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High Precision Slow Motion Monitoring with Low Cost GPS Receivers in Real Time

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Abstract

A new high precision and reliable method for monitoring slow motions or movements of buildings or other objects in real time with low cost GPS receivers has been developed at the FH Bochum. The method is based on a new semi-kinematic real time algorithm and specific filter techniques. One of the systems installed continously operates since February 1996 to monitor the motions of a dam. The results collected over nearly two years demonstrate that accuracies of better than 1 mm can be achieved.

1 Introduction

The Global Positioning System (GPS) has been established since more than a decade as an excellent system for many navigation and positioning purposes. While at the beginning accurate positions required long observation time and static conditions the newest generation of GPS systems are able to deliver accurate positions already in real time and even under kinematic conditions. But the main application area for monitoring tasks is still restricted to the establishment of high precision control networks which are normally observed with dual frequency receivers in the static mode with long observation time and in postprocessing [Fr92], [Wi92]. In principal, the new real time systems (RTK) are also suited with some limitations to montitor the motions of objects, such as dams, bridges or other buildings but the reliability and the costs of these RTK-systems based on dual frequency receivers prevent till today their practical use [He95].

Alternatively for short baselines (< 2 km) cheaper single frequency receivers can be used but such systems do not fulfill the requirements needed in Engineering Geodesy. For this reason in 1995 at the FH Bochum especially for the oberservation of slow motions a new semi-kinematic real-time algorithm and specific filter techniques have been developed using low cost single frequency GPS receivers. After an evaluation phase a first system was already installed in February 1996 to monitor the motions of a dam in real time. The new method and the results collected over two years are presented.

2 The Semi-Kinematic Method for Monitoring of Slow Motions in Real Time

Monitoring of objects with GPS requires in most applications the installation of the GPS systems at exposed sites to receive the signals of enough satellites. For these reasons expensive RTK-systems based on dual frequency receivers are neglected from the beginning. Single frequency receivers used for geodetic purposes must at least deliver code and phase measurements to achieve centimeter accuracies. Favourite candidates are the single frequency receivers MX 4200 (6 channels), MX 9212 (12 channels) from Magnavox (now LEICA), and the ONCORE receivers (6 or 8 channels) from Motorola. Due to the lack of the second frequency and the noise of the code and carrier phase measurements these receivers are not well suited for real time kinematic applications - even for short baselines. But when considering the objects of interest in most cases only slow motions have to be monitored. For these tasks a specific semi-kinematic algorithm can be applied. In conjunction with additional filters very reliable and high precision positions can be achieved in real time with lost cost GPS receivers if the motion is less than 10 cm/min.

The new semi-kinematic algorithm developed for real time applications is based on a Kalman Filter [Br92] which does not propagate the position changes between two measurement epochs deterministically like in real time kinematic applications but stochastically as a random process. The state vector **X** of the Kalman Filter consits of the 3D- rover position (coordinates X, Y, Z) and the ambiguities ΔN_{ij} to be solved:

$$\boldsymbol{X}^T = [X, Y, Z, \Delta N_{12}, \Delta N_{13}, ..., \Delta N_{1n}] \tag{1}$$

For the state vector **X** the corresponding variance-covariance matrix **P** is introduced which has to be propagated between two consecutive epochs k-1 and k using the transition matrix **Φ** and a process noise matrix **Q**. This is done as follows:

$$\boldsymbol{X}_k^* = \Phi_k \cdot \boldsymbol{X}_{k-1} \quad \text{and} \quad \boldsymbol{P}_k^* = \Phi_k \cdot \boldsymbol{P}_{k-1} \cdot \Phi_k^T + \boldsymbol{Q}_k \tag{2}$$

The transition matrix **Φ** represents the deterministic and the process noise matrix **Q** the stochastic (random or uncertain) part of the propagation. The measurement vector **Y** of the Kalman Filter is formed by the double differences of the carrier phases $\nabla\Delta\phi_{ij}$ corrected for inospheric and tropospheric effects:

$$\boldsymbol{Y}^T = [\nabla\Delta\phi_{12}, \nabla\Delta\phi_{13}, ..., \nabla\Delta\phi_{1n}] \tag{3}$$

