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# Recent Advances of Structures Monitoring and Evaluation Using GPS-Time Series Monitoring Systems: A Review

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**Abstract:** This paper presents the recent development in Structural Health Monitoring (SHM) applications for monitoring the dynamic behavior of structures using the Global Positioning Systems (GPS) technique. GPS monitoring systems for real-time kinematic (RTK), precise point positioning (PPP) and the sampling frequency development of GPS measurements are summarized for time series analysis. Recent proposed time series GPS monitoring systems, errors sources and mitigation, as well as system analysis and identification, are presented and discussed.

**Keywords:** GPS; SHM; dynamic; monitoring; evaluation

## 1. Introduction

The process of implementing damage detection and performance analysis strategies for engineering structures are defined as Structural Health Monitoring (SHM) [1–6]. SHM systems are utilized to analyze and predict the health state of structures under unknown future environmental conditions [7]. SHM deals with monitoring systems over time through collecting sampled dynamic response measurements using an array of sensors. The extraction of performance-sensitive features from these measurements, and the analysis of these features are usually used to determine the current state of a given system's health. In other words, it is defined as the use of in situ, non-destructive techniques and analysis of structures' response in order to identify if damage or movement has occurred, determining its location, severity and evaluating the consequences of damage on structures [2,8,9].

Two types of monitoring systems are usually used: long- and short-term systems. A specific type of monitoring system is selected based on its cost and the importance of the monitored structure. Long-term monitoring systems are designed to measure structures' behavior along their lifetime and used for important structures, like tall buildings and long-span bridges [2,10,11]. Short-term monitoring systems are used to check the status of a given structure to ascertain whether it is healthy or damaged. For example, Annamdas et al. [12] presented the application of monitoring systems for important structures in Asia, and they concluded that long-term SHM systems have rapidly grown in pace with the economic growth of Asian countries. Moreover, Ou and Li [13] evaluated the sensors used for long-term monitoring systems in China, and they concluded that the lifecycle behavior of structures can be measured and evaluated based on long-term monitoring system. In addition, short-term monitoring systems can be used to assess the sensors design experimentally. Impeded sensors are used with long-term monitoring systems, while attached sensors are used in short- and long-term monitoring systems. Different types of sensors are used to detect both structures' static and dynamic behavior. The dynamic behavior of structures is measured using accelerometers, and displacement sensors are used to measure static and semi-static behavior, while strains are used for assessing structures' reliability. Global Positioning Systems (GPS) sensors are used in long- and short-term monitoring systems. Relative displacement is used to assess structures' performance where the principals of the geodetic monitoring system are applied. Although the absolute measurements of movements are more accurate than the relative measurements, the development, evaluation, and the design of monitoring systems for the absolute measurements are still limited.

Recently, geodetic monitoring systems are developed especially for structures' monitoring [14]. GPS or global navigation satellite systems (GNSS) represent the highest advanced geodetic monitoring systems used to evaluate structures' behavior [15]. The GPS measurements concepts and monitoring system design are presented in [1–3]; GPS monitoring systems are improved to measure dynamic responses up to 50 Hz [10,16]. Monitoring structures' behavior is extended to different structures types such as dams, long- and short-span bridges, seismic evaluations, and tall buildings [10,15,17–20]. The GPS used to measure the positions of the monitored points in three directions in both static and dynamic cases. However, with the development of GPS sampling frequency, structures' full behavior can be monitored in both time and frequency domains [15].

The GPS measurements are classified as static, semi-static and dynamic measurements [16,21,22] with accuracy modes of 0.5–2 and 1–5 cm for the static, semi-static and real-time kinematic (RTK), respectively [10]. The dynamic measurements accuracy using the precise point position (PPP) system can reach 2 cm in horizontal directions based on an experimental study conducted by Moschas et al. [23]. Yigit and Gurlek [24] conducted an experimental study to evaluate cantilever structures' dynamic behavior based on PPP-GNSS (between 0.94–2.90 Hz), and they reported that the accuracy of the monitoring system approaches 1 cm in the vertical direction. The measurements modes are affected by GPS errors, and this is the main disadvantage of GPS sensors [23,25,26]. Multipath errors are the main source of measurements' errors and, accordingly, limit GPS applications [27,28]. Therefore, signal processing and different measurements techniques are applied with high sampling frequency with GPS sensors to enhance the dynamic measurements accuracy of structures [3,29].

Given the cost of high-accuracy GPS monitoring systems, some researchers recently developed monitoring systems based on GPS sensors to decrease the monitoring cost. However, their results still have limited accuracy. Therefore, these results can be utilized to estimate sensors locations. For example, Zhao et al. [30] examined the use of smartphones in measuring bridges vibration, and they found that the developed monitoring systems have a significant accuracy with small error under 1.1%. Ozer and Feng [31] examined the use of smartphones for displacement measurement and evaluating the dynamic behavior of structures. They concluded that the developed system is sensitive to structures' behavior and can be used as an initial stage to check structures' behavior. In addition, Jo et al. [32] evaluated a low-cost GPS receiver and found that the accuracy for the dynamic accuracy of designed system is low. More detail of these systems can be found in [33–35].

This review summarizes the main points of the GPS monitoring techniques. These points include the theory, the errors, the recent advances in GPS sampling frequency and the monitoring evaluation techniques for assessing structures' dynamic behavior.

## 2. GPS Measurement Theory, Errors and Recent Developments

GPS measurements basics are presented in [10,36], while GPS signals, contents, and principals are presented in [15,37]. The GNSS details, design of the coordinates' measurements, and satellite signals and components are described in [37,38]. In relative measurements, GPS data collection is similar to other monitoring sensors. However, dynamic GPS or GNSS signals are collected based on the RTK or PPP monitoring systems. GPS sensors are attached with software to calculate coordinate positions of the measured points [26,37,39]. Data collected based on relative base station is used to measure the accurate position of the monitoring points [15,16,19,21]. Previous GPS monitoring systems are dependent on a wire system to collect data, but nowadays, wireless GPS systems are developed to decrease the monitoring cost [40–43]. Figure 1 shows the GPS collection data from antenna to data processing.

