A review of satellite positioning systems for civil engineering

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Abstract

This paper informs and updates engineers of the status and advances of GNSS (Global Navigation Satellite Systems), and how this will affect civil

engineers in the near future. An overview of the various GNSS as well as RNSS (Regional Navigation Satellite Systems) is given. Real data are used to show the potential precision of GPS (Global Positioning System) and other GNSS, as well as the advantages of using a multi-GNSS approach. The results illustrate that there is a clear increase in the availability of satellites through a multi-GNSS approach, as well as an improvement in the resulting coordinate precision.

Introduction

This paper informs and updates engineers [Roberts and Brown, 2006], [Cruddace and Faye, 2009], [Hancock, Roberts and Taha, 2009] on the advances of Global Navigation Satellite (Positioning) Systems (GNSS) technologies, and how this will affect engineering surveys in the near future. The paper introduces the variety of GNSS, and shows how a multi-GNSS approach can improve the precision, reliability and increase the availability of satellites for civil engineering applications. A study in 2003 [Parker, 2003] stated that research into the availability of GPS signals for positioning in urban areas in Leeds and London found that GPS positions were only possible on 60% of the points surveyed to the required accuracies in order to position utility cables and pipes. The previous work [Cruddace and Faye, 2009], [Hancock, Roberts and Taha, 2009] highlighted the upcoming advancements in GNSS, and the use of simulation to predict the scenarios with more GNSS satellites, as well as using pseudolites to augment the GPS signals [Hancock, Roberts and Taha, 2009]. Research has been carried out, illustrating the advantages of integrating GPS with other GNSS, or even a multi-GNSS solution [Teunissen, Odolinski and Odijk, 2014], [Roberts and Tang, 2015], [Zhang *et al.*, 2011]. This paper illustrates, using real data, the potential accuracies and availability of a multi-GNSS approach over GPS alone.

Global Navigation Satellite Systems

GNSS is the generic term used for all the satellite navigation systems that have a global coverage [Lekkerkerk, 2014a]. The most established GNSS is the USA's Global Positioning System (GPS), but there are currently a further three GNSS either in operation or under development. These are the Russian "Globalnaya Navigatsionnaya Sputnikovaya Sistema" (GLONASS), the European system (Galileo), and the Chinese BeiDou System (BDS) [Cruddace and Faye, 2009], [Hancock, Roberts and Taha, 2009]. Currently there are 31 operational GPS satellites [GPSWORLD, 2015], GLONASS has 24 operational satellites [Dvorkin, Karutin and Kurshin, 2012], [Krasovskii, 2010], [Nikitin, 2008], Galileo has 6 operational satellites [Cai *et al.,* 2014], [Lekkerkerk, 2014b], [Mastracci and Fromm, 2004], and BeiDou has 15 operational satellites [Chen *et al.,* 2009], [Yuan, 2014]. Both GPS and GLONASS are now (2015) fully operational, while both Galileo and BeiDou are planned to be fully operational by 2020. All the GNSS orbits comprise of Mid Earth Orbiting (MEO) satellites, at altitudes ranging between 19,130km and 23,222km above the Earth's surface. In addition to the MEO, the BeiDou satellite constellation also includes a number of Geostationary (GEO) and Inclined Geosynchronous Orbits (IGSO) satellites at altitudes of 35,786km above the Earth's surface [CSNO, 2013]. Table 1 illustrates the current and optimal number of operational satellites in orbit. This is a snapshot, as satellites will be launched, and ones in orbit will gradually come to the end of their lives.

Table 1, Current and optimal numbers of satellites in the GNSS orbits. These include MEO (M), IGSO (I), and GEO (G) orbits [information sourced from www.gpsworld.com/the-almanac].

In addition to GNSS, there are Regional Navigation Satellite Systems (RNSS) in various parts of the world, providing Spaced Based Augmentation Systems (SBAS) to GNSS. This is where countries or regions have placed additional satellites that both behave as GPS satellites, providing additional ranges from the satellites to the users, and are also being used to transmit corrections for a Differential GPS (DGPS) solution within that region.

