision RTK receivers; 2 Trimble R7 (R701 and R702) and 1 Trimble 5700 (5700). The locations of the receivers are shown in Figure 2 and 3.

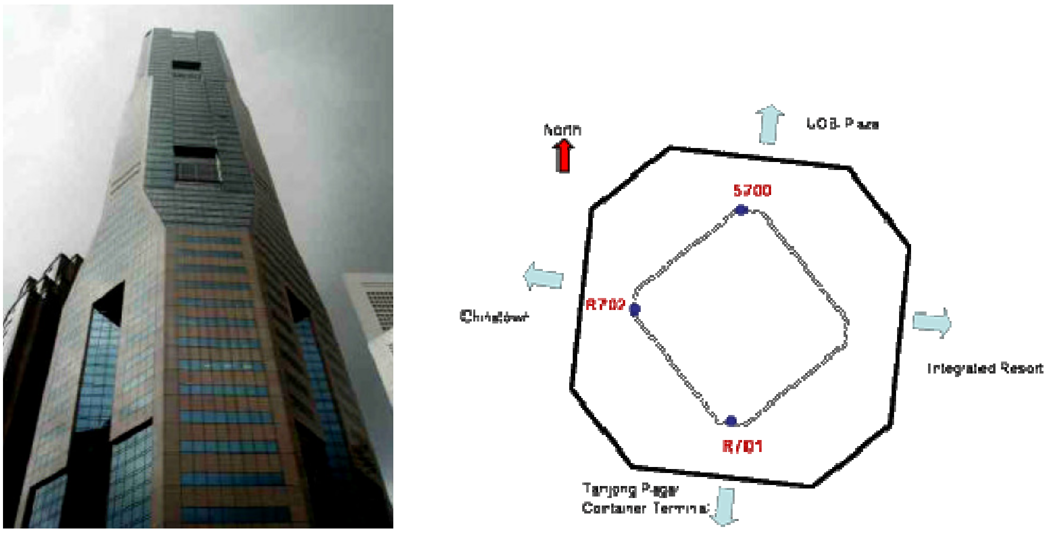


Figure 2: Republic Plaza (left) and the location of the 3 GPS antenna on the roof-top (right)