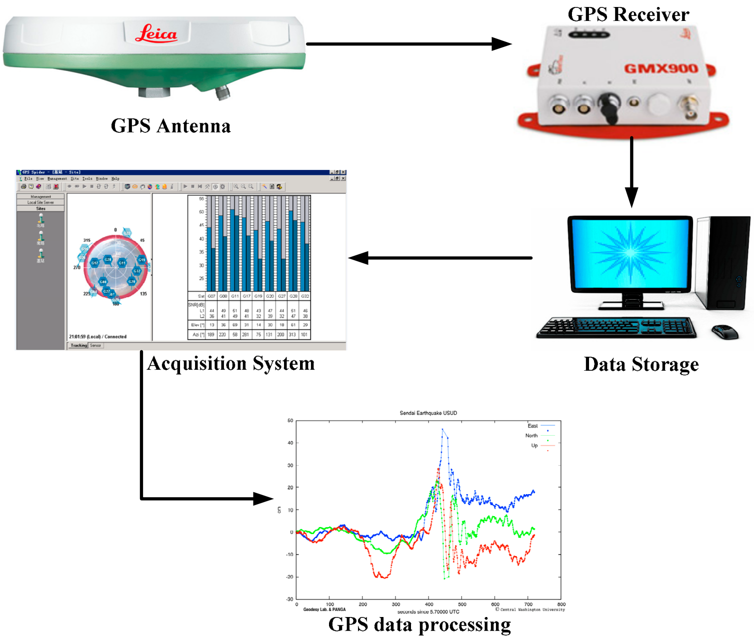



**Figure 1.** Global Positioning Systems (GPS)-Structural Health Monitoring (SHM) network scheme [44].

In addition, some software packages are designed to improve GPS static and dynamic measurements [24,26]. The collected data are processed in World Geodetic System (WGS-84) coordinates and then converted to local coordinate system. Ogundipe et al. [45] and Kuan [46] presented the coordinate transformation technique that can be used in GPS monitoring systems. Local structures coordinate system should be established for the analysis and the evaluation of GPS measurements data. Monitoring systems require measurements with high accuracy in the three directions. GPS monitoring systems require clear visibility to the sky as existing obstructions can reflect incoming GPS signals, causing what is known as multipath [37]; therefore, to monitor points close to structures, assistant members should be designed and attached to the monitored structures to overcome the multipath effects [47]. GPS errors resulting from ionosphere, troposphere, satellites and receivers are presented in [37,38,48]. In addition, vibration noises affect collected signals from any used sensors. Figure 2 represents the long (semi-static), short and dynamic components of the displacement measurements. Moschas and Stiros [26] concluded that these types of noises affect the monitoring systems for both short and long monitoring times. Table 1 presents the noise type of different durations of monitoring systems [26]. Herein, it should be mentioned that some researchers introduced methods that can be used to detect the behavior of structures using noise and error performances. For example, Peppa et al. [49] used the signal-to-noise ratio of GPS measurements to detect structures movements. Moreover, Souza and Negri [50] utilized the multipath effect to detect structure movements.

GPS sampling frequency is one of the important parts in dynamic performance analysis. Over the past five years, there was significant improvement in the development of new methods and new GPS hardware that increase the GPS sampling frequency, improve signals collection and remove GPS errors. Such improvements enhance the analysis of GPS measurements, as presented in [26,28,29].

The GPS measure structures' displacement responses to a satisfactory level at which the structural displacement response is large enough. However, it is questionable whether the GPS can provide accurate dynamic displacement measurements to sub-centimeter or sub-millimeter level. Recently, the significant progress made in hardware technology has resulted in new types of GPS receivers being explored to enhance the dynamic measurement accuracy [16,28,29].

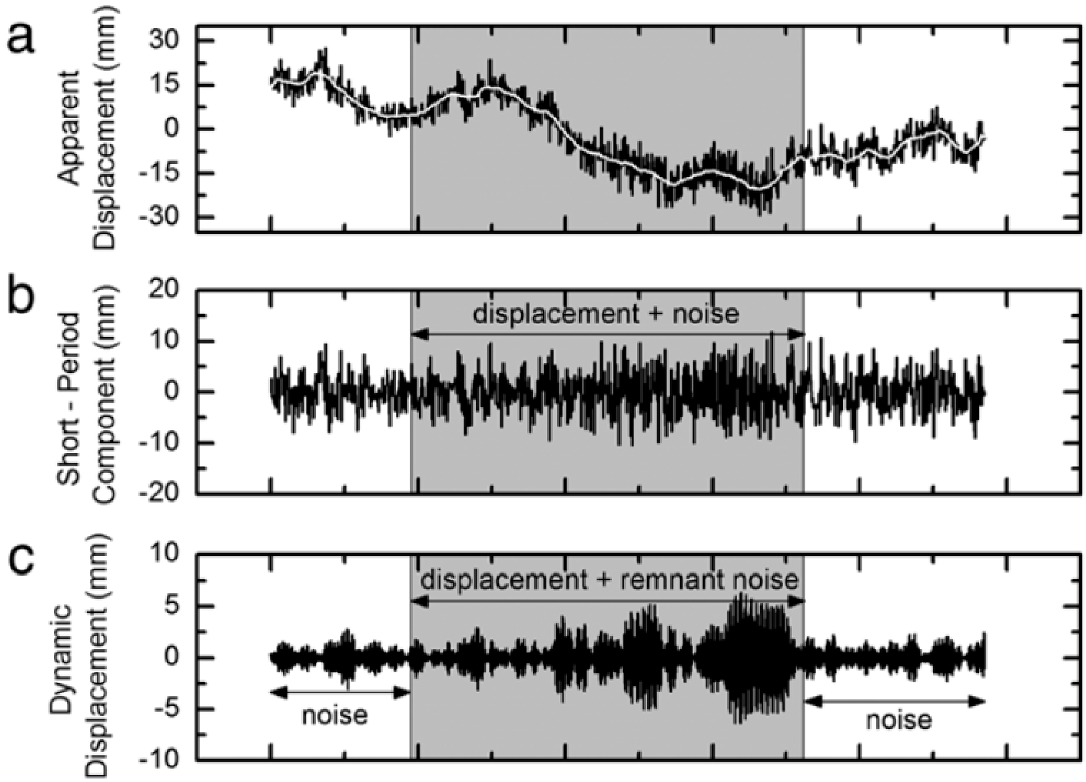



**Figure 2.** (**a**) Apparent displacement and smoothed displacement; (**b**) Short-term apparent vertical displacement component showing noisy oscillation signal; and (**c**) Dynamic displacement with remnant noise computed from the time series [3].

**Table 1.** Summary of previous studies on the GPS noises [26].

| Duration | Sampling Frequency | Noise Type |
|---|---|---|
| 12.5 years | Weekly solution | White + flicker noise (FN) |
| 10 to 13 years | Daily solution | White + FN |
| 7 years | 30 s | 1st order Gauss-Markov + white noise |
| 6 years | Daily solutions | White + FN + random walk noise |
| 3 years | Daily solutions | White + FN |
| 3 years | Daily solutions | White + FN + random walk noise |
| 2.5 years | Daily solutions | White + FN |
| Up to 1.5 years | Daily solutions | White + FN + walk noise |
| 0.3 years | 1 Hz | White + FN |
| 0.2 years | 30 s | White + FN |
| 2 h | 1 Hz | White + FN |
| ~1 h–121 days | 1–50 Hz | Random walk + white noise |
| ~15 min | 1 Hz | FN |
| ~1 h | 1 Hz | Time-correlated noise + white noise |
| 3.3 h | 1 Hz | Colored noise + white noise |

According to a survey conducted on eight manufactures who supplied the market with survey-grade receivers, 10 to 100 Hz sampling frequencies are developed. Table 2 represents the last developments of the GPS receivers [15].