The various generations of GPS satellites have gradually evolved to improve not only the users' positional accuracies, and signal quality and strength, but also the lifespan of the satellites. The expected lifespan of the satellites has increased over the generations from 7.5 years for the initial GPS operational block II and IIA satellites, to 12 years for the current block IIF satellites, and 15 years for the next generation is anticipated. The reality is that these satellites have been lasting much longer. For example, on January 6th 2015, the final GPS Block II satellite was taken out of service, after being in operation for over 22 years [NAVCEN, 2015]. The system itself has also been modernized through the introduction of more ground monitoring stations. These give the capability to improve the accuracy of the satellites' coordinates, and hence the users' coordinates, as well as reliability through being able to constantly monitor the satellites' characteristics from an increased number of ground control points. The more recent and future generations of satellites transmit additional frequencies as well as new signals. This will improve the potential applications of such systems [Hofmann-Wellenhof, Lichtenegger and Wasle, 2003], [Hofmann-Wellenhof, Lichtenegger and Wasle, 2008].

GNSS signals can be processed and analyzed in many ways, each resulting in different levels of accuracies and precision [Cruddace and Faye, 2009], [Hancock, Roberts and Taha, 2009], [Hofmann-Wellenhof, Lichtenegger and Wasle, 2003], [Hofmann-Wellenhof, Lichtenegger and Wasle, 2008]. The GNSS receivers used for engineering surveying applications use a part of the satellite signal called the carrier phase. The resolution of the carrier phase signal is of the order of better than 0.5 mm, and can result in coordinates with precisions from a few millimetres to a couple of centimetres depending on the type of equipment used and processing carried out. There are a number of ways that this type of

GNSS data can be processed, including static GNSS, stop-and-go kinematic GNSS, and full kinematic GNSS using what is called On-The-Fly ambiguity resolution [Hofmann-Wellenhof, Lichtenegger and Wasle, 2003], [Hofmann-Wellenhof, Lichtenegger and Wasle, 2008]. These are all relative positioning techniques, whereby the GNSS receiver whose position is being calculated is located relative to a GNSS receiver located at a known coordinate, or even a network of GNSS receivers with known coordinates [Hofmann-Wellenhof, Lichtenegger and Wasle, 2008]. The data can be gathered and post-processed, or all the data can be brought together, typically at the unknown GNSS receiver, and processed in real time by connecting the GNSS receivers with a low powered 0.5Watt UHF data link, or mobile phone based telemetry. This real time approach is usually only carried out for the stop and go, and full kinematic positioning techniques, and known as Real Time Kinematic GPS (RTK-GPS). Table 2 illustrates some of the main processing techniques, indicating the potential accuracies, as well as their limitations and advantages.

Table 2, The nominal horizontal accuracies with the main advantages and disadvantages of the most commonly used GNSS positioning techniques. Please note that the errors indicated are an indication, as these vary due to the signals and environment. Height errors are typically 2-3 times worse than plan.

Today, there are some 73 operational GNSS, and a further 15 or so SBAS/RNSS [GPSWORLD, 2015]. It is planned that Galileo will grow to a constellation of 27 operational plus 3 active spare satellites by 2019, and BeiDou will grow to 35 satellites by 2020. The regional Japanese QZSS currently has one satellite, but is planned to grow to 4 by 2017. In addition to this, there are 6 SBAS satellites in Europe in terms of the European Geostationary Navigation Overlay System (EGNOS), 3 USA Wide Area Augmentation System (WAAS) satellites operating over North

America, 7 planned Indian Regional Navigation Satellite System (IRNSS) satellites, 2 Japanese Multi-functional Satellite Augmentation System (MSAS) satellites, 8 OmniSTAR satellites. Further to this, there are ongoing discussions in many other parts of the World with regards planned SBAS and RNSS. This means that within the next handful of years, the number of operational positioning satellites will be over 30 RNSS and approximately 120 GNSS, compared to the originally planned 24 GPS satellites when it was first conceived in the 1970s.

While any future approach to positioning using a multi-GNSS satellite solution will improve and extend the capabilities of GPS alone it is not a simple task to fully integrate these systems, due to the nature of the signals, and this in itself is a large area of research in the GNSS community.

An increase in the number of available GNSS satellites used to process a positional solution will enhance the time required for an On-The-Fly positional fix, as well as the resulting precision of the solution. The multi-GNSS approach in built up areas, such as city centres, should also allow positions to be achieved where they are sometimes not available through using GPS alone. However, the end solution may be skewed slightly due to having a black spot in the sky where there are no satellites seen, due to building obstructions.

