Using GPS to Monitor Movement of a Cable-Stayed Bridge

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Editor's note: *This article has been excerpted and condensed from a somewhat longer, very scholarly paper. The complete paper can be viewed on our website. That complete version includes more detailed text, an extensive bibliography, additional graphics, and acknowledgments of appreciation. We felt that it was important that we provide the excerpt to broaden the audience for this account of a significant project.*

If you were charged with proving that static GPS could reliably be used to monitor the movement a bridge, or other large structure, undergoes under traffic load, how would you go about it? The common-sense (as in "surveyor style") response is, "measure the movement by best conventional methods, under actual load, and measure with the same load by GPS; then compare results." That is exactly the approach taken in October 2003, by a group of Brazilian scientists, on a cable-stayed bridge in New Brunswick, Canada.

One of the most interesting parts of this research, at least as far as surveyors are concerned, is a significant revision of the way the GPS data is treated. The typical method of handling static observations, widely used by surveyors since the 1990s, is to use the logged carrier phase signals to determine distances from satellites to antenna. That is, as opposed to accepting the coded information being transmitted by the satellites. That carrier-phase measured data, hopefully from several satellites, is post-processed to determine 3D positions of antennas (*i.e.*, receivers, or points). But the method used in this research isolated specific satellites in certain positions in the sky. Generally, the desired geometry for this application is one satellite near the zenith, with another near the