**Table 2.** Recent manufactured GPS receivers. Real-time kinematic (RTK).

| Manufacturer | Model | Direction | Accuracy | | Sampling Frequency (Hz) |
|---|---|---|---|---|---|
| | | | Fast Static (mm ± ppm) | RTK (mm ± ppm) | |
| Leica | Viva GS15 | H | 5 ± 0.5 | 10 ± 1 | 20 |
| | | V | 10 ± 0.5 | 20 ± 1 | |
| Javad | Triumph-1 | H | 3 ± 0.5 × baseline | 10 ± 1 × baseline | 100 |
| | | V | 5 ± 0.5 × baseline | 15 + 1 × baseline | |
| NovCom | SF-3050 | H | — | 10 ± 0.5 | 100 |
| | | V | — | 20 ± 1 | |
| NovAtel | ProPak-V3 | H | — | 10 ± 1 | 50 |
| | | V | — | — | |
| Septentrio | AsteRx2e | H | — | 6 ± 0.5 | 25 |
| | | V | — | 10 ± 1 | |
| Sokkia | GRX1 | H | 3 ± 0.5 | 10 ± 1 | 20 |
| | | V | 5 ± 0.5 | 15 ± 1 | |
| Topcon | GR-5 | H | 3 ± 0.5 | 10 ± 1 | 100 |
| | | V | 5 ± 0.5 | 15 ± 1 | |
| Trimble | NetR9 | H | 3 ± 0.1 | 8 ± 1 | 20 |
| | | V | 4 ± 0.4 | 15 ± 1 | |

The accuracy of the GPS displacement measurements depends on many factors such as sampling frequency, multipath effect, satellite coverage and satellite and receiver-dependent biases. With the dynamic as the main displacement component, the main factor that affects structures' dynamic behavior is the sampling frequency, especially for stiff structures. Major suspension bridges and other structures' oscillations due to dynamic loads (vehicles, wind, etc.) were presented using GPS measurements with sampling rate of 1 Hz [51,52]. The investigated structures were flexible (dominant frequencies < 1 Hz), with displacements of the order of tens of centimeters, which exceeded the noise limit of GPS kinematic. To date, the understanding of structures' dynamics was limited, such as oscillations in the crosswind direction recorded for the first time in real structures, and was regarded as measurement errors [16].

Gradually, the use of GPS monitoring systems was extended to stiffer, shorter-span bridges and other structures with frequencies of 1–2 Hz [3,15]. More recently, a combination of high-frequency (1–10 Hz and sometimes 20 Hz) GPS receivers and filtering techniques permitted measuring stiff structures' oscillations with 3 and 4 Hz natural frequencies and semi-static and dynamic movements of a few millimeters [3,21,23,24]. With fast advancement in sampling rates and tracking resolution, high GPS receivers are becoming available, as shown in Table 2.

Moschas and Stiros [16,28] stated that the GNSS receivers are able to track GPS, GLObal NAvigation Satellite System (GLONASS) (Russian GPS equivalent), and Galileo satellites. They can also provide sampling rates of up to 100 Hz, which raises the question of whether these systems can be used to monitor stiff structures, especially bridges and cantilever structures members with dominant frequencies greater than 3–4 Hz, and dynamic movements of the order of a few millimeters. Such short-span bridges represent the majority of bridges on a global scale [3,16], as well as stadiums [53] and wind turbines [54]. Such structures represent a challenge because the 100 Hz GPS sampling rate is compatible with the accelerometers' sampling rate (100–200 Hz) that are systematically used for structural analysis, whereas 100 Hz data make it possible to overcome any problem of aliasing in stiff structures' spectral data [28]. In addition, such data can typically overcome the problem of loss of peaks or of amplitude amplification [16,23,28]. Second, small and stiff bridges are not regularly inspected to assess their status and are exposed to decay and damage risks (foundation settlement, damage due to fire, collisions by cars, seismic loads, fatigue, and decay). Third, very few studies [28,29] have investigated experimentally the noise characteristics of 100 Hz GPS data. In addition, this technology has been applied only in very few cases of relatively flexible structures (dominant frequencies of approximately 1.5 Hz) [29].

The applications of high rate sampling frequencies (>25 Hz) for the deformation of structures was presented and evaluated by Yi et al. [29]. Yi et al. [29] presented large number of experiments to test high-rate GPS receivers performance (50 and 100 Hz) in terms of their accuracy, limitations, and potential use for structures' health monitoring. They used high-rate carrier phase GPS receivers to investigate bridges' deformation. The receivers adopted in their study included the NovAtel ProPak-V3 that is capable of sampling data up to 50 Hz, and JAVAD TRIUMPH-1, which is capable of gathering data up to 100 Hz (the highest sampling frequency in the market). Static experiments are conducted in order to investigate the frequencies and amplitudes of the receivers' noise, as well as the potential applications of such high-frequency data rate. Kinematic experiments are performed in a controlled steel frame model and comparisons are made with a Lance LC0161A accelerometer (Figure 3). A monitoring experiment on a real large-scale bridge (Dalian BeiDa Bridge) is presented in their study. Some results and preliminary conclusions are presented as follows [29]:

- The static trial was conducted to investigate both the frequencies and amplitudes of the receivers' background noise. The minimum, maximum and mean values of the GPS measurements displayed very low-frequency drifts of relatively small amplitude, though on average, the mean of the measurements tends to zero. The standard deviation (SD), skewness and kurtosis analysis of the results show that the background noise follows, to some extent, Gaussian distribution. Also, the standard Gaussian distributions provide a conservative measure of the spread of the background noises, which captures the majority of the background noises within three SD from the mean. The power spectrum density (PSD) reveals that the background noise demonstrates broadband nature and the dominant noise energy distributes over a relatively low-frequency range without a distinct periodic tendency.
- Data analytical results prove that the wavelet packet-based filtering scheme based on denoising procedure method is simple and effective to remove the background noise of GPS high-rate measurements.
- A major output of this study is the potential of using high-rate GPS to measure stiff structures' high frequencies up to 10 Hz. GPS receivers with high logging rates can directly provide data in high-frequency range comparable with accelerometer data accuracy. However, it is not desirable to replace an accelerometer network completely; geodetic sensors could provide important information to allow fast determination of structural modal parameters for bridge online health monitoring.
- The results show that high-rate GPS receivers can successfully quantify both environmental induced bridge displacements and vehicles' transient motion, which are in good agreement with the predictions from the developed finite element (FE) model, as presented in Table 3. The displacement responses caused by vehicle loading after statistical analysis may be adopted for identifying the vehicle classes with different weight, as presented in Figure 4.

