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REAL-TIME MONITORING OF HIGHWAY BRIDGES USING "DREAMS"

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Abstract

GPS has proven its high accuracy and flexibility when large manmade structures are under investigation. The deformation monitoring system DREAMS, developed during the last years at our institute, has been designed to provide a flexible tool for undertaking such measurements. The paper presents results obtained with a set of up to 6 GPS receivers on a motorway bridge near Würzburg and two network master stations located within a few kilometres next to the bridge. Data was collected with an update rate of up to 10 Hz and processed at the network master station.

Multipath as main problem in near-distance DGPS-networks is treated with special signal processing strategies implemented as part of the data processing engine. The software of our deformation monitoring system is fully configurable during run-time and may be used for small and also for large networks only limited by the performance of the computers and communication infrastructure. It is capable of being run in real-time or in postprocessing using the same algorithms.

Long-term and short-term results are presented showing the oscillation of the bridge depending on the daytime and the load (e.g. trucks) that is crossing. The height-deflection of the bridge is mainly induced through the moving vehicles. In the middle between two pillars the bridge shows a motion of up to 5 centimeters in the vertical axis.

One major advantage when bridges are equipped with such a monitoring system is, that any change of the bridge's behavior may be detected in or near real-time during its operation.

Our deformation monitoring system may also be utilized successfully when monitoring other man-made structures like dams or towers or in regions with volcanic activity.

1. Introduction

When monitoring deformations of man-made or natural structures one can distinguish between two types of movements. The first category comprises slow movements as we find them with dams, dumps, slopes or in seismic active regions. The second one consists of high-frequency changes of the observed point or the object under investigation itself. The goal of our monitoring system is to enable us to detect, observe and visualize both kinds of deformation and to automatically generate alarms when certain thresholds are exceeded. GPS is the basis of our experiments and proves to be a valuable tool also for short-term deformation monitoring.

To verify the capability of the monitoring system DREAMS (Differential Real-time Monitoring System) we conducted tests on a motorway bridge. This bridge is made completely out of steel and therefore shows considerable displacements in the vertical axis.

In the following we present the design and installation of the monitoring system, and some processing results.

2. System design

As already mentioned the object under investigation was a motorway bridge – the Haseltal bridge –, located between Würzburg, Germany and Frankfurt am Main on the motorway A3 and in a forest area called Spessart near the service station Rohrbrunn. Fig. 2.1 shows the overall location of the area we conducted our tests. In Fig. 2.2 the exact position of the bridge spanning a valley and the location of the reference station are marked.

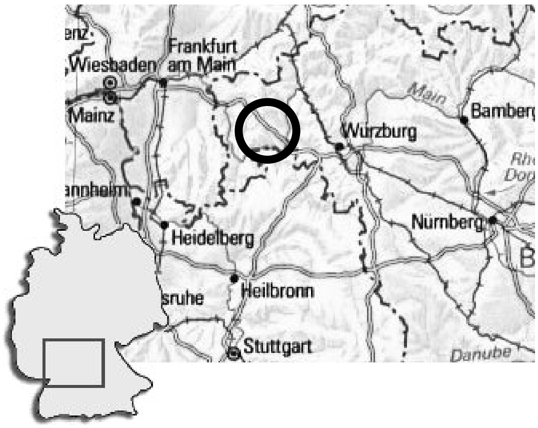

Fig. 2.1: Map showing the motorway from Würzburg – Frankfurt am Main, Germany

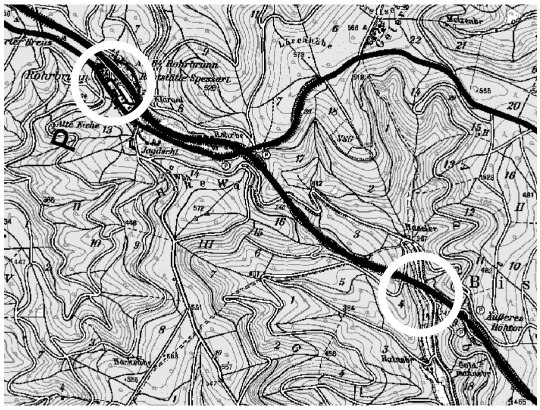

Fig. 2.2: Haseltal bridge (right circle) and reference station at the service station Rohrbrunn on the A3