When at least three measurements (equivalent to four satellites tracked) are available the double differences are used to get a new estimate for the state vector **X** and its corresponding variance-covariance matrix **P** will be updated by calculating the measurement matrix **H** and the gain matrix **K**:

$$\boldsymbol{X}_k = \boldsymbol{X}_k^* + \boldsymbol{K}_k \cdot (\boldsymbol{Y}_k - \boldsymbol{H}_k \cdot \boldsymbol{X}_k^*) \quad \text{and} \quad \boldsymbol{P}_k = \boldsymbol{P}_k^* - \boldsymbol{K}_k \cdot \boldsymbol{H}_k \cdot \boldsymbol{P}_k^* \tag{4}$$

with

$$\boldsymbol{K}_k = \boldsymbol{P}_k^* \cdot \boldsymbol{H}_k^T \cdot (\boldsymbol{H}_k \cdot \boldsymbol{P}_k^* \cdot \boldsymbol{H}_k^T + \boldsymbol{R}_k)^{-1} \tag{5}$$

The elements of the time depending measurement matrix **H** have to be calculated by

$$h_{ij} = \left(\frac{\partial \boldsymbol{Y}_i}{\partial \boldsymbol{X}_j}\right)_0 \tag{6}$$

If less than four satellites are tracked no measurement update will be performed and the state vector **X** and its variance covariance matrix **P** for the new actual epoch k is calculated by

$$\boldsymbol{X}_k = \boldsymbol{X}_k^* \text{ and } \boldsymbol{P}_k = \boldsymbol{P}_k^* \tag{7}$$

The major advantage of this procedure is the robustness in respect to the loss of one or even all satellite signals (e.g. cycle slips) and its reliability. After the first initialization of the ambiguties for which 10 min to 20 min are needed the position accuracy depends only on the measurement noise of the double differences. Because of the stochastic modelling of the slow motion (< 10 cm/min expected) between two epochs a reinitialization of the ambiguities after short interrupts or power interrupts is normally performed within 1 to 2 epochs.

The user defined computation interval between two epochs is normally set to 10 s but can be reduced to 1 s or changed to other intervals if necessary.

3 Additional Filters

Carrier phase measurements are effected by the quality of the phase tracking loop of the receivers and by signal interferences leading to the so-called multipath effects. Additionally for highest precision applications variations of the antenna phase centre in dependency of the direction of the satellite tracked have to be considered [Wü96]. These errors result in high frequency errors (e.g. noise) and low frequency errors. The low frequency errors are mainly caused by multipath effects and antenna phase centre variations which are highly correlated with the satellite constellation (azimuth and elevation) and with the rotation rate Ω_S of the satellites varying from $14.58466 \cdot 10^{-5}$ rad/s to $14.58517 \cdot 10^{-5}$ rad/s for the different satellites in use. But if the site of the antenna varies only slowly the effects are repeated after a definite first time interval ΔT_1 which can be derived from the earth rate Ω_E ($\Omega E = 7.292115 \cdot 10^{-5}$ rad/s) and the rotation rate ΩS of the satellites as follows:

$$(\Omega_S - \Omega_E) \cdot \Delta T_1 = 2\pi \text{ or } \Delta T_1 = \frac{2\pi}{\Omega_S - \Omega_E} \tag{8}$$

This leads to time intervals of 86153 s to 86159 s resp. $23^h55^{min}53^s$ and $23^h55^{min}59^s$ and to a mean low frequency of $1.161 \cdot 10^{-5}$ Hz with which multipath and antenna phase centre effects are repeated.

While the high frequency errors (noise) can be easily removed in real time with recursive first order filters with a time constant of several minutes the low frequency errors need an extra analysis and treatment. The design of an appropriate filter depends on the frequency of the slow motion to be monitored and of the sampling period of the observation data [Ste84]. Moving average (MVA) filters with a filter length of 1 h up to 24 h or longer are an efficient method to cancel multipath effects and antenna phase centre errors. The longer the average time the better their cancellation. The general gain characteristic of such filters is shown in Figure 1. The advantage of this filter type is its constant phase lag and its easy application in real time, e.g. the computation of mean one-hour values or mean day values. The disadvantage is that the signals (the motion to be monitored) in the same frequency domain are also cancelled. In this case a special *Notch filter* has to be designed. Such a filter cancels only the frequency domain (see Figure 1) in which the multipath and phase centre errors occur. But its application needs data continously gathered at least over several weeks and extensive computation time and is therefore only suitable for postprocessing.