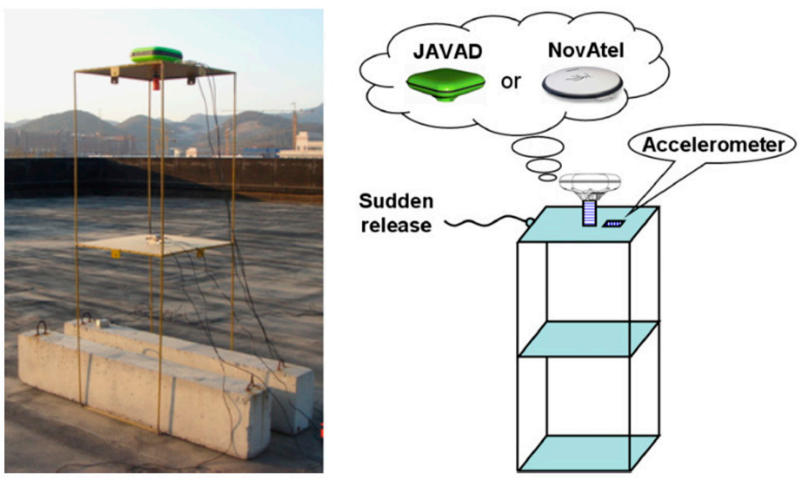
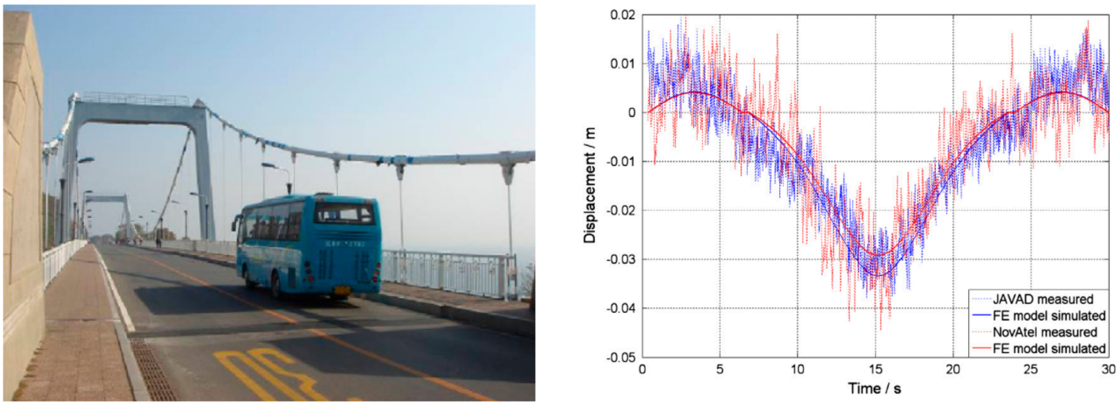



**Figure 3.** Test method and equipment for kinematic experiments [29].

**Table 3.** Finite element (FE) model and GPS measurements modal frequency values for the Dalian BeiDa Bridge [29].

| Mode | FH (Hz) | GPS (Hz) | | Relative Change (%) | |
|---|---|---|---|---|---|
| | | NovAtel | JAVAD | NovAtel | JAVAD |
| 1 | 0.66 | 0.68 | 0.68 | 3.03 | 3.03 |
| 2 | 1.08 | 1.01 | 1.02 | 6.48 | 5.56 |
| 3 | 1.48 | 1.42 | 1.42 | 4.05 | 4.05 |
| 4 | 1.58 | 1.77 | 1.76 | 12.03 | 11.39 |




(**a**) (**b**)

**Figure 4.** (**a**) Heavy bus passing and (**b**) bridge observation response and simulation due to the passing bus [29].

From Table 1, Figure 4 and the conclusion of Yi et al. [29] study, the JAVAD receiver performance was slightly better than the NovAtel in the signal-to-noise ratio and in high-frequency tracking ability. The reason, to some extent, is that low-frequency sampling may lead to certain cycle's loss of oscillation and its having high-frequency high-amplitude events. Therefore, in practical applications, receivers with higher logging rate should be adopted in order to trace the high-frequency transient motion.

Moschas and Stiros [16,28] presented case studies and error effects for the GNSS-100 Hz, and they concluded that this sampling frequencies are able to detect the strong attenuating oscillations. In addition, the proposed weak fusion of the GNNS and accelerometer data may lead to accurate results, even for vertical movements. As such, this can push the limits of the GNSS application to stiff structures monitoring and identification with natural frequencies of 6 Hz and movements of a few millimeters only, representing the majority of structures. Moreover, many studies used the 10 to 20 Hz sampling frequencies of the GPS monitoring systems applications for the different cases of structures performances evaluations [3,18,19,25,52,55–59].

## 3. GPS Monitoring Techniques

Kinematic point positioning is composed of a hand-held GPS which displays instantaneous, changing coordinates derived from the analysis of satellite signals. Such kinematic techniques still offer limited accuracy and, in most cases, coordinates are derived not only from satellite data, but from a combined analysis of satellite data with other sensors (odometer, compass, etc.) [15]. The reason why point positioning techniques permit noisy results is that the signal of each satellite is deformed (corrupted) when crossing the atmosphere and because of other local effects. For this reason, the position of a stable point appears variable (apparent displacement), even offset from the real position. A remedy to this problem is by using differential-GPS (DGPS), in which two nearby GPS instruments receive satellite signals, following a nearly similar path and corrupted by the same effects. One is recording in a fixed position while the other is moving. The apparent wandering of the stable (base) receiver reflecting noise is used to correct the apparent wandering of the moving (rover) receiver, reflecting real displacement plus noise, and to radically improve the accuracy of its instantaneous coordinates [26]. Moreover, whether the DGPS accuracy can approach a sub-centimeter to millimeter level depends on many factors, such as GPS sampling frequency, satellite coverage, multipath effects and GPS commercial methods for data processing [60,61].