Unfortunately the situation around the bridge does not allow placement of the reference station next to the bridge. The trees obstruct most of the area around the bridge (Fig. 2.3). This turned out to be true for the service station, too. But we were able to install the antennas on top of a building, thus extending the visibility to include satellites with lower elevations.
The bridge deck is built upon six 75-meter-tall piers and has an approximate length of 660 meters. For ease of installation we decided to use the span No. 6, located between pier 5 and 6 (Fig. 2.4). The piers are the abutment of the bridge deck and are also called axes of the bridge. The reason for installing the monitoring system on span 6 was the 220V power source at the end of the bridge. A central computing unit, which can be reached by a gangway under the bridge's deck, was established below the bridge. Data were collected most of the time with 1 Hz update rate. This is a reasonable compromise between quantity of the collected data and the necessary resolution for analyzing the data in a kinematic solution. And the data rate depends on the length of the bridge's span and therefore on the frequency of the bridge's movements. As a rule of thumb the shorter the bridge, the higher the frequency and as a consequence the necessary data rate. 6 Antennas – three on each side – were fixed on the southern and northern handrail with special mountings. The antennas labeled A1-1 and A3-1 are mounted in the middle of the span. Whereas the two other antennas are at a distance of about 10 m to the center antennas. Data were collected with the following types of receivers and antennas (Tab. 2.1).

Tab. 2.1: GPS-receivers mounted on the Haseltal bridge

	Receiver		**Antenna**
R1	NovAtel Beeline	A1-1	NovAtel 503 (+ Chokering)
		A1-2	NovAtel 501 (+ Chokering)
R2	NovAtel Millennium RT2	A2	NovAtel 503 (+ Chokering)
R3	NovAtel Beeline	A3-1	NovAtel 503 (+ Chokering)
		A3-2	NovAtel 501 (+ Chokering)
R4	Javad Eurocard	A4	Javad Regant1 (incl. Chokering)

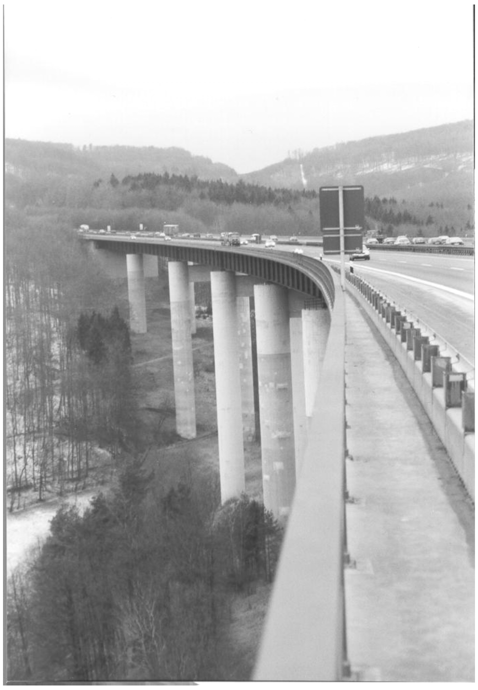

Fig. 2.3: Haseltal bridge (looking from Würzburg in the direction of Frankfurt)

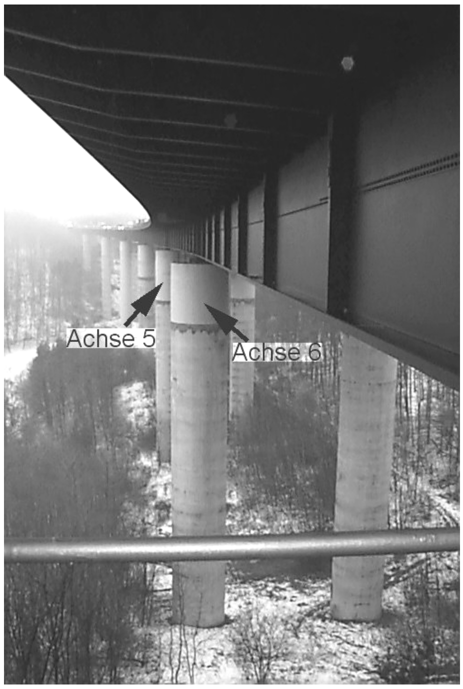

Fig. 2.4: Axes 5 and 6 of the Haseltal bridge (looking from Würzburg's abutment pier to the Frankfurt side of the bridge)

