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Advances in GNSS RTK

Structural deformation monitoring in regions of high ionospheric activity

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GNSS TECHNOLOGY is being extensively used for monitoring the movement of engineering structures such as bridges, tall buildings, dams and breakwaters. Large structures increasingly have one or more GNSS receivers installed on them and this trend is expected to continue unabated. Several other trends are also emerging:

- Integrated deformation monitoring systems, consisting of some or all of the following hardware components; GNSS receivers, optical total stations, digital levels, laser alignment devices, inclinometers, accelerometers, strainmeters, anenometers, meteorological sensors.
- Real-time kinematic (RTK) being almost exclusively the GNSS technique that is used.
- The use of low cost L1-only GNSS sensors on the deforming structure.
- System control platforms that link to and manage the data logging and control of many sensors (including GNSS), as well as real-time generation and analysis of resulting displacement time series.
- Increased use of sophisticated time series analysis to characterise the movement of structures.
- Use of installed permanent GNSS reference station infrastructure.

Although GNSS RTK technology is the core component, there are nevertheless a number of challenges in using GNSS. For example, bridges may provide few points where the GNSS sensors can have clear sky view, and GNSS coordinate accuracy is vulnerable to satellite geometry. In addition, GNSS operations are degraded at certain times of the day at low latitude locations (equatorial regions) due to ionospheric disturbances which cause extreme variations in the quality of the measurements. GNSS is also vulnerable to signal multipath disturbance from the structure itself.

Another challenge is logistical, as GNSS RTK requires a reference station located nearby, on a stable ground mark. The use of clusters of continuously operating reference stations (CORS) to support network-RTK (NRTK) operations is now common. NRTK is a viable technique for use as the underlying technological basis for regional and local high productivity, real-time, high accuracy services, with less installed CORS infrastructure than would otherwise be necessary if the single base GNSS RTK technique was to be used. The Hong Kong satellite positioning reference station network, established by the government's lands department, is one example of such a CORS network.

Background

To achieve high GNSS RTK accuracy in monitoring projects, the baselines between the reference station(s) and the monitoring receivers are kept as short as possible. However, there is always the challenge that the reference station(s) could be inadvertently installed in the deformation area itself (in the case of volcanoes, dam or building monitoring) or the signals tracked by the GNSS antennas are obstructed by the structure itself (as is the case for bridges and buildings).

Hong Kong's GNSS NRTK service was installed some years ago and consists of a network of dual-frequency GPS CORS and associated network processing software.

An idea developed by one of the authors (Chris Rizos) about ten years ago to combine a GPS CORS network with several low cost, single-frequency receivers (GPS L1-only) in Indonesia for volcano monitoring has encouraged the execution of a pilot project in Hong Kong. A combination of a subset of the Hong Kong GNSS CORS network and single-frequency GPS receivers was used to evaluate how the ionospheric delay errors could be mitigated in an application of NRTK for sea wall structural monitoring.

Figure 1: GPS monitoring antenna installed on a sea wall in Hong Kong. The Leica GPS GMX902 dual-frequency monitoring receiver and the Leica GNSS AX1202 antenna have been installed with a power supply and the communication equipment in an all weather instrument cabinet.

The first results are indeed very promising and the comparison between single-base GNSS RTK and the one obtained by using the GNSS NRTK corrections suggests a new and improved approach for GNSS RTK monitoring.

Single-base GNSS RTK for structural monitoring

The standard mode of precise differential positioning is for one reference receiver to be located at a reference station whose coordinates are known, while the second receiver's coordinates are determined relative to this reference receiver. The use of carrier phase data in real-time, single baseline mode (one reference station and one rover or user receiver's coordinates to be determined in a relative sense) — also known as single-base mode — is now commonplace. These systems are also referred to as RTK systems, and make feasible the use of

GNSS RTK for many time-critical applications such as engineering surveying, GNSS-guided earthworks/excavations, machine control and structural monitoring applications.

Over the last decade and a half, the use of GNSS for structural monitoring of dams, bridges, buildings and other civil structures has grown considerably and nowadays the GNSS RTK technique is widely used around the world. Such systems output continuous streams of coordinate results (or time series). The dynamics of the structure typically define the nature of the coordinate analysis. For example, if a structure vibrates or deflects due to wind or surface loading, the time series analysis is conducted in the frequency domain, otherwise standard geodetic deformation monitoring techniques, based on advanced network least squares analysis, are used. However, the limitation of single-base RTK is the distance between reference receiver and the rover receiver due to distance-dependent biases such as orbit error and ionospheric and tropospheric signal refraction. This has restricted the inter-receiver distance to 10km or less (depending upon the latitude). However in low latitude regions, the ionospheric variability is so high that the use of single-base GNSS RTK over short baselines may not even be possible in the local afternoon period. Yet in the case of short baselines, there is a risk that the GNSS reference station could be located in the area that is subject to deformation. Furthermore, the object itself may cause signal refraction and, in the worst case, reduced signal availability impacting on the geometry (GDOP) of the solution.