DGPS measurements' accuracy were examined and evaluated by some researchers [60,62,63]. Chan et al. [60] examined the DGPS (Leica GX1230, and AT504 choke ring antennas with 20 Hz) using experimental movement of plate in three directions; the table is shocked by a computer system. In addition, they checked different motion cases, and their results found that the DGPS measurements' accuracy percentage reached 19.2% and 28.78% with strong plate motion in horizontal and vertical directions, respectively. Moreover, a real wind load is applied on the plate and the accuracy of the plate movements using the DGPS are 3.8 and 7.62 mm, respectively [60]. In addition, Ge et al. [62] tested the DGPS to measure a simulation for real seismic observation in Japan, the results for the system used (Trimble MS750 GPS, 20 Hz) are compared with the accelerometer and velocimeter measurements. It is found that the DGPS system has a good agreement with the acceleration and velocity measurements' results. Moschas and Stiros [63] studied the accuracy of small bridge movements for the GPS 100 Hz monitoring system and they found that the accuracy of the bridge displacement measurements is 1–2 mm and 4–6 mm for the horizontal and vertical directions, respectively. Yi et al. [29] (GPS with 50 and 100 Hz), Moschas and Stiros [16,63] (GPS with 100 Hz), Casciati and Fuggini [64] (GPS with 20 Hz) and Kaloop and Hu [19] (GPS with 20 Hz) evaluated real structures and, from these studies, it is concluded that the typical error accuracies of moving points of structures in DGPS may reach 15 mm in horizontal and 25 mm in vertical coordinates.

However, high-frequency receivers (10-Hz sampling rate or even more) and high-pass filtering of data allow to record dynamic displacements with a frequency of more than 3–4 Hz and amplitude up to few millimeters. As such, they are used for monitoring flexible structures like cable-stayed bridges and high-rise buildings, (see Yi et al. [29]; Breuer et al. [65]) and relatively stiff structures like short-span bridges [3]. DGPS is still not suitable for earthquake studies because the base receiver should be stable, away from the meizo-seismal area of the earthquake; otherwise, the movement of the base receiver, induced by the earthquake waves, will noise the coordinates of the rover receiver [23,66,67]. Using a base receiver hundreds of kilometers away from the rover receiver (i.e., beyond the meizo-seismal area of the earthquake) will result in satellite signals following different paths, subject to different along-path bias and will lead to noisy instantaneous coordinates [67]. PPP is relatively a new technique for accurate point positioning especially for kinematic applications. The basic function of this technique is to make the necessary corrections to the moving receiver using data from a relatively large number of remote receivers, permanently operating receivers, the recordings of which are kept in specific data bases [68]. PPP analysis can be made either in local computers or using online services [63]. Currently, PPP processing is available in GPS software packages such as GIPSYOASIS [69] and BERNESE [70]. PPP was clearly developed for static applications and the dynamic analysis of structures, as presented in [21,24]. It is, also, used in kinematic applications, but in this case, it requires a data set consisting of static data to compute certain variables (ambiguity resolution) and then to analyze the kinematic data. Usually, there exist limitations in the bulk of observations to be analyzed, and this is a problem for high-frequency sampling. Recently, these limitations have solved by using a GNSS-PPP using high rate GPS (10 Hz) [24]. The following subsections present the GPS monitoring systems.

### *3.1. Methodology for Assessment of DGPS*

DGPS is mainly used to detect important structures' behavior such as: bridges, dams, buildings, etc. The main advantage of the DGPS is the improvement of the measurements with low errors. The DGPS technique uses base and rover receivers where the data processing is divided into post-process and real-time kinematic (RTK) [26,36,38,56]. Moschas and Stiros [3] presented the assessment of dynamic behavior based on RTK monitoring system as follows: The data analyzed in part came from a GPS (rover) receiver positioned at the mid-span of the bridge at the top of the truss. A compact-type rover Topcon HipperPro receiver was used recording at a rate of 10 Hz. The e receiver was free of any obstructions and 7–8 satellites were continuously tracked. Furthermore, the surrounding area was practically free of surfaces producing secondary reflections of the satellite signal and causing multipath measurement errors (secondary reflections of the signal). Another GPS receiver was utilized as a reference (base) receiver and placed approximately 60 m away from the bridge at a stable ground recording at 10 Hz. In addition to that, the bridge movements were recorded by accelerometer, recording at a rate of 250 Hz, with an attached, dedicated single frequency GPS receiver providing GPS precise time constraints. This allows for full synchronization of the two instruments. During no traffic period and negligible wind, the bridge was excited several times by synchronized jumps of a group of six people with a total weight ~450 kg at its mid-span. Several excitation events, with a duration of approximately 1 min, as well as intervals of no excitation between them, were recorded by the redundant system of collocated instruments described above, as shown in Figure 5.

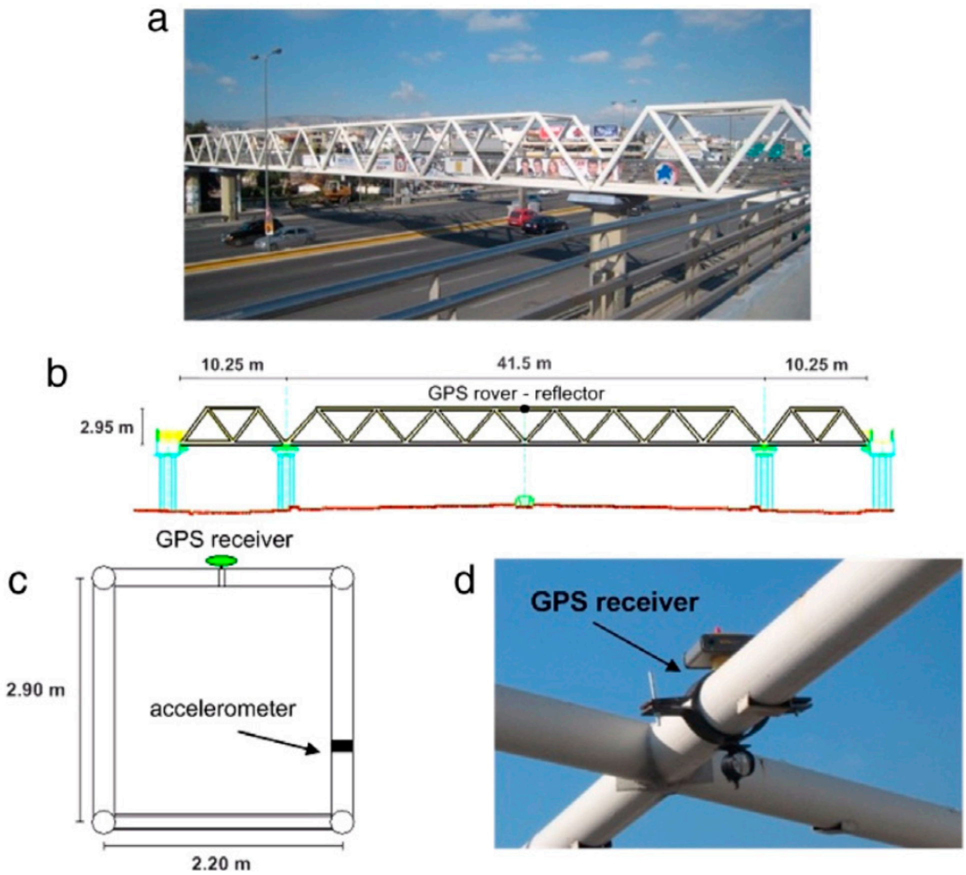



**Figure 5.** (**a**) View of the stiff, steel pedestrian bridge; (**b**–**d**) Longitudinal and cross sections of the bridge and location of the sensors used to measure the bridge deflections [3].