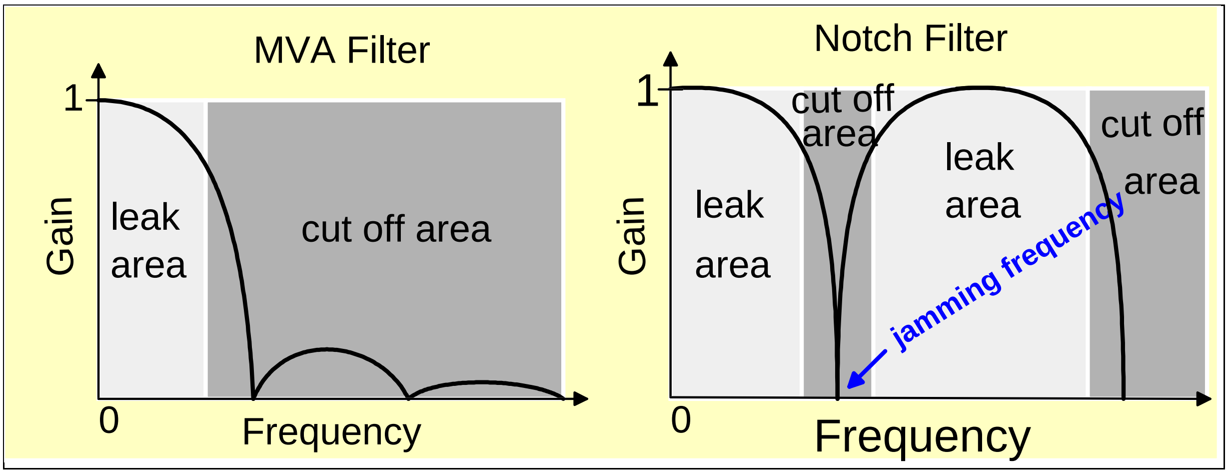

Figure 1: Gain characteristic of a moving average (MVA) and a *Notch filter*

4 Monitoring the Motion of a Dam Wall in Real Time

In February 1996 a first system was installed at the *Bever-Talsperre* [NN88] to monitor the motion of the dam wall. The dam wall has a length of 500 m and an overall height of 41.50 m (Figure 2). An 8 mm thick wall of steal fastened on a concrete socket with integrated control tunnel is used as seal and the dam itself consists of different layers of loam, gravel, slate and stones.