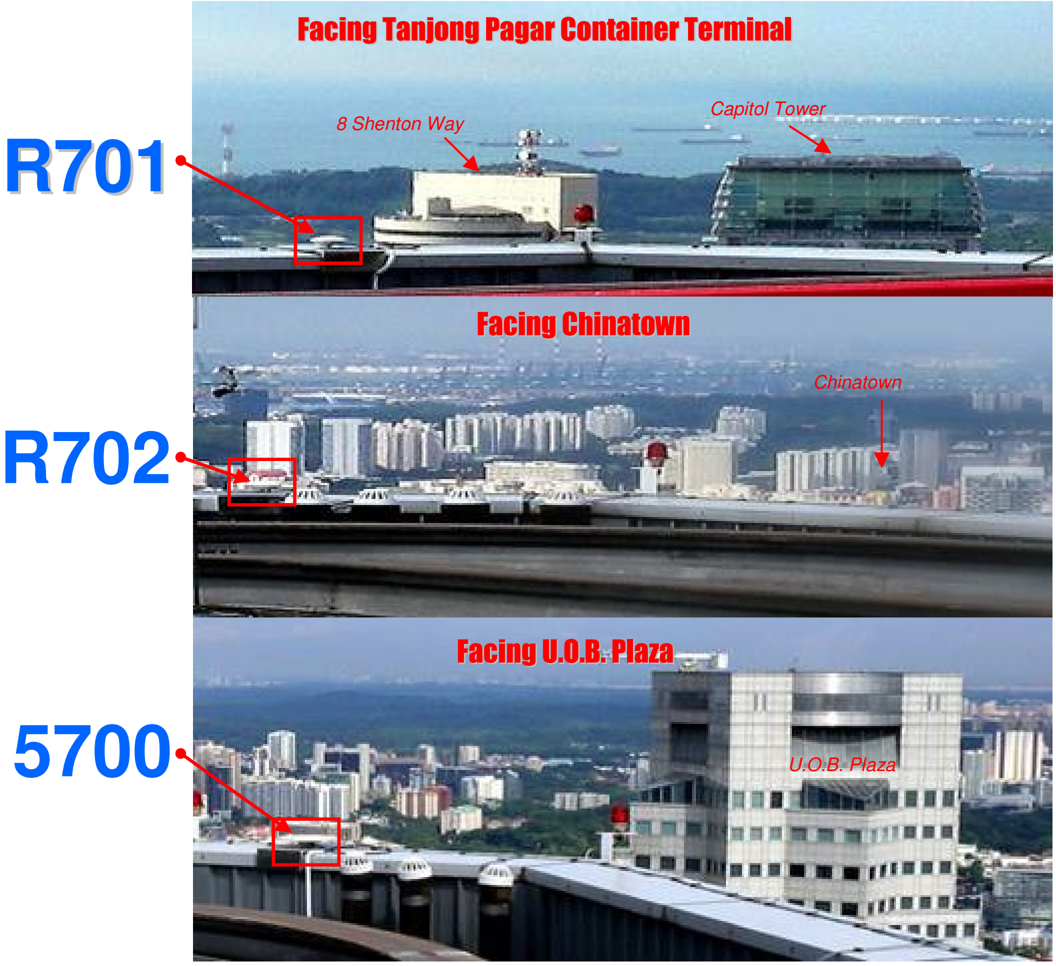


Figure 3: Installation of the 3 GPS antennas on the roof-top of Republic Plaza

The receivers, terminal servers and a router are installed in a custom-made weatherproof cabinet located on the 65th floor of the building. See Figure 4. The location of the cabinet is situated near to the existing internet communication point. Figure 5 is the schematic diagram of the monitoring system. The three antennas have known positions and are constantly receiving satellite signals at 10Hz and 1 Hz (Trimble 5700 is receiving at 1 Hz). Each antenna relays its received satellite signals the receiver that is connected to it. The receiver process the satellite signals and perform position computation with the SiReNT VRS-RTK corrections in real-time on site. The system is also sending raw GPS data back to monitoring control centre which has capability of processing the data real-time.

Figure 4: Installation of the GPS receivers and communication devices on the 65th floor