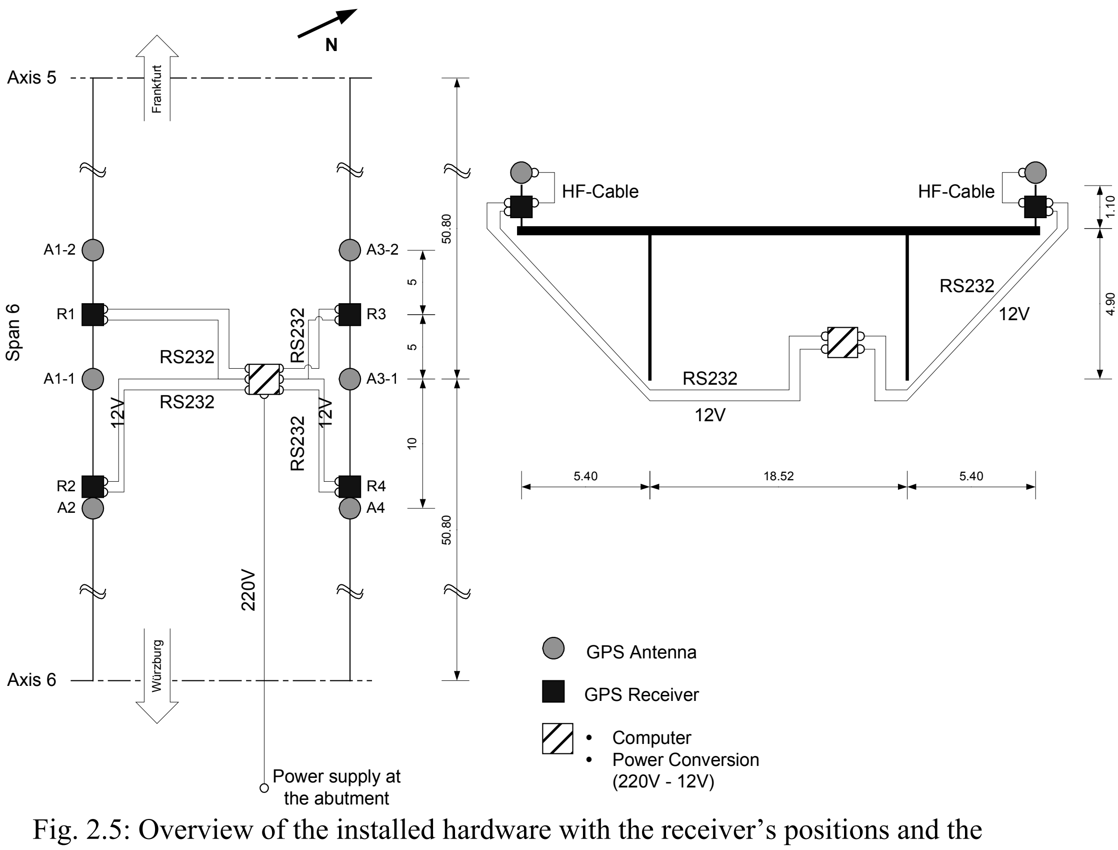

Fig. 2.5: Overview of the installed hardware with the receiver's positions and the cabling between the individual devices

The connection scheme of the installed GPS-receivers, antennas and the computer system can be found in Fig. 2.5. All utilized cables (HF, RS232, power supply) were specially tailored for this bridge.
The outline of the Haseltal bridge is depicted in Fig. 2.6. Shaded is the area where the monitoring system was installed. Fig. 2.7 shows the three antennas mounted on the southern side of the bridge looking to Würzburg.