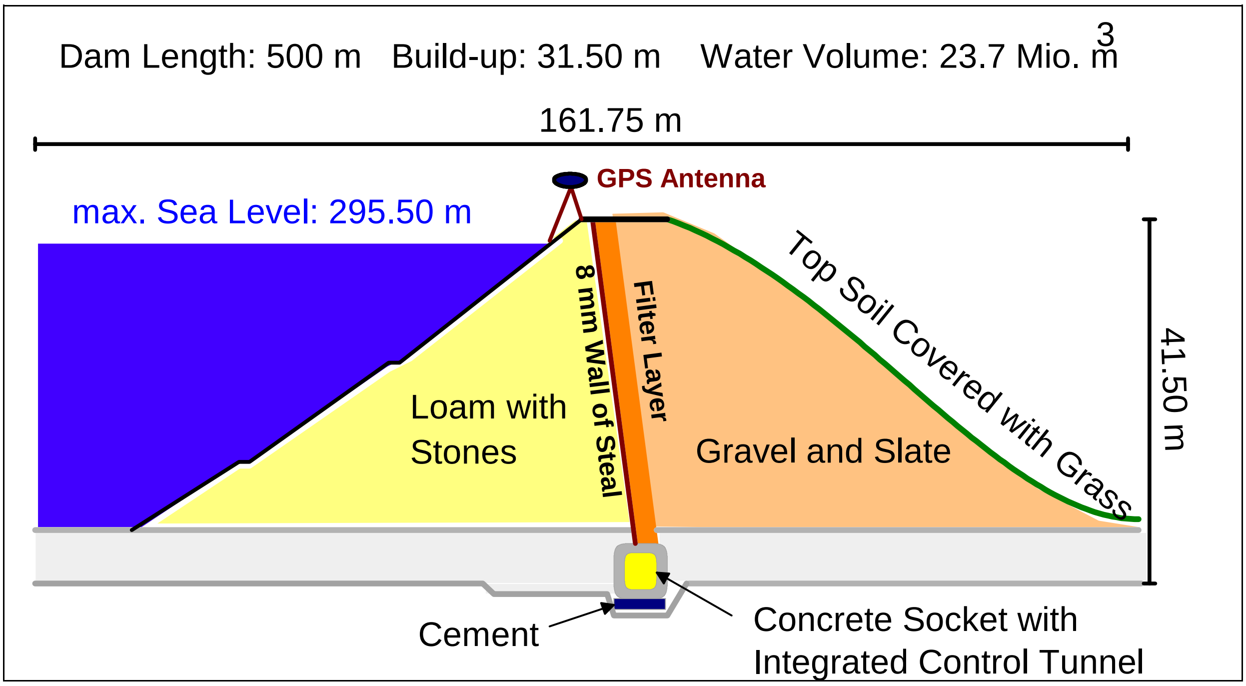

Figure 2: Dam of the *Bever-Talsperre*

The GPS system installed is based on two single frequency receivers: the MX 9212 receiver with 12 channels (as reference receiver) and the Motorola ONCORE receiver with 8 channels (as rover receiver). During an evaluation phase in which these receiver types were examined togehter with the dual frequency RTK- system SR 399 from LEICA it could be proved that slow motions can also be monitored with low cost receivers by using the new semi-kinematic method. If additional filters are applied accuracies of ±1 mm or better are achievable [Bäu95]. For this application the rover receiver and its antenna was directly put on a well-founded solid tripod at a point in the middle of the dam where the biggest motion was expected. A data and a power cable connect the receiver with a standard 486 PC and the power supply in the office close to the dam. The antenna of the reference receiver was mounted on the chimney of the office house. The receiver itself is placed in the office and connected to the second COM line of the PC. The PC additionally incorporates an internal modem to control the PC from a second PC via the telephone line (see Figure 3).

