Using Multi-constellation GNSS and EGNOS for Bridge Deformation Monitoring

X. Meng [a, *], N. Gogoi [a], A. H. Dodson [a], G. W. Roberts [a, b], C. J. Brown [c]

[a] Nottingham Geospatial Institute, The University of Nottingham, United Kingdom - xiaolin.meng@nottingham.ac.uk
[b] Faculty of Science and Engineering, The University of Nottingham Ningbo, China - gethin.roberts@nottingham.edu.cn
[c] School of Engineering and Design, Brunel University, United Kingdom - chris.brown@brunel.ac.uk

KEY WORDS: GNSS, EGNOS/EDAS, Bridge Monitoring, Network RTK, Accelerometer, Deformation Analysis

ABSTRACT:

Bridges are important transport nodes and play a vital role in socio-economic development across Europe and worldwide. The investments for constructing major bridges are enormous and the associated inspection and maintenance costs can also be very significant. Bridges must survive the attacks of high speed wind loading, earthquakes and current scouring. Aging, and increasing traffic volume and single vehicular weight are other factors affecting bridge serviceability. The University of Nottingham in the UK is one of the world leading institutions that initiated GPS-centred bridge monitoring in the mid 1990s. The first part of this paper is an overview to the past research and development that were carried out by the University of Nottingham on almost all the major bridges in the UK such as the Humber Bridge, the Forth Road Bridge and London Millennium Bridge. Through extensive simulation, the authors introduce achievable positioning performance using GPS and Galileo systems. A latest Structural Health Monitoring System (SHMS) that is based on real-time high-precision GNSS positioning that could take the maximum benefits offered by the European Geostationary Navigation Overlay Service (EGNOS) and the EGNOS Data Access Service (EDAS) is also presented. The final part of this paper covers the deformation monitoring results based on the network RTK GNSS positioning that is integrated with precisely synchronised tri-axial accelerometer to enhance the positioning accuracy, quality (integrity), availability, and robustness of the proposed monitoring system. It is concluded that millimetre 3D positioning accuracy could be achieved using the system proposed in this paper.

* Corresponding author. Tel.: +44 115 84 66029.

1. PAST RESEARCH AND DEVELOPMENT IN GPS-BASED BRIDGE DEFORMATION MONITORING

Many bridges are built in earthquake prone areas, and need to operate under capricious weather conditions. Such bridges are experiencing inevitable ageing and it is estimated that thousands of bridges around the world are obsolete or structurally deficient (Meng, 2002). With increased traffic volumes and single vehicular weights and also due to too often occurrences of natural disasters such as earthquakes, hurricanes, flooding and landslides in recent years, bridge authorities are facing unprecedented challenges in how to safeguard continuous operation of these bridges, to support healthy social and economic development. Furthermore, due to wide adoption of new construction materials, innovative technologies and design codes, modern bridges are built longer and longer, and some of them have single spans approaching 2 km. Table 1 lists the top-ten longest suspension bridges around the world. However, the designs and specifications of these modern bridges might not have been properly tested and verified due to the complexity of the operation conditions of individual bridges, and this is perhaps the reason for the recent closure of the London Millennium Bridge (Roberts, et al., 2006) and complete collapses of several bridges around the world. Therefore, to assess and extend the life spans of those legacy bridges, especially long suspension bridges, without compromising safety concerns, rigorous inspections are essential. Traditional visual inspection technique is a very costly, time consuming and labour intensive approach. It can only be used to partially and qualitatively identify the surface damage at set points in a time frame such as every two years.

The Global Positioning System (GPS) has been utilised for more than two decades in the deformation monitoring of a variety of structures, such as dams, building, bridges, slopes, etc., around the world (Meng, 2002). With the technological advent of GPS positioning, telecommunications, and signal processing as well as public awareness, GPS has been widely tested in recent years for monitoring slender structures such as large suspension bridges and high-rise buildings and gradually becomes an alternative tool for structural health monitoring (SHM) (Meng and Huang, 2009). GPS based bridge monitoring has many appealing advantages over more traditional bridge monitoring sensor systems. For instance, GPS monitoring could be carried out in a real-time and automatic manner for the provision of timely geometric displacements under different weather conditions.