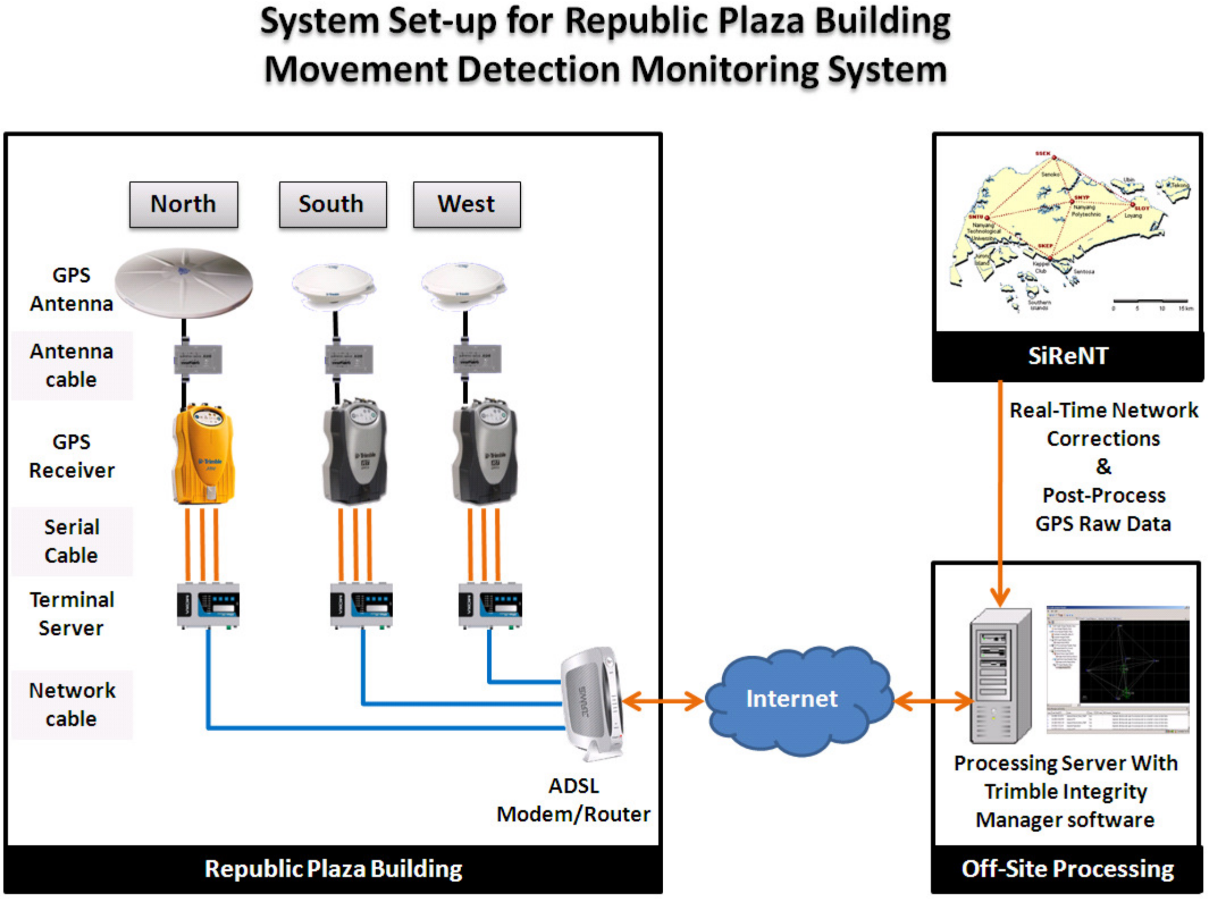


Figure 5: Schematic diagram of the monitoring system

2.2 Real-time Monitoring Software

The Trimble Integrity Monitoring (TIM) is used for managing and monitoring of the data sent back from the GPS receivers on top of Republic Plaza. The TIM monitoring system is a 24/7 continuously operating system which aids in the monitoring and assessment of the structural health of a building. It has 4 main engines to monitor movement:

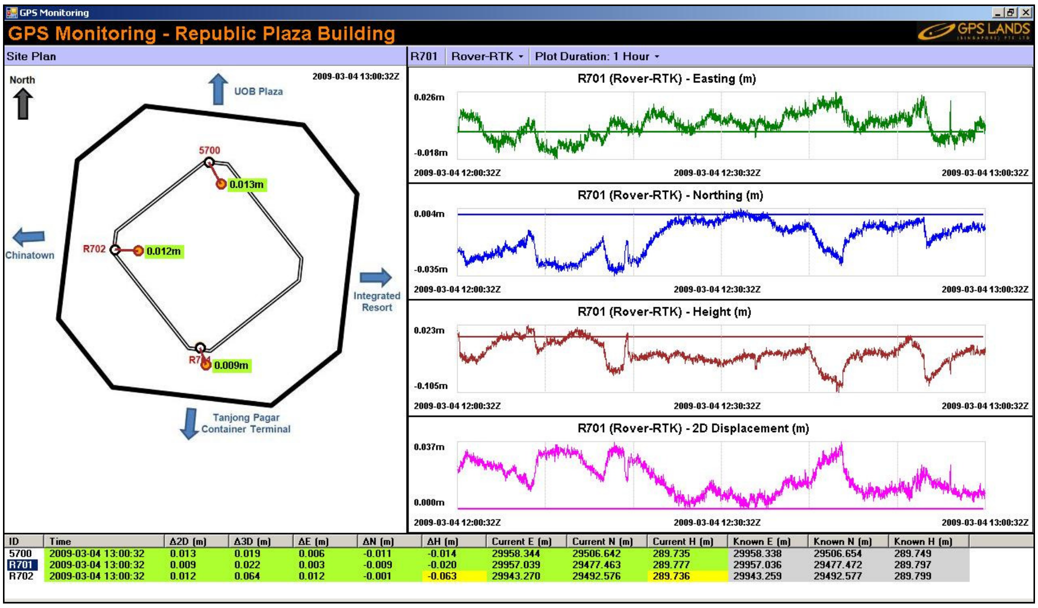
- RTK engine;
- Network Motion engine;
- Rapid Motion engine; and
- NMEA engine.