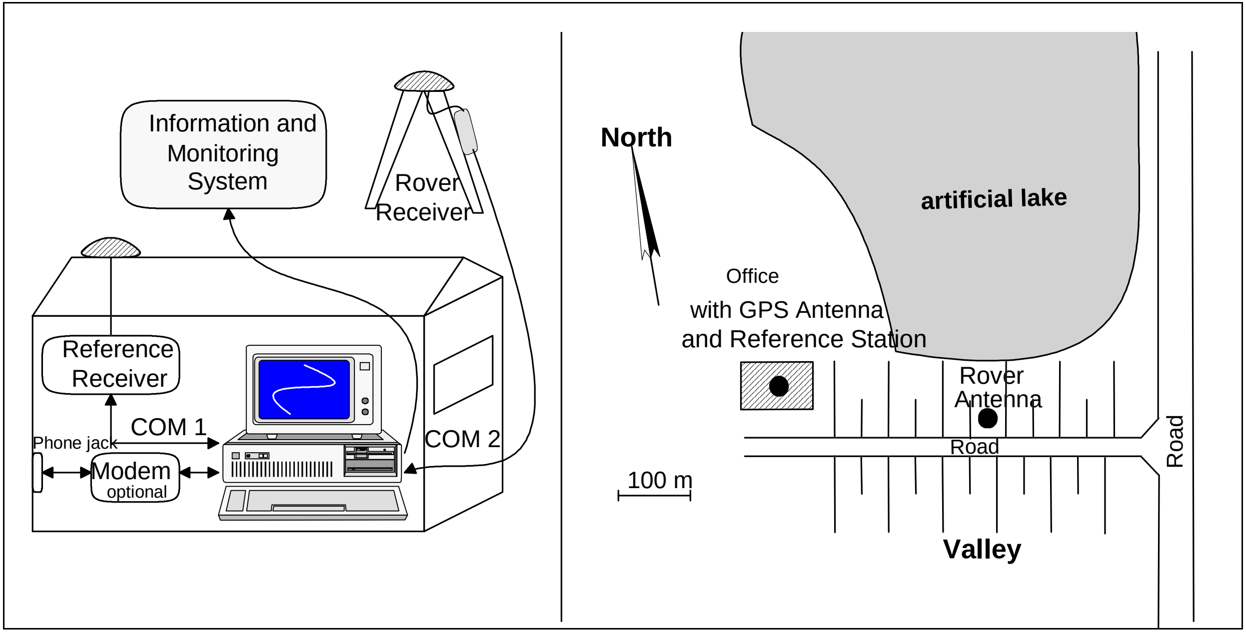

Figure 3: Installation of the system at the dam

The raw data of both receivers (code and carrier phase measurements) are acquired via the two COM lines of the PC and processed in real time to positions using the specific semi-kinematic method. Additionally the positions are transformed to a local datum and filtered with a first order filter to compensate for the noise of the carrier phase measurement. A further filtering is applied by calculating mean one-hour positions and mean day positions. These filters operate independently from the semi-kinematic calculations. The actual tracking status the different filtered positions and its standard deviations can be displayed on the information system of the dam and are stored on the hard disk of the PC. To reduce the amount of data stored the positions calculated every 10 s are only stored every 100 s. This enables the user to apply extra filters in proprocessing and to comprehensively examine and to remove multipath effects and antenna phase centre errors. The data files are closed weekly leading to appr. 0.5 MByte data per week.

The position data are fetched once per month via the internal modem and the telephone line and are analyzed together with the additionally collected water level measurements. A further transformation of the local coordinates into the dam coordinate system across and along to the dam direction is performed. Figure 4 shows the results collected from February 28th 1996 to January 31st 1998 (appr. two years!) and the water level measurements. During the whole time the system has worked properly and very reliable. The only data gaps are due to cuts of the data and power line by the gardener and a marten in July resp. August 1997. The positions recorded with a time interval of 100 s are additionally filtered with a double moving average filter (MVA filter) with a total filter length of some days. Thus multipath and antenna phase centre errors as well as possible motions in this frequency domain are completely cancelled. The horizontal position changes in the critical direction across to the dam direction (y-coordinate, positive down to the valley) are highly correlated with the water level changes. Between the lowest (283.7 m) and highest (295.6 m) water level motions of about 14 mm are found out in this direction. Comparisons with conventional geodetic measurements regularly performed two times a year show that accuracies of better than ±1 mm were achieved. The non-critical direction along to the dam nearly remains unchanged with one exception: an unknown person has shifted the GPS antenna in June 1996 by turning the tuning screw by exact 5 mm which was exactly monitored by the GPS system. After recognizing the reason the antenna was shifted back. The accuracies of the uninteresting vertical coordinates not shown here is twice lower than the horizontal components.

