Presented at the International Technical Meeting, *ION GPS−01*, September 11.−14., 2001, Salt Lake City, Utah.

Permanent Object Monitoring with GPS with 1 Millimeter Accuracy

Gerhard Wübbena, Andreas Bagge, Gerald Boettcher, Martin Schmitz
Geo++® Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH
D−30827 Garbsen, Germany

Peter Andree
AGC Ingenieurbüro für Spezialapplikationen in Hydrographie und Ingenieurgeodäsie
D−21073 Hamburg, Germany

BIOGRAPHY

Dr. Gerhard Wübbena received his degrees in Geodesy from the Universität Hannover. He has worked in the field of GPS since 1983. In 1990 he founded the company Geo++®, which develops satellite navigation and positioning software and systems. Among these are the post−processing system GEONAP and real−time system GNSMART.

Andreas Bagge got his Dipl.−Ing. in Geodesy from the Universität Hannover. Since 1986 he works in the field of GPS, first at the Universität Hannover, and now for several years at Geo++®.

Gerald Boettcher received his degree in surveying from the Fachhochschule Oldenburg. Since 1998 he is involved in the application and evaluation of GPS projects.

Dr. Martin Schmitz received his degrees in Geodesy from the Universität Hannover. He is working in the field of GPS for the industry and as a research fellow at the Universität Hannover since 1991.

All four are currently employed at Geo++®. They are concerned in research and development in satellite positioning. One current project focus on real−time GPS deformation monitoring systems. Further projects among others are active reference networks for highly precise RTK phase positioning (GNSMART) and GPS station calibration project.

Prof. Peter Andree received his Dipl.−Ing. in Geodesy from the Universität Hannover. He is professor at the Fachhochschule Hamburg and also head of his company AGC.

ABSTRACT

GPS is best suited to permanently monitor the deformations of buildings, dams etc. in real−time. However, there often exist some additional requirements, e.g. higher accuracy, multiple sensors, cheap equipment, which cannot be solved with standard RTK solutions.

Geo++® has developed their system GNPOM (Geodetic Navstar − Permanent Object Monitoring) to overcome these restrictions. GNPOM is based on the multi−station real−time software GNNET, which is able to process the carrier phase observations of multiple receivers simultaneously. The result is not a set of single baselines, but a homogeneous set of coordinates with a realistic variance−covariance estimation for all stations. Cheap GPS sensors without any RTK or memory can be used,

because all processing is done with separate software on standard PC hardware.

Object monitoring is normally done within small areas. Over short distances the most limiting factors for accuracy are antenna phase center variations (PCV) and the influence of multipath propagation. GNPOM takes advantage of absolute calibrated antennas, so antenna PCV induced errors can be reduced below the sub−millimeter level.

Multipath is very often present in construction and urban environments, and can amount to an error of a few centimeters. For individual GPS satellites, multipath influence is significantly correlated between subsequent days, because the satellite constellation repeats after a siderial day, and thus multipath geometry is very similar for a given station environment. Using the data from previous days, GNPOM is able to separate multipath from the carrier phase observations. Other limiting error sources like orbit, ionosphere or troposphere are either not significant, due to small distances, or can be eliminated by use of several base stations in the GNNET multi−station adjustment. The remaining observations are free from any systematic errors, with an accuracy better than 1 millimeter.

Recent results allow to track the dynamic deformation of a building with amplitudes of 25 millimeters and accuracy of 1 millimeter.

INTRODUCTION

Multipath (MP) is the most limiting factor for very precise positioning applications with GNSS. Several MP mitigation techniques are known and implemented in many receiver types (Van Dierendonck et al. 1992, Townsend et al. 1995, Garin, Rousseau 1997). However, these techniques normally only attack the code MP effects. MP errors in carrier phase measurements are much more complicated to be mitigated through signal tracking techniques.

The multipath may also be mitigated through the use of new antenna designs like antenna arrays (Brown 2001) etc. Several groups are currently working and researching in this field.

For static setups MP may even be calibrated (Böder et al. 2001). Such calibration methods however are still not operational and may cause additional efforts.

Siderial day differences of GPS carrier phases are much less influenced by multipath errors than original phase measurements due to the daily repetition of satellite positions. Intensive use of such observations has been made in the development of the absolute antenna calibration method (Wübbena et al. 1997, 2000).

The use of siderial day differences for deformation analysis has been investigated in the early 1990’s. Some experiments have been carried out in 1996 and reported in 1997 (Seeber et al. 1997).

One antenna was put on a device allowing very small and precise manually controlled movements, which was positioned relative to an approximately 8 km apart reference station. The antenna was moved in steps of 2 mm over a range of 2 cm. Fig. 1 shows the absolute trajectory from a kinematic solution in post−processing. Fig. 2 shows the results from siderial difference processing relative to a static observation on the preceding day. From fig. 1 the overall trend of the movement can be seen, but the 2 mm steps are not obvious. From the siderial difference position however, one can clearly recognize the step movements. The conclusion of these results was, that siderial differences of carrier phase measurements are a very good and promising method to very precisely determine small movements.

