

Real-Time Monitoring with SiReNT

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Abstract

The geotechnical and structural monitoring scheme of today utilizes sensors such as accelerometers, strain gauge, tilt metres and automatic 3-D displacement monitoring system. Each of these sensors has their limitation, whether in the relative measurement or from our extreme environmental influence which causes lower accuracy or delayed information. With the exception of the 3-D displacement (monitoring being able to provide 3D displacement information) the critical limitation of is greatly subject to the environmental factors and the "delay in computed results" renders it ideal only for monitoring in a controlled environment. With respect to the above mentioned sensors, none is able to give an absolute measurement in real time.

However, with proper system design architecture, the GPS system is able to comply with such a requirement and even exceeding expectations in certain potential applications. Having a quick set-up time and absolute measurement of a structure of interests, in relation to globally unified coordinate system, is a huge advantage. While it is known that GPS cannot replace certain sensors, it provides an avenue as an alternative to combine several sensor functions. GPS monitoring can be deployed in many deformation monitoring work such as the structural health and damage detection.

The Singapore Land Authority (SLA) has launched a new GPS reference station network infrastructure in September 2006. The infrastructure known as the Singapore Satellite Positioning Reference Network (SiReNT), is a nation-wide infrastructure developed to support various Differential GPS (DGPS) positioning businesses and industries. These include applications such as tracking, navigation, structural monitoring etc. In the geodetic perspective, SiReNT ensures a homogeneous geographical reference system for land surveying and mapping activities in Singapore. The system consists of 5 reference stations connected to a Data Control Centre (DCC). It adopts the cutting-edge technology of Network-DGPS both for Real-Time Kinematic (RTK) and code-based DGPS techniques. The system supports the Network-DGPS technique known as the Virtual Reference Station (VRS).

Conventionally, the RTK technique has been deployed as it is the most precise technique in real time. However, the RTK technique is limited by the baseline length caused by the distance-dependent biases. A proof-of-concept was carried out to demonstrate the usage of the VRS-RTK technique provided by SiReNT for deformation monitoring applications. This paper describes the proof-of-concept test and shows the feasibility of the technique for deformation monitoring.

Introduction

For many years, 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 data provided by such instruments generally require integration process to obtain the relative displacements value.

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 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. GPS can measure at the rate of 1 Hz or higher.

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

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.

Several structural monitoring systems have been implemented for bridges and buildings since 1980s. For examples, a RTK-GPS system has been developed and installed on the Humen Bridge (China) for the on-line monitoring of bridge deck movement, which may occur as a result of seismic activity, traffic load, and such environmental elements as temperature and wind (Jiang *et. al*, 2002). In the Human Bridge monitoring project, the cost of GPS method is higher during the installation period, as the GPS receivers are more expensive compared to the total stations. However, the GPS method need less man-power and will not disrupt the usage of the bridge (no traffic disruption). The GPS method is also not affected by the extreme weather such as the heavy fog, rain, strong wind etc.

In Hong Kong, the Highways Department has set up GPS systems for real-time monitoring of 3 major bridges, the Tsing Ma Bridge, Kap Shui Mun Bridge and the Ting Kau Bridge. The monitoring system is used to detect displacement due to wind, temperature, seismic and traffic load (Wong *et. al*, 2001)

A structural monitoring project in Singapore has been described by Brownjohn *et al.*, 2004 and Ogaja *et al.*, 2001 in which an RTK-GPS system comprising a pair of GPS receivers installed on the roof top of the Republic Plaza building (at 280m). The aim of the project is to capture the building loading and dynamic response during strong winds and remote earthquakes to aid local design code development. The RTK-GPS system supplemented the project of monitoring that commenced in 1995 with the installation of two pairs of accelerometers and two UVW anemometers.

Wan Aziz and Khamarrul, have demonstrated the usage of rapid-static and RTK technique for landside monitoring at several sites along east-west highway in Malaysia. (Wan Aziz and Khamarrul, 2003). Several other investigators have reported on the usage of RTK for dams and volcanoes monitoring (i.e. Janssen, 2002).

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;
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.

Virtual Reference Station (VRS) System

The limitation of single base RTK technique is the distance between base receiver at reference station and the rover receiver due to distance-dependent biases, i.e. the orbit bias, ionosphere bias and troposphere bias. Several techniques have been developed to overcome this distance dependence using a network of GPS reference stations that spread over a wide geographic area.

Over the last 5 years, the Network-DGPS technique has been introduced and extensively developed for high accuracy positioning in many countries. Network-DGPS is an improvement over the conventional DGPS method based on single reference station. The principle of Network-DGPS is that a significant portion of ionospheric, tropospheric and ephemeris errors are estimated over a region and this information is provided to rovers GPS receivers in the field.