Some of these problems can be addressed using techniques where the GNSS reference station(s) are located as far away from the monitoring points as possible without being influenced too greatly by residual (double differenced) atmospheric biases. Network-RTK is a centimetre-accuracy, real-time, carrier phase-based positioning technique capable of operating over inter-receiver distances up to many tens of kilometres (the distance between a rover and the closest reference station receiver) with equivalent performance to single-base RTK systems (operating over much shorter baselines). The reference stations must be deployed in a dense enough pattern to model distance-dependent errors to such an accuracy that residual double-differenced carrier phase observable errors can be ignored in the context of rapid ambiguity resolution. NRTK is therefore the logical outcome of the continuous search for a GNSS positioning technique that challenges the current constraints of single-base, centimetre-accuracy, high productivity, carrier phase-based positioning.

GNSS NRTK for structural monitoring

All GNSS-based positioning techniques operate under a set of constraints. These constraints may be baseline length, attainable accuracy, assured reliability, geometrical strength, signal availability, time-to-solution, instrumentation, operational modes, cost and so on. GNSS product designers must develop systems (comprising hardware, software and field procedures) that are optimised for a certain target market, by addressing only those constraints that are crucial to the most common user scenarios. For example, single-base RTK systems are capable of high performance when measured in terms of accuracy, time-to-solution (i.e. speed of ambiguity resolution after signal interruption), utility (due to the generation of real-time solutions), flexibility (being able to be used in static and kinematic applications), ease of use, autonomy (operate their own reference station) and cost-effectiveness. However, the 10km baseline (or less in low latitude regions) constraint, the increasing availability of GNSS CORS networks (no need to operate their own), and the desire to use lower cost (i.e. single frequency) user receiver hardware means that engineers are looking to alternative, more efficient GNSS RTK based techniques for structural monitoring applications.

GNSS NRTK is a technique that takes advantage of a network of permanently installed CORS streaming in real time their raw observations to a central computing facility. Due to the more sophisticated modelling of residual spatially correlated biases (due to atmospheric refraction of GNSS signals), the distances between CORS stations may be relaxed to many tens of kilometres (well beyond the baseline constraints of single-base GNSS RTK). Hence the economics of operating CORS networks is significantly improved when NRTK services are provided. There are a number of implementations of NRTK (the most common are VRS – virtual reference station – and FKP – the German flächenkorrekturparameter) which involve processing CORS network data in order to generate empirical correction data (to principally account for the unmodelled residual double-differenced atmospheric biases) that are transmitted to users in RTCM-type messages. Alternative modes, such as MAC (master-auxiliary concept) place some of the burden of NRTK processing on the user's receiver.

In the case of structural monitoring, the CORS need to be located on very stable sites and the coordinates of the antenna phase centre for each CORS are determined with a relative accuracy of a few millimetres. If monitoring over a long period of time, due regard must also be taken of reference frame stability – something beyond the scope of this paper. Another distinguishing characteristic of most structural monitoring applications is that the continuous stream of 3D coordinates is needed at a monitoring centre, not at the monitoring site's receivers. Hence other modes of NRTK, such as reverse or serverside, may be more appropriate.

In the pilot project described in this paper, the monitoring receivers deployed over the deformation area stream their observations to a PC server running the GNSS NRTK modelling software, to generate corrections in real time, and integrated as master auxiliary or virtual reference stations in the processing. Because of the advantages that a GNSS NRTK approach to structural monitoring can offer, there is increasing worldwide interest in positioning infrastructure – national and regional CORS