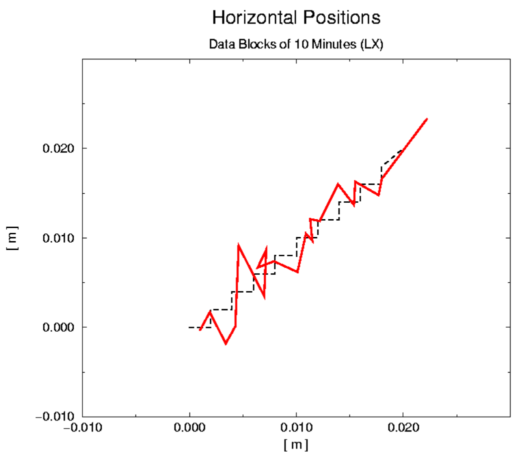

Fig. 1: Absolute trajectory from standard post−processing

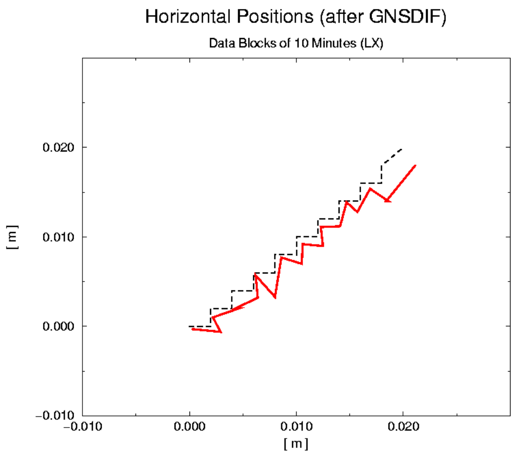

Fig. 2: Trajectory from siderial difference post−processing

At the same time, Geo++® started to develop and integrate this technique into their real−time software systems. A product called GNPOM for permanent and precise object monitoring has been developed. The system has been used in a few projects and could demonstrate its excellent performance. Recent improvements have been made to overcome the problem of relative movements between two consecutive days and to achieve millimeter accuracy for absolute kinematic positioning.

The following chapters describe the basic principles to overcome the multipath problem using standard GPS receivers, the software implementation and some results from recent projects.

GPS CARRIER PHASE MULTIPATH REDUCTION METHODS

AVERAGING OR LONG TERM FILTERING

To show the effect of carrier phase multipath a small experiment has been carried out. A reference receiver with antenna has been installed on the roof of the Geo++® building. A second receiver with antenna has been operated in southern direction near the 2.5 storied building (Fig. 3). At this place one can expect strong multipath effects, since the signals of satellites in the southern direction are reflected at the wall. The distance between the two receivers was approximately 10 m.

Fig. 3: MP test site in front of the Geo++ building

The static measurements were taken at two consecutive days for a period of a few hours. The post−processing was done with the Geo++® GEONAP package.

All measurements were corrected for absolute antenna phase center variations (PCV). Both antennas have been individually calibrated with the Geo++® absolute field calibration procedure utilizing a robot for antenna rotation and tilts (Menge et al. 1998, Wübbena et al. 2000).

The relative positions of both antennas have been determined from all observations. The residuals (double differences) of the observations will contain only multipath effects and random measurement errors. Due to the short baseline there is no significant distance dependent effects. PCV is eliminated through the individual elevation and azimuth dependent calibration parameters.

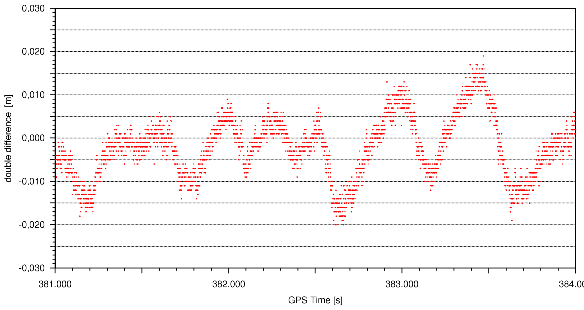

Fig. 4: Unfiltered L1 double difference residuals for a selected pair of satellites

Fig. 4 shows the double difference residuals for a selected pair of satellites. It can easily be seen that systematic multipath errors in the order of +/− 25 mm are overlayed by a much smaller measurement noise.

The fact that MP of such magnitude might be present in GPS carrier phase measurements limits the accuracy for kinematic positioning to the level of one or more centimeters. For static observations it is well known that an accuracy in the order of 1 mm may be achieved after a sufficient long observation time.

This is due to the fact, that MP typically shows a periodic behavior. The period of such a MP cycle depends mainly on the distance of the reflecting objects. Periods are in the order of minutes.