In real-time carrier phase measurement, the network technique is known as the Network-RTK. This technique has become very popular due to the short observation time needed and high accuracy obtained.

One of the Network-RTK methods is known as the Virtual Reference Station (VRS) technique. The VRS concept was introduced as part of the German reference station network SAPOS in 2000. The name of this approach results from the fact that observations for a "virtual" non-existing station are created from the real observation of a multiple reference station network. This allows eliminating or reducing systematic errors in reference station data resulting in an increase of distance separation to the reference station for RTK positioning while increasing the reliability of the system and reducing the initialization time. The VRS-RTK concept is illustrated in Figure 1. A further advantage of the VRS concept is that in the rover receiver standard RTK processing algorithms are employed and no modification of the receiver hardware or software is required.

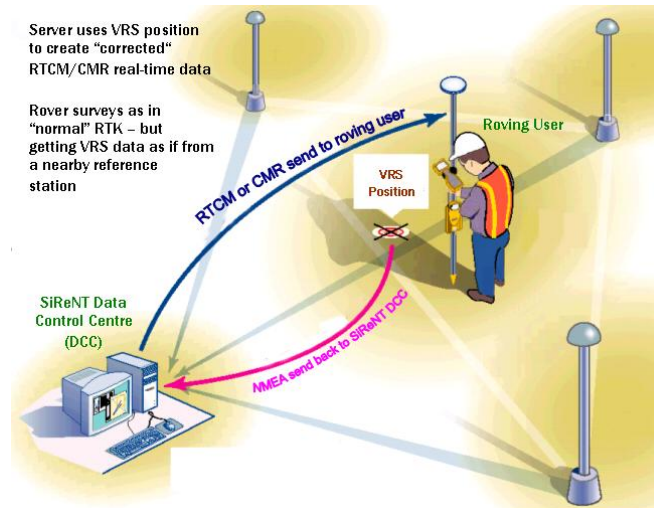


Figure 1: VRS-RTK concept (graphic source from Trimble)

Permanent GPS Reference Station Network

Permanent GPS reference station infrastructures are being increasingly established 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) has launched a new 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 new 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.

The SiReNT system, consists of 5 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. Figure 2 shows the location of the 5 GPS reference station within SiReNT.

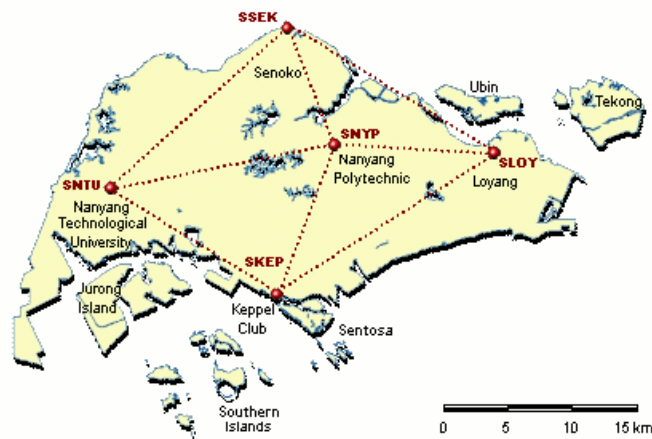


Figure 2: Singapore Satellite Positioning Reference Network, SiReNT

SiReNT users make use of the SiReNT website to access the post-process GPS data via iGate. RINEX version 2.1 and Compact RINEX can be generated from the website under the PP On-demand product. User is able to generate up to 12 months of data from SiReNT website. Data older than 12 months will be archived. To access the old data, users need to put up a request.

For real-time applications of RTK and DGPS services, users will be connected to SiReNT server via wireless Internet. Currently, rover users can subscribe to GPRS data plan from mobile provider. SiReNT adopts the NTRIP for the real-time dissemination of DGPS corrections. NTRIP (Networked Transport of RTCM via Internet Protocol) is an application-level protocol used for streaming Global Navigation Satellite System (GNSS) data over the Internet. NTRIP is a generic, stateless protocol based on the Hypertext Transfer Protocol HTTP/1.1. The standard is meant to be an open none-proprietary protocol. NTRIP is designed for disseminating differential correction data (e.g. in the RTCM or CMR format) or other kinds of GNSS streaming data to stationary or mobile users over the Internet, allowing simultaneous PC, Laptop, PDA, or GPS receiver connections to a broadcasting host. NTRIP supports wireless Internet access through Mobile IP Networks such as GPRS. The use of NTRIP allows rover users to be controlled using registered usernames and passwords. The source file of NTRIP allow SiReNT user to choose the different DGPS services provided i.e. RTK, VRS-RTK, code-base DGPS.