RTK GNSS Precision

The integration of multiple GNSS has many advantages. These include an increase in the number of satellites seen at any one time, as well as the positional distribution of these GNSS satellites, which improves the precision due to a better geometrical solution.

An instantaneous snapshot of the location and number of satellites is important when using kinematic GNSS. Figure 1 illustrates a 5-minute snapshot of the 6 GPS satellites available during this period, and Figure 2 the 25 GNSS satellites available during the same 5-minute period. These data were recorded in Ningbo, China, at the University of Nottingham's campus. The GNSS satellites consist of 6 GPS, 7 GLONASS, 1 Galileo, 6 BeiDou, 1 Japanese Quazi Zenith Satellite System (QZSS) SBAS satellite and a further 4 SBAS from India and Japan. An elevation angle cut off of 15° was used, which is typical when using GNSS for engineering surveying.

Figure 1, A 5-minute sky-plot of GPS on the 1 July 2014, between 21:00 to 21:05 at Ningbo, China.

Figure 2, A 5-minute sky-plot of GNSS on the 1 July 2014, between 21:00 to 21:05 at Ningbo, China.

Figure 3 illustrates the total number of GPS satellites available over a 20 minute period. The number can be seen to fluctuate between five and four satellites. It can also be seen that the various Dilution of Precision (DOP) values fluctuate [Hofmann-Wellenhof, Lichtenegger and Wasle, 2003], [Hofmann-Wellenhof, Lichtenegger and Wasle, 2008]. The DOP values are an indication of the precision expected as a result of the location and geometry of the satellite constellation - the lower the number, the better the expected precision. These DOP values are calculated in the various components, such as the overall Geometry (GDOP), Position (PDOP), Vertical (VDOP) and Horizontal (HDOP). Figure 4 illustrates the number of GNSS satellites available over the same time period. Here it can be seen that the number of satellites fluctuates from 21 to 24, and more importantly the DOP values are constantly low. There are satellites that go in and out of view in both plots in Figures 3 and 4, but this has less of an effect on the GNSS solution compared to that obtained using GPS alone. This shows that a multi-GNSS solution is far more stable.

Figure 3, The total number of GPS satellites seen on the 1 July 2014, between 18:30 to 18:45 at Ningbo, China, with a satellite elevation mask of 15°, in an open sky environment without any obstructions.

Figure 4, The total number of GNSS satellites seen on the 1 July 2014, between 18:30 to 18:45 at Ningbo, China, with a satellite elevation mask of 15°, in an open sky environment without any obstructions.

Figure 5, The results from a zero baseline kinematic GPS test, using a Leica 1200 GPS receiver data, over a 45 minute period.

Figure 5 illustrates the eastings and northings results derived from a zero baseline, gathering GPS data using a Leica 1200 GPS/GLONASS receiver over a 45 minute period at a data capture rate of 1Hz. A zero baseline is where two GNSS receivers are connected to a single antenna, through a signal splitting device. This results in both receivers obtaining identical signals from the GNSS antenna, including the same error components. All external signal noise will be the same for both receivers, as they receive the same data from the same antenna. The resulting apparent relative movement is due to the noise of the signals, as well as any satellite constellation geometry induced noise. The external noise will cancel out in processing the relative coordinates [Roberts *et al.,* 2012]. Only the GPS data were used in the kinematic GPS solution presented in this paper. It can be seen in Figure 5 that it is possible to obtain coordinate precisions of the order of millimetres. The north-south error is greater than the east-west due to the satellite constellation geometry i.e. there are no satellites due north in northern latitudes such as the UK. The Root Mean Square (RMS) of these data are 0.7mm in the north-south direction, and 0.4mm in the east-west direction. The RMS of the corresponding height component is 1.2mm.

Figure 6 illustrates the results in the east-west component of another zero-baseline experiment, this time using two ComNav GNSS receivers (GPS, BeiDou and GLONASS). By comparing the GPS and BeiDou solutions; using the BeiDou solution alone gives the least precise results with an RMS positional error of 1.22mm, 1.03mm and 3.70mm in the north, east and height components respectively. This is due to the BeiDou constellation not yet being complete. The GPS solution is more precise than the BeiDou with a positional RMS error of 0.81mm, 0.67mm and 1.94mm in the north, east and height components respectively. The combined solution is the most precise with a positional RMS error of 0.69mm, 0.62mm and 1.71mm in the north, east and height components respectively. This is due to the overall satellite constellation giving a better distribution of signals. This illustrates that even though the BeiDou constellation is not yet complete; the results are still pretty decent. However the main point is that the incomplete satellite constellation's data combined with that of GPS can improve the results of GPS alone.