The Rapid Motion engine in particular can monitor sudden big movement in a network that is usually caused by an earthquake or other seismic activity. The system can also be configured such that alarms are delivered to relevant personnel when the building movement exceeds certain pre-defined tolerance.

The NMEA engine collect the NMEA output from receivers directly, synchronises the data and possibly applies a filter upon it. The NMEA output is from receivers directly and is VRS-RTK solution computed by the receiver itself.

The dedicated graphical user interface shown in Figure 6 was developed to present the data from TIM in a user friendly manner. The interface is able to combine the various outputs and to visualise them in:

- several time series plots;
- graphical vector plots which shows the magnitude and direction of displacement; and
- displacement value



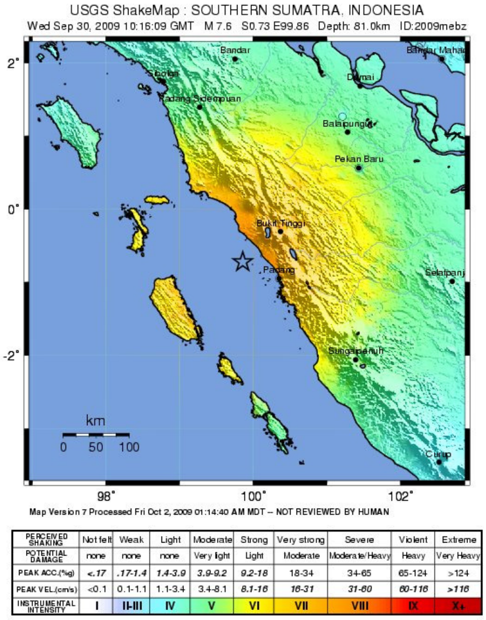
ID	Time	Δ2D (m)	Δ3D (m)	ΔE (m)	ΔN (m)	ΔH (m)	Current E (m)	Current N (m)	Current H (m)	Known E (m)	Known N (m)	Known H (m)
5700	2009-03-04 13:00:32	0.013	0.019	0.006	-0.011	-0.014	29958.344	29506.642	289.735	29958.338	29506.654	289.749
R701	2009-03-04 13:00:32	0.009	0.022	0.003	-0.009	-0.020	29957.039	29477.463	289.777	29957.036	29477.472	289.797
R702	2009-03-04 13:00:32	0.012	0.064	0.012	-0.001	-0.063	29943.270	29492.576	289.736	29943.259	29492.577	289.799

Figure 6: Real-time graphical user interface

3. RESULTS

3.1 Effects of Sumatran Earthquake As Recorded By Monitoring System

A 7.6-magnitude earthquake occurred off the southern coast of Sumatra at 10:16:09 (UTC Time) on 30th September 2009. The epicentre of the earthquake is about 497km from Singapore. Tremors were felt by occupants of high-rise buildings in Singapore and Malaysia. Figure 7 shows the intensity map of the earthquake taken from the USGS website.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 7: Intensity Map of Sumatran Earthquake on 30th Sept 2009 (taken from USGS Website, http://earthquake.usgs.gov/earthquakes/eqinthenews/2009/us2009mebz/)

Figure 8 below shows the displacement plot of point R701 during the time of the 30th September, 2009 earthquake in Sumatra. The 1-hour plot has a window that starts from 10am and ends on 11am UTC. The displacement is provided by the TIM NMEA engine against the known coordinates of point R701. In this time series plot, the effects of seismic wave are not visible. Figure 9 shows the 12-minutes displacement plot of the same point R701. This plot has a window that starts from 10:15am. It is significant to note that the magnitude of the displacement caused by the earthquake’s shockwave (about 1mm peak-to-peak, Figure 9) is much smaller compared to the hourly and daily displacements (20~30mm daily, Figure 8). This proves the sensitivity of the system in capturing both the magnitude and period of motion caused by earthquake in neighbouring region.