Real-Time Monitoring with VRS-RTK using SiReNT

A proof-of-concept test using VRS-RTK technique was conducted to demonstrate its feasibility for deformation monitoring. The VRS-RTK was carried out using the Singapore GPS reference station infrastructure, SiReNT. VRS-RTK service is one of the several DGPS services supported by SiReNT via Internet.

The SiReNT system was put into operation since 2006 to support various DGPS applications in Singapore. A test was carried out to ascertain the accuracy and the time-to-fix (TTF) of VRS-RTK technique using SiReNT. VRS-RTK observations were carried out over 40 known points which were selected to be well spread for the test area (main island of Singapore). A total of 360 VRS-RTK observations were collected. The results are shown in Figure 3. Taken together, anywhere in Singapore, the 2-D positioning accuracy for VRS-RTK using SiReNT is 0.035m (98%). The statistics also show that 90% of the time, TTF is 60 seconds or less with VRS-RTK.

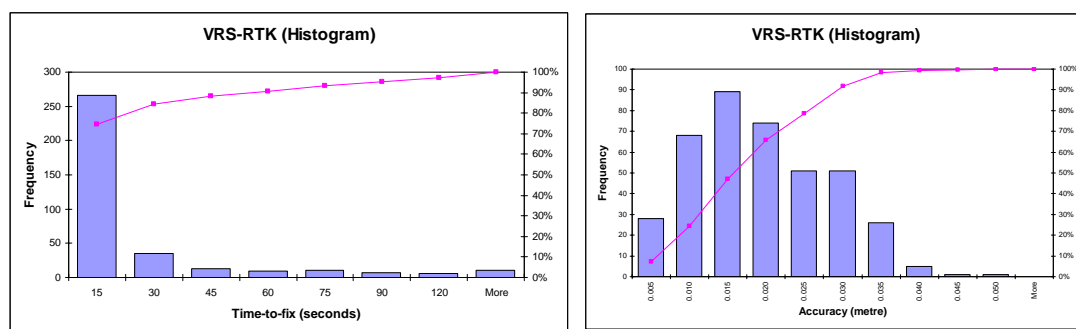


Figure 3: Time-to-fix (left) and 2-D positioning accuracy (right) achievable with SiReNT

The proof-of-concept test was carried out over 2 periods of time, from 14 Jan to 28 Feb and from 18 May to 30 June, 2007. Some results of the test were selected to be reported in this paper. The test point is located on the roof-top of a building situated approximately in the central location of Singapore. The point is not expected to have any movement as the building is a low rise. The GPS antenna was placed at the test point on the roof-top and the cable was connected from the roof-top to the office in the building where the receiver and a PC was located. The VRS corrections were obtained from the SiReNT Data Control Centre (DCC) via the Internet connection available in the office. A program was developed to enable connection to the VRS correction (SIRENT-RTKCMR stream) over NTRIP and forwards the RTCM corrections to the receiver via a serial connection. The receiver was configured to operate in the RTK On-The-Fly (OTF) ambiguity resolution mode and to stream out GPK NMEA strings at 1 Hz rate. The program will then log the NMEA strings to data text files. A new file is created daily. Figure 4 shows the schematic of the test setup.

Another program processes the NMEA text files and converts the geodetic coordinates (WGS84 Latitude and Longitude) to plane coordinates (SVY21). In addition to the plane coordinates, the height above ellipsoid (HAE), the PDOPs, the GPS quality indicators (e.g. Autonomous, RTK float, RTK fixed, DGPS solution etc.) and the number of satellites for each epoch is recorded. The graphs presented here were plotted off-line. In real-time application, the NMEA can be directed into any GPS monitoring analysis software. Overall, the graphs show data analysis and performance of VRS-RTK over 24-hour observation.