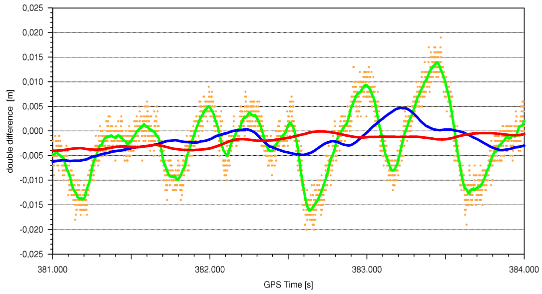

Fig. 5: Moving averages over double difference residuals

Fig. 5 shows the result of computing a moving average over the double difference residuals. An averaging time of 1 minute reduces mainly the measurement noise, but the periodic MP signal clearly remains. Increasing the averaging time to 30 and 60 minutes shows, that the MP signal is now reduced. For the 60 minutes average we get remaining MP errors in the order of a few millimeters. This value can further be reduced through longer averaging times. Depending on the number of satellites and the satellite geometry, the effect of MP in the position domain is usually smaller, because not all satellites are affected by the same magnitude and a reduction is achieved through redundant satellites.

However, averaging can only be achieved if static observations are performed or if the dynamic model of the expected movements introduce enough constraints into the filter process to get something like an averaging effect. This means, that kinematic observations with expected movements in the order of millimeters over short periods of time cannot take advantage of filtering or averaging and thus cannot eliminate or reduce MP.

SIDERIAL DAY DIFFERENCES

The orbit parameters of GPS satellites around the earth are designed to yield two revolutions within one siderial day (approximately 23 hours and 56 minutes). Due to this fact, the satellite constellation, as visible from a certain position on the earth, repeats every siderial day, i.e. the same satellite is visible at the same elevation and azimuth angles.

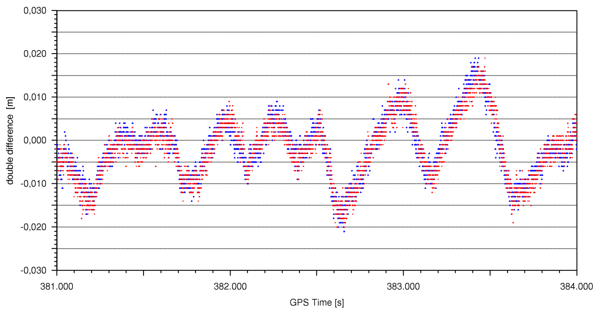

Fig. 6: L1 double differences of two consecutive days

MP errors are resulting from the interference of the directly received signal from the satellite with a signal received after reflection at objects in the vicinity of the receiving antenna. The amount of the MP error depends on the delay path length of the reflected signal and the relative amplitude or signal to noise levels of direct and delayed signal. If the local environment of the antenna is unchanged from one day to another, the geometry of the direct and reflected signals and the relative signal strength are the same. I.e. the MP error will also be the same. The difference between two measurements at a time difference of one siderial day should therefore be free of MP errors.

Fig. 6 shows the double differences of the same two satellites for the observations on the two consecutive days with the time of the second day shifted by one siderial day to the time of the first day. It is obvious that both systematic MP signals are more or less identical.

The double differenced siderial day differences residuals are plotted in fig. 7. The amplitude of the residuals has been significantly reduced. The periodicity is no longer obvious. The characteristic is similar to a random noise process. The standard deviation of this process is in the order of 1−2 millimeters.

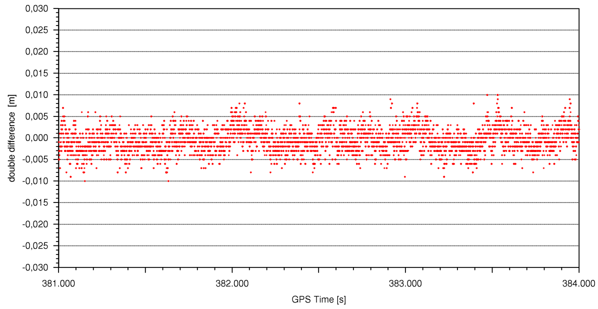

Fig. 7: L1 double differences siderial day differences

Depending on the application, this noise may be further reduced through filtering. Figure 8 shows the results of moving averages over 10 seconds and 1 minute respectively. The remaining errors in the derived positions can be reduced to the sub−millimeter level.

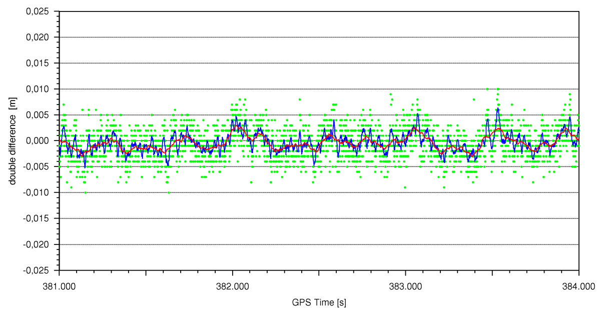

Fig. 8: Moving averages over double differenced siderial day differences

Through differencing observations in time the absolute position information is lost. From siderial day time differences therefore only position changes between the two days can be determined. The benefit of this type of information depends on the application.