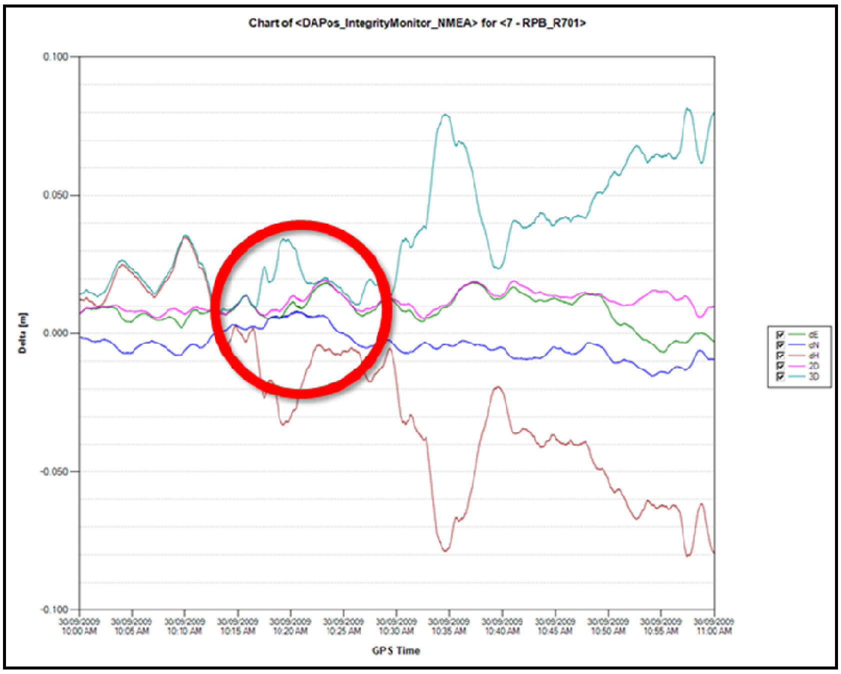


Figure 8: 1-hour displacement plot for station R701 provided by TIM NMEA engine

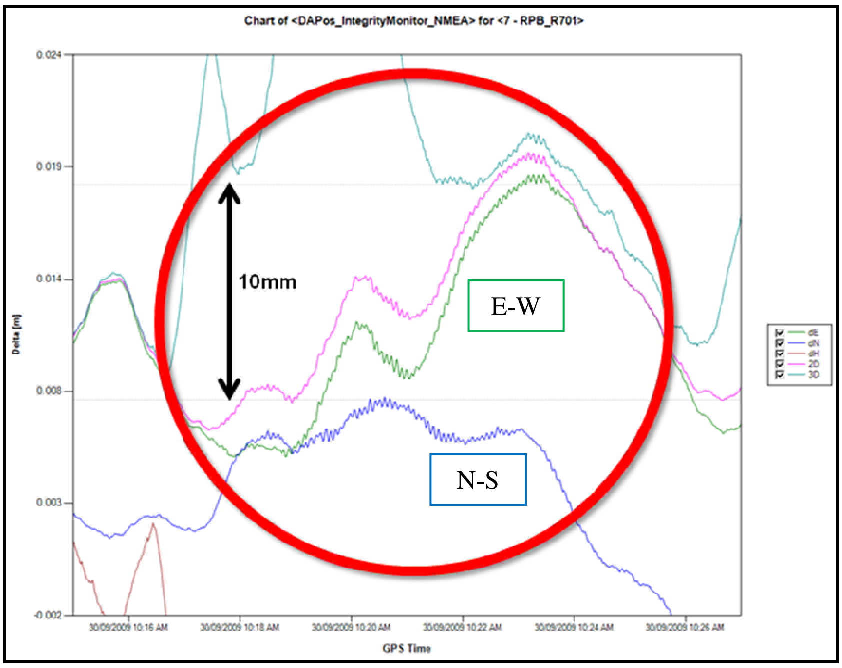


Figure 9: 12-minute displacement plot for station R701 showing high-frequency periodic motion caused by earthquake's shockwave as captured by the monitoring system (provided by TIM NMEA engine)

