Quality Analysis of the GPS Observations for Rapid-Static and On-The-Fly Applications: Problems and Solutions

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The paper deals with the quality of the GPS observations. A technique for assessing the noise level of the code and phase pseudoranges as well of their double differences is described. A method is proposed for considering the individual noise of each observable in the processing. The obtained code and phase solutions are more precise and more accurate. Another point investigated here is the behaviour of geodetic receivers in kinematic environment. The relation between the L1 and L2 phase is distorted due to changes in dynamics, a fact that prevents the ambiguity resolution.

Der Artikel befaßt sich mit der Qualität der GPS Beobachtungen. Ein Ansatz für die Schätzung des Rauschpegels von Code- und Phasenpseudostrecken und deren Doppelten Differenzen wird beschrieben. Eine Methode für die Berücksichtigung des individuellen Rauschens jeder Beobachtung bei der Ausgleichung wird vorgeschlagen. Weiterhin wird hier das Verhalten geodätischer Empfänger in kinematischer Umgebung untersucht. Die Beziehung zwischen den L1 und L2 Phasen wird wegen Änderungen in der Dynamik verschlechtert, was manchmal die Ambiguitätenlösung erschwert.

1. Introduction

At the end of 1993 it was officially declared, that GPS constellation has achieved Initial Operational Capability. The 24 satellites in orbit allow full exploitation of the system for the daily surveying and navigational practice. Nowadays, the classic static method with occupation times of one to two hours is being used only for determining quite long baselines with millimeter precision. Rapid-static yields centimeter accuracy and is the mostly used technique for modern surveying. The requirements are calling for shorter observation times and increased accuracy.

Although most of the rapid-static software producers are promising subcentimeter accuracies for small baselines, experienced geodesists are always aware of wrong solutions. To be more exact, the problem is not so much the wrong position, as the inefficiency of the software to detect such a mistake. Many of the researchers working with known baselines have faced errors up to few meters, while the testing quantities given (reference variance, ratio test, observable's RMS) seem to be quite good. But in the practice the user does not have any other possibility to test the results and such mistakes can have considerable consequences. Clearly, there is a demand for having a way to control the reliability of the solution.

But let us start with the reasons of these problems. Why are sometimes found wrong ambiguities? Mostly, due to either insufficient or bad data. The second case is more dangerous because the surveyor can not always be aware of it. Pure geometry or cycleslips are easily detectable by means of PDOP values and cycle-slips indicators. An experienced researcher can easily recognize such problems by simply looking at a RINEX file. The real troubles begin when the observations seem to be perfect and, nevertheless, wrong ambiguities are found.

This paper deals with such problems. Some methods for detecting and quantifying signal distortions are given. Different kinds of data problems are demonstrated and (where possible) the causes are explained. For these measurements, the results of the attempts to resolve ambiguity, as well as some ways to avoid wrong ambiguity fixing are given. Furthermore, the general problem of noisy data will be discussed. As known, GPS signals are very susceptible to electromagnetic interferences, a fact that leads to increased measurement noise and inaccurate positions. A method, which overcomes this problem to a large extent, is described. To demonstrate its effectiveness the derived solutions are compared with those of other methods for noise reduction.

2. Theoretical background

The techniques used for assessing the measurement quality are given, as well as some methods for overcoming the problem of bad quality of the data.

2.1 Measurement noise detection

The general problem of noise detection is a rather complicated one. In the Electrical Engineering terminology noise is called the undesired component of a measurement. But this definition can sometimes lead to misunderstanding, because there are many undesirable effects in the measurements. Noise describes rather phenomena with stochastic properties, or even deterministic ones for which a modeling is completely impossible. Selective Availability for unauthorized users belongs to the last category.

Noise of GPS measurements can be satellite-, medium- or receiver-induced. Phase and code pseudoranges give the distance between satellite and receiver. The mathematical expression of the distance as a function of time is a little complicated due to the simultaneous orbital motion of the satellite and the earth rotation. Of course, this function take extrema when the satellite-user distance becomes smallest or largest. Between these extrema the distance-time curve is strictly monotonously increasing or decreasing. After eliminating "known" effects such as cycle slips, SA etc. this should be valid also for the pseudoranges measured by static receivers. But due to measurement noise this can never be the case.