Bridge Name	Rank	Country	Year in Service	Main Span (m)
Akashi Kaikyo Bridge	1 (The longest since 1998)	Japan	1998	1,991
Xihoumen Bridge	2	China	2009	1,650
Great Belt Bridge	3	Denmark	1998	1,624
Runyang Bridge	4	China	2005	1,490
Humber Bridge	5 (The longest from 1981 until 1998)	UK	1981	1,410
Jiangyin Suspension Bridge	6	China	1999	1,385
Tsing Ma Bridge	7	China	1997	1,377
Verrazano-Narrows Bridge	8	USA	1964	1,298
Golden Gate Bridge	9 (The longest from 1937 until 1964)	USA	1937	1,280
Yangluo Bridge	10	China	2007	1,280

Table 1. The World Top-ten Longest Suspension Bridges (http://en.wikipedia.org/wiki/List_of_longest_suspension_bridge_spans)

When GPS is utilised to monitor bridges, it has the capacity to detect two kinds of distinct deformation simultaneously, i.e. the long-term movement caused by the foundation settlement, bridge deck creep and stress relaxation and the short-term motion, or bridge deflection, such as those activated by wind loading, tidal current, earthquake, or traffic loading as shown in Figure 1.

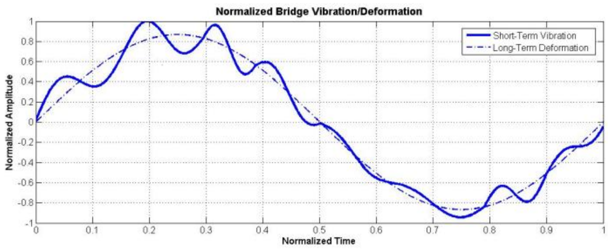

Figure 1. Two typical bridge displacements

Analysis of the response of a long bridge to the short-term irregular loading is much more important in terms of risk level of major damage and its significance for the improvement of bridge design code. However, this deformation is more difficult to measure compared with the identification of long-term deformations. For instance, averaging GPS time series of a few hours or longer can produce a position accuracy of a few millimetres since error sources such as multipath signature which characterises as a low period of movement could be effectively removed. To measure the deformations occurring over a time interval of a few seconds, there is a very short or even no averaging time available for mitigating GPS errors or even to fix the initial integer ambiguities to achieve high positioning solutions. This significantly restricts the usage of GPS positioning in monitoring short-term movements of flexible structures. Furthermore, to measure short-term effects, sampling rates of GPS sensors must be significantly increased, which will incur heavier onboard data processing and communication overloads if Real-time Kinematic (RTK) GPS positioning is required. This is one of the reasons for conducting integrated GPS and tri-axial accelerometer bridge monitoring at the University of Nottingham a decade ago (Meng, 2002). Inadequate positioning accuracy of GPS positioning for monitoring short-span bridges is another constraint to a wide adoption of GPS for bridge monitoring since the majority of bridges around the world are short- to medium-span bridges.

In summary, the major difficulties for the bridgemasters to adopt GPS as a routine monitoring tool to support decision making include:
• High implementation and maintenance cost,
• Low sampling rate, positioning accuracy, reliability, integrity and availability,
• Lack of proper and effective procedures to handle oceanic measurements and extract useful information, and this is extremely true when continuous monitoring is implemented at a high sampling rate, and,
• Low sensor integration capacity to make the monitoring systems more robust.