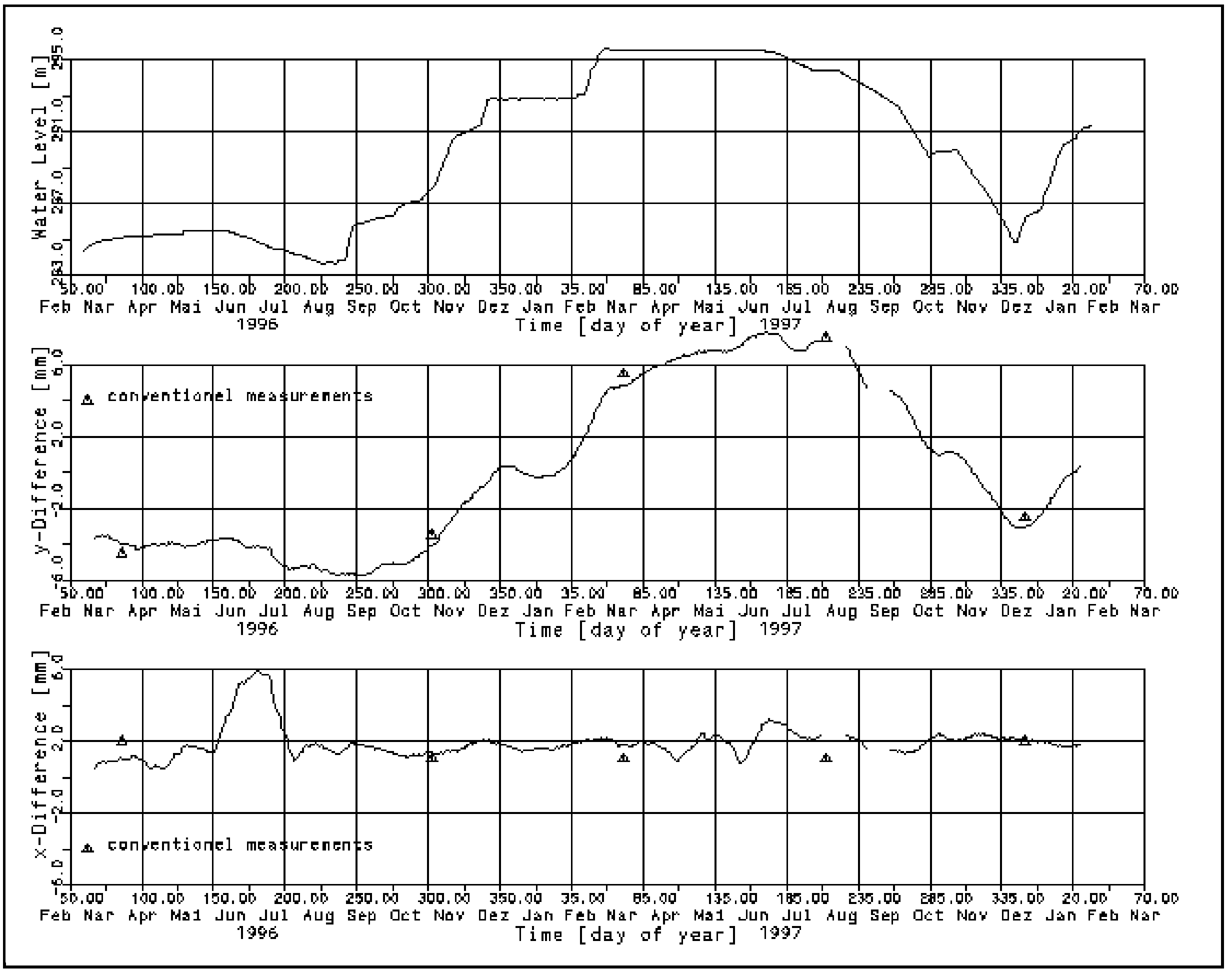

Figure 4: Water level measurements (upper plot), positions changes across to the dam (y-coordinate with the positive direction down to the valley, middle plot) and along to the dam (x-coordinate, lower plot) from February 1996 to January 1998, and conventional measurements