Figure 6, Position Error in the East-West component for GPS-only BDS-only and Integrated GPS and BDS solutions.

Some Civil Engineering Applications of GNSS

There are numerous applications of GPS and GNSS in civil engineering, which replicate to some extent the traditional nature of static engineering surveying, such as coordinating control points, deformation monitoring, setting out or detail surveys. There are also dynamic applications such as deflection monitoring of large structures [Roberts and Brown, 2006], [Roberts *et al.,* 2012], [Roberts, Brown and Tang, 2014] positioning and controlling construction plant such as bulldozers, graders, piling rigs, mining plant, drilling rigs and excavators [Carter, 2005], [Ritter, Herzog and Drebenstedt, 2014], [Steward, 2002], [Carter, 2011], [Steward *et al.,* 1997], [Makkonen, Nevala and Heikkila, 2006], [Moon *et al.,* 2010], [Bouvet, Froumentin and Garcia, 2001], [Navon, Goldschmidt and Shpatnisky, 2004]. Figure 7 illustrates an excavator being controlled by RTK GNSS, while Figure 8 illustrates a GNSS antenna located on the Severn Suspension Bridge cable in order to measure its deflections. Typically such GNSS results are integrated with other sensors. The excavator, for example, has its body coordinated and orientated using the two GNSS antennas. The bucket is then coordinated relative to the body, using gravity sensors or angle encoders placed on the three moving arm and bucket sections.

RTK GNSS results in real time, 3-Dimensional coordinates, commonly at a rate of 20Hz, but potentially at rates up to 100Hz with some modern receivers. This means that a dynamic system, such as a swaying bridge or moving excavator, can have its location coordinated at this rate in real time with a precision of a few millimetres. The real time aspect of kinematic positioning is as important to some applications as the precision itself. For example, both setting out applications and construction plant control require real time capabilities.

Figure 7, An excavator using RTK GNSS for control. Notice the lack of setting out sight rails and batter rails (Courtesy of Leica Geosystems).

Figure 8, A GNSS antenna located on the Severn Suspension Bridge's suspension cable.

Figures 9 and 10 are used to illustrate the type of results that are possible using kinematic GPS. Figure 9 illustrates the deflection measurements of the GNSS antenna seen in Figure 8. The data were gathered at 20Hz, but processed at 10Hz in order to investigate the movements of this location on the Severn Bridge. The data gathered included dual frequency GPS and GLONASS using Leica 1200 series receivers and choke ring antennas used to reduce the multipath noise [Roberts *et al.*, 2015]. Figure 9 illustrates the typical movements, after converting the GPS coordinates into coordinates relative to the axes of the Bridge. The GPS data were processed in an on-the-fly manner. Here it can be seen that the Bridge deflects due to the external forces, such as traffic loading, wind loading and temperature changes. For example, the overall drop in height over the 4-hour period in Figure 9 is 65.8mm. This corresponds to an increase in the steel temperature of 1.7°C, causing the steel to elongate, and hence the Bridge to dip down. There are also short term movements seen, mainly due to the traffic loading, and variation in this loading. For example, at around 13:13, there is a height movement from -40.2mm to -438mm, over a time of approximately 30 seconds. This corresponds to a change in the traffic loading from 24,030kg to 170,460kg and then to 4,530kg. The overall mass of traffic on the Bridge at various instances were calculated using measurements from a Weigh In Motion (WIM) system, located approximately 1km off of the Bridge [Roberts *et al.*, 2015]. Figure 10 illustrates the results from carrying out a Power Spectral Density (PSD) analysis of the vertical data over a 5 minute period. It can be seen from Figure 10 that there is a fundamental frequency of 0.1416Hz in the vertical direction from these data. These results help to illustrate the possibilities using kinematic GPS. These types of data rates and precisions could be re-produced in other civil engineering scenarios, such as construction plant control, land surveying and setting out and deformation monitoring of other types of man-made and natural structures to name a few.

Figure 9, the lateral, longitudinal and vertical movements calculated using kinematic GPS at location C on the Severn Bridge, 18^{th} March 2010, 11:30 to 15:30.

