Structural Health Monitoring using a GPS sensor network

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Abstract

Over the last decade, the rapid expansion of Global Navigation Satellite Systems (GNSS) coupled with the incremental improvements on the existing GPS constellation has continuously increased the robustness of satellite positioning, therefore significantly improving the reliability and the possibilities of a GNSS-based structural health monitoring system. Moreover, thanks to constant evolution, GPS-only receivers have proven to be more and more efficient with relatively simple hardware, provided that they are used in an appropriate workflow such as relative positioning with short baselines. This paper presents an application of a network of cost-effective GPS receivers as a part of a monitoring system. Monitoring data are acquired from a network of a dozen of GPS “Geocube” stations installed on a suspended bridge, the Brotonne Bridge, in France. One main objective of this network is to be able to detect some changes in bridge behaviour. Data from GPS sensor is analysed and correlated with traditional data, such as piers temperature. This study validates that a GPS sensor network can provide useful and reliable data for structural monitoring.

1. Introduction

Global Positioning System (GPS) is a satellite constellation providing a positioning service on almost every part of the globe. Launched in 1973 by the US military in order
to provide global and accurate navigation data to their fleets, GPS positioning was made publicly available in 1983 with downgraded accuracy (~100m). It wasn’t until 2000, with the context of multiple scientific breakthroughs to use the supposedly militaryreserved signal and the lowering interest of hexametric positioning accuracy, that the full GPS service was released to the public. It has then been joined by the compatible Russian clone, Glonass, and the upcoming Galileo and Beidou systems, thereby forming the Global Navigation Satellite Systems (GNSS).

GPS positioning relies on three segments: the space segment, constituted of a constellation of satellites broadcasting their coordinates and time data; the ground segment, constituted of dedicated control stations regularly calculating satellites’ positions and clock corrections; and a user segment. The user segment requires a GPS receiver, which is able to retrieve broadcasted data, and use it to estimate distances between itself and each satellite, known as pseudoranges. Pseudorange with each satellite is expressed in (Eq. 1), where \((X_r, Y_r, Z_r)\) are the receiver’s coordinates and \((X_s, Y_s, Z_s)\) the coordinates of the satellite. The estimations are polluted by wave propagation inaccuracies and clock (receiver and satellite) errors. With at least four satellites in view, a receiver is able to compute a position in a global frame with a metric precision (Fig. 1).

\[
\rho_r^s = \sqrt{(X_r - X_s)^2 + (Y_r - Y_s)^2 + (Z_r - Z_s)^2}
\]  

\((X^2, Y^2, Z^2)\)  \((X^3, Y^3, Z^3)\)  \((X^4, Y^4, Z^4)\)

\((X^1, Y^1, Z^1)\)  \(\rho^2_r\)  \(\rho^3_r\)  \(\rho^4_r\)  \(\rho^1_r\)

\((X_r, Y_r, Z_r)\)

Figure 1. Schematic representation of the pseudoranges

Using the phase of the signal carrier wave requires a denser processing to eliminate errors and uncertainties, but it allows a much more precise positioning, offering up to millimetric precision with specific methods. Multiple techniques have therefore been developed, such as Precise Point Positioning (PPP), relying on the use of adjusted corrections of wave propagation in the atmosphere and orbit parameters; and Relative Positioning, using a fixed station of known position to correct observations. Continuous evolutions of hardware technologies and processing techniques over the last two decades have made GPS a versatile tool.

With strong capabilities in terms of precision in local or global frame, long term stability and native synchronization, GPS positioning has become a good candidate for structural monitoring applications in civil engineering. While this potential has already been under investigation over past years with high-end GNSS receivers, the abilities of a cost-effective operational network of GPS receivers requires further investigations.
This paper proposes a short review of applications of GPS techniques in SHM through the last two decades, followed by a presentation of a GPS-based monitoring system installed on the Brotonne Bridge, and a brief analysis of acquired datasets.

2. Global positioning in structural health monitoring

The first experimentations using GPS to analyse structural characteristics have been realized during the 90s, before official opening of full GPS signals to public access. In 1995, an experiment conducted by Lovse et al.\(^{(1)}\) used GPS receivers to estimate low frequency and large amplitude displacements of the Calgary Tower in Canada. In 1997, Ashkenazi et al.\(^{(2)}\) used differential GPS to analyse the lateral movements at midspan of the Humber Bridge in England. Nakamura et al.\(^{(3)}\) (2000) compared the static displacements of a bridge girder measured with GPS receiver to a Finite Elements Model (FEM), with encouraging results. However, these studies also pointed out that GPS was a new approach, with relatively short datasets, and positioning errors prevented the monitoring of small displacements and higher frequency dynamic response.