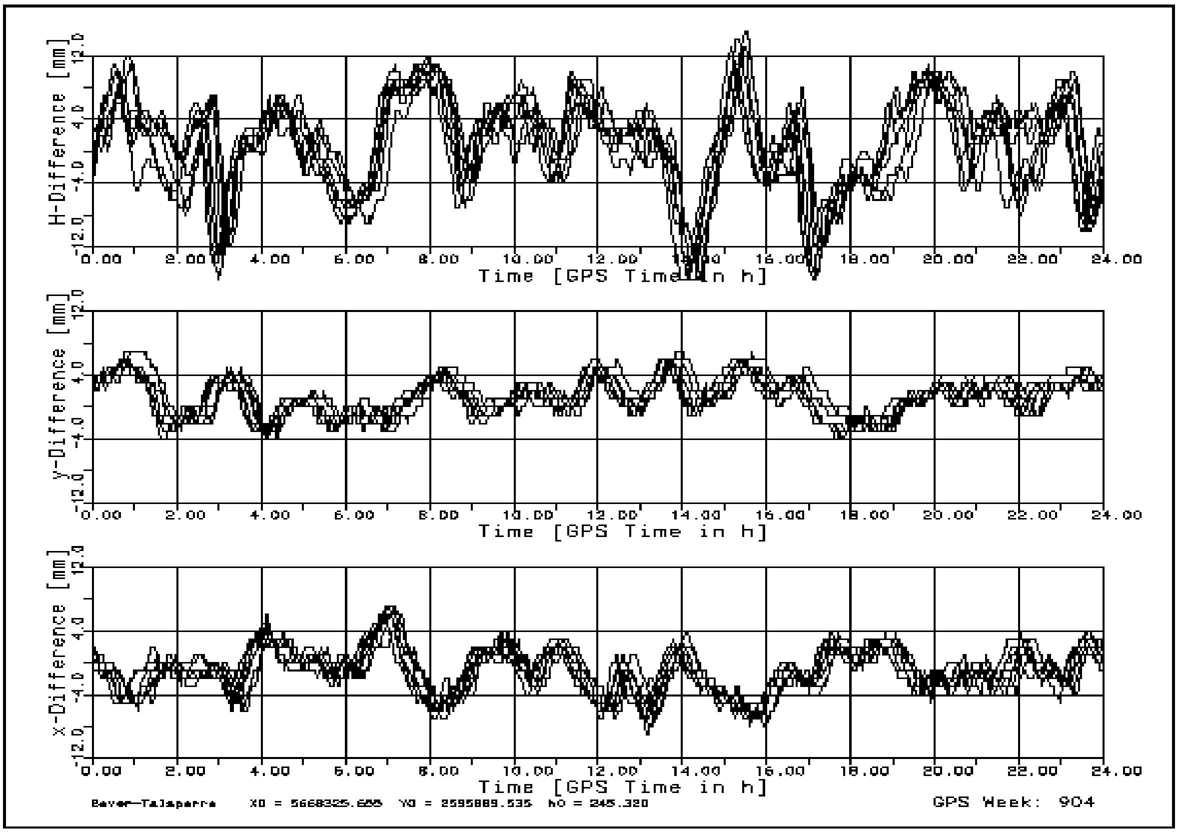

Figure 5: Original 100 s- coordinates of a complete week (7 days) commonly plotted from 0 h to 24 h GPS time containing multipath and antenna phase centre errors

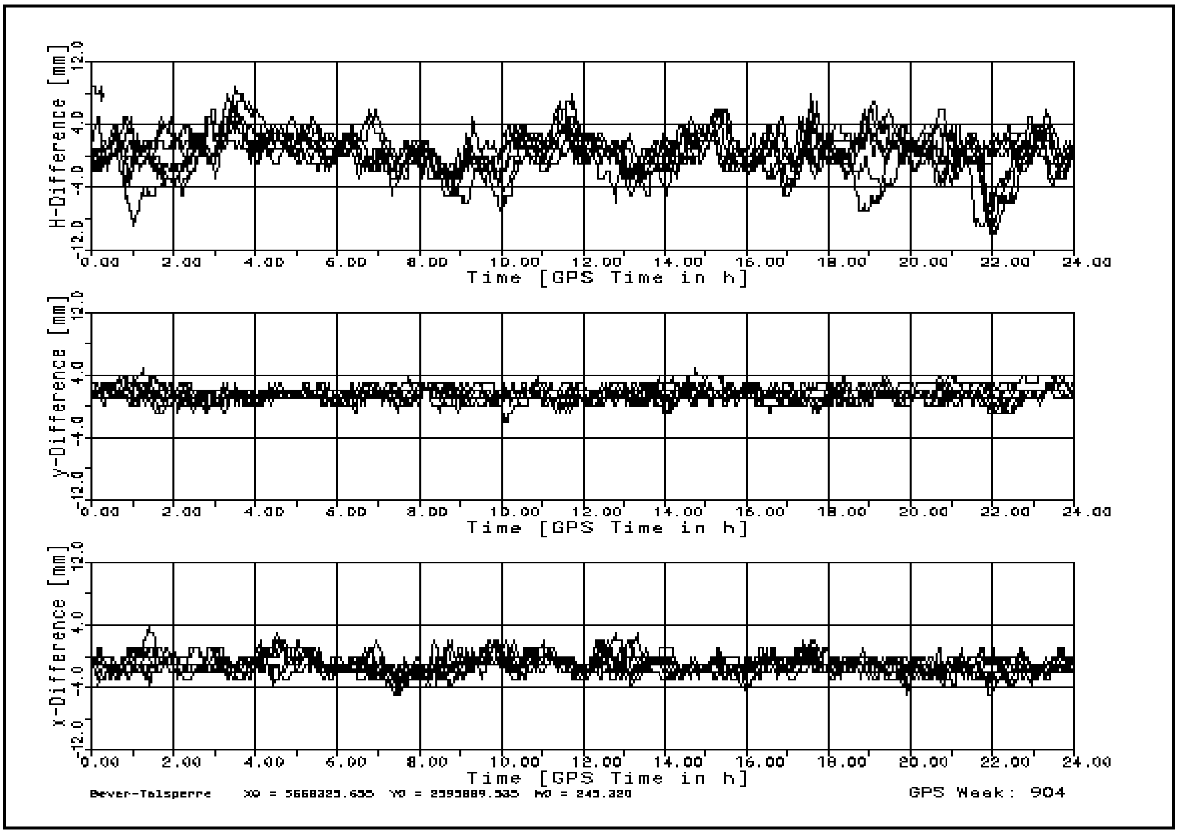

Figure 6: *Notch filter* compensated 100 s- coordinates of a complete week (7 days) commonly plotted from 0 h to 24 h GPS time (multipath and antenna phase centre effects removed)