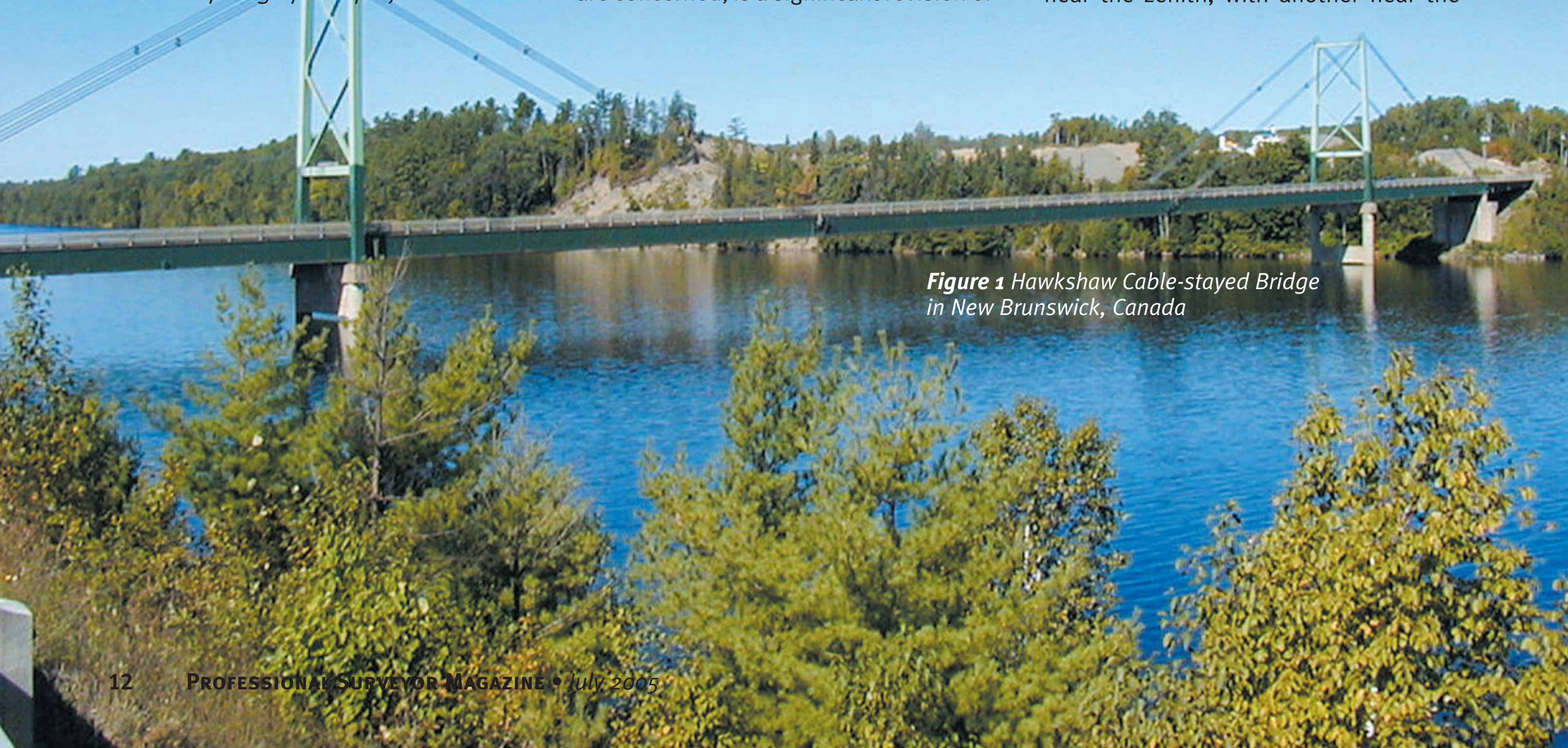

Figure 1 *Hawkshaw Cable-stayed Bridge in New Brunswick, Canada*

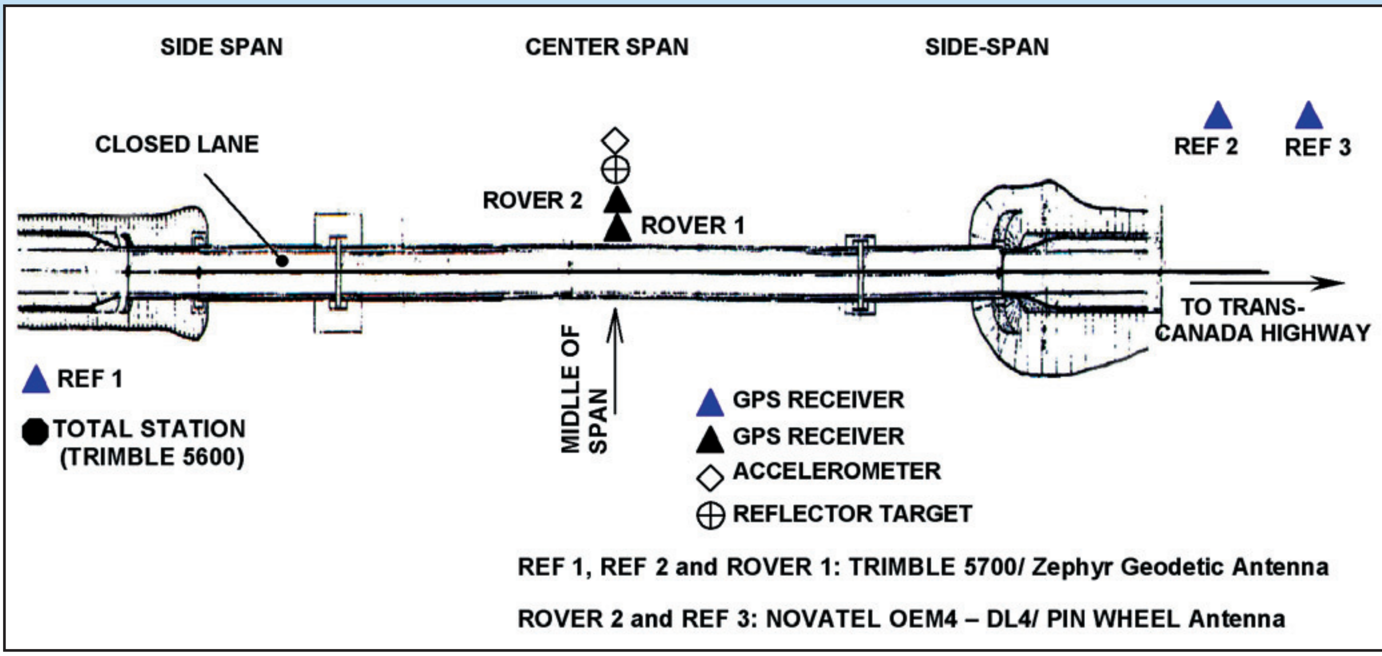

Figure 2 *Instruments configuration of Hawkshaw Cable-stayed Bridge*

horizontal, or a zenith angle approaching 90 degrees. From our GPS 101 courses, we remember that data is normally logged under a "mask" of 10-15 degrees above horizontal, to avoid receiving signals subjected to excessive distortion from passing through the ionosphere. So the usual desired position of the "lower" satellite, under this application, is around 80 degrees from zenith, or 10 degrees above horizontal. Most of the reports of data use the convention of a vertical angle rather than a zenith, so for these purposes a satellite near overhead would have an angle of, say, 85 degrees, while the lower one, nearer the horizon, might be around 10 degrees. Right away, we see a difference in this approach versus the typical static surveying scenario. The static GPS surveyor doesn't usually care which satellites are located where; as long as there is an adequate number of satellites, with acceptable geometry, he or she is happy. But the method used for this research looks for isolated instances of one bird overhead, one near horizon. Similarly, this research uses the data in a different way.

The method employed on this work, to detect the dynamic behavior of the bridge, is based on the analysis of the GPS L1 carrier double difference phase residuals of regular static data processes. Most scenarios of displacement control like this include a reference point in the vicinity of the structure. Limiting the length of the baselines allows the use of single frequency receivers. The method needs data collected from two satellites, one close to zenith and other in the general direction of the horizon. This specific satellite geometry permits that the phase residuals incorporate all position changes during the observation. These phase changes can be assumed as a vectorial sum of the rover antenna movement and phase deviation sources. Most of these deviations are receiver phase noise and multipath, leaving actual movement of the antenna the real variable.

The bridge in question is described as follows: it has 2 full lanes, length 301.20 m. The main span of 217.32 m is supported by two towers 36 m tall. The equipment used for the monitoring: 5 GPS receivers (NOVATEL OEM4-DL4 and TRIMBLE 5700) were used, observing at a data rate of 0.2 seconds. One triaxial accelerometer and one total station were also used, although the accelerometer data were ultimately not used (**Figure 1**).