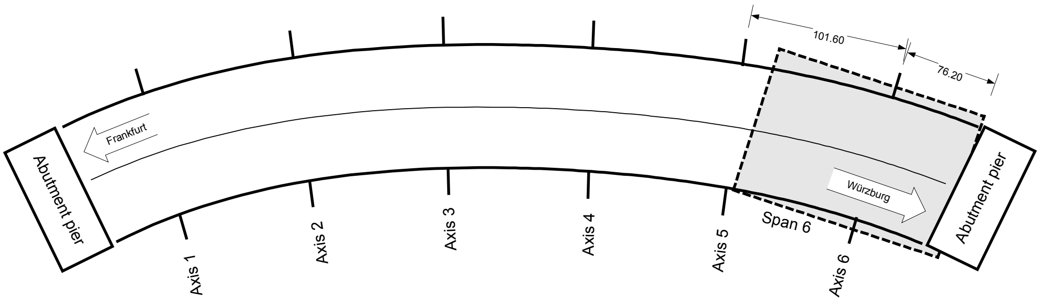

Fig. 2.6: Outline of the bridge

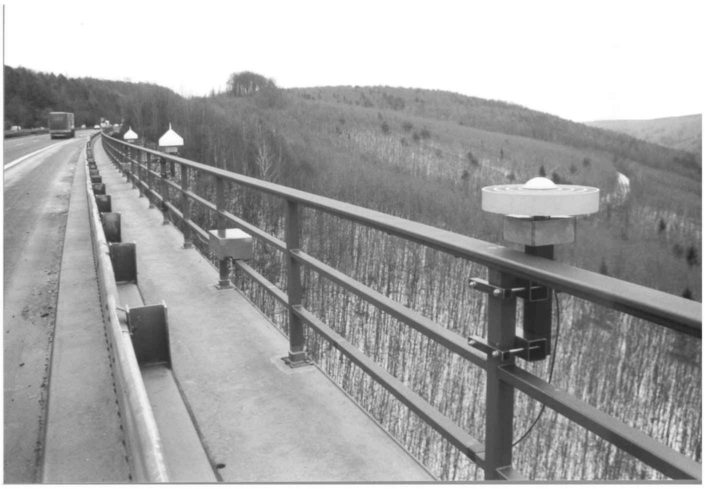

Fig. 2.7: Antennas installed on the southern railing in the middle of span 6

3. Data processing and results

Up till now the paper has dealt with the set-up of the monitoring system on Haseltal bridge. This chapter presents a short overview of the software side of DREAMS and – more important – some results obtained with our system.
In Fig. 3.1 the main structure of DREAMS' software components is visualized. Data are transmitted from the GPS-receivers to the data-IO module specialized for collecting data via RS232 or other computer interfaces. Afterwards data are decoded and stored in an internal storage area and routed to the processing engine. This engine – responsible for preprocessing, synchronization of the various data streams, computing the navigation solution and for statistics – is the central component of the monitoring system DREAMS. The final position and deformation solutions are stored as output on the hard-disk.
One major advantage of DREAMS is its universal und fully configurable data processing engine. All parameters may be set-up during run-time and are suited for flexible measurement applications. During processing the satellite data quality is checked. In addition satellites that lost lock or are newly included in the observation matrix are rejected till they provide stable carrier-phase measurements. A multipath filter – specially designed for the short-term behavior

of the monitored structure – is built in to reduce this major error source in this short-distance application. It consist mainly of an FFT-filter (Schüssler, 1992) removing detected lower frequency components (mostly multipath) from the observation data. For solving the observation equations a Kalman-filter design is implemented. Output to log-files with statistics and system parameters is generated after each time step.