Siderial differences can be used to monitor position changes in a kinematic sense, since systematic MP errors are mostly eliminated. The accuracy level is the same as with averaged observations over long periods of time.

COMBINED METHODS

Depending on the object to be monitored, the long term filter and siderial difference MP reduction methods may be combined to get millimeter accuracy for the small sized kinematic movements in an absolute sense.

For example, if an antenna is known to be static at the first day, a one millimeter accuracy level of the position can be achieved through static modeling. If kinematic movements are expected on the second day, these can then be determined from the siderial difference to the first day. The known static position on the first day serves as an absolute reference for the second day. I.e. in such a scenario very precise absolute kinematic positions can be determined.

If the characteristics of the movements of an object are known as a function of acting forces, information about these can be used to drive the parameters of the Kalman filter. For example, the movements of the wall of a lock are initiated by filling the lock with water or emptying it. After a certain period of time after such a process the velocity of movement will decrease and stop. The information about the filling or emptying process can be used to switch the filter parameters from static or very slow movements to faster movements during the process. In such a situation the reduction of multipath through filtering and siderial differencing can be combined in an optimum way for maximum accuracy of the absolute movements of object points.

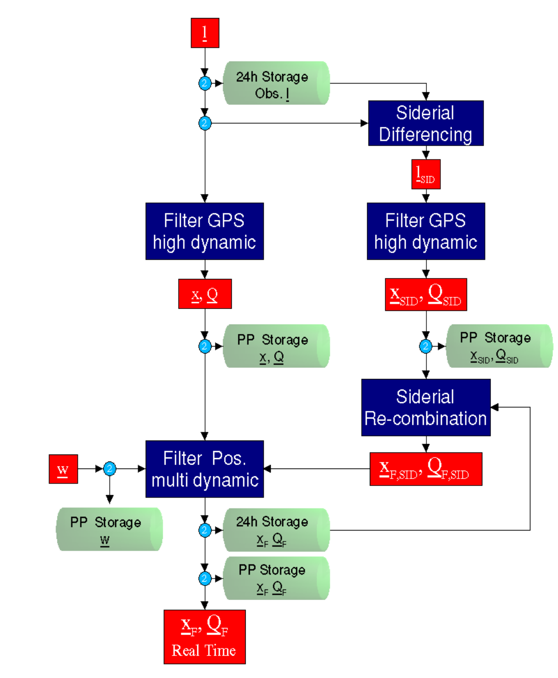

Fig. 9: GNPOM real−time data flow

Figure 9 shows the principle of data flow in a system using both types of MP reduction simultaneously. The original or linearized observations are stored on disk and split in real−time into two chains of processing. On the right hand side the siderial day difference is build by subtracting the stored values of the preceding day. These observations are filtered with high dynamic parameter settings to yield the position difference between the two days together with its variance−covariance matrix. These values $(\boldsymbol{x}_{SID}, \boldsymbol{Q}_{SID})$ are combined with the filtered position $(\boldsymbol{x}_F, \boldsymbol{Q}_F)$ of the preceding day which results in an estimate for the absolute position $(\boldsymbol{x}_{F,SID}, \boldsymbol{Q}_{F,SID})$ of the current day.

In the chain on the left hand the observations are first processed in a high dynamic filter yielding absolute coordinates with its stochastics. The filter parameters are similar to the corresponding filter for the siderial day differences. The main purpose of these filters is to solve all the GPS related parameters like carrier phase ambiguities etc. and to provide “unfiltered” coordinate information with complete stochastic information. The second filter in the left hand chain works in the position domain. It uses external forcing function information to continuously adjust its stochastic parameters. In addition to the observations also the position resulting from the siderial chain is introduced into the filter. The result is a filtered position for the current day $(\boldsymbol{x}_F, \boldsymbol{Q}_F)$ which contains the combined effects of MP reduction.

The MP reduction through averaging only applies to periods with known low dynamic movements. Depending on the object to be monitored these periods may be at the same solar times on consecutive days or may be totally independent. In case of independent periods the length of the effective period for MP reduction increases through the siderial day difference processing. This applies not only to two days, but in principle to the complete runtime of the system. The amount of MP reduction however is smaller the longer the low dynamic period (measured in days) has gone. For solar time related periods there exists an approximately 4 minute shift in siderial time. I.e. even for such objects a combined effect of MP reduction will be achieved after a certain period of time.

The result of the preceding discussion is that absolute accuracy of kinematic movements can be improved through combining averaging effects from observations which are a multiple of siderial days apart in time. This also applies to such periods in the future. This means that a backward filtering will improve results in the past.