Some initial tests were conducted on the bridge to provide an idea about its dynamic behavior for establishing the necessary rate of data logging for the GPS receivers. Initially, the behavior over the deck under its normal operating conditions was observed with the total station and it was possible to closely determine the number of oscillations of a fixed target on the deck. The intensity of local traffic on Hawkshaw Bridge Road is low, with one truck crossing the deck each five minutes on average. Hence, GPS receivers, triaxial accelerometer, and total station were installed and a trial was conducted on the cable-stayed bridge. A pair of NOVATEL OEM4-DL4 receivers (one as reference station and the other as rover station) with two PIN WHEEL antennas, three TRIMBLE 5700 receivers with two Trimble Zephyr Geodetic antennas (on reference stations), one Trimble Stealth Ground Plane (as a rover antenna on the middle of the deck), and one ENTRAN EGA3 triaxial accelerometer (as mentioned, the accelerometer data were eventually decreed not usable). In addition, a TRIMBLE 5600 total station (distances to an accuracy of +/-0.8 mm +1 ppm) for measuring the vertical displacement of the middle span caused by chosen design trucks namely, one truck full of wood (60 ton); the same truck empty (18 ton) and a truck loaded with paper (40 ton). It was possible to choose these types of trucks because there are paper and wood factories near the bridge.

The trial on Hawkshaw Bridge was authorized by New Brunswick Department of Transportation and was assisted by the bridge superintendent and the senior technical advisor who provided all existing structure information about bridge and traffic agents to control the local traffic during the trial. This support was particularly important because one lane was closed and trucks of local traffic were used as design trucks. Twelve tests were performed on the bridge

Figure 3 *GPS antennas, reflector target and accelerometer housed together on the guardrail near the middle of the span*

The limitation of satellite geometry configuration necessary for this method requires attention to conduct the trial during a time when the constellation had one highest satellite and one lowest satellite.