Figure 10, Power Spectral Density Analysis of Location C on the Severn Bridge, illustrating a fundamental frequency of 0.1416Hz in the vertical direction.

Final Comments

Cruddace and Faye [2009] stated "the future for GNSS plans to be very exciting over the next 5 years where 100+ positioning satellites could be available to users". The development of GNSS is ongoing, while the multi-GNSS concept has been available for 15 years or so, initially through the introduction of GLONASS by Ashtech's GG24 GPS/GLONASS receiver. Today, however, there are a multitude of existing and developing GNSS and RNSS, which results in an improvement in precision and availability, as well as reliability of using such systems. The monitoring rates are determined by the quality and capability of the equipment to gather data.

The quality of the satellites' signals, the GNSS receivers and the expected accuracies and precisions are also under improvements.

The use of multiple GNSS has a very bright future, for civil engineering in particular, and will be developed to enable surveying and positioning tasks in built up areas such as city centres. An integrated GNSS approach will improve the accuracies and precision of the results, as well as allowing positioning in difficult environments. Further to this, the various GNSS are introducing new signals in the new satellites that are being launched. This means that the various GNSS will have triple frequencies, rather than dual. This will also have an advantage in being able to calculate the errors due to the upper atmosphere (ionosphere), as well as accelerating the integer ambiguity resolution. Further to this, a multiple GNSS approach will allow more rigorous self-checking to take place.

The results presented in this paper illustrate the accuracies and precisions possible using kinematic GPS and kinematic GNSS. This is also possible in real time. The paper also presents some results, illustrating that even though the BeiDou constellation is not yet complete, it is already possible to use the existing satellites, in addition to GPS, to improve the results of GPS alone. By 2020, when BeiDou and Galileo are planned to be fully operational, the benefits of the 120+ GNSS plus extra RNSS constellation will be felt in many areas, including the many applications within the civil engineering field.

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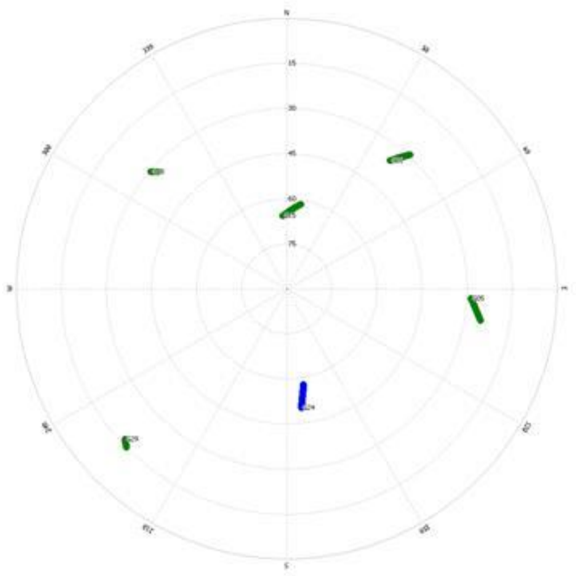

Figure 1, A 5 minute sky-plot of GPS on the 1 July 2014, between 21:00 to 21:05 at Ningbo, China.

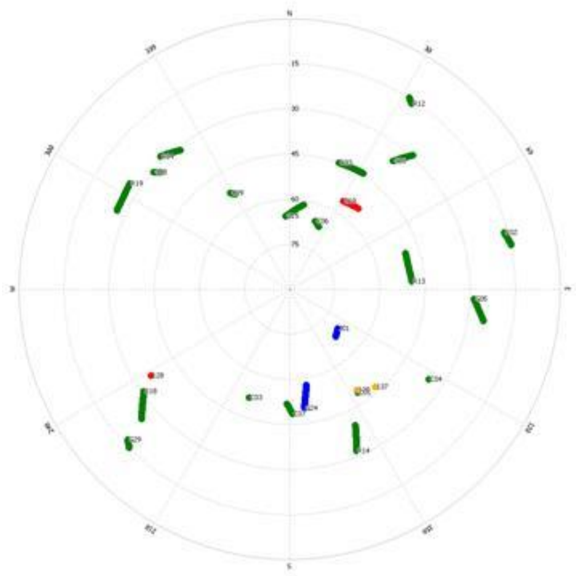

Figure 2, A 5 minute sky-plot of GNSS on the 1 July 2014, between 21:00 to 21:05 at Ningbo, China.