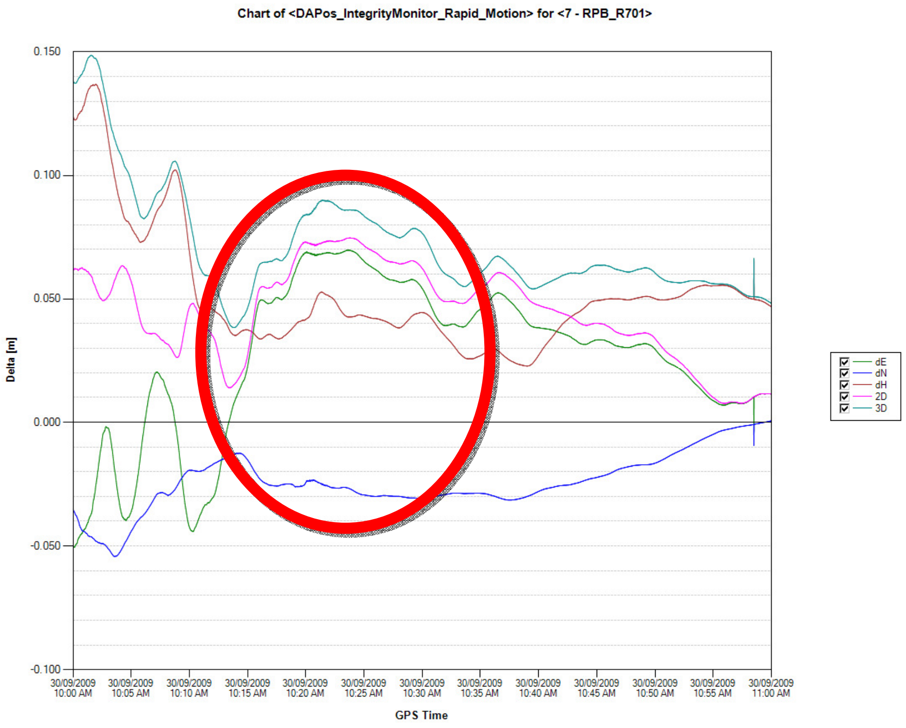


Figure 10: 1-hour displacement plot for station R701 provided by TIM Rapid Motion engine