How could one see this jittering in the (code and phase) pseudoranges due to the noise? A possibility would be to subtract a best fitting curve from the measurements. The first difficulty here is to find the appropriate formula of the curve to be fitted. For long times even a polynomial of high degree with additional trigonometric terms is not adequate. A second difficulty is the SA effect. Although it is a zero-mean system, the magnitude of some low frequency components can be in the order of few meters. So, a curve fitted to a data set of duration of about one period of these terms will probably follow the sinusoidal variations of the SA.

Here, for detecting noise fluctuations, the Newton's devided-difference method:

$$x_0 < x_1 < x_2$$

$$\delta f(x_1) = \frac{f(x_1) - f(x_0)}{x_1 - x_0} \qquad (1)$$

$$\delta\delta f(x_2) = \delta f(x_2) - \delta f(x_1)$$

is used. By doing so, offsets and trends cancel out. Furthermore, this scheme is adequate for treating unequally spaced data. This is important because the drift and drift rate of the receiver clock error lead to a non-constant sampling rate. It should be mentioned that coloured noise becomes uncorrelated when differentiated and vice versa. Figures (1) and (2) show the results of two times differentiation of the good and noisy code pseudoranges. The linear and quadratic trends as well as the SA variations disappeared and what is left is mainly the observation noise. At last, it should be emphasized that only periodic effects with periods sufficiently longer than the differentiation interval disappear.

2.2 Developed Approach

Figures (1) and (2) demonstrated how variable the measurement noise can be and how easy it is to detect it by differentiating numerically. In practice, noisy measurements result in inaccurate solutions. Filtering and smoothing are the most used techniques for noise elimination. But almost all of them require knowledge of noise characteristics. On the contrary, for the approach presented here there is no such a-priori information needed. The basic idea is very simple: Take into account the noise level by the design of the observations covariance matrix. The difficulty is in the implementation of this idea. First, how can I associate a variance with each pseudorange and second, how can I pass from this value to the variance of the used observable, namely the double-difference?

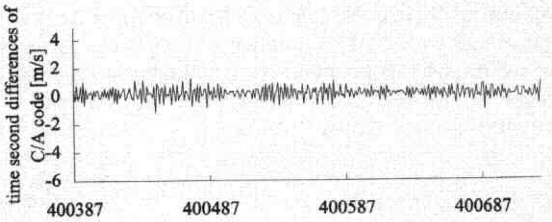

Figure 1: Time second differences of good quality pseudoranges (PRN 5)

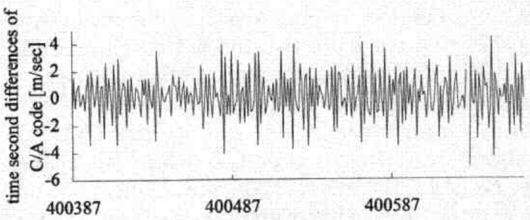

Figure 2: Time second differences of noisy pseudoranges (PRN 26)

Let us start with the second problem. Assume that two receivers are observing simultaneously four satellites and let

$$\sigma_i^{j^2},\ i = ref/mob, j = 1..4$$

be the corresponding variances. According to the variance-covariance propagation the covariance matrix for the DD (with reference the satellite 1) will be:

$$\begin{aligned} c_{11} &= \sigma_{ref}^{1^2} + \sigma_{mob}^{1^2} + \sigma_{ref}^{2^2} + \sigma_{mob}^{2^2} \\ c_{22} &= \sigma_{ref}^{1^2} + \sigma_{mob}^{1^2} + \sigma_{ref}^{3^2} + \sigma_{mob}^{3^2} \\ c_{33} &= \sigma_{ref}^{1^3} + \sigma_{mob}^{1^2} + \sigma_{ref}^{4^2} + \sigma_{mob}^{4^2} \\ c_{ij} &= \sigma_{ref}^{1^2} + \sigma_{mob}^{1^2} \qquad i \neq j \end{aligned} \qquad (2)$$