The apparent displacements is collected using RTK monitoring systems with no evidence of any dynamic displacement due to the dominating ambient (long-period) noise [3]. The main purposes of this experiment were to denoise the measurement time series and to extract useful signals describing the bridge dynamic displacements. For this reason, a multi-step filtering procedure is adopted, with external constraints for the analysis of the apparent vertical displacements time series. ***First***, the apparent vertical displacements short-period component is computed based on supervised learning-derived filtering (first-level filtering). In particular, this is based on the results of the analysis of numerous systematic experiments of oscillations of known characteristics. It was found that a simple high-pass filter (a moving average filter with a step of approximately 4 s) permits to separate apparent vertical displacements into long-period and short-period components. The long-period component is sometimes identified with the background or ambient noise [26,27], but in this case it contains both the background noise and the quasi-static displacement. The short period component contains the dynamic displacement of the oscillation signal plus some noise. The filtering validity was assessed in comparison to the records of the accelerometer as far as the timing of the excitation is concerned: filtering is valid only when two independently defined intervals coincide. Similar approaches, though with different filters, have been proposed by various authors [16,59,71], but this approach allows an independent assessment of its validity, concerning the precise excitation intervals defined by the accelerometer record. ***Second***, the frequencies have been identified dominating the spectrum of the displacement short-period component. This step output was the unambiguous identification of dominant frequencies range during the oscillation, known as pass-band range in the following step analysis. ***In the third step***, since the significant information was determined, the noisy apparent displacement time series are filtered (second level filtering) in order to remove any noise out of the pass-band range frequencies defined previously. This was based on a Chebyshev band-pass filter with appropriate parameters. This solution is used to remove noise or subtract certain frequencies from GPS or accelerometer time series (low-pass or band-pass filtering). A new time series, free of most noise, is produced based on this second filtering, representing the real dynamic displacement though still contaminated by some remnant noise (bias). In conclusion, the assessment was made in three levels, namely, testing the sensitivity, the accuracy in recording amplitudes of oscillations and the spectral content of DGPS records, as presented in Figure 6. It is noted that most real-time monitoring processes for the bridges or buildings and dams are monitored and evaluated using DGPS [2,10,11,15].

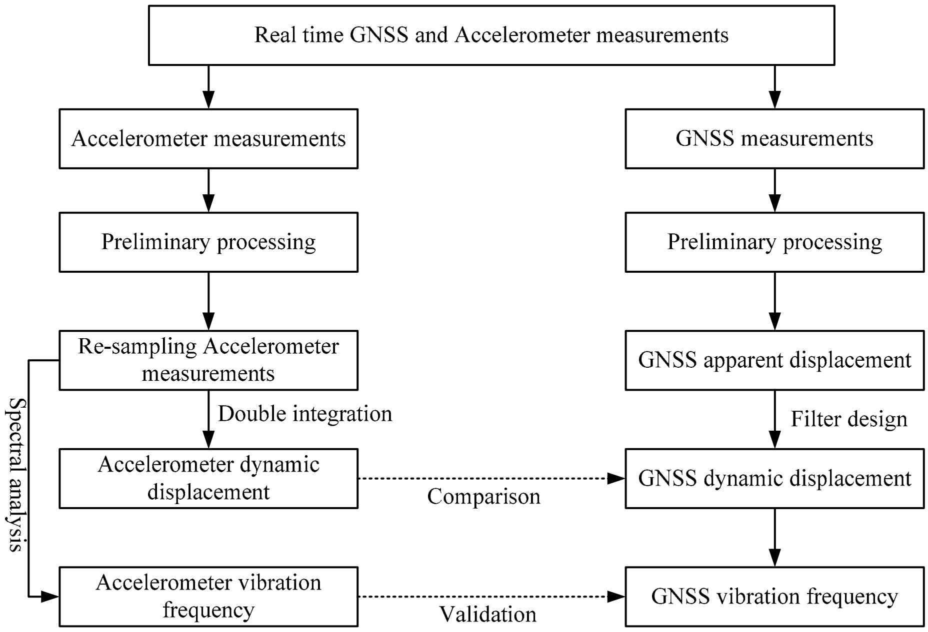



**Figure 6.** The procedure for the global navigation satellite systems (GNSS) processing and assessment.

### *3.2. Methodology for Assessment of PPP*

The PPP is used to record real seismic motions, for example, in 2006, the National Research Institute of Astronomy and Geophysics (NRIAG) in Egypt started the establishment of the Egyptian Permanent GNSS Network (EPGN) [67]. Also, the Geospatial Information Authority of Japan (GSI) uses over 1200 continuously observing GPS receivers, known as GPS Earth Observation Network (GEONET), covering Japan's land area with an average distance of about 20 km between neighboring points [72,73].

Moschas et al. [23] presented the experimental assessment of the PPP dynamic measurements of seismic motion as follows: They produced a sequence of semi-static displacements followed by free oscillations, and these motions were recorded by GPS, as well as by an accelerometer and a robotic total station (RTS) (Figure 7). The collected data permit to compute apparent displacements in three axes, but the main focus of the study was the horizontal (axial) oscillation along a vertical plane defined by the base of the oscillator and the RTS. This leads to no lack of generality, for in most regions the GPS accuracy is similar in northing and easting; hence, the analyzed experiments are representative of any horizontal earthquake-induced movement. GPS recordings were analyzed using different PPP software packages and DGPS. The PPP time series apparent displacements were then compared with those derived from DGPS and other sensors, where time series of known accuracy are assumed to provide "true" or reference values. The quality and limitations of the DGPS technique and adopted RTS outputs have been documented in experiments and studies of monitored structures (e.g., see [24,29]).