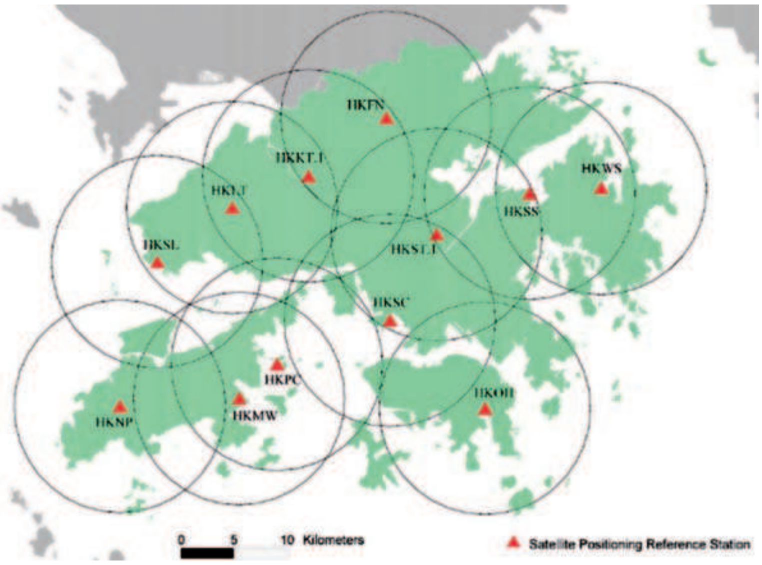
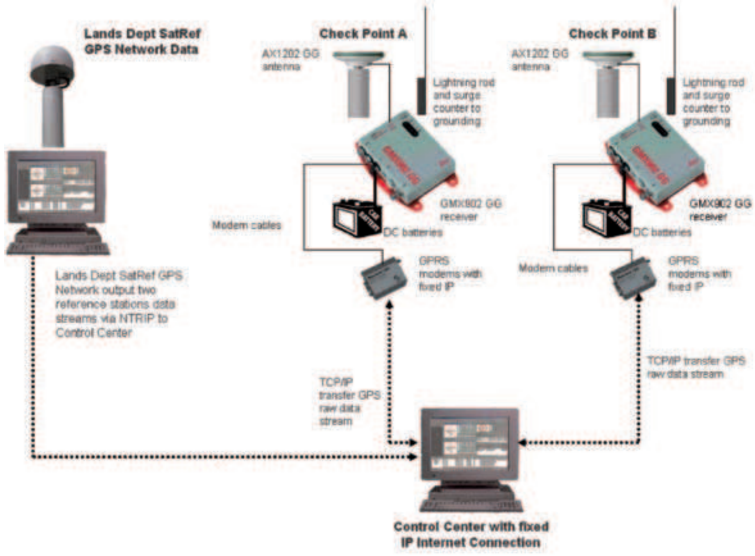


Figure 2: The Hong Kong satellite positioning reference station network.



networks. Then, the focus of the monitoring project becomes the deployment of a sufficient number of receivers at monitoring points to derive detailed enough deformation signals to help structural engineers determine whether the structure is responding to loads within design specifications, or whether the structure has suffered serious damage.

While the use of installed CORS infrastructure makes GNSS more attractive for structural monitoring, the high cost of dual-frequency receivers is still a constraint to a massive expansion in the number of monitoring receivers on a project. How can the cost of GNSS monitoring be driven down even further? The use of low cost GPS L1-only monitoring receivers was proposed almost ten years ago.

Mixed-mode GNSS for structural monitoring

Data from single frequency GNSS receivers cannot be corrected for ionospheric delay, as is the case with dual frequency data. Therefore a combination of single and dual frequency instrumentation in a mixed mode network could, in principle, ensure high accuracy coordinate results using a large number of receivers deployed across a region experiencing deformation, while keeping GNSS hardware costs as low as possible.

Such an approach was used to develop a monitoring system for Indonesian volcanoes. This is possible by augmenting the single frequency receivers with a small number of dual frequency receivers surrounding the zone of deformation. The primary function of this outer network is to generate empirical correction terms to the double-differenced phase observables within the deformation monitoring network. This mixed mode methodology can, in fact, be implemented in real time using a cluster of CORS – that has its raw observations processed using GNSS NRTK software to generate 2D spatial models for residual tropospheric and ionospheric biases. These models then can be used to correct the monitoring receivers' single frequency data, either by software in the monitoring receiver itself (standard NRTK approach) or at the monitor centre if the reverse NRTK approach is used.

Hong Kong pilot

For demonstrating the benefits of the GNSS technology for monitoring sea walls, a pilot project in Hong Kong was setup by an engineering company. It used equipment and software developed and delivered by Leica Geosystems. The CORS data were provided as a service by the Hong Kong Lands Department, by its satellite positioning reference station network. The processing of the real-time data was carried out by the centralised RTK processing software, GNSS Spider Positioning. Initially this was performed using the single-base GNSS RTK approach. It appeared, however, quite clearly that in the local afternoon period, but also randomly sometimes throughout the day, sudden jumps occurred in the coordinate time series (easting, northing and height), making reliable structural monitoring difficult or even impossible. It should be noted that the standard noise-like variation in GNSS RTK time series is something users have to cope with via some form of smoothing and filtering. However, in this case the outliers were due to large biases resulting from extreme and highly variable ionospheric conditions.