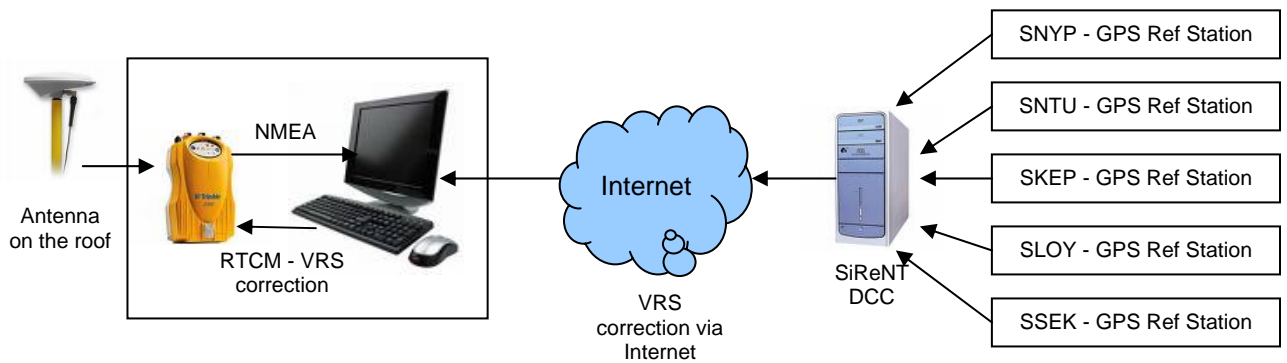


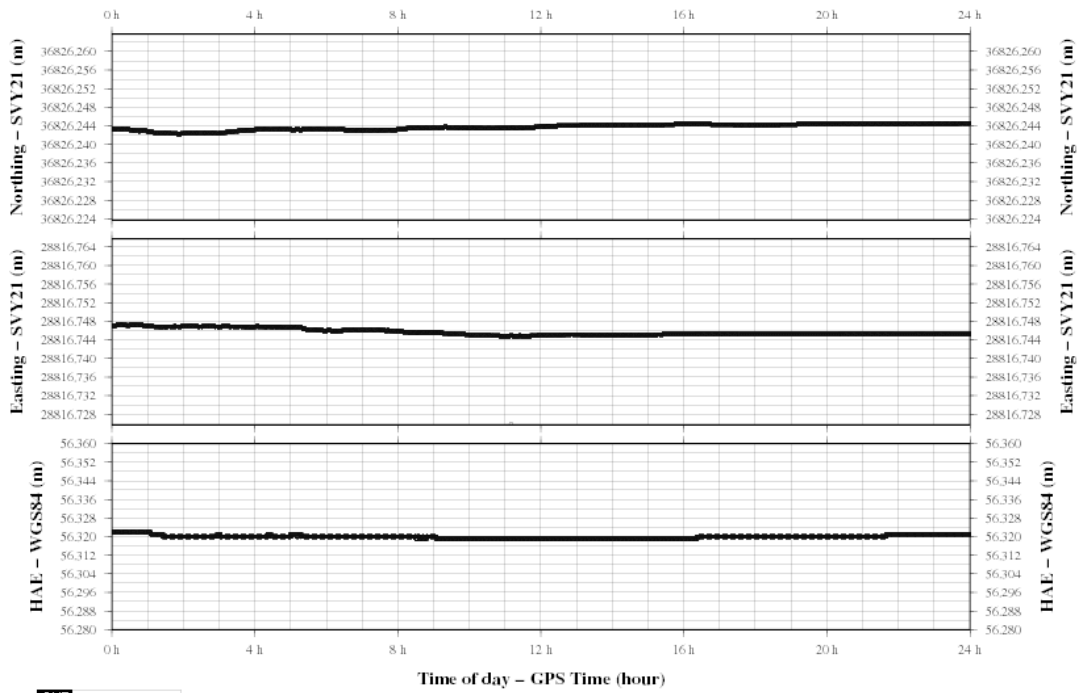
Figure 4: Schematic of the test setup

The first value that is analyzed is the availability of ambiguity-fixed (RTK fixed) positions. Ambiguity-fixed positions (RTK fixed) provide the highest accuracy possible with GPS and so are preferred for monitoring applications. The SiReNT is able to provide 87.2% of RTK fixed solution over the period of testing. On some days, the fixed solutions were disrupted once or on a few occasions. This is due to the changes to the master reference station of VRS technique. The GPSnet software automatically selects a master reference station for every VRS point. When there is drop of communication from one of the reference station in the GPS network, the GPSnet will recompute the VRS corrections. This event causes the disruption to the RTK fixed at the rover.

The upper plot in Figure 5 shows 24-hour time series of the northing, easting coordinates and height above ellipsoid (HEA) of the test point on 28 January 2007. The lower plot in Figure 5 shows the correspondence GPS fix quality indicator, PDOP value and the number of satellites observed at during the same period of time.

Figure 6 shows the 24-hour time series of northing, easting coordinates and HEA on 25 January 2007. There were 2 occasions of RTK fixed disruptions during the day as indicated by the correspondence GPS fix quality plot.