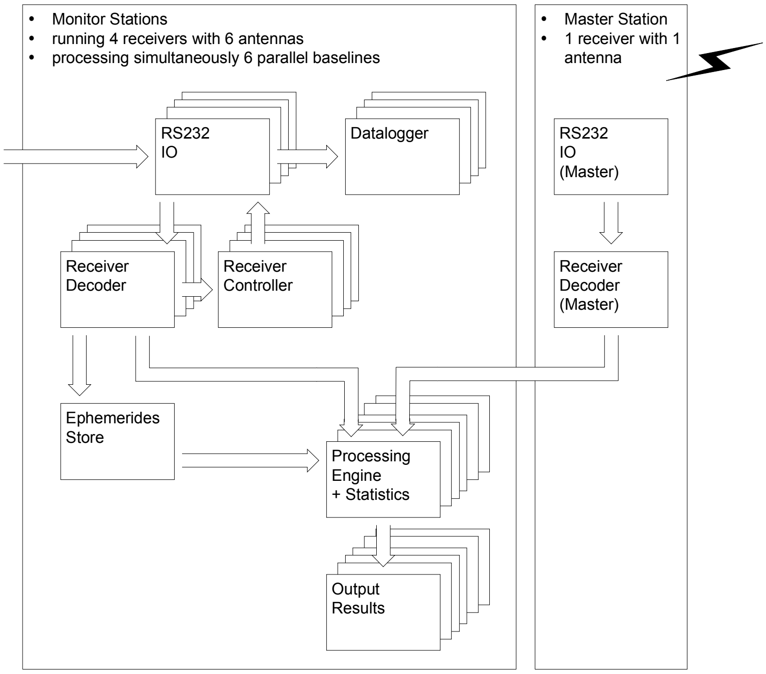

Fig. 3.1: Block diagram showing DREAMS' software architecture and the data flow between the SW-modules for real-time operation

More implementation details can be found in (Hein and Riedl, 1995).
The final step in computing the current position of the GPS-antenna is a transformation of the WGS84-coordinates in a "bridge"-coordinate system. The positions are already converted from cartesian WGS84-coordinates to an ellipsoidal representation. Afterwards they are transformed with a rotation operation to the bridge's longitudinal axis as shown in Fig. 3.2 and in (3.1). The rotation angle α can be obtained by positioning two of the antennas and then deriving the angle between this baseline and north.

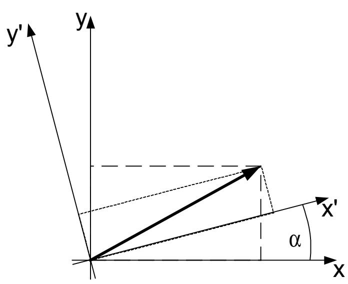

Fig. 3.1: Transformation between two horizontal coordinate systems

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) & 0 \\ -\sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{3.1}$$

All data were processed with a NovAtel Millennium RT2 receiver as reference station. Only the L1 observations were used, since the NovAtel Beeline receivers on the bridge solely support this observation type. As already mentioned, the resulting time series were transformed to adopt the lateral and longitudinal axis of the bridge.
The figures 3.3 – 3.6 show the height component of the four antennas for a period of 1000 seconds starting with 21:00 hours UTC. Note that Fig. 3.4 is processed with some modifications in the Kalman-filter parameters and thus is slightly less noisy than the other three plots.

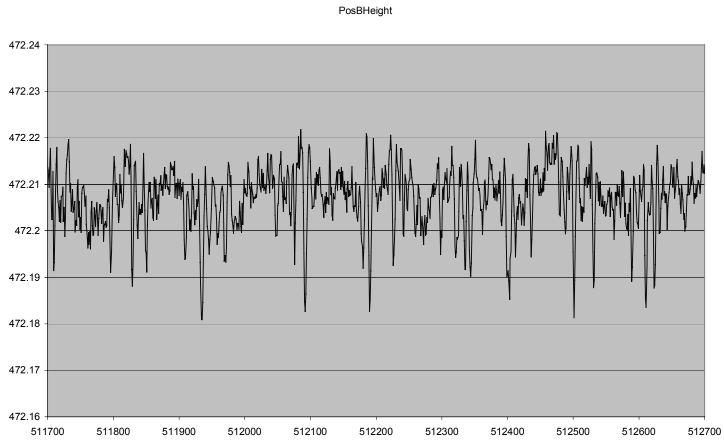

Fig. 3.3: A3-1 (NovAtel Beeline), Height (1000 epochs)

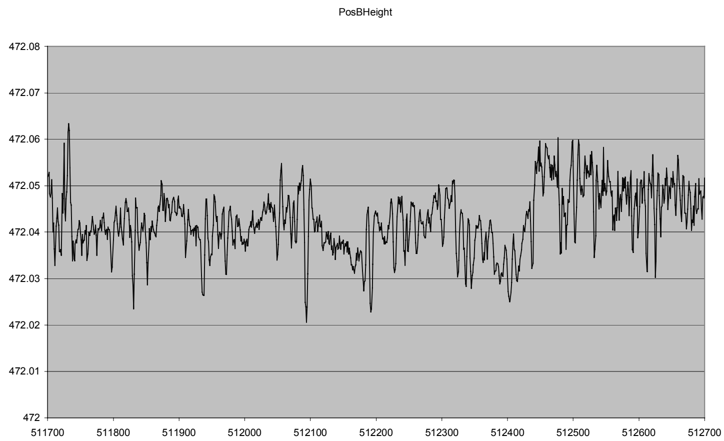

Fig. 3.4: A3-2 (NovAtel Beeline), Height (1000 epochs)