With the incremental updates of hardware technologies, and developments of processing techniques, experiments have been conducted to assess the capabilities of GPS in order to characterize oscillations and dynamic behaviour (Kijewski-Correa et al.\(^{(4)}\), Nickitopoulou et al.\(^{(5)}\) and Psimoulis et al.\(^{(6)}\)). In experimental conditions, relative positioning techniques are able to observe oscillations up to 4Hz with amplitudes down to 5mm, with high-end 20Hz sampling receivers, thus confirming their potential on various types of structures.

Investigations have been carried on to confirm performances with in-situ conditions. Xu et al.\(^{(7)}\) designed a monitoring network based on Real Time Kinematic (RTK) processing to identify wind-induced harmonic modes of a suspended bridge. Meo et al.\(^{(8)}\) were able to extract, via wavelet transform, modal properties of a small footbridge, with encouraging results for monitoring of smaller and more rigid structures. Cazzaniga et al.\(^{(9)}\) conducted a 3 months experiment on the chimney of a power plant in Italy including GPS receiver, in order to evaluate the integrity of the structure. Breuer et al.\(^{(10)}\) were able to quantify the responses to temperature variations and wind loads of the Stuttgart TV Tower, proposing a monitoring approach based on threshold surveillance. In 2011, Kaloop et al.\(^{(11)}\) evaluated the sensitivity of GNSS signals to structural damage on a cable stayed bridge.

State of the art studies often rely on high-end GNSS solutions, whose prices have not lowered during the last decade, if not the opposite. Industry leaders price high-end monitoring solution up to 20–25k€ per station. Moreover, with large antennas and not particularly low power consumption, high-end GNSS hardware is often not adapted for dense network applications. A need for affordable or low-cost solutions has emerged, sacrificing multiple frequency/constellations abilities and/or sampling rate. In this context, the Institut National de l’Information Géographique et Forestière (IGN) developed a single-frequency GPS module, the Geocube, for network monitoring purposes. Its performances have been investigated by Benoit et al.\(^{(12,13)}\) with applications on ground deformations and landslides movements. With very encouraging
results, its performances could make it an affordable, accurate and versatile tool for SHM applications.

3. Data acquisition system

The Brotonne Bridge is a 1,280m long cable-stayed bridge built in 1977 in the region of the Upper Normandy in France. It has a 320m main span made of concrete lying 50m above the Seine River, with two 70m high concrete pylons. Over the last decade, reparations were undertaken in order to reinforce the piers and to change the bearings.

3.1 A single-frequency GPS solution

The Geocube is a compact GPS sensor (Fig. 2) developed by the Opto-Electronics, Metrology and Instrumentation Laboratory (LOEMI) of the IGN. The small-packaged sensor consists of three modules:

- A GPS module, single-frequency, based on a U-Blox Neo6 receiver chip, with integrated antenna on top of the module;
- A management module, responsible of the input/output streams, data backup, communication control and power management;
- A radio module, offering a low power consumption transmission between sensors.

The Geocube is designed to work in a wireless network setup: each sensor transmits data with its radio/Wi-Fi module, using bounce transmission if needed, to a centralized coordinator. The coordinator will either compute positions and transmit them to a dedicated server, or directly transmit for off-site processing. The GPS data is post-processed via relative positioning: one (or more) of the Geocube is used as a reference station to compute Double Differences (DD) and correct the observation data of the rover stations.

![Figure 2. A Geocube sensor installed on the Brotonne Bridge](image)

The main advantages of the Geocube rely on its ease of deployment, its wireless connection, its accuracy at a relatively low price (1200€ per sensor). However, the processing uses specific constrains over the position and the velocity of the sensor, thus
restraining the application to slow displacement observations (under 10cm per minute). The sensor is also sensitive to multipath effects, with notable degradation of the precision with the presence of obstacles or rain.

3.2 On-site sensors

The bridge is instrumented since May 2017 with 14 Geocubes, installed on strategic points (Fig. 3) and recording at synchronized sampling rate of 30 seconds:
- 3 receivers located at the main span’s center (S);
- 2 receiver on the pylon summits (P1,P2);
- 4 receivers around the joint (J1) between abutment and bridge’s southern section;
- 1 receiver located 40m northern of J1;
- 2 receivers around the joint (J2) between southern section and main section;
- 2 receivers located on bridge’s northern region.