Bridge Trial Results

Data from the trials were processed on OMNI software (free download from NGS) which permits the user to choose the reference satellite for data processing as well as provide detailed results from individual satellites and epochs. MathCAD 2001 software was used to treat and to apply Fast Fourier Transform (FFT) on the raw residuals.

During the first trial, the highest satellite (G16) was at 82 of elevation and the lowest satellite (G31) at 7. **Figure 4** shows the phase raw residuals obtained from data processing of all satellites where it is possible to clearly see the vertical displacement of the deck at the middle of the center span when one empty truck (18 ton) crossed the bridge. It took around 40 seconds. **Figure 5** illustrates the power spectrum of residuals with two peaks. One close to zero frequency is due to slow varying phase disturbances caused by multipath effects (LANGLEY, 1997); the second peak at 0.57 Hz represents the vertical periodic displacement that the GPS antenna was submitted by the vibration caused on the deck by the loading test with an empty truck crossing the deck.

The amplitude of vertical displacement caused by the empty truck and detected by GPS is approximately 3 cm; the same value was obtained by the Trimble 5600 total station. Another truck with the same characteristics was stopped in the middle of the span of the bridge and three more measurements were made with the total station. Other measurements were also done when the truck was not over the deck.

During the second trial, the highest satellite (G02) was at 77 of elevation during three hours, on October 30, 2003. The objective of the trial was to detect the dynamic behavior of the deck in the vertical and horizontal directions and the maximum vertical displacement of the deck when one or more trucks began to cross the deck. When one desired design truck was approaching the deck the driver was requested to stop before crossing the deck. Sometimes, the local traffic was stopped to wait to gather more than one truck .

The layout of all instruments used can be seen in **Figure 2**. GPS rover stations were installed on the guardrail near the middle of the span (**Figure 3**). For this purpose, a support was fabricated from wooden boards to house the electro-mechanical device, the two GPS antennas, and the accelerometer. The total station mini reflector target was fixed on the rover antennas support. Two reference GPS stations were installed on the southeast side of Hawkshaw Bridge. The third reference station was on the northwest side of the bridge.

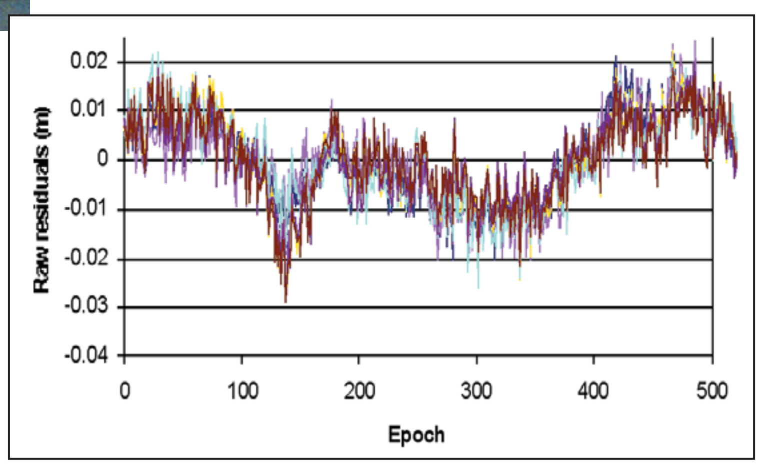

Figure 4 *Raw phase residuals of vertical displacement response caused on the deck by one empty truck crossing the bridge (NOVATEL OME4 GPS data)*