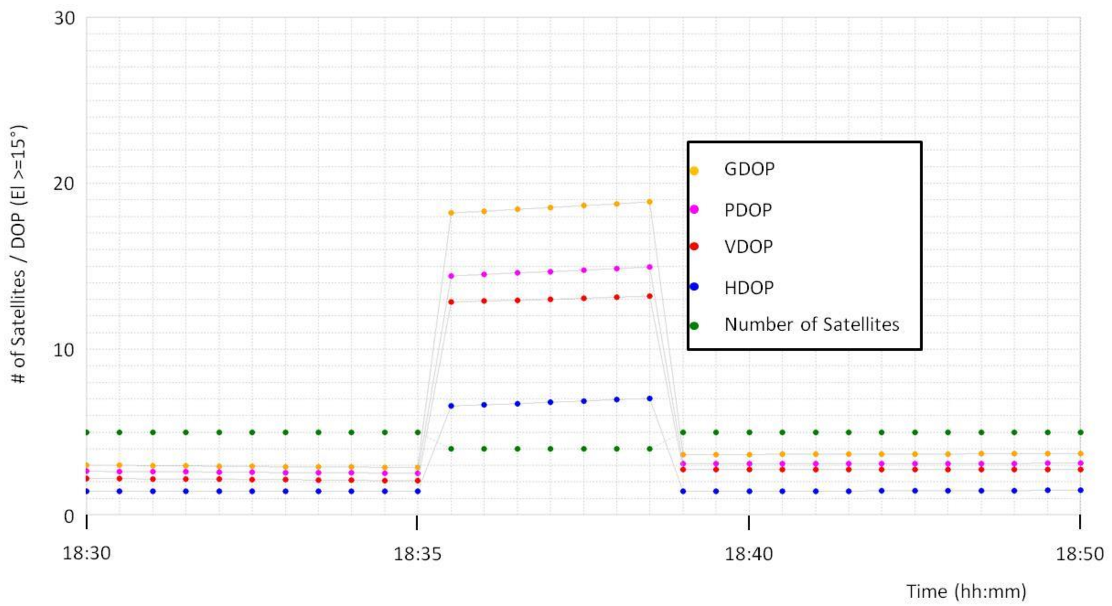

Figure 3, The total number of GPS satellites seen on the 1 July 2014, between 18:30 to 18:45 at Ningbo, China, with a satellite elevation mask of 15°, in an open sky environment without any obstructions.

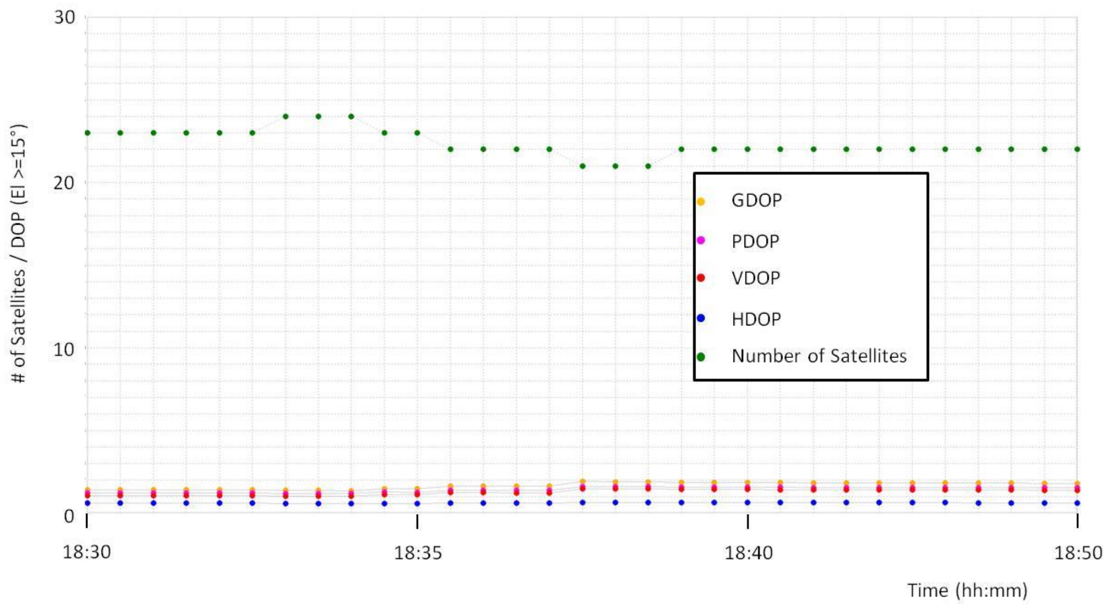

Figure 4, The total number of GNSS satellites seen on the 1 July 2014, between 18:30 to 18:45 at Ningbo, China, with a satellite elevation mask of 15°, in an open sky environment without any obstructions.

