Analysis of Bridge Deformations using Continuous GPS Measurements

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Abstract

In this presentation we describe the application of a continuously operating GPS monitoring system to determine the short term deformations of the suspension bridge at Tulln/Austria. Two experiments were carried out using stable reference stations at the embankment and monitoring points placed at the top of the pylon and directly at the bridge deck close to the steel cables.

The results clearly show that the bridge point is not well suited for high precision GPS measurements due to the shading and diffraction effects caused by the steel cables. The attainable precision of position for the bridge point is about 1-2cm, and even worse for the height component. However, the experiments yielded a precision of 2mm for the position of the pylon point, with a time resolution of a few seconds. Diurnal variations of the top of the pylon can clearly be correlated with temperature variations.

Our experimental data demonstrate the real time capability of GPS monitoring to determine load dependent (e.g., temperature dependent) behaviour of the pylon points of a bridge. We suggest to use GPS as the basis of a bridge monitoring system which yields long term deformation information related to structural fatigue and thus safety of the bridge.

1 INTRODUCTION

Continuous monitoring of bridges may lead to the early detection of changes of the bridge's response to traffic load, temperature and wind load. It is thus an important step towards increasing safety and life-time of the bridge.

Several authors have applied continuous GPS to monitoring bridges, and have reported excellent results, e.g., Roberts et al. (2000). However, our own investigations have shown that GPS is prone to signal distortion effects which may result in cm-biases of kinematic processing results. Above all, such effects are to be expected on a suspension bridge, where the cables may cause multipath and diffraction effects.

We have therefore selected a suspension bridge in Austria to investigate the application of GPS to bridge monitoring in the presence of signal distortion effects. In this paper we show that the top of the pylon is an excellent GPS site, and the correlation between temperature variations and deformations of the pylon can be clearly detected using GPS. However, we also show that points on the bridge deck cannot be accurately monitored using GPS if there
are obstacles like the steel cables close to the GPS antenna, and if the vertical displacement due to traffic load is on the order of a few cm only.

2 THE BRIDGE

The bridge used for the monitoring experiments is the "Rosenbrücke" at Tulln/Austria, Beschorner (1996). It is about 400m long and crosses the river Danube at an azimuth of 359.6°, i.e. almost perfectly aligned to the north-south direction, see fig.1 (left). The southern part of the bridge is built as a suspension bridge with an A-shaped pylon 70m high, and an array of steel cables on both sides of the bridge deck, see fig.1 (right).

3 THE EXPERIMENTS

We have carried out two experiments to investigate the capabilities of continuously monitoring bridge points using GPS. The goals were (i) to determine the response of the bridge to traffic load, temperature and wind load, (ii) to demonstrate that GPS is well suited for monitoring selected points at the bridge, and (iii) to find out the influence of the steel cables on the GPS signals and thus on the coordinate results.

The GPS monitoring system was originally developed for continuous monitoring of land slide motions and its hardware was described by Hartinger et al. (1999), and Brunner et al. (2000). Here, we used four Ashtech choke-ring antennas and four Ashtech L1/L2 receivers (2 Z-XII and 2 Z-Surveyors).
3.1 EXPERIMENT I

In July 1999, two of the pillars of the local geodetic network, and two points on the bridge were equipped with GPS receivers. Measurements were obtained at a sampling interval of 3s during a session of 48 hours. At each of the GPS sites, a radio modem was used to transmit the data to a PC in real-time. The PC was used for data storage and centralized control of the four receivers. In this paper we shall only use the data obtained at pillar S4 and at the monitoring point PYLA on top of the pylon, see fig.1.

In addition to the GPS measurements, meteorological data i.e., air temperature, wind speed and direction, were continuously measured and recorded on top of the pylon.

3.2 EXPERIMENT II

The experiment was repeated using additional sensors in November 2001, because the data of experiment I did not allow to distinguish between the actual motion of the monitoring points and the apparent motion due to GPS signal distortion and propagation effects. This time the data were stored internally every 3s to avoid the additional effort of establishing a reliable data link between the receivers and a local PC. In the present paper, we shall only use the measurements recorded at pillar N7 and the monitoring point BRUA.

Additionally, the air temperature, wind speed and direction, and the temperature of the pylon on the eastern, southern and western concrete surface were recorded continuously. In order to obtain an independent observation of the motion of the monitoring points and to aid in data interpretation, two tacheometers were set up on the pillars S3 and S4, fig.2 (left). They were used to continuously monitor a prism on site BRUA and prisms on top of the pylon and at the northern bank of the river, respectively. A special prism and antenna mount was used at BRUA, see fig.2 (right).

From 8:00 to 9:00 on both days of the 48 hour experiment, the actual traffic load was recorded using a digital camera triggered approximately every 10s.

Fig.2: Tacheometer on pillar S4 (left), GPS antenna and prism mount at site BRUA (right), a steel cable next to the antenna can be seen in the top left corner.
4 ANALYSIS OF THE DATA

4.1 PYLON POINT

There are absolutely no obstructions above an elevation angle of 0° at the top of the pylon, and multipath effects caused by the water surface are mitigated by the choke-ring antenna. So, very high quality of the results may be expected.