Obviously, this matrix is achieved considering uncorrelated pseudoranges, i.e. diagonal covariance matrix for the (undifferrenced) pseudoranges. But this it not realistic. Pseudoranges (code and phase) are correlated and it is exactly on this fact that the receiver-satellite double-difference method is based! An estimation of their noise leaving out all the effects that cancel out by the DD is practically impossible. A way to overcome this problem is to evaluate directly the noise of the DD. For this purpose the scheme of equations (1) becomes:

$$\delta\delta\nabla\Delta(t_2)=\delta\nabla\Delta(t_2)-\delta\nabla\Delta(t_1) \quad (3)$$

where Δ,∇ denote differences between receiver and satellite, respectively. Here, denotes differentiation in time. The covariance between the DDs is estimated from the single difference for the reference satellite, as can be seen in equations (2). Figures (3) and (4) show the results of two times differentiation of code DD. The noise of the (undifferenced) pseudorange of satellite PRN 26 is bigger than that of PRN 5 by a factor of about 3 (see figures (1) and (2)). This is also the case for the code DD, which means that this method yields nearby the same results as the application of variance-covariance propagation. But this would not be the case if there were systematic errors, e.g. receiver oscillator instabilities. This can be seen in figures (5) and (6) which give the time second differences of raw phases and phase DD. Clearly, the phase measurements to two satellites are affected in the same way by some noise effects, which vanish in the receiver-satellite DD. Note the different scales of y-axes in the two figures.

Now is the right moment to treat the first problem mentioned at the beginning of this paragraph, namely the association of a variance with each observation. The formula (3) can be directly used to compare the noise levels of the particular DDs. But this is not enough in order to build the covariance matrix where a value for each DD variance must be known. The described approach uses for this purpose the variance of the quantity given in (3). This is advantageous, because any offset in the quantity of equation (3) does not affect its variance. The offset in figure (5) indicates simply that the number of successive time derivatives of the phase DD is greater than two. It must be further investigated to what extent this fact influences the application of the approach to the phase DD. For the code DD there is not such a problem. Another critical point is that the sampling rate should be sufficient high. All data shown here are sampled at a rate of one second.

The building of the covariance matrix of the observations with the method described here, leads to higher precision and accuracy as it will be demonstrated in chapter 3. The only disadvantage of this technique is that nothing guarantees a positive definite weighting matrix. This point will be discussed in chapter 4.

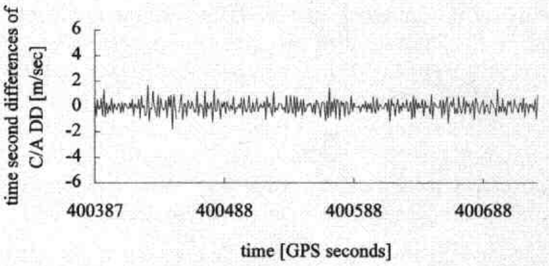

Figure 3: Time second differences of good quality code double differences (between PRN: 9 and 5)

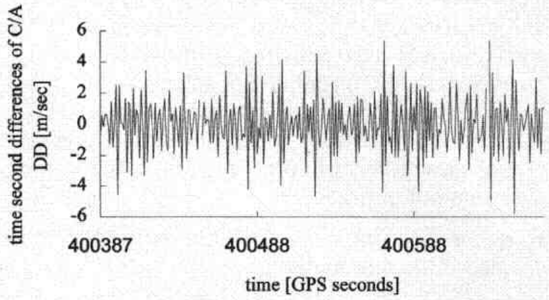

Figure 4: Time second differences of noisy code double differences (between PRN: 9 and 26)

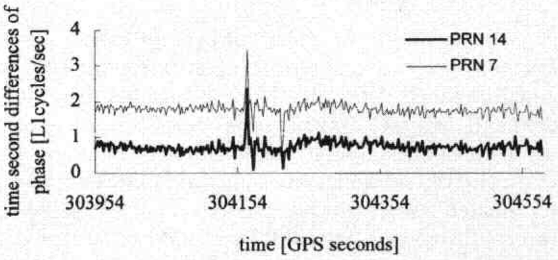

Figure 5: Time second differences of raw phases. (For clarity the curve for PRN 7 is shifted by 1 cycle)