VRS-RTK Coordinate plots for RND1-MON1 on 2007-01-28 (REF=SiReNT)



VRS-RTK Supplementary plots for RND1-MON1 on 2007-01-28 (REF=SiReNT)

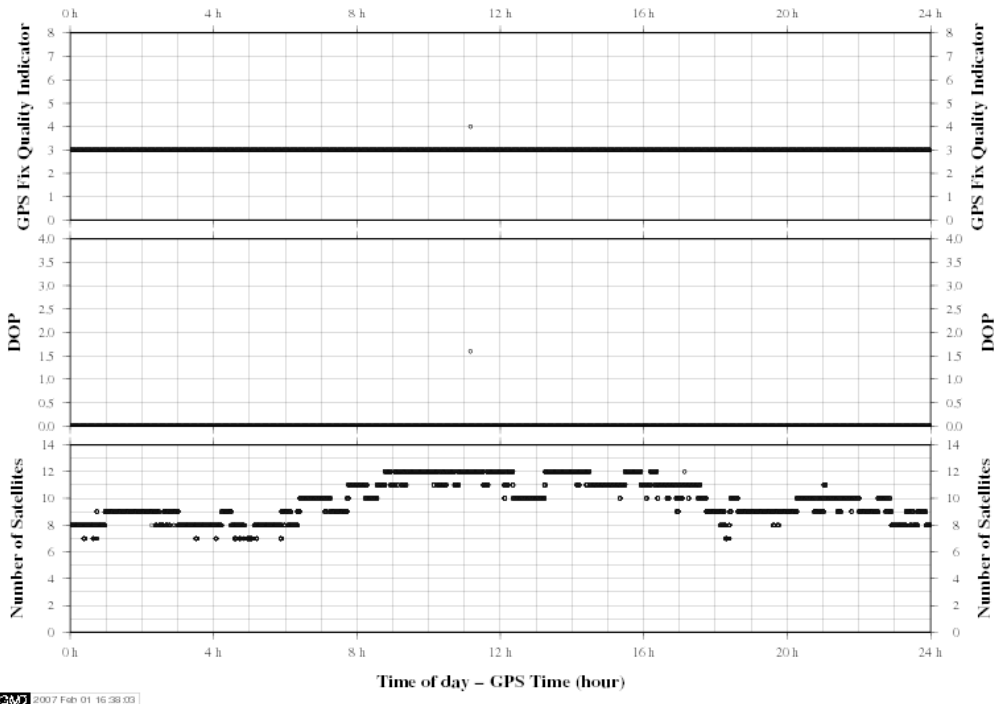
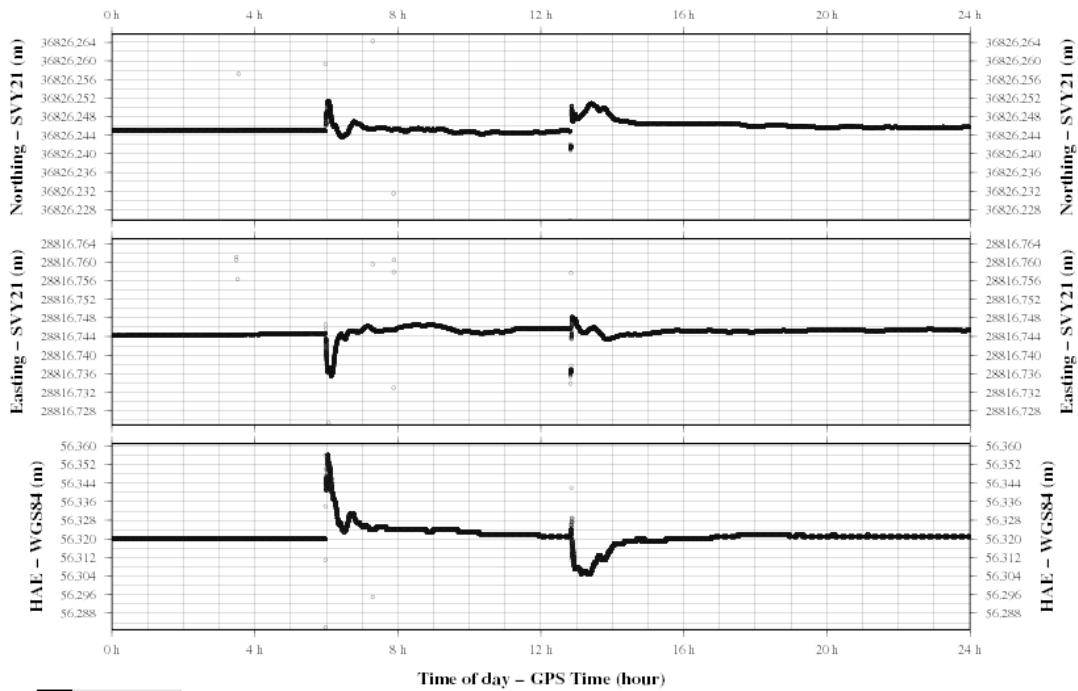


Figure 5: 28 January- 2007 -Time series of northing, easting coordinates and height above ellipsoid (top) and the correspondence GPS quality, PDOP and number of satellites (bottom).