Progresses achieved in the Galileo system, EGNOS and EDAS services in recent years have paved the way for their early adoption for mass market applications. However, the benefits offered by these systems and services have not yet been explored in bridge engineering and other civil engineering applications, due to several apparent reasons. For instance, Galileo is still under the development/deployment stage and there are only two testing satellites in space. Furthermore, only a few Galileo capable COTS receivers are available but they are very expensive. Hence, very few projects have so far been focused on this domain. The authors appreciate that there is a big gap in public awareness about the Galileo system itself, especially in civil and environmental engineering communities. This situation should be properly addressed after a successful promotion of Galileo system and EGNOS to both niche and mass market application areas such as transport, geodesy, and Location-based Services (LBS).

This paper consists of the following contents: the potential use and the performance analysis of multi-constellation GNSS and EGNOS for bridge deformation monitoring; recent practice at the University of Nottingham in using integrated network real-time kinematic (NRTK) GNSS and triaxial accelerometers for bridge deformation monitoring; and the latest results and findings.

2. MULTI-CONSTELLATION GNSS AND EGNOS FOR BRIDGE DEFORMATION MONITORING

2.1 Combined GPS and Galileo Positioning

Signal obstruction and reflection by dense cables, supporting towers, passing vehicles and other surrounding structures are the major problems for GNSS based bridge monitoring. Tracking a sufficient number of healthy satellites proves to be very difficult. Launch of Galileo system will significantly increase the number of observable satellites. Whilst Galileo satellites are still under development and it is not anticipated that the Galileo system will enter its full operational capacity (FoC) by 2020, a software based simulation tool was employed to analyse the possible performance of multi-constellation GNSS (Meng, et al., 2003). This in-house Navigation Performance Tool (NPT) was developed at the University of Nottingham to analyze the Dilution of Precision (DOP) statistics for the current GPS constellation both operating alone or when augmented by the proposed Galileo constellation. The NPT has been used as a research and teaching aid and not only performs DOP analysis but also provides statistics for the availability of Receiver Autonomous Integrity Monitoring (RAIM) for multiple user-supplied constellations.

In the simulation computation, the Galileo system is defined as a satellite constellation of 30 in-orbit spacecraft (including 3 spares) with their orbital altitude of 23,222km (MEO) in 3 orbital planes of 56° inclination. Nine operational satellites and one active spare per orbital plane are equally distributed in the three orbital planes. Figure 2 shows the maximum GPS/Galileo HDOP and VDOP value changes against the latitudes in the northern hemisphere during a 24-hour period. Illustrated in the same figure are the ratio changes of VDOP over HDOP values (top curve). It is evident that the HDOP values of combined GPS and Galileo constellations are quite flat along the latitudes, the HDOP values are much smaller than the VDOP values, but the VDOP values have a general increasing trend.

Figures 3 and 4 further illustrate the global GDOP variations. To obtain sound positioning solutions with GNSS, the GDOP value should be less than 6. From Figure 3, it is apparent that with the GPS only system the positioning accuracy would not be guaranteed, even along the equatorial regions.

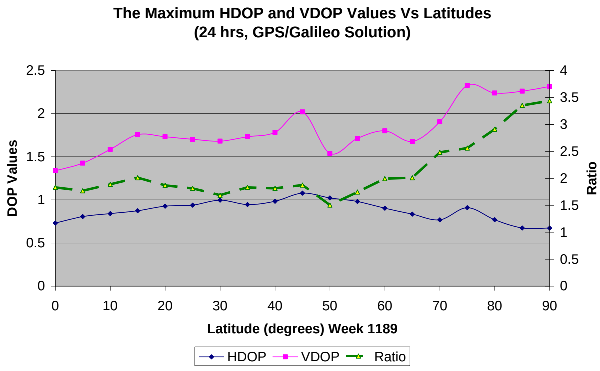

Figure 2. Simulated HDOP and VDOP values, DOP ratios of combined GPS and Galileo constellation against the Changes of Latitude.