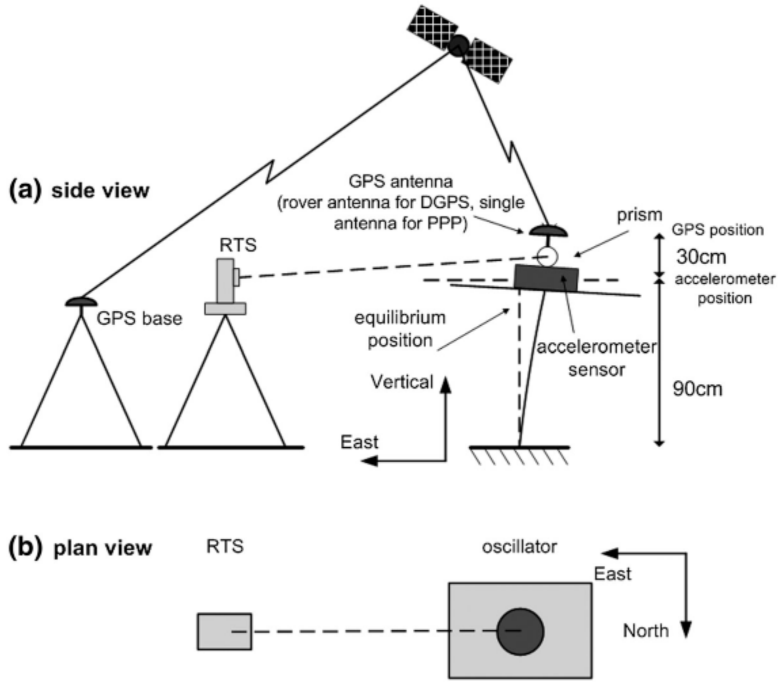



**Figure 7.** Schematic representation ((**a**) side view and (**b**) plan view) of the experimental setup used in the study [23].

In particular, DGPS can successfully capture semi-static and dynamic displacements that exceed its noise levels, while RTS captures semi-static and dynamic displacements, but tends to miss oscillation cycles during high-frequency (>2–3 Hz) oscillations [23]. Time series of coordinates are transformed into apparent axial displacements that, in the case of GPS, are contaminated by long-period noise. The short-period components of the apparent PPP and DGPS displacements were then computed using high- or band-pass filtering. The short-period component of each reference data set (DGPS, RTS) reflects the corresponding dynamic motion plus some noise [16,19]. Moving average is the optimal filter for common problems because it reduces long-period noise while keeping the sharpest step response [23]. The application of this filter in the analysis of 10-Hz GPS data has been validated on the basis of supervised learning experiments [23,26], and the filter has been used in applications of structural monitoring [23]. Several types of filters and filtering procedures were proposed in the past for filtering GPS data, including wavelet based filters, Chebyshev filters, or other filters based on the sidereal repeatability of the constellations of GPS satellites [15,16,27,29].

The potential of PPP time series to record real motions was subsequently assessed on the basis of comparison of the output of PPP with the output of RTS, DGPS and of the accelerometer.

This assessment was made in three levels, namely, testing the sensitivity, the accuracy in recording amplitudes of oscillations, and the spectral content of PPP records, as presented in Figure 6. The application of the PPP for the seismic motion can be found in [67,73]. On the other hand, structural health monitoring systems using the GPS-PPP for assessing structures' behavior are still limited. Yigit [21] and Yigit and Gurlek [24] studied structures' behavior using PPP techniques experimentally, and they concluded that the dynamic performance of structures can be detected with high accuracy. Yigit [21] compared the PPP and DGPS solutions for cantilevers dynamic behavior in both time and frequency domains. As presented in [48], the DGPS is highly accurate to measure structures' static and dynamic responses. Figure 8 illustrates the experimental results of the PPP and DGPS monitoring techniques for cantilevers dynamic assessment [21].

As presented in Figure 8, the PPP results are very close to the DGPS extraction dynamic behavior. Therefore, it is concluded that the PPP can be used with real monitoring of structures and can decrease the cost of the GPS-SHM monitoring systems.

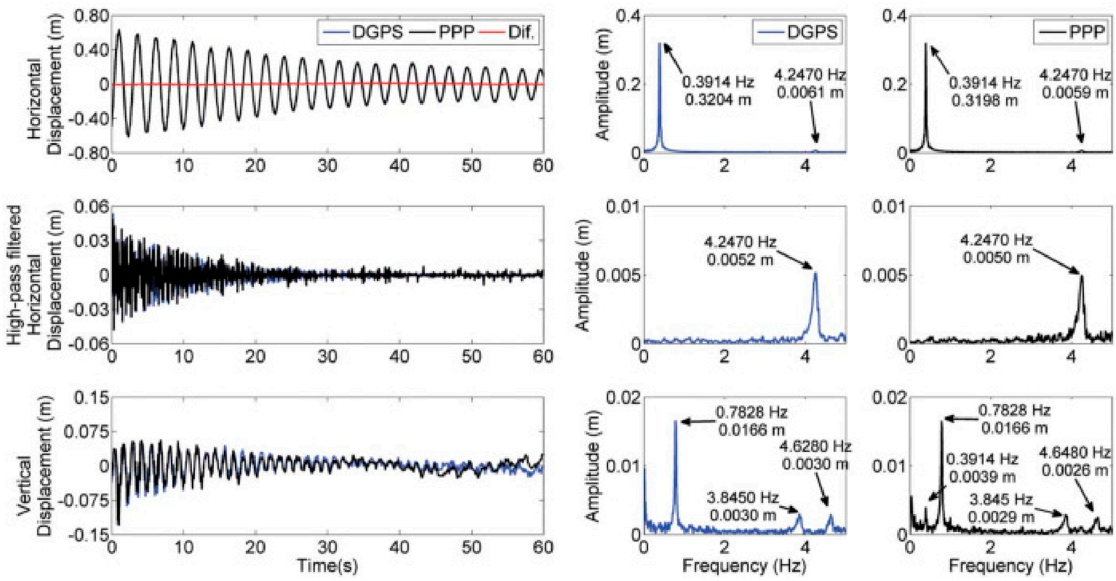



**Figure 8.** Time and frequency contents of differential-GPS (DGPS) and precise point positioning (PPP) for cantilever dynamic behavior [21].