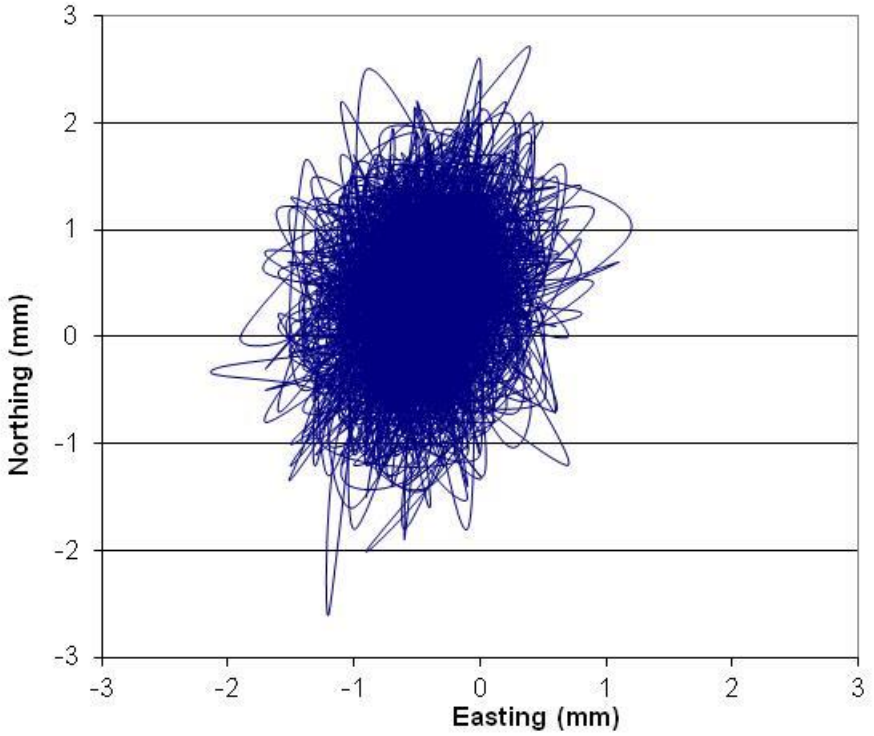

Figure 5, The results from a zero baseline kinematic GPS test, using a Leica 1200 GPS receiver data, over a 45 minute period.