After a meeting with the engineering company, who reported similar phenomena in other monitoring projects in Hong Kong, we approached the Hong Kong Lands Department and requested its assistance in delivering the real-time data streams of several CORS located in and around the monitoring project. GNSS SpiderNET software was installed with the necessary options to process the CORS network cluster and to redirect the RTK network corrections as observations for one of the closest reference stations located near the monitoring receivers (see Figure 4). That reference station acted as a MAX station (RTCM v3.n master-auxiliary concept, via

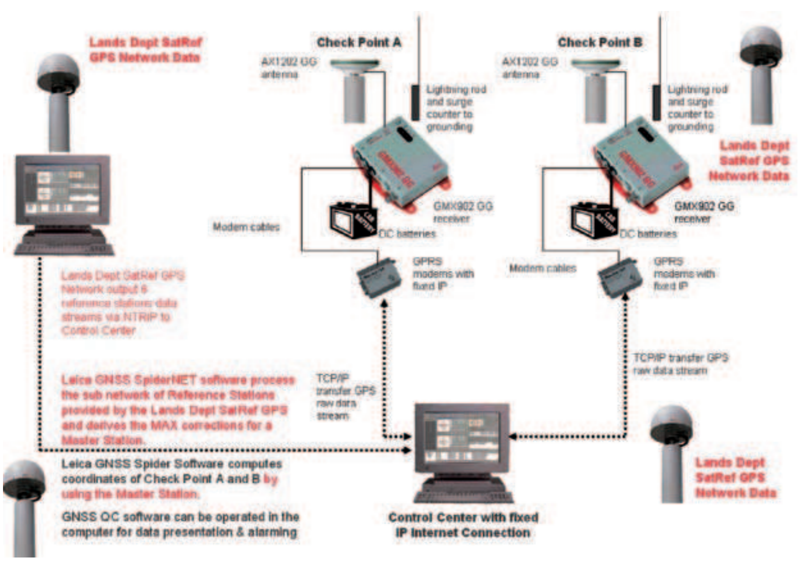
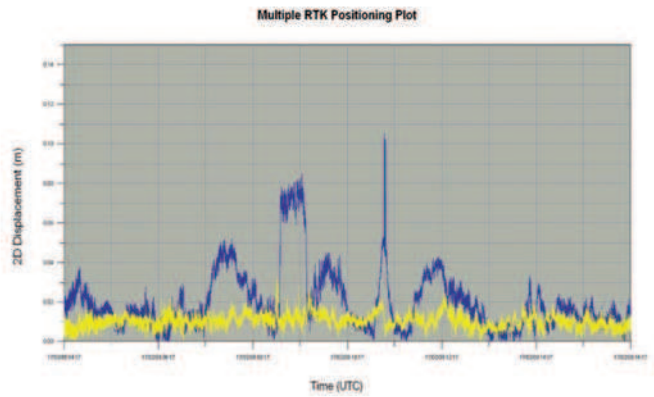
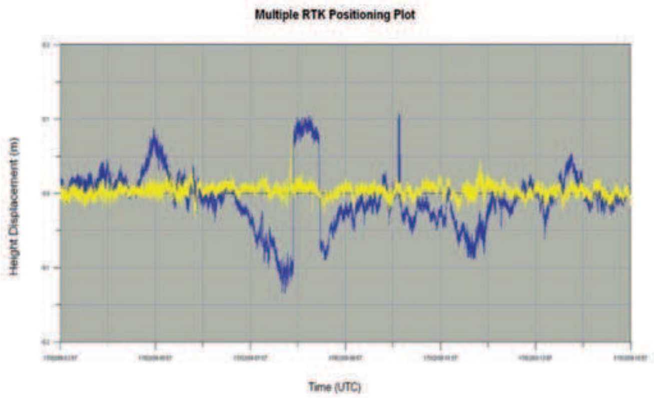


Figure 3 (top): GNSS single-base RTK system architecture.
Figure 4 (right): GNSS NRTK system architecture.





master-auxiliary corrections, or MAX) in the Spider site server. It should be emphasised, however, that any other reference stations participating in that cluster could have been selected without affecting the results. Comparison was made between the standard single base GNSS RTK solution (Figure 3) and the GNSS NRTK solution (Figure 4), in 2D and height, using the GNSS QC software. The plots (Figures 5 and 6) show clearly that the GNSS NRTK corrections dramatically improved the results. Note that the 2D and height plot scales are different – each horizontal line is 1cm and 5cm respectively. Apart from occasional outliers, the variability is less than 2cm for horizontal components and less than 5cm for the height component.