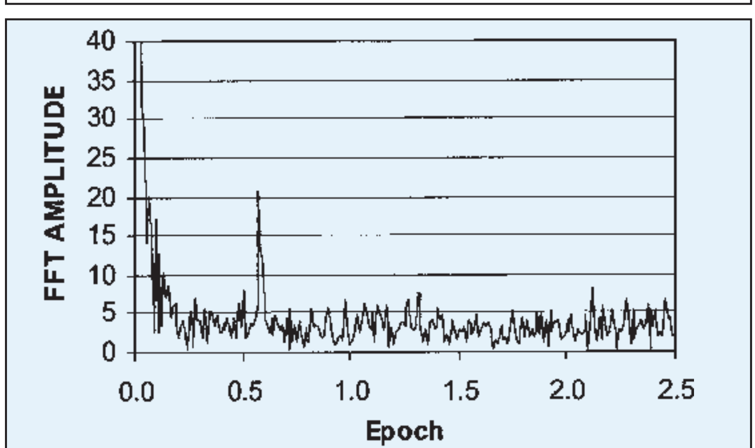

Figure 5 *Peak in the power spectrum of raw residuals with peak due to vertical dynamic response of the deck*

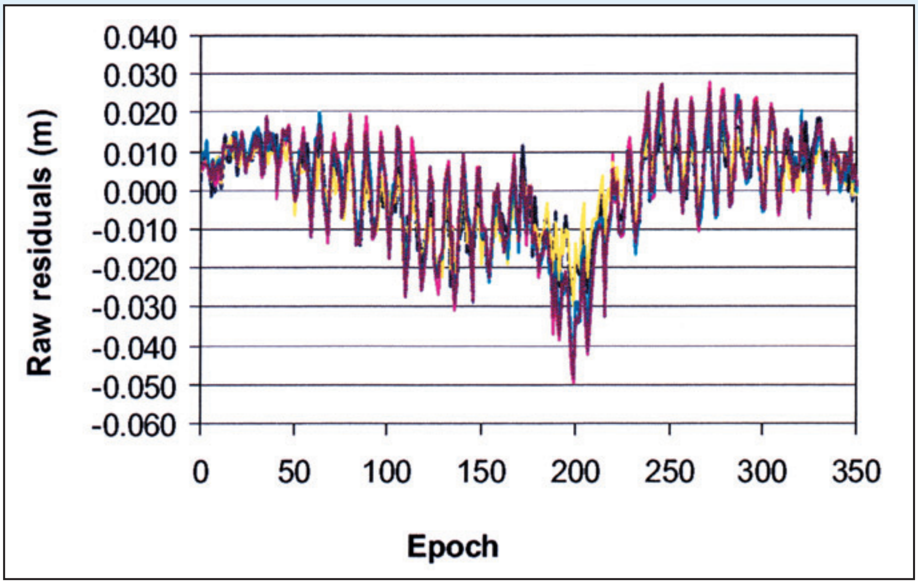

Figure 6

and the lowest satellite (G31) was at 8. **Figure 6** shows the phase raw residuals from NOVATEL OME4 GPS receivers of all satellites, where it is possible to clearly see at the epoch 200 a deep change in the amplitude. This occurred due to the vertical dynamic displacement of the deck at the middle of center span when a full truck (60 ton) crossed the bridge. It took around 45 seconds. At the same time, noticeable oscillations can be observed when the truck began to cross the deck sustaining until it leaves it.

Conclusion

In all trials carried out in Hawkshaw Cable-stayed Bridge GPS, data collected and treated by the method used on this research matches well with the results obtained from the measurements by the total station, confirming that GPS receivers can be used to characterize dynamic displacements.

The center span of Hawkshaw cable-stayed Bridge, under trials carried out with truck loading presented vertical frequency of 0.57 Hz and lateral frequency of 0.60 Hz. These values agree exactly with the theoretical values of the frequencies for the cable-stayed bridge with an orthotropic deck presented by HIRSCH et al. (1991). A vertical dynamic displacement of the center span has values around 2.5 cm. The center span presents vertical displacements around 4 cm during the entrance and the exit of a truck. On the other hand, center span presented a maximal vertical displacement around 8 cm during entrance and exit of four trucks. The amplitude precision ranges between 0.5 mm and 0.8 mm and the frequency precision presents values that match exactly with values measured by conventional instruments because both are based on GPS time.

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The bridge crew