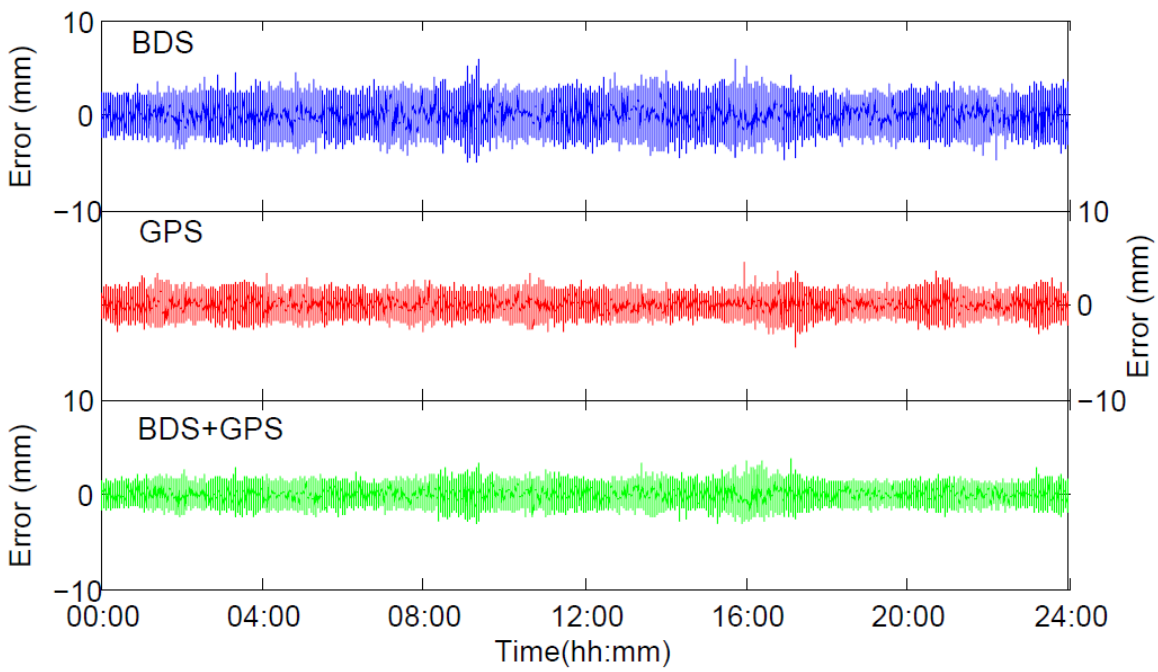

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Figure 8, A GNSS antenna located on the Severn Suspension Bridge’s suspension cable, Location C.

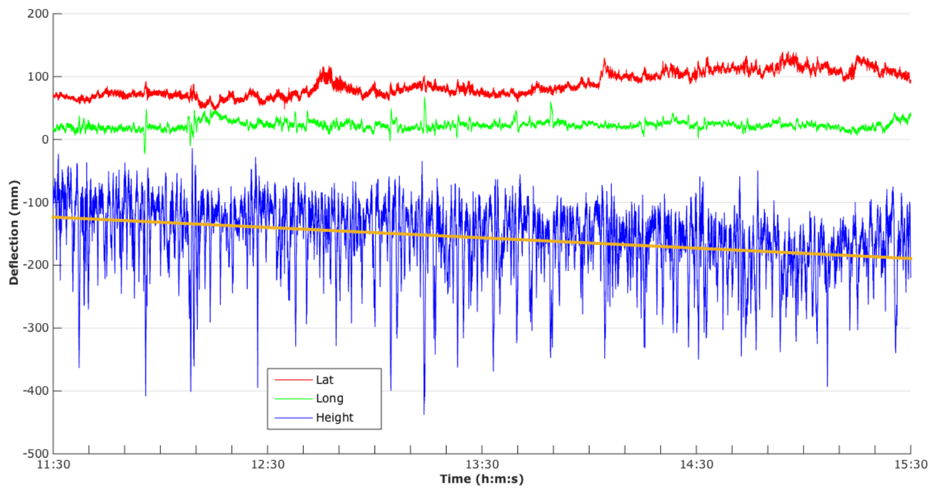

Figure 9, the lateral, longitudinal and vertical movements calculated using kinematic GPS at location C on the Severn Bridge, 18th March 2010, 11:30 to 15:30.

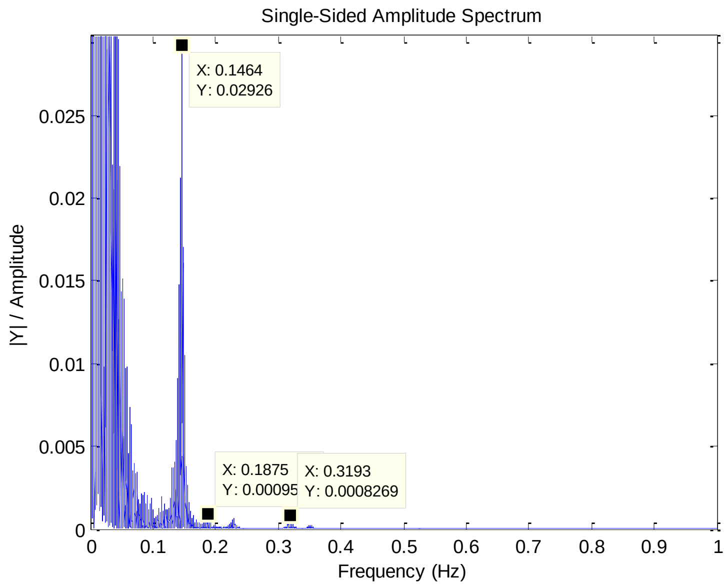

Figure 10, Power Spectral Density Analysis of Location C on the Severn Bridge, illustrating a fundamental frequency of 0.1464Hz in the vertical direction.