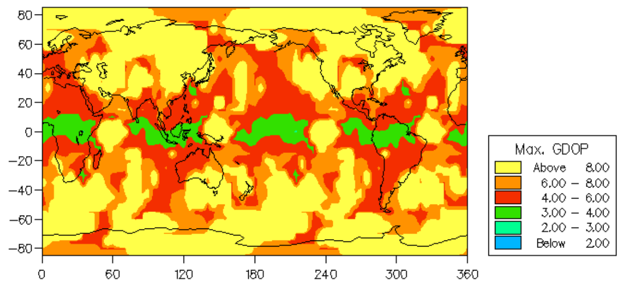

Figure 3. Global Distribution of GDOP Values for the GPS only System

In Figure 4, the fact that the GDOP values of combined GPS and Galileo positioning are less than 4 implies that it is possible to conduct continuous and precise positioning for most demanding engineering applications such as bridge deformation monitoring with the launch of Galileo satellites. It can also be found from this figure that the GDOP values along the equatorial regions are less than 2. However, high ionospheric effect would compromise the positioning quality in these regions.

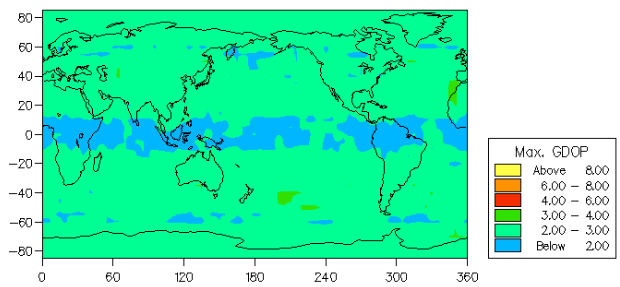

Figure 4. . Global Distribution of GDOP Values of Combined GPS and Galileo

2.2 Potential Contribution of EGNOS/EDAS for Bridge Deformation Monitoring

EGNOS is the acronym for the European Geostationary Navigation Overlay Service that consists of three geostationary satellites and a network of ground stations. EGNOS achieves its aim by transmitting a signal containing information on the reliability and accuracy of the positioning signals sent out by the GPS satellites (http://www.esa.int/esaNA/egnos.html). The EGNOS Data Access Service (EDAS) offers a ground-based access to the EGNOS data collected and generated by the

EGNOS infrastructure which is composed of ground stations (currently 34) distributed over Europe and North Africa (http://www.gsa.europa.eu/go/egnos/edas). The main data sets provided via EDAS include:

- Raw GPS, GLONASS and EGNOS GEO observations and navigation data collected by the entire network of Ranging and Integrity Monitoring Stations (RIMS) and Navigation Land Earth Stations (NLES)
- EGNOS augmentation messages such as integrity, ionospheric delay corrections and other relevant corrections, as normally received by users via the EGNOS Geostationary satellites.

When considering the potentials of EGNOS/EDAS for the provision of ultra precision bridge deformation monitoring, we need to use the information gathered from them for the generation of highly accurate network RTK (NRTK) GNSS corrections. The NRTK Central Processing Facility (CPF) has the fundamental mission of generating in real-time the required NRTK user products for the precise, fast, and reliable positioning and navigation. One important difference, however, is that the NRTK user's real-time positioning is based on the carrier phase measurements and data integrity provided by EDAS RIMS servers. Integrity information will be received from the EDAS service by the CPF. Only those GNSS satellites that have passed the integrity checks will be used to generate the final NRTK corrections. This is true for de-selecting the satellites with a high level of noise using the EDAS service. It is also envisaged that the availability of the EDAS service will also make the CPF capable of providing precise troposphere residual delay as well as precise estimation of total electron content (TEC) delay and inter-frequency delay code bias (DCB). This will create an unprecedented capability of providing NRTK users with very precise corrections without requiring high bandwidth for the transmission of the messages, when compared to other carrier phase based navigation techniques. The envisaged optimized low broadcast rate is based on the fact that the extra information in its broadcast messages (e.g., ionospheric corrections, DCBs, and ambiguities) will take advantage of typically slow variations of those parameters. However, it needs to be pointed out that the current EGNOS and EDAS service do not provide relevant observations and correction information for the Galileo system. To achieve the above goals, a brand new NRTK processing engine also needs to be developed. This is the work that is being carried out at the University of Nottingham.