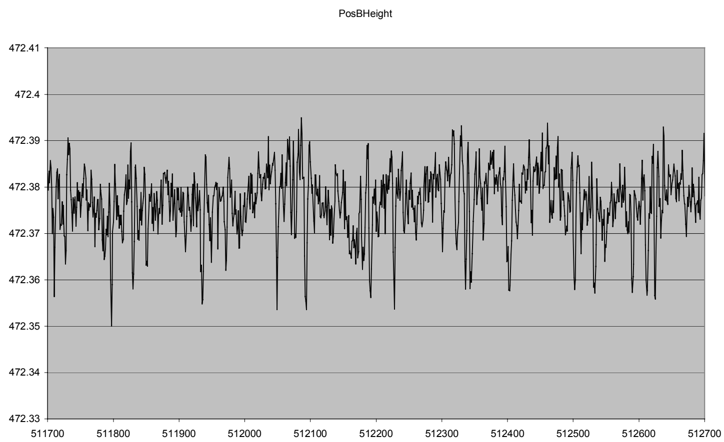

Fig. 3.5: A4 (Javad), Height (1000 epochs)

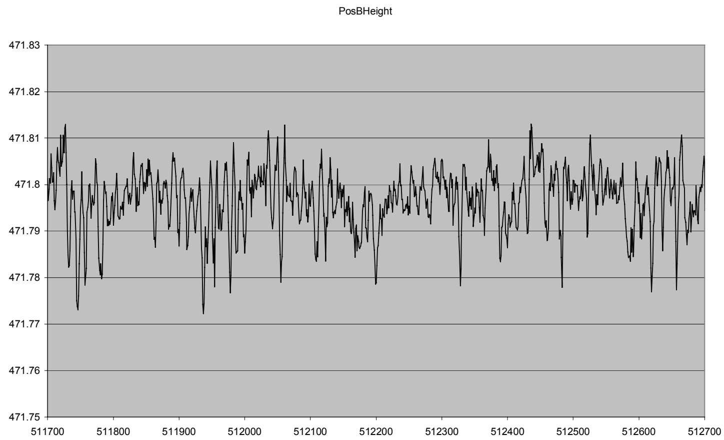

Fig. 3.6: A2 (NovAtel Millennium RT2), Height (1000 epochs)

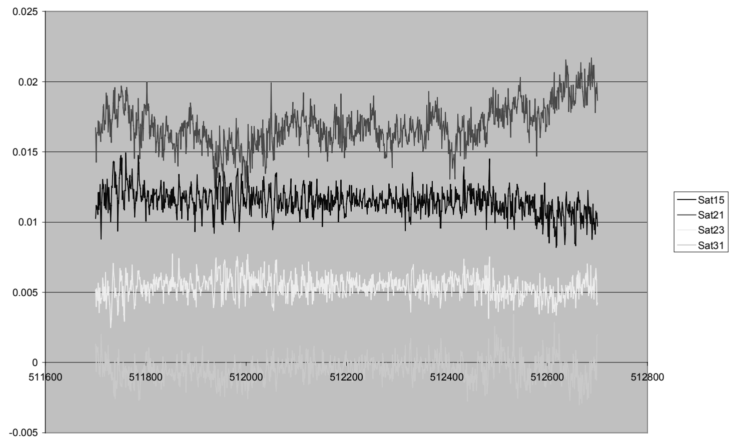

Fig. 3.7: Carrier phase double difference residuals after one time-step in the Kalman-Filter