## 4. Recent Dynamic Behavior Assessment of Structures

When studying structures' movements, structures' dynamic behavior (damping and frequency) should be investigated. Limited studies, currently, investigated the dynamic behaviors of structures based on GPS monitoring techniques [16,19,74]. Moreover, denoising the GPS signals is an important process to evaluate structures' dynamic behavior. Recent studies stated that GPS noises and errors can be eliminated using wavelet analysis [10,15,27]. Figure 9 illustrates the GPS measurements process to estimate the behavior of structures. Many types of filters are used to decrease the noise effects and estimate the accurate behavior of structures. The low-pass filter was utilized to estimate the semi-static behavior, while the band-pass and high-pass filters were applied to extract the dynamic behavior. Kalman filter is a popular filter used to eliminate the GPS noises [75], moreover, a moving average filter is a simplified filter to extract the semi-static movement of structures [3]. Also, an adaptive filter is applied alone or integrated with Kalman filter to denoise the GPS measurements for structures [76]. Additionally, a high-pass and a low-pass Type I Chebyshev filter are used to estimate the behavior of structures based on GPS measurements [3,49]. Recently, with the development of GPS sampling frequency, the studies stated that GPS noises and errors can be eliminated using wavelet analysis [10,15,27]. Details of the wavelet analysis process of the GPS can be found in [56,59].

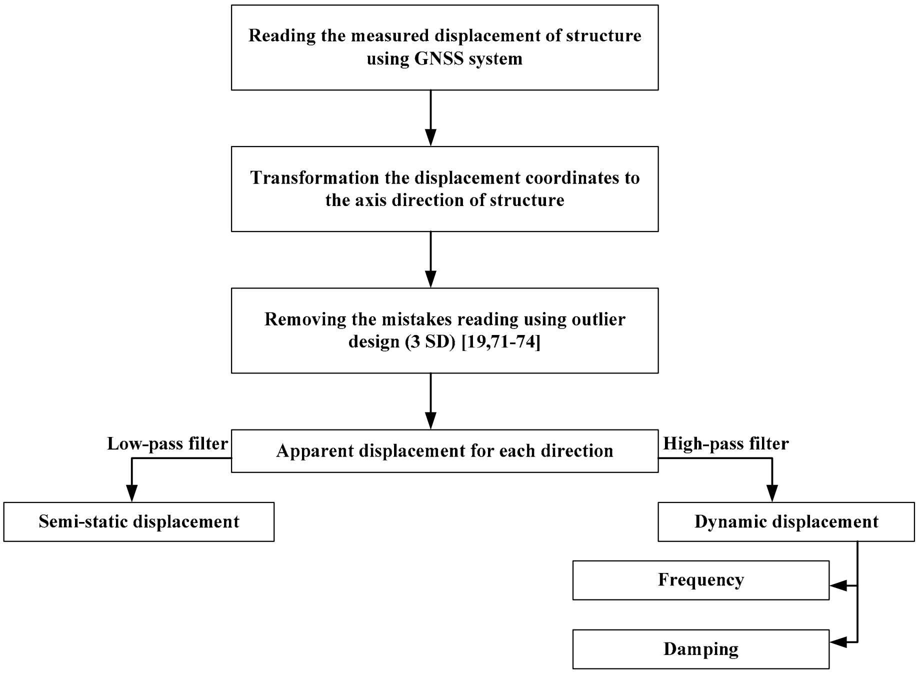



**Figure 9.** Extracting the structure behavior using GPS measurements (SD is standard deviation).

The dynamic behavior studies of real structures based on PPP are still limited. As presented in [21,24], the PPP technique can be used to detect the dynamic behavior experimentally. In contrast, the PPP is widely used to evaluate the seismic motion [23,67]. The full behavior of structures (frequency and damping) using DGPS monitoring system is introduced by Gorski [74]. In that study, the full behavior of a tall chimney (flexible of structure) using the RTK-GPS technique and the random decrement method (RDM) is presented, and the results proved that tall slender structures' dynamic characteristics under wind excitations can be effectively determined using RDM GPS measurements. Gorski [74] studied a chimney using 10 Hz GPS and found the range of frequency and damping are 0.212~0.219 Hz and 0.52~0.61%, respectively. Kaloop and Hu [19] applied outliers solution to improve the noisy data of high-rate sampling of GPS. They utilized the RDM with Hilbert envelope method (HEM) to estimate long-span bridge (flexible of structure) full behavior under traffic and environmental effects. They reported that the RTK-GPS is significant for extracting the full performances of the bridge. Therefore, the damping and frequency of flexible structures can be estimated using GPS measurements.

Moreover, Moschas and Stiros [16] utilized an ultra-high-rate (100 Hz) GNSS to evaluate stiff bridge behavior, and they used the process evaluation, as shown in Figure 6, to estimate the monitoring system accuracy. They reported that the results can push the limits of the application of GNSS in structural-health monitoring and identification to stiff structures, and it can be used to estimate the damping ratio up to 3.22 [16]. Finally, Yu et al. [59] introduced a dynamic network-based real-time kinematic (NRTK) GNSS monitoring system of bridges. The main advantage of the NRTK monitoring system is its low cost. While the correction base depends on the available global network for the country; therefore, the designed system used one receiver to collect the structure's data and solved it using a DGPS system [59]. The results of this study showed that the NRTK-GNSS can be used to detect the bridges dynamic behavior [59]. Also, the results show that the NRTK-GNSS accuracy is good enough for monitoring purposes, with peak differences less than 2 mm, SD less than 1.8 mm, and correlation coefficients higher than 93.4% between the NRTK and accelerometer displacements [59]. The proposed NRTK-GNSS technique accuracy is higher than the conventional RTK-GNSS technique, although the latter has many successful applications of bridges and tall buildings dynamic monitoring [59].

## 5. Summary and Conclusions

There have been a large number of studies of GPS-based SHM systems over the last decades, as well the development of the monitoring systems and sampling rate of instruments. The studies that have been summarized in this state-of-the-art review focused on the recent development of sampling rates, GPS monitoring systems, and dynamic behavior evaluations of structures based on GPS techniques. From the presented review, the following conclusions are pointed out along with a view for further improvement of the GPS-SHM system for supporting structures' maintenance and rehabilitation decision-making:

1. The GPS sampling rate has, until now, been developed to reach 100 Hz, and this sampling rate gives flexibility to measure the high accurate real-time positions of monitoring points in static and dynamic measurements. This reveals that the stiff and flexible of structures can be assessed, and the behavior of structures can be measured in time and frequency domains with high accuracy.
2. RTK monitoring systems assess the behavior of structures, but their cost is greatly increased when increasing the sampling rate. Therefore, recently, two systems have been developed: the NRTK and PPP-GNSS systems, which are now effectively used to measure highly accurate positions of the monitoring points at low cost. Moreover, some developments for the GPS receivers have been established, but the accuracy is still limited.
3. By increasing the sampling rate of GPS monitoring techniques and developing low-cost monitoring systems, the dynamic behavior of structures (frequency and damping) can be extracted based on the random decrement method, with the denoising of the GPS data. The wavelet analysis methods are effectively used to denoise signals when coupled with advanced GPS instruments. Currently, RTK monitoring systems are used to detect the dynamic behavior, while the PPP is still under study to measure the full behavior of structures.

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