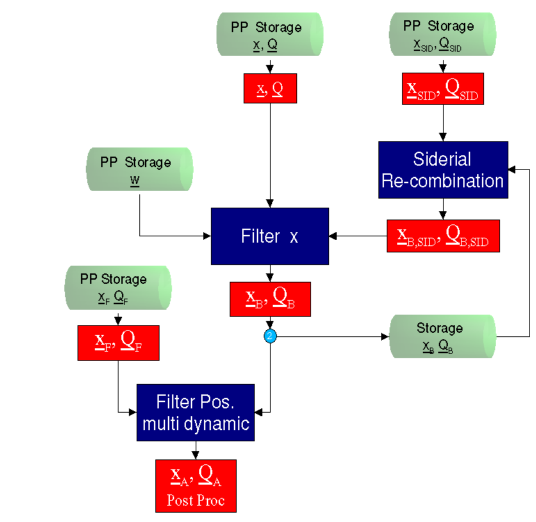

Fig. 10: GNPOM backward filtering

Figure 10 shows the principle data flow for this backward filtering with GNPOM. The real−time coordinates from the GPS filters $(\boldsymbol{x}, \boldsymbol{Q})$ and $(\boldsymbol{x}_{SID}, \boldsymbol{Q}_{SID})$ as well as the information about the forcing function are used as an input for the backward filter. This results in a second estimate for the absolute coordinate for all past epochs $(\boldsymbol{x}_B, \boldsymbol{Q}_B)$. In a final step these may be combined with the forward filter results to the final absolute coordinates and covariance information $(\boldsymbol{x}_A, \boldsymbol{Q}_A)$.

THE GEO++® − GNPOM SYSTEM

Geo++ has developed the software GNPOM for permanent object monitoring with highest accuracy. The system is designed for different applications ranging from static deformation monitoring with sub−millimeter accuracy to high dynamic monitoring of even kinematic objects.

One kernel part of the system is the main processing module GNNET. GNNET is a general purpose multi−station software for the adjustment or filtering of undifferenced GNSS code and carrier phase measurements. The rigorous modeling of observations within GNNET allows it to be used for many different applications.

APPLICATION EXAMPLE: THE LOCK

Deformation monitoring tasks exist is many fields of engineering. One special field is hydraulic engineering with its different types of objects.

A lock is an object where movements of the walls can be expected as a function of the forces introduced by the water through the filling or emptying periods.

By order of the German “Bundesanstalt für Wasserbau (BAW)”, the object “Schleuse Uelzen” has been monitored for several weeks in real−time with the Geo++® GNPOM system. One reference station and six object points have been equipped with GPS antennas. The reference station has been setup in a distance of approximately 300 m from the lock.

Dual frequency receivers have been used in order to be able to analyze the performance compared to single frequency equipment. The results of this analysis show, that single frequency measurements are sufficient for this type of monitoring, as long as the distances between the antenna locations are small. Choke ring antennas have been used for the project due to the fact that they were available and equipped with radomes. However, single frequency receivers and cheaper antennas will be sufficient as long as they are calibrated and stable.

All antennas were calibrated using the absolute field calibration procedure with sub−millimeter accuracy.

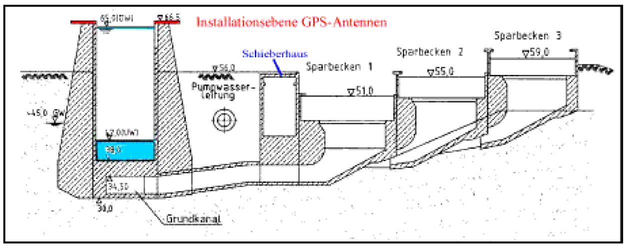

Fig. 11: Cross section of the lock

Figure 11 shows a cross section of the lock. A longitudinal section is given in figure 12. The antenna positions are marked in red. The lock has a length of 190 m, a width of 12 m and a lift height of 23 m.

Figure 13 shows the location of four antennas on the lock. For all sites we could expect strong MP influences.

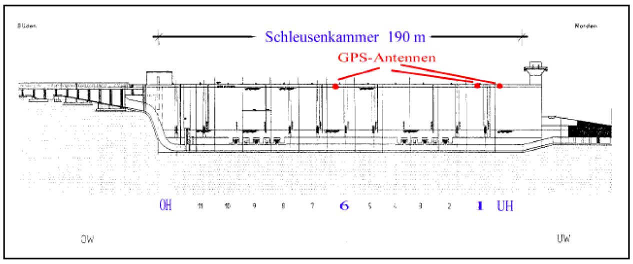

Fig. 12: Longitudinal section of the lock


Fig. 13: The lock "Schleuse Uelzen"

The processing with GNPOM was distributed on two computers. The first did the GNNET multi−station processing for the actual data (Fig. 14). The raw measurements of the receivers have been transmitted through radio for the reference station and TCP/IP communication for the object sites. The RCVR_IN modules provide an input interface for different receiver types. GNRT is responsible for some initial data checks and the linearization of the observations. The multi−station processing with high dynamic filter settings has been performed with GNNET. GNSOLF allows the filtering in the position domain. Several simultaneous filters may be run with different setting. Unfortunately, there was no online information on the forcing functions available (start and end of locking). I.e. the complete process as described above could not be performed in real−time. However, the complete computations could be done in post−processing through some additional data analysis.