VRS-RTK Coordinate plots for RND1-MON1 on 2007-01-25 (REF=SiReNT)



VRS-RTK Supplementary plots for RND1-MON1 on 2007-01-25 (REF=SiReNT)

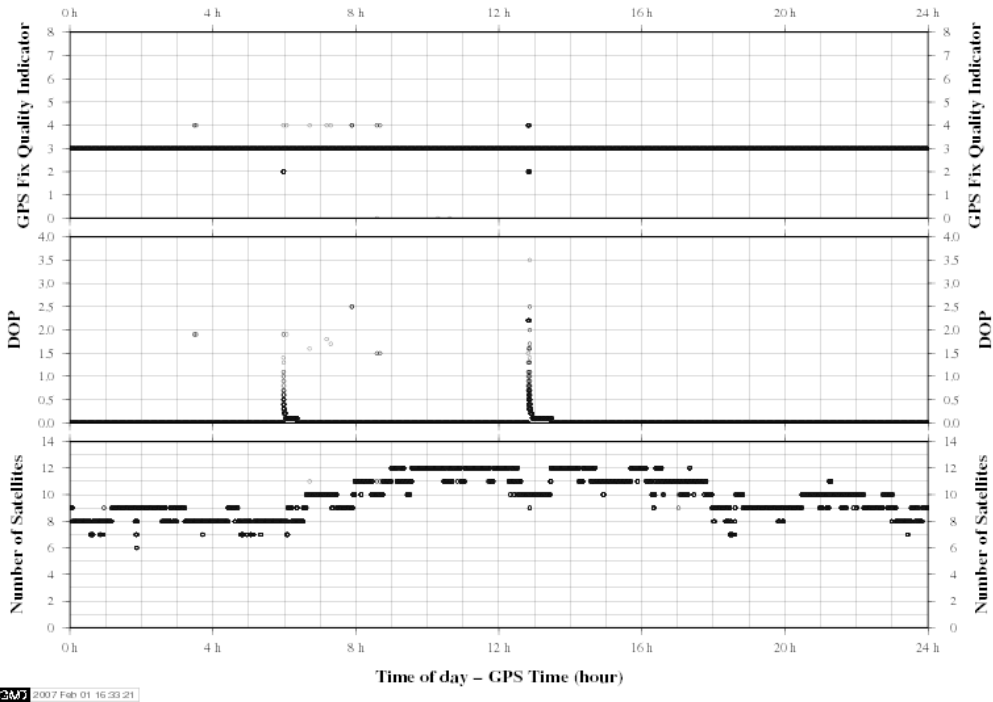


Figure 6: 25 January 2007 - Time series of northing, easting coordinates and height above ellipsoid (top) and the correspondence GPS quality, PDOP and number of satellites (bottom).

Figure 7, 8 and 9 show daily and weekly (average) deviation of coordinates in northing, easting component and height for the period of 14 January to 28 February. The daily average was computed using the values for RTK fixed solutions during the entire day. The weekly values were obtained by averaging the coordinates and height over a week (from Sunday to Saturday). It shows a stable trend of coordinate deviation within 7 mm for northing, 5 mm for easting and height deviation of 14 mm.