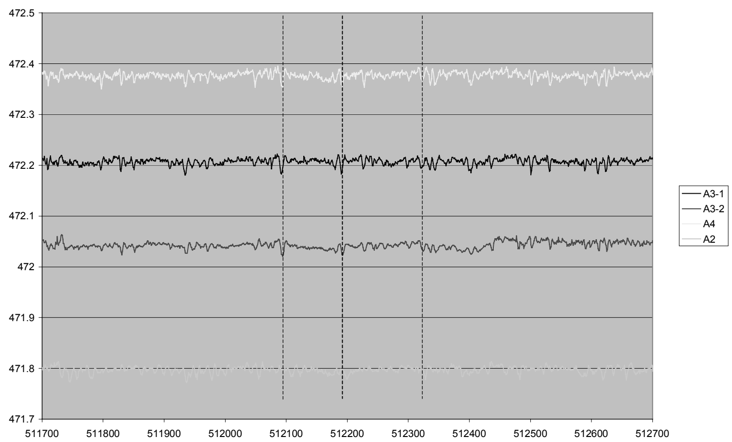

Fig. 3.8: Height component of all 4 antennas

Double difference residuals for antenna A3-1 are plotted in Fig. 3.7. Graphs are shifted by 5 mm to avoid superposition. The other antennas show similar residuals.

The bridge itself is inclined in the transverse axis. The north-side is elevated higher than the south-side. This can also be seen in Fig. 3.8, where the resulting heights of all 4 antennas are superimposed. The only antenna on the south-railing is A2. The figure illustrates clearly that the three antennas A3-1, A3-2 and A4 show an equal displacement near the dotted lines, whereas the antenna A2 is not synchronized with these changes. Obviously the bridge's height variation

depends mainly on the traffic on the corresponding side, so as a result the structure is not only deformed in the vertical axis but also torqued.
Fig. 3.9 shows the height changes of the bridge for the period 12/17/1999 to 12/20/1999. These data are processed in a different manner, since in this case we are mainly interested in the long-term changes of the bridge. The same data as for the short-term deformation analysis are used, but the results are not computed epoch by epoch but instead on an hourly basis. This leads to a much more stable solution since effects like multipath are reduced over time. On Sunday the bridge deck tends to be slightly higher than during the other days. A possible explanation is the reduced number of vehicles crossing the bridge, but especially the fact that large trucks are prohibited to drive on Sundays. All days have the variation depending on the daytime in common. During morning hours, around midday and in the evening there is a significant change in the height of the bridge. On the one hand we can identify the rush-hour traffic from about 8 to 9, on the other hand there are two peeks at 18 and 21 hours in the evening.

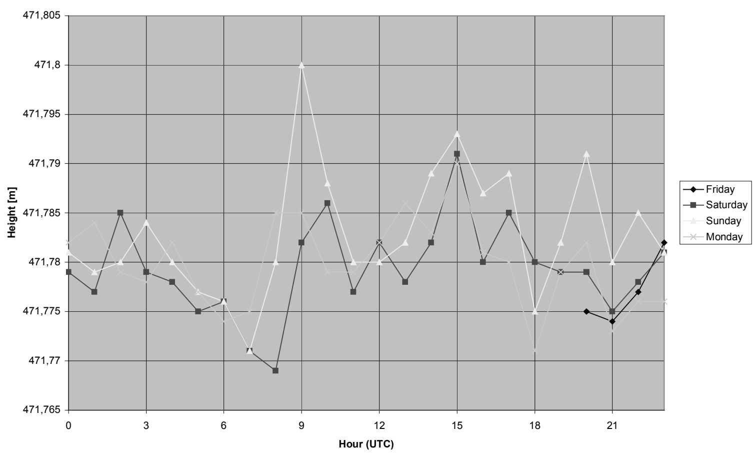

Fig. 3.9: A2 (NovAtel Millennium RT2), Height, Friday 12/17/1999 – Monday 12/20/1999

4. Conclusion

By means of the presented results the DGPS deformation monitoring system DREAMS proves its ability to examine and monitor not only structures with deflections over a few hours or days, but also of bridges or towers that are influenced by large loads or higher wind speeds. This calls for high update rates of the GPS receiver and as a consequence requires specially designed software components. DREAMS provides such flexibility and a scalable software architecture.
Short-term data that show clearly the vertical movements of the bridge deck were presented. The multipath mitigating FFT-filters remove most of the induced errors. Data from several antennas are correlated and confirm the quality of the vertical deformations found. Investigating a longer period of time results in a more thorough view of the daily repetition of traffic load and the total deflection of the bridge structure.

References

Hein, Günter W. and Bernhard Riedl. First Results Using the new DGPS Real-time Deformation Monitoring System „DREAMS“. *Proc. ION GPS-95*, Palm Springs, USA, Sept. 12-15, 1995

Schüssler H. W. *Digitale Signalverarbeitung* Springer Verlag Berlin, 3. edition, 1992