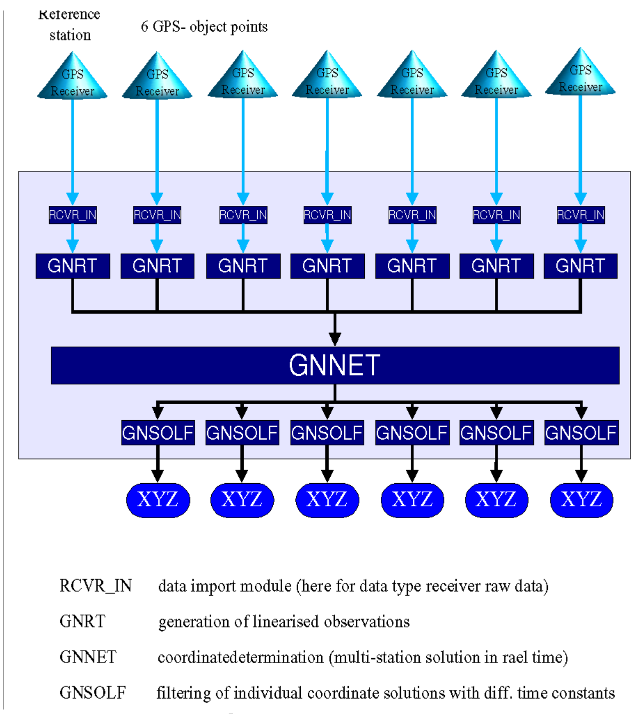

Fig. 14: GNNET multi−station processing

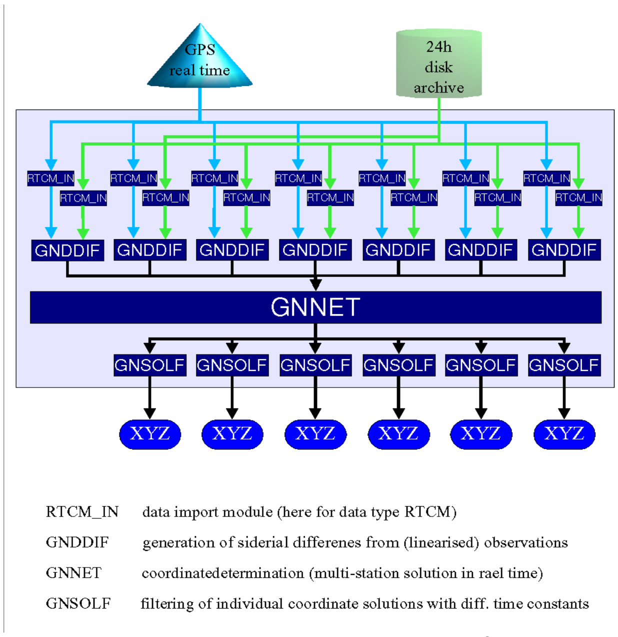

Fig. 15: GNNET multi−station processing of siderial day differences

The second computer was responsible for the processing of the siderial day differences (Fig. 15). The real−time data transfer between the computers has been done through a TCP/IP interface using the RTCM format. The RTCM_IN module was used for the real−time input as well as for the input of the data from the preceding day. GNDDIF is a module which allows the computation of the siderial day differences of the linearized observations. Again GNNET was used to compute with the high dynamic settings the siderial coordinate differences with the corresponding covariance information.

APPLICATION RESULTS

Data analysis has been carried out in many different ways. Some of the results are presented in the following figures.

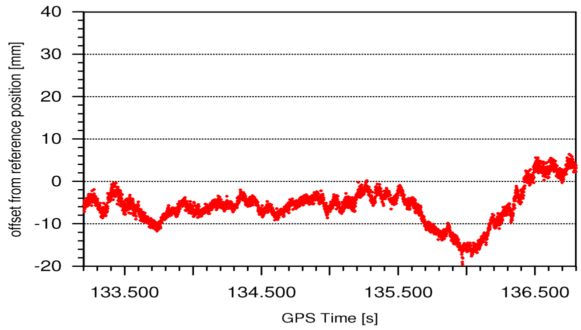

Fig. 16: Unfiltered easting differences during locking, pillar B1E, doy 015 n

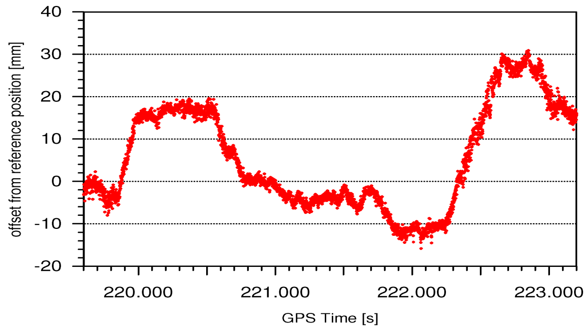

Fig. 17: Unfiltered easting differences during locking, pillar B1E, doy 016 n

Figure 16 and figure 17 show the time series of the unfiltered easting component of one pillar compared to its reference position on two subsequent days. Only on the second day two locking events occurred within one hour. There are some systematic multipath effects visible, while the bandwidth of the positions is in the order of 5 to 8 mm for the “static” situations of the lock.