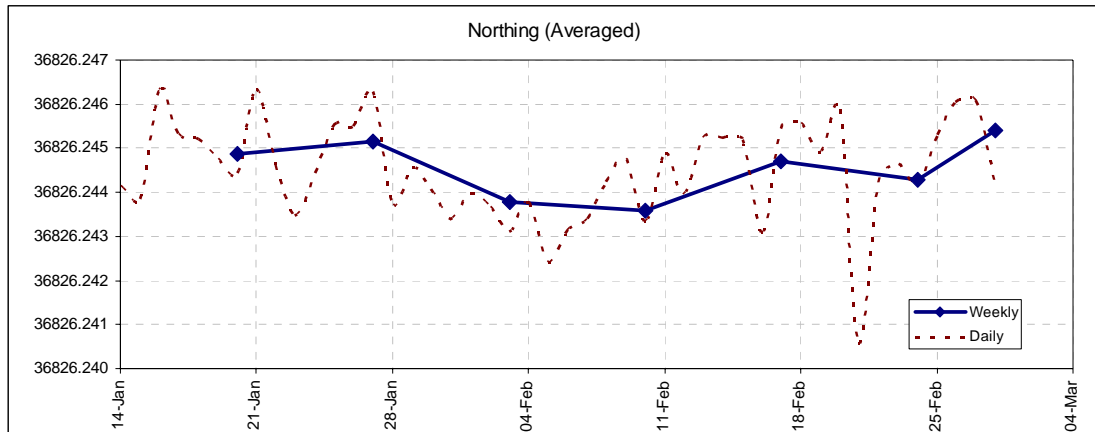


Figure 7: Daily and weekly coordinate deviation in the northing component

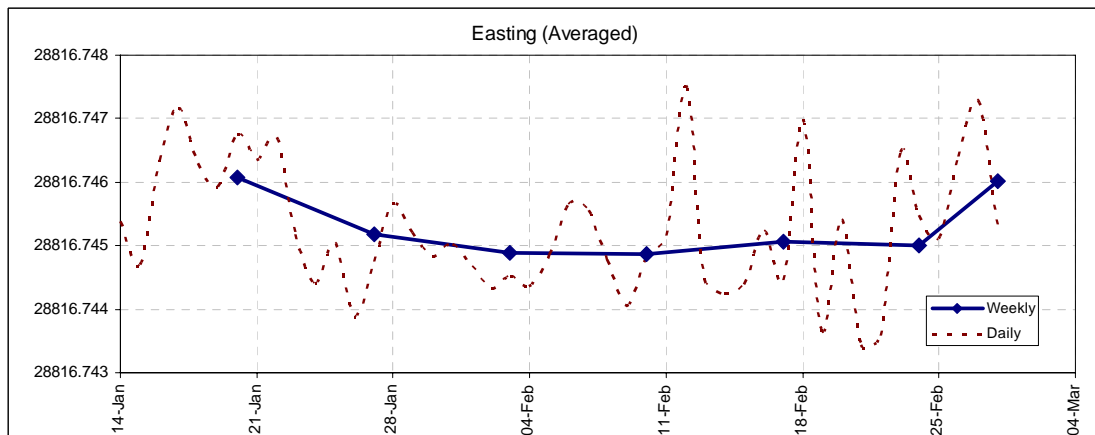


Figure 8: Daily and weekly coordinate deviation in the easting component

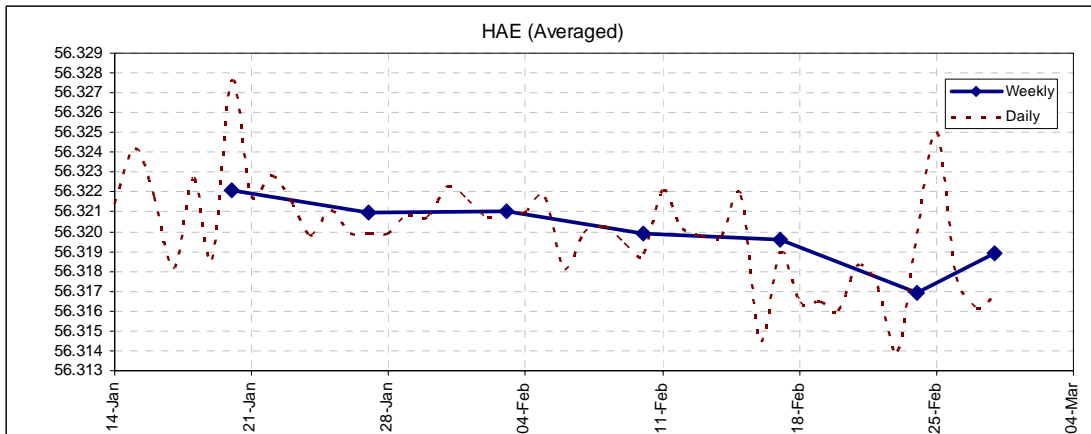
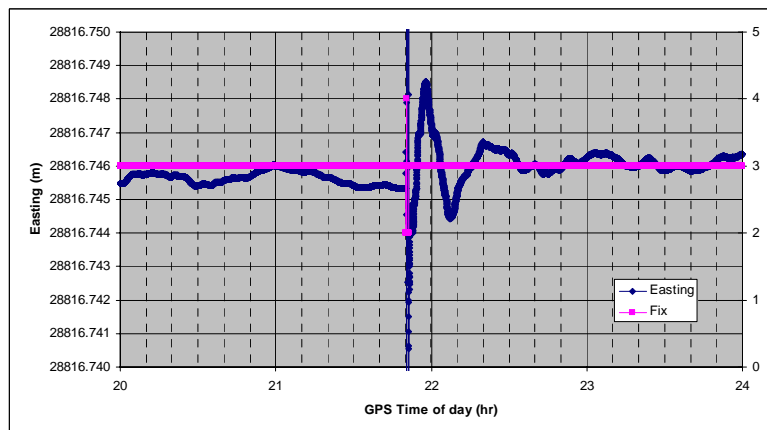
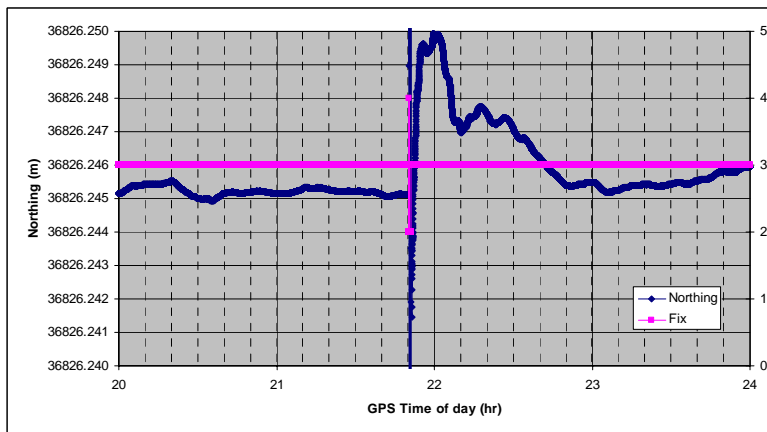