As already mentioned due to the extra filtering with a MVA-filter (mean day values) multipath errors and antenna phase centre variations as well as possible motions are filtered by such a low pass filter. But if higher frequent motions are expected or possibly present an especial *Notch filter* has be used to only filter the unavoid jamming frequency caused by multipath and antenna phase centre errors. Such an filter needs data collected with short time interval (e.g. 100 s) and sampled over a long time (several weeks or better months). Figure 5 shows as an example the original unfiltered coordinates for a whole week in which the multipath and antenna phase centre effects can be observed. The coordinates of all 7 days are commonly plotted from 0 h to 24 h GPS-time and the drift of the effects of 243 s each day can be easily recognized. The effects reach during times with a bad satellite geometry amounts of up to ± 8 mm for the horizontal components and of up to ± 15 mm for the vertical component. When applying the appropriate *Notch filter* (see Figure 6) these errors could be already reduced to ± 2 mm for the horizontal and to ± 5 mm for the vertical components without cancelling the motion. In this case no further motion with short periods of 15 min or several hours could be observed so that in this case the application of the MVA filter is justified. For other applications in which dayly periods or shorter periods of the motion are expected such a *Notch filter* is absolutely necessary if accuracies of better than 3 mm are required.

5 Conclusions

A new semi-kinematic method especially designed to monitor slow motions of buildings or other objects has been developed at the FH Bochum. A first system was installed at the dam of the *Bever-Talsperre* in February 1996 and consits of two low cost single frequency receivers. The raw data of both receivers are processed in real time on a standard PC to calculate motions of the dam. Additional filter approaches are presented and applied to remove carrier phase noise, multipath effects and antenna phase centre errors. The very reliable system continously operates since two years. The high correlation of the motion observed with the water level measurements and with the conventional geodetic measurements shows that the system is able to monitor the motion of the dam with an accuracy better than ±1 mm.

References

[Bäu95] M. Bäumker and H.-P. Fitzen: *Permanente Überwachungsmessungen mit GPS*. In: Beiträge zum XII. Internationalen Kurs für Ingenieurvermessung. Graz, 9.-14. Sept. 1996.

[Br92] R.G. Brown: *Introduction to Random Signals and Applied Kalman Filtering*. Second Edition, John Wiley Sons, Inc., USA, ISBN 0471-52573-1,1992.

[Fr92] E. Frei, A. Ryf and R. Scherrer: *Das GPS und seine Anwendungsmöglichkeiten in der Ingenieurvermessung*. In: Ingenieurvermessung 1992, Hrsg. H.J. Matthias, A. Grün, Dümmler Verlag Bonn 1992.

[HE95] G. HEIN and B. RIEDL (1995): *First Results Using the New DGPS Real-Time Deformation Monitoring System "DREAMS"*.In: Proceedings of ION GPS-95, Palm Springs, USA, Sept. 12-15, Part 2, S. 1467-1475.

[NN88]: *Bever-Talsperre*. Printing of Wupperverband, D-42220 Wuppertal, 1988.

[Ste84] S.D. Stearns: *Digitale Verarbeitung analoger Signale*. R. Oldenbourg Verlag GmbH, München 1984.

[Wi92] A.A. Wiget and D. Schneider: *Erfahrungen mit GPS in Staumauer-Überwachungsnetzen*. In: Ingenieurvermessung 1992, Hrsg. H.J. Matthias, A. Grün, Dümmler Verlag Bonn 1992.

[Wü96] G. Wübbena, F. Menge, M. Schmitz, G. Seeber, Ch. Völksen: *A New Approach for Field Calibration of Absolute Antenna Phase Center Variations*. In: Proceedings ION GPS-96. Kansas City, Missouri, USA, 1996.