The orientation of the lock is almost north−south, i.e. the east−west coordinate approximately describes the across object movements of the wall.

The siderial day difference position between the two days is displayed in figure 18. The easting coordinate component clearly shows the repeatable movement of the wall for two lock cycles.

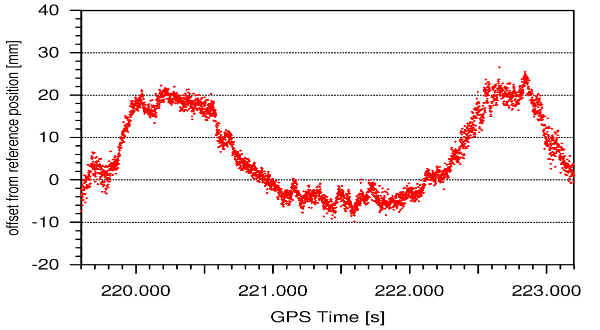

Fig. 18: Unfiltered easting differences during locking, pillar B1E, doy 016 n

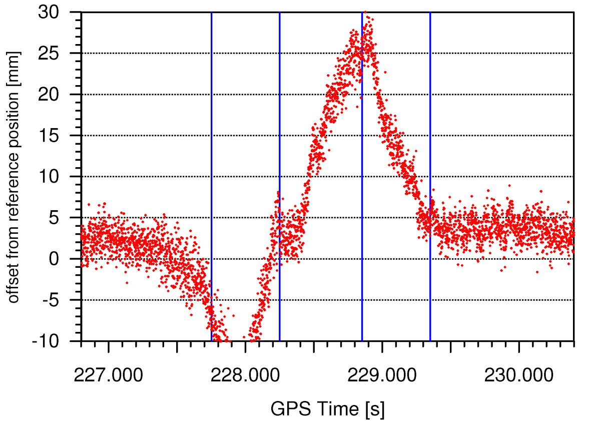

Fig. 19: Unfiltered siderial easting difference during locking, pillar B6E, doy 015/016 p

Figure 19 depicts the siderial day difference of the easting coordinate component for the special case, that on both days overlapping lock cycles are present. Due to the overlapping of the lock cycles a unique interpretation is difficult.

The forcing function used for post−processing analysis is indicated by vertical lines and has been determined manually from the absolute data sets itself. It is hardly possible to distinguish between the individual lock cycles. However, such situations are automatically handled in the real−time and post−processing version of GNPOM, because the combination of absolute and siderial differences maintain the individual events with improved accuracy through the different techniques of multipath reduction.

Figure 20 shows the final result for one lock cycle and one of the object points. The maximum variation in height (green) during the complete period is 1 mm even during the dynamic parts. Since the height can be expected to be stable one gets some impression for the absolute accuracy. The coordinate component across the axis of the lock (red) shows the absolute movement of the wall. There is a change in the position from −5 mm to +21 mm with respect to an initially defined position. After the lock cycle the position comes back to a level of −6 mm. The longitudinal component (blue) estimates to −1 mm during the static periods and varies in the range of −3 mm to +1 mm during the filling or emptying periods. This behavior is repeatable, i.e. it most probably describes a true movement.

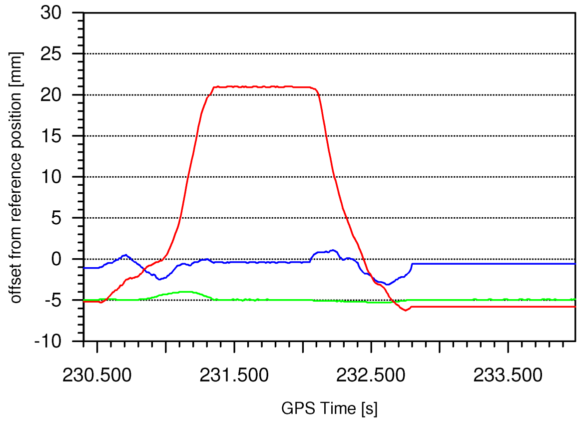

Fig. 20: Final result for one lock cycle in longitudinal, cross axis of object and height

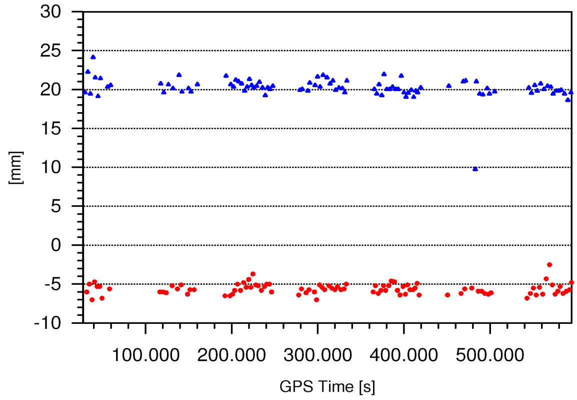

Fig. 21: Final positions in the across object axis, B6E, full (triangle) and empty (dot) lock

Figure 21 show the final position in the across object axis for all observations during one week. It can be seen that the position of the wall in general repeats with a variation of +/− 1 mm. This gives a very reliable and precise information about the true movements of the wall.