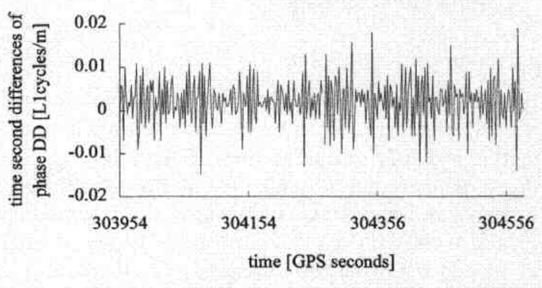

Figure 6: Time second differences of phase double differences (between PRN: 7 and 14)

2.3 Relation between L1 and L2 frequency

The robustness of many ambiguity resolution algorithms is based on the exploitation of the relationship between the L1 and L2 carrier phases, i.e.:

$$\phi_{L_1} = \frac{\lambda_2}{\lambda_1} \phi_{L_2} \tag{4}$$

considering no initial ambiguities. For example, the algorithm described in [MATHES and GIANNIOU, 1994] uses this relation to reject integer N1 candidates around the float solution. Due to the measurement noise a tolerance must be introduced when applying the restriction resulting from (4). An extensive discussion of this point for static applications can be found in the mentioned paper.

Here, the relation (4) will be tested for kinematic applications. The reader will probably ask himself what is the reason for that. Why should the relation (4) depend on the dynamics of the receiver? Actually, the author has been motivated to investigate this from some kinematic data, where the ambiguity resolution was problematic.

For testing the relation (4) the following quantities are used:

$$\sum_{epoch=1}^{n} \left(\delta\phi_{L_1} - \frac{\lambda_2}{\lambda_1} \delta\Delta\nabla\phi_{L_2} \right) \tag{5}$$

$$\sum_{epoch=1}^{n} \left(\delta\Delta\nabla\phi_{L_1} - \frac{\lambda_2}{\lambda_1} \delta\Delta\nabla\phi_{L_2} \right) \tag{6}$$

Here, phase ambiguities vanish due to the time differentiation. Figure (7) shows the values of the quantity in (5) for kinematic measurement with a van. The two lines correspond to two satellites observed by the same receiver. The velocity did not exceed 100 km/h. In order to show the impact of this distortion on the phase DD, the values for the formula (6) are given in figure (8). Obviously, the effect is eliminated to a large extent, but not completely. Note the different scales of y-axes in figures (7) and (8). These data are collected with Trimble SSE receivers under anti-spoofing. On May 8, 1995, (AS was not enabled) test measurements were conducted with Leica SR 299 and SSE receivers. They were mounted at the same time on a van, which performed high dynamic manoeuvres. Effects like that of figure (7) took place for both receivers. They were of similar form but not of the same magnitude.

The arising question is what is causing this effect. The received frequency is shifted due to the Doppler effect [SPILKER, 1978]:

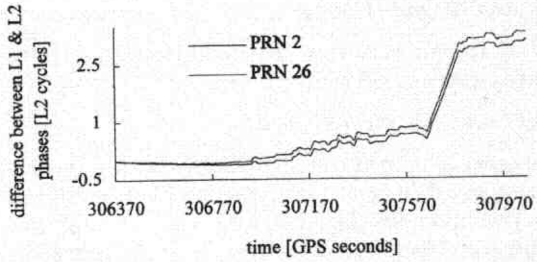

Figure 7: Impact of the receivers motion on the relation between the L1 and L2 raw phases

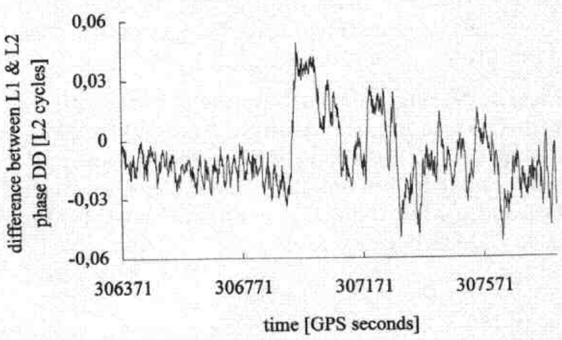

Figure 8: Impact of the receivers motion on the relation between the L1 and L2 phase double difference