3. INTEGRATION OF NETWORK RTK GNSS POSITIONING WITH TRI-AXIAL ACCELEROMETERS

The major deficiencies of previous research in the integrated GPS and accelerometer monitoring system that was carried out by the University of Nottingham include: the difficulties in synchronising the measurements attained from two completely independent sensor systems, and the difficulties in precisely indentifying the deformation signatures from both GPS and accelerometer measurements due to lack of advanced data processing and fusion algorithms (Meng, 2002). Figure 5a shows a Precise Time Data Logger (PTDL) that was developed by the Geospatial Research Centre (a spin-off company of the NGI) for logging, capturing and time stamping the digital data from multiple sources to a very high degree of accuracy. Figure 5b is the set-up of a GNSS antenna on the Wildford Bridge in Nottingham. More details about this bridge could be found from Meng (2002). This solved the synchronisation problem when fusing the data sets from a tri-axial accelerometer when it is used together with a GNSS receiver.

Figure 5a (left). A PTDL that was used for logging the tri-axial accelerometer data; 5b (right). An antenna set-up with a clasp on the bridge handrail.

Due to the size of the Wilford Bridge and the nature of a suspension bridge, a little force applied will easily make this bridge move a few centimetres. During a recent trial, the bridge was excited to identify the response that could be measured with NRTK GNSS positioning and the accelerometer. Precisely synchronized acceleration measurements were double integrated to obtain the geometric deflection of the bridge using the algorithms presented by Gogio (2011). Figure 6 consists of five particular events that were activated by the forced movements. Figures 7 to 12 show the bridge deflections for each individual event. Through comparison of the vertical movements by two systems it can be found that both the network RTK GNSS and the accelerometer had picked up the bridge responses of a few millimetres precisely but differences in the responding amplitudes are evident. Due to a higher noise level in GNSS solutions it might be difficult to identify these responses from GNSS only solutions.

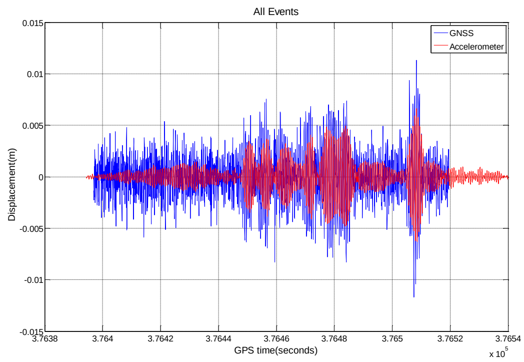

Figure 6. Vertical deflections in all events excited by external forces.

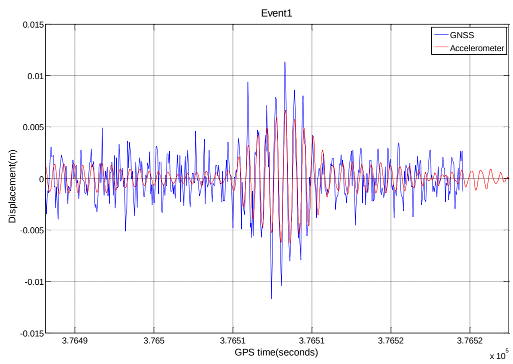

Figure 7. Vertical bridge deflection in event 1.