The GPS data were processed in a baseline-mode using our own kinematic software GRAZIA, Hartinger and Brunner (1999). The station S4 was used as reference station. Fig.3 shows the variations of the north component of the pylon point with respect to the mean value of the whole session (top), the air temperature (center), and the corresponding component of the wind speed (bottom).

Fig.3: Experiment I, PYLA, variation of north component (top), air temperature (center), and south component of wind speed (bottom). North component and wind speed have been low-pass filtered (bold lines).

The plots clearly indicate a correlation between the north component and the temperature which is confirmed by an analysis of the cross-correlation between the two time series. After low-pass filtering the original time series using a FIR filter with cut-off frequency 0.001Hz, the maximum cross-correlation is 0.8 for a delay of 2 hours. So e.g., the temperature difference of about 7°C between noon and midnight of day 2, causes a reversible south-bound displacement of about 10mm at PYLO, see fig.3. The correlation is mainly explained by the steel cables which run in a north-south direction but are shorter to the south of the pylon than to the north, see fig.1 (right). So, when the length of the cables reduces as the temperature falls, the
top of the pylon is pulled southwards. Correspondingly, there is no correlation between the east component (fig.4) and the temperature variations (fig.3).

The quality of the GPS results is extremely high. This is shown by the rms of the original time-series about the low-pass filtered result, which is 2.2mm for the north component, 1.3mm for the east component, and 4mm for the height, see also fig.4.

A correlation between wind speed and motion of the pylon cannot be detected using this data. One of the reasons may be that the wind load was not sufficient to cause deformations which may be detected given the GPS resolution of a few mm.

Processing the GPS baseline without a tropospheric model yielded double-differenced phase residuals as large as 20cm, and made correct integer ambiguity fixing almost impossible. The reason is that the pylon penetrates the atmospheric layers orthogonally. So, the whole height difference of about 60m between the reference station and the antenna on top of the pylon causes differences of the actual path delay. For the results plotted in fig.4, we have applied an a-priori atmospheric model consisting of zenith path delay values computed using the Saastamoinen model and the Neill mapping function. The height component shows a periodic pattern similar to that of the north component, which may partially be explained by the temperature response of the 70m high pylon, but also by unmodelled residual tropospheric effects.

Similar results were obtained using the data of experiment II, confirming the high precision routinely attainable for points on top of the pylon.
4.2 BRIDGE DECK

The monitoring point BRUA was placed where the maximum vertical motion of the bridge deck was expected i.e., in the middle between the pylon and the next pillar of the bridge to the north. However, this means that the GPS antenna is very close to the steel cables, see fig.2 (right), which compose an array of obstructions to the west of the antenna. Poor signal quality was to be expected, but the results published by other authors for similar situations, suggested that GPS might still be useful, see e.g., Roberts et al. (2000).

Fig.5 shows the time series of coordinate variations of BRUA as obtained from an epoch-to-epoch processing with fixed ambiguities. N7 was used as a reference station in this case. There was almost no temperature variation during the 48 hours of experiment II. So the high rms of 12mm, 8 mm and 20mm about the mean value for north, east and height component respectively are mainly a result of traffic load and GPS signal quality.

![Graph showing coordinate variations](image)

Fig.5: Experiment II, BRUA, unfiltered time series of coordinate variations.

A detailed investigation of the deteriorating influence of the steel cables is given in Wieser (2002). Even using sophisticated variance models for the GPS processing, like the SIGMA-Δ and SIGMA-F weight models, Brunner et al. (1999) and Wieser (2002) respectively, the results cannot be improved. The main conclusion is that the cables cause multipath and diffraction effects which affect almost all GPS signals recorded. As a consequence, the time series of the coordinate results are significantly contaminated and exhibit variations of several centimeters in all three components. Fig.6 is a zoom into the GPS derived height variations of BRUA and a comparison with the tacheometer results and the photographs. In addition, fig.6 shows that a number of heavy vehicles passing the bridge at about 8:06 cause a reversible vertical displacement of more than 20mm at BRUA. This actual vertical displace-
ment is also shown in the GPS results but it can hardly be separated from the signal distortion effects.

The results could not be improved by filtering, since the main spectral components of both, the vertical motion and the signal distortion effects overlap. Furthermore, the actual motion is a transient signal while the GPS effects exhibit a nearly periodic pattern.

Fig. 6: Experiment II, BRUA, comparison of height variation obtained using tacheometer (light line) and GPS (bold line). The inserts show the traffic load at two instants in time, and how the traffic load affects the height of BRUA.

5 CONCLUSION

The experiments show that the pylon point is perfectly suited for GPS monitoring. The precision of the GPS results is about 2mm for the horizontal coordinates and 4mm for the height without filtering. This allows to study the response of the building to temperature variations and makes it feasible to determine long term building fatigue effects.

However, the bridge deck is not a suitable GPS environment because the steel cables exhibit severe multipath and diffraction effects which yield cm-level variations of the coordinate results. For large bridges with vertical deck displacements of several dm this may not be a serious limitation but for bridges like the one under investigation this means that GPS cannot be used to monitor the bridge deck. So, in this case, the quality of the GPS results does not allow for long-term monitoring of the bridge with sufficient accuracy.

We suggest that a GPS antenna on top of the pylon point be used for continuous GPS monitoring, and the bridge deck be tied to the pylon point by means of relative measurements using other sensors.
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References