$$\frac{f_r}{f_t} = 1 + \frac{1}{c^2}(\varphi_t - \varphi_r) + \frac{1}{2}\left(\frac{\vec{V}_r^2}{c^2} - \frac{\vec{V}_t^2}{c^2} \right) + \frac{\vec{k}}{c}(\vec{V}_t - \vec{V}_r) \tag{7}$$

where r denotes receiver, t transmitter and $\vec{k}$ the unit vector from receiver to satellite. The second and third terms account for general (gravitational potential) and special relativistic effects, respectively. Clearly, the Doppler shift is proportional to the transmitted frequency and does not affect the relation (4). A very small influence on this relation can be explained by the different optical paths of L1 and L2. A detailed explanation of this can be found in [KURSINSKI, 1994]. However, for usual applications this influence is negligible (probably under the noise level) and furthermore it should not depend on the receiver's motion.

The quartz oscillators are susceptible to acceleration which causes jumps in the clock drift [LIPP and GU, 1994]. But this should not affect the relation (4) as far as the L1 and L2 phases are measured simultaneously. Maybe, another receiver's problem causes this effect. The problem should be further investigated.

3. Analysis of field data

Various data sets from static and kinematic DGPS measurements are analyzed here.

3.1 Code static measurements

In order to demonstrate the effectiveness of the method described in section 2.2 the results of adjustment of (mainly) noisy data are given. The measurements had been conducted at the campus of the University of Darmstadt. Known baselines up to 600 m had been occupied for 5 minutes using TRIMBLE SSE receivers. At the region there are two sources of noise: First, some stations are near buildings causing multipath and second, there is an interfering frequency. From these measurements are the data shown in figures (3)-(4).

Figures (9) and (10) illustrate the Z coordinate of code DD solution. The results of figure (9) are obtained by uniform weighting of the pseudoranges (ordinary) and that of figure (10) using the new approach (advanced). The following covariance matrix for the code DD has been used:

$$\begin{array}{r} 5 \\ 21 \\ 7 \\ 26 \\ 12 \end{array}\begin{bmatrix} 0.29 & 0.14 & 0.14 & 0.14 & 0.14 \\ 0.14 & 2.10 & 0.14 & 0.14 & 0.14 \\ 0.14 & 0.14 & 0.43 & 0.14 & 0.14 \\ 0.14 & 0.14 & 0.14 & 0.99 & 0.14 \\ 0.14 & 0.14 & 0.14 & 0.14 & 0.18 \end{bmatrix}$$

The indices outside the brackets are the PRN numbers. Reference satellite was PRN 9. Note that only the satellite PRN 21 is mainly affected by noise. There is a strong relation between the noise level and the elevation, which can be clearly seen in figure (11). The epoch by epoch coordinates obtained from the advanced adjustment are more stable (standard deviation 0.65) compared to those of the ordinary adjustment (standard deviation 0.77). Even more interesting are the results when using the whole data to compute the coordi- nates. Here, the differences between computed and true (Z) coordinate are 0.311 m and 0.038 m for the ordinary and advanced solution, respectively.

For demonstrating the effectiveness of the new approach on all three coordinates, the following quantity is introduced:

$$\text{Total Error} \equiv |\Delta X| + |\Delta Y| + |\Delta Z| \quad (8)$$

where Δ denotes difference between computed and true coordinate. The Total Error for ordinary and advanced adjustment for various baselines is given in figure (12). It is interesting that the baseline 2008 is located at an old airport in Griesheim. This place is frequently used by our Institute for test purposes because of an outstanding GPS signal reception. This

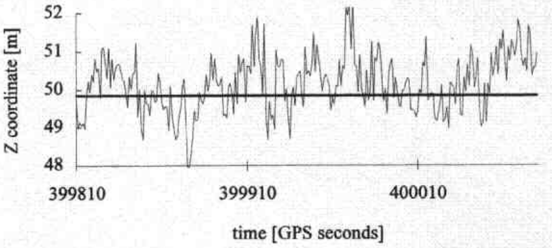

Figure 9