Figure 9: Daily and weekly height deviation

Figure 10 captured an event of RTK fixed disruption that occurred on 21 May 2007. The figure comprises of 3 graphs showing the deviation of northing, easting and height above ellipsoid (HAE) of the test point over a period of 2 hours before and after the event. The GPS fix quality indicators are shown on the right axis. During the event, the GPS quality indicators recorded 4 indicating that the solution is code DGPS solution for 20 seconds followed by indicators recorded as 2 indicating RTK float solution for 7 seconds. It took a total of 27 seconds to gain back the RTK fixed (as indicated by 3).

The plots show that sub-centimetre precision can be obtained immediately after the RTK fixed solution is attained. The results also shows that it took approximately 40 minutes to reach the ± 1 mm precision in easting and northing component and about 70 minutes to reach the ± 3 mm precision for height component.



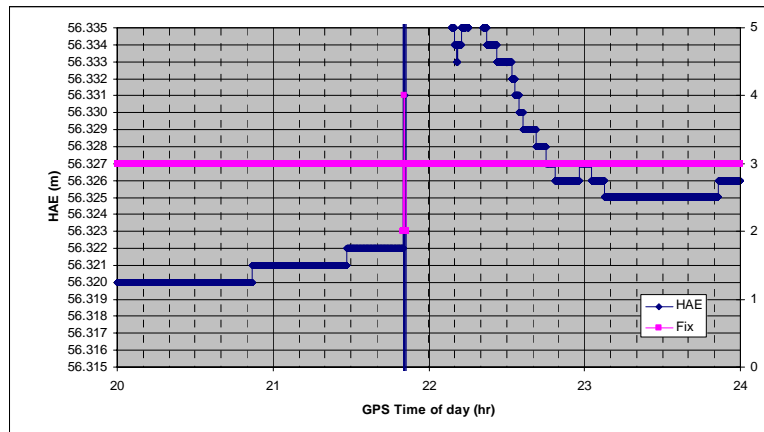


Figure 10: RTK fixed disruption on 21 May 2007

Conclusions

The preliminary results of this proof-of-concept test demonstrate that the VRS-RTK using SiReNT is a feasible technique for real-time continuous deformation monitoring in Singapore. The precision achievable is ± 1 mm for horizontal component and ± 3 mm for height component (long observation over 60 minutes).

The results show that VRS-RTK technique is capable for real-time detection of tall building response to extreme loading 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 monitoring solution.

The past 5 years have seen dramatic reductions in GPS hardware cost coupled with significant increases in performance and the introduction of new techniques such as On-The-Fly (OTF) ambiguity solution, Network-DGPS and VRS. Such improvements as seen in GPS are also occurring in key related communication technologies such as spread-spectrum data radios and wireless internet. The use of mobile phone technology overcomes the limitation of the range of radio communications. The network reference stations (Network-DGPS) configuration and algorithm increases the data redundancy and thus the confidence in the resulting rover positions. These developments have made GPS becoming a powerful and cost-effective tool for deformation monitoring applications of natural features as well as man made structures.

Although the fixed ambiguity of VRS-RTK may drop intermittently due to the data interruption from reference station to DCC, fix carrier phase solution (ambiguity fixed) can be regained in rather short time (less then 60 seconds).

More investigations are needed to further establish the feasibility and performance of the VRS-RTK technique in deformation monitoring. Further tests are required:

- at different locations in Singapore to ascertain the effective coverage of SiReNT;
- on a tall building to demonstrate the capability in detecting harmonic movement;
- using higher data rate;
- using the “known point initialisation” method.

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.

Acknowledgements

The authors would like to thank Mr. Teo Swee Tiong of GPS Lands Pte Ltd for preparing the data and Ms Lee Siok Tin for proofreading the paper.

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