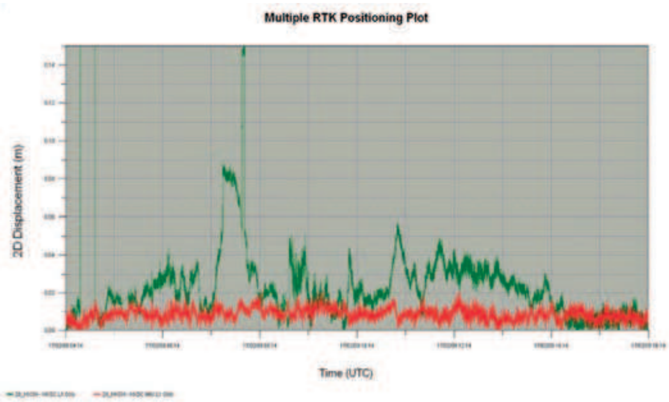
The results presented here are not filtered or smoothed, as they were just the output in the NMEA format of the baselines solutions computed by the GNSS Spider site server (positioning option). (A recursive low bandpass filter – exponential weighted moving average – could now be applied on these unbiased NRTK generated results in order to deliver a few millimetres of accuracy and in real time.) At the same time, in order to verify whether single-frequency GPS L1-only receivers could also benefit from the GNSS NRTK, it was decided to simultaneously process the different baselines using only the GPS L1 frequency observations. The quasi-static method of initialisation was used to effect fast L1 RTK.

The results were even more impressive in terms of initialisation (ambiguity resolution) and accuracy (Figures 7 and 8). Note that the 2D and height plot scales are different – each horizontal line is 1cm and 5cm respectively. Apart from occasional outliers, the quality of the time series is very similar to that in Figures 5 and 6, computed using higher cost dual frequency monitoring receivers, i.e. the variability is less than 2cm for horizontal components and less than 5cm for the height component.

Conclusions

The results presented here of a sea wall monitoring project in Hong Kong demonstrate that the combination of GPS NRTK resources (CORS network and NRTK modelling software) delivers outstanding advantages, such as maximum (unbiased) accuracy and reliability. The following summary comments can be made with regard to the GNSS NRTK based monitoring technique:

- Better control over the operations and the results by taking advantage of installed CORS infrastructure.
- Reliable time series solutions for projects located in low latitude regions where the ionospheric turbulences severely affect signal and data processing.



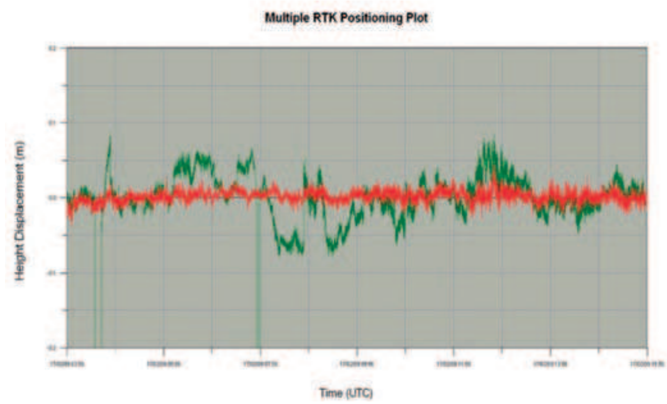


Figure 5 (above top): Comparison of RTK positioning 2D results –the blue line is the single-base RTK solution and the yellow line is the NRTK solution (each horizontal line is 1cm).
Figure 6 (above bottom): Comparison of RTK positioning height results – the blue line is the single-base RTK solution and the yellow line is the NRTK solution (each horizontal line is 5cm).
Figure 7 (right top): Comparison of RTK positioning 2D results – the green line is the single-base RTK L1- only solution and the red line is the NRTK L1-only solution (each horizontal line is 1cm).
Figure 8 (right bottom): Comparison of RTK positioning height results – the green line is the single-base RTK L1-only solution and the red line is the NRTK L1-only solution (each horizontal line is 5cm).

- The possibility to mix dual frequency receivers (GNSS CORS) with affordable single frequency receivers for slow deformation motion monitoring.
- No need for subsequent networked baselines adjustment.
- No need to establish single CORS in urban areas (obstructions) for high rise building or long bridge monitoring projects.

Although implemented for a trial in Hong Kong, we believe that with the return of high solar cycle activity, the proposed mixed mode solution strategy could find application in many other places than only those currently exposed to severe ionospheric disturbances (i.e. low latitude regions). We are working on similar projects in South Korea.

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