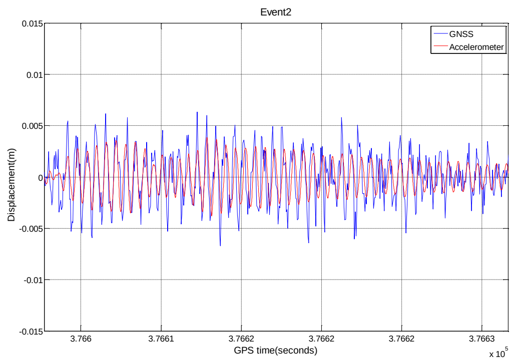

Figure 8. Vertical bridge deflection in event 2

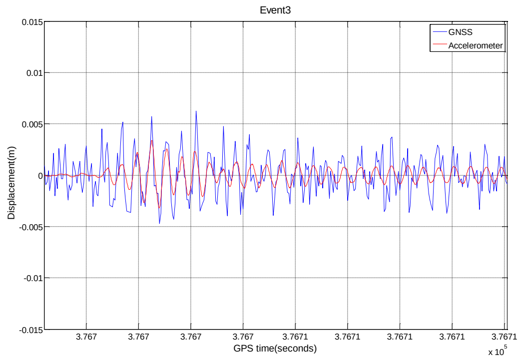

Figure 9. Vertical bridge deflection in event 3

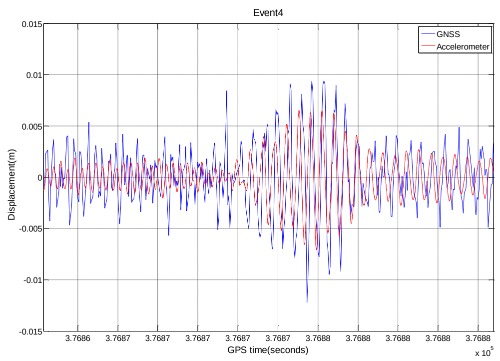

Figure 10. Vertical bridge deflection in event 4

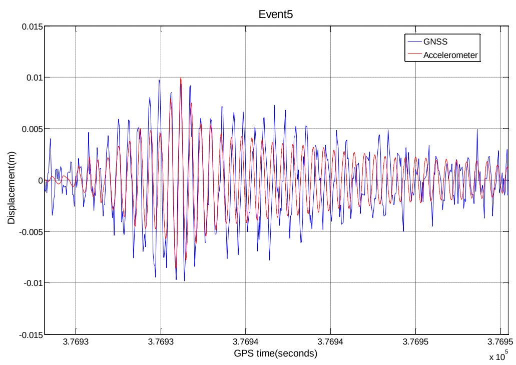

Figure 11. Vertical bridge deflection in event 5

4. CONCLUSIONS

This paper discussed how multi-constellation GNSS could improve the performance of GNSS based bridge deformation through adoption of EGNOS and EDAS services in Europe. Simulation results show that with the addition of the Galileo satellites into GPS positioning it is possible to significantly improve positioning accuracy, integrity, availability and robustness. This paper also discussed how an integrated monitoring system that consists of network RTK GNSS and a tri-axial accelerometer could be utilised to monitor bridge deformation of a millimetre level.

References from Journals:
Roberts, G. W., Meng, X., Brown, C. J. and Dallard, P., 2006. GPS Measurements on the London Millennium Bridge, ICE Bridge Engineering Journal, 159(BE4), 153-161.

References from Books:
Meng, X. and Huang, W., 2009. Global Navigation Satellite Systems (GNSSs) for Monitoring Long Suspension Bridges, Encyclopaedia of Structural Health Monitoring, John Wiley & Sons. DOI: 10.1002/9780470061626.shm079.

References from Other Literature:
Gogio, N., 2011. Structural Health Monitoring System based on GNSS and Accelerometers, MSc Dissertation, The University of Nottingham.

Meng, X., 2002. Real-time Deformation Monitoring of Bridges Using GPS/Accelerometers, PhD Thesis, The University of Nottingham.

Meng, X., Dodson, A. H., Noakes, C. and Roberts, G.W., 2003. GPS satellite geometry and its implications for structural deformation monitoring. *In:* The 16th International Technical Meeting of the Satellite Division of the Institute of Navigation, September 9-12, 2003, Portland, Oregon, USA.