The two central piers (Pier 11 and 12), are instrumented with draw wire sensors in order to measure convergence inside the piers, and both internal and external temperature with resistance temperature detectors, at a sampling rate of 30 minutes.

3.3 GPS data processing

Geocubes initial positions are calculated to obtain preliminary coordinates. One of the Geocubes, installed next to the bridge, is selected as reference station, and its coordinates are considered as fixed. The relative positions of all the Geocubes on the
structure are then computed for each epoch (synchronized observation) from this reference using raw carrier phase observations.

Observed phase between emitted and received signals \( \phi^s_r \) is expressed in (Eq. 2), where \( p^s_r \) is the pseudorange as expressed in (Eq. 1), \( dt_r \) is receiver clock bias, \( dt^s \) is satellite clock bias, \( \lambda \) carrier signal wavelength, \( \tau^s_{r,iono} \) and \( \tau^s_{r,tropo} \) are errors due to wave propagation in the ionosphere and the troposphere, and \( \varepsilon \) is residual error. Finally, \( N^s_r \) is known as the integer ambiguity, and represents an integer number of wavelength \( \lambda \). It needs to be estimated in order to get a valid position: this is often referred to as Ambiguity Resolution.

\[
\phi^s_r = \frac{1}{\lambda} \cdot p^s_r + \frac{c}{\lambda} \cdot (dt_r + dt^s) - N^s_r + \tau^s_{r,iono} + \tau^s_{r,tropo} + \varepsilon
\]  

(2)

Double differences of carrier phase equations are applied between satellites/receivers pairs in order to remove most of error terms in (Eq. 2). With the short baseline of the network (under 2km), all errors due to clocks biases and ionosphere are considered mitigated. Remaining troposphere-induced errors are corrected using Saastamoinen model. An Extended Kalman Filter (EKF) is the used to compute receivers’ positions using double differences for each epoch.

4. Acquired data

This section presents observations acquired by the Geocube network on the Brotonne Bridge, and compares them to other sensor data in order to validate Geocube performances.

GPS data are transformed to an arbitrary local reference frame, aligned with the bridge’s orientation. X component is defined as transverse component, mostly east-west oriented (east is positive); and Y as the Longitudinal component (mostly north-south oriented, north is positive). Data in the following section consist in two month datasets, acquired during May and October 2017.

4.1 Pylons

Time series of both pylons P1 and P2 (Fig. 3) display highly visible daily phenomenons (Fig. 5). On the X (transverse) axis, highly correlated, if not identical, periodic displacements are observed between the two pylons. While amplitude (up to 15cm) may vary, period is stable, with daily negative peak every noon (west-oriented), and maximum (east-oriented) at night. These displacements are induced by daily heating of concrete pylon east and west sides. In the morning, sun heats pylon east side, and thermal expansion tilts the structure to the west (negative X component). Peak is at noon, with the maximum temperature gradient (East/West external probes) between pier two sides. As the sun starts heating the other side of the piers, pylon tilt progressively changes.

This direct relation can be visualized by estimating a ‘virtual’ temperature gradient along the piers (Fig. 5). Temperature gradient is calculated between western probe on
Pier 11 and eastern probe on Pier 12 (Fig. 4). As the thermal probes used are near the exterior of the piers, a two hours delay is observed, highlighting thermal inertia of the concrete to surface heating.

![Figure 5. X component of summits and estimated W/E temperature gradient](image)

The Y-component also displays daily periodic displacements, with much lower amplitudes (around 2cm, Fig 6a.). Pylons are in opposite phases. This behaviour may be explained by the tension applied by the main span on the two pylons. With higher inner temperatures, the span expands, pushing away the pylons; and with lower temperatures, it constricts, pulling the pylons towards each other.

![Figure 6a. (up) Y component of pylon summits](image)

![Figure 6b. (down) Distance between summits vs average external temperature](image)
GPS allows to easily estimate the distance between the two pylons summits, which can be correlated with ambient temperature variation of the structure (calculated as the mean external temperature of the piers). A twelve hours phase offset is observed, representing thermal inertia of the structure (an offset is added to temperature estimation in Fig. 6b). This delay is significantly longer than the one observed for the X-axis oscillations, as it depends on the inner temperature of the structure instead of surface heating of the concrete. Not only daily oscillations can be correlated, but also the longer-term temperature changes over the week.