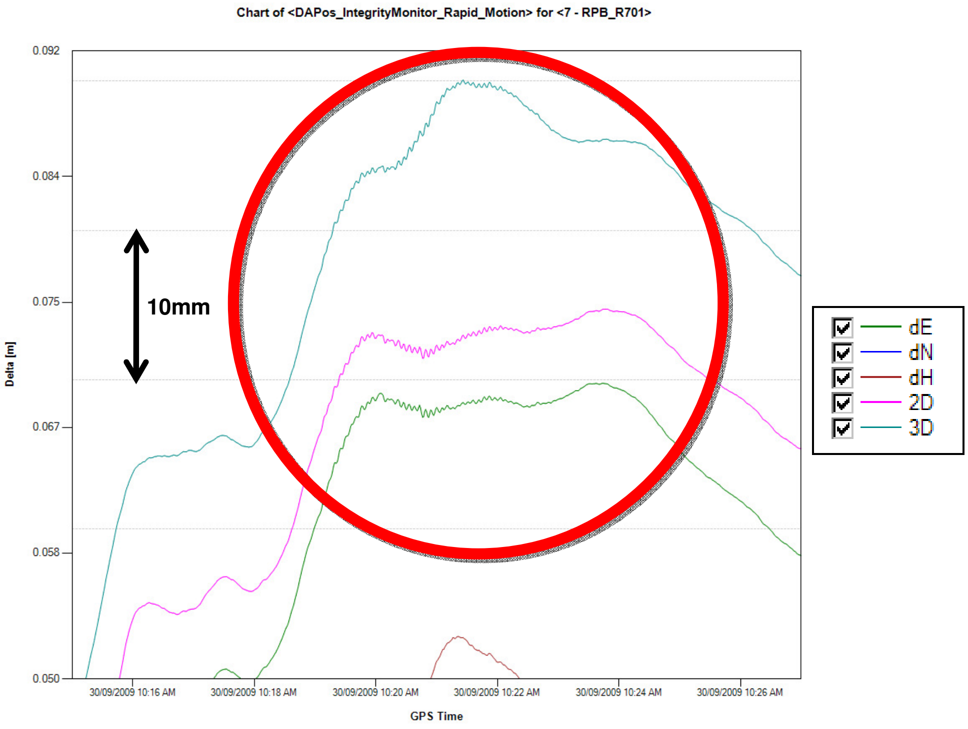


Figure 11: 12-minute displacement plot for station R701 showing high-frequency periodic motion caused by earthquake's shockwave (provided by TIM Rapid Motion engine)

Similarly, the output from TIM Rapid Motion engine was plotted for the same event. Figure 10 shows the 1-hour displacement plot of point R701. In this time series plot, the effects of seismic wave are also not visible. However, in Figure 11, the displacement caused by the earthquake's shockwave (about 1mm peak-to-peak) is noticeable. The Rapid Motion Engine module accurately tracks the positions of the antennas within a network that is established for the purpose of monitoring slow deformations but with occasional rapid motion due to events such as earthquakes or landslides. In this case, the SiReNT network is providing the reference data needed by the Rapid Motion Engine.

Both methods i.e. the TIM NMEA and the TIM Rapid Motion engines are able to detect the shockwave motion of the building caused by the earthquake on 30th September. Although the peak-to-peak magnitude of the motion is small, its periodic nature was captured by the monitoring system. The system can thus be used as a supplement to structural engineers in their building assessment.

4. CONCLUSIONS

A real-time building monitoring prototype system has been implemented under this project. The monitoring control centre is located off-site away from the building under monitoring. A dedicated interface for monitoring was developed to enable the access to the system from anywhere via internet. Setting up of the building monitoring system allows for both short-term and long-time behaviour of the building's motion to be recorded and analysed.

The results show that VRS-RTK technique provided by SiReNT and TIM software is capable for real-time detection of tremors from distance earthquake events. This technique can also be used to estimate displacement of a point and detecting long-term deformation due to ground movements. The data obtain from the VRS-RTK technique need to be integrated into monitoring analysis procedures and filtering techniques in providing a complete monitoring solution. The results shown here are generated purely based on the commercially available software without additional processing or filtering.

At this point of time, separate work is in progress to study and compare the GPS data with data from accelerometer which is co-located with the GPS antenna on the building. The main objective is to compute thresholds for drift ratio (roof displacement) and roof acceleration.

With SiReNT infrastructure, deformation monitoring applications using VRS-RTK can be implemented with relatively lower cost as the user does not need to establish and operate his own reference station.

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BIOGRAPHICAL NOTES

Victor Khoo is a Senior Manager with the Survey Services Department of Singapore Land Authority (SLA). He received his Ph.D. from the Nanyang Technological University (NTU), Singapore and his Bachelor degree in Land Surveying from the University Technology of Malaysia (UTM). Victor is a Registered Surveyor; a professional surveyor registered under the purview of Singapore's Land Surveyors Act. He works in diverse geospatial related subjects that encompass the collection, management and dissemination of geospatial data. His specific areas of interest include Differential GPS, Cadastral Surveying and Spatial Data Infrastructure.

Tor Yam Khoon is an Associate Professor in the School of Civil and Environmental Engineering, Nanyang Technological University, Singapore. Prior to becoming an academic in 1992, Dr Tor has 16 years of professional experience in the building industry. His current research activity lies mainly in precise engineering survey and 3D GIS.

Gerry Ong, founder and managing director of GPSLands (S) Pte Ltd, Gerry has spent the past 20 yrs within the Spatial Science industry. Gerry was instrumental in the set up of the only GPS positioning infrastructure in Singapore.

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