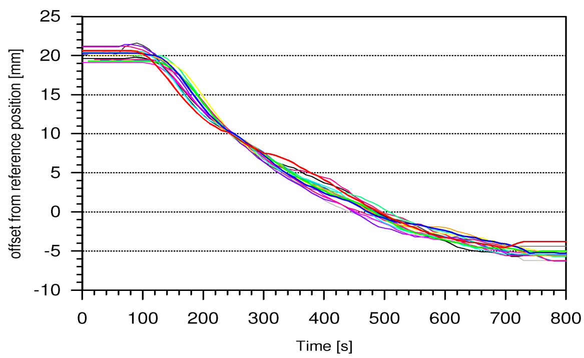

Fig. 22: Repeatability of the moving phases from 16 emptying processes

In order to analyze the repeatability of the moving phases 16 emptying processes have been shifted in time and plotted together in Fig. 22. Since the opening times of the flood−gate were not exactly recorded each curve may be shifted by a small amount of time. However, it can clearly be seen that the behavior of the wall and the measurement is consistent within a +/− 1 mm range.

SUMMARY AND CONCLUSIONS

Multipath (MP) is the main limiting factor for precise positioning applications over short distances with GPS. Two different principles of reducing the effect of MP have been explained and demonstrated. The first is the MP reduction through static or low dynamic modeling. The second is the use of siderial day differences, where MP is dramatically reduced due to the repeated geometry of satellite positions.

The combination of both methods of MP reduction can be used to determine absolute kinematic positions with 1 millimeter accuracy.

An example of the system setup of GNPOM has been given. Some results of recent measurements on a lock have been presented and show the capability of the approach.

ACKNOWLEDGMENTS

The cooperation of Dipl.−Ing. C. Kunz from Bundesanstalt für Wasserbau (BAW), Karlsruhe, and the people operating the lock is kindly appreciated.

REFERENCES

Böder, V., F. Menge, G. Seeber, G. Wübbena, M. Schmitz (2001). How to Deal With Station Dependent Errors−New Developments of the Absolute Calibration of PCV and Phase−Multipath With a Precise Robot. To be presented at the International Technical Meeting, *ION GPS−01*, Salt Lake City, Utah.

Brown, A. (2001). High Accuracy GPS Performance using a Digital Adaptive Antenna Array. Proceedings of the National Technical Meeting, *ION NTM−01*, Long Beach, California.

Dierendonck, A.J., P. Fenton, T. Ford (1992). Theory and Performance of Narrow Correlator Technology in GPS Receiver. *Navigation*, Journal of the Institute of Navigation, Vol. 39, No. 3, USA.

Garin, L., J. Rousseau (1997). Enhanced Strobe Correlator Multipath Rejection for Code & Carrier. Proceedings of International Technical Meeting, *ION GPS−97*, Kansas City, Missouri, USA,.

Menge, F., G. Seeber, C. Völksen, G. Wübbena, M. Schmitz, (1998). Results of Absolute Field Calibration of GPS Antenna PCV. Proceedings of the International Technical Meeting, *ION GPS−98*, Nashville, Tennesse.

Seeber, G., F. Menge, C. Völksen, G. Wübbena, M. Schmitz (1997). Precise GPS Positioning Improvements By Antenna and Site Dependent Effects. Presented at the IAG Symposium, IUGG Assembly, September 1997, Rio de Janeiro, Brasil. *IAG Symposium*, No. 115, Springer Verlag.

Townsend, B., R.D.J. van Nee, P. Fenton, K. Van Dierendonck (1995). Performance Evaluation of the Multipath Estimation Delay Lock Loop. Proceedings of the National Technical Meeting, *ION NTM−95*, Anaheim, California.

Wübbena, G., M. Schmitz, F. Menge, G. Seeber, C. Völksen (1997). A New Approach for Field Calibration of Absolute Antenna Phase Center Variations. *Navigation*, Journal of The Institute of Navigation, Vol. 44, No. 2, 247−256.

Wübbena, G., A. Bagge (1998). GNSS Multi−Station Adjustment for Permanent Deformation Analysis Networks. Proceedings of the *Symposium on Geodesy for Geotechnical and Structural Engineering* of the IAG Special Commission 4, 20.−22. Apr. 1998, Eisenstadt, Austria, 139−144.

Wübbena, G., A. Bagge, G. Seeber (1995). Developments in Real−Time Precise DGPS Applications − Concepts and Status. Paper presented at the *IAG Symposium* G1, IUGG General Assembly, July 1995, Boulder, Colorado, USA.

Wübbena, G., M. Schmitz, F. Menge, V. Böder, G. Seeber (2000). Automated Absolute Field Calibration of GPS Antennas in Real−Time. Presented at *ION GPS−00*, 19−22 September, Salt Lake City, Utah, USA.