These observations show that the Geocube network is able to detect and quantify static deformations due to thermal response of the structure most flexible parts. Moreover, a simple health control of the pylons could be considered by following linear correlation coefficients between both summits horizontal displacements, and between the summits and external temperature.

### 4.2 Main span

Two GPS sensors installed on the main span (S), one at each side of the road, display nearly identical behaviours in vertical component. These displacements can be compared to external temperature cycles (Fig. 7). Like previous GPS datasets, temperature cycle is in opposite phase (twelve hours phase), but sensor positions do not seem to be affected by weekly temperature variations.

![Z Component of GPS sensors on the main span](image)

**Figure 7. Vertical displacement at the center of the main span compared to external temperature measurements**

The transversal component is also similar between the two sensors (Fig. 8a), with slightly higher amplitudes of displacement observed on the western sensor. This may be explained by the western side of the span (aval) being exposed to higher wind loads. Moreover, daily span lift-up is synchronized with pylon spreading (Fig 6b).

An unusual behaviour of the western sensor is observed during October (Fig. 8b), with a 3cm movement towards west. Only one of the two sensors shows this temporary displacement. The abruptness of the movement, with return to initial position, and the absence of particular wind or temperature conditions makes it difficult to distinguish between an unknown phenomenon and a potential GPS error. However, similar
behaviour has been observed on some other Geocubes during the same period (but not all of them, suggesting this is not an issue with the reference station). This observed phenomenon will need further investigations to understand its causes, and shows that peculiar care must be taken when interpreting GPS time series.

Figure 8a. (up) X component of GPS sensors on the main span (May)
Figure 8b. (down) X component of GPS sensors on the main span (October)

4.3 Southern abutment & joints

Bridge deck is linked to southern abutment (fixed section) with a deformation joint (J1), on which two pairs of Geocubes have been installed on both sides of the road (Fig. 9a). The two sensors on the moving part display symmetrical behaviours (Fig. 9b), which are in good accordance with movements observed on the other end of the southern bridge section (Fig. 10). However, it should be noted that western abutment Geocube (supposedly fixed) displays irregular daily oscillations which are not observed on its eastern counterpart. Interpretation of those observations is still under investigation, as the source is unknown (gps error, sensor placement issue, local thermal expansion, ground displacement, etc…). In any case, sensors provide reliable information on mobile section movements, and joint expansion cycles can be monitored by using the distance between the sensors (similarly to what has been shown with pylons in section 4.1).

In a similar way, Geocubes can also be used to monitor cantilever joint (J2) expansion, on which a single pair of Geocubes has been installed in the center of the road. Both sensors show a symmetrical behaviour between the two bridges sections (Fig 10). Data
from the all sensors installed on this section can be used to monitor potential geometrical deformations of this road segment.

![Image](image.png)

**Figure 9a.** (left) Pair of sensors on joint J1  
**Figure 9b.** (right) Relative displacements on longitudinal components of both pairs

**Figure 10.** Sensor data on both sides of the cantilever joint

5. Conclusions

In a context of recent scientific interest in low-cost GNSS receivers, the Brotonne Bridge was equipped with a network of cost-effective GPS receivers (Geocube) to monitor potential structure deformations. A brief analysis of two monthly datasets pointed out the following network characteristics:

- Despite relying on single-frequency/single-constellation receivers, the use of a short baseline (under 2km) in relative GPS positioning combined with appropriate processing steps and parameters produces data with sufficient accuracy for monitoring of slow displacements/deformations of slender civil engineering structures.
- With a synchronized 30s sampling, the Geocube network is able to identify static response of bridge critical elements (pylons, main span, joints), with coherent results between receivers and temperature measurements. The relation between different sensors time series can be used to monitor the behaviour of specific bridge sections.
- GPS receivers proved to be a useful tool to generate dense time-series of distance between two very distant points, which could be used as structural
health indicators. Such time series would otherwise be difficult to monitor with conventional instrumentation, due to the complexity of using a common reference.

- However, due to the nature of the information generated by GPS (a single tri-dimensional point), the nature of positioning errors, and sensor placement constrains, it is difficult to identify the source of phenomenon and to mitigate errors from unknown phenomenon on the time series.

Further investigations need to be done to confirm system reliability and the previous conclusions over a full-year of data, taking in account seasonal effects. Comparison with reference data from bridge numeric model, will be undertaken to definitively validate GPS network performances and to highlight additional information that might be extracted from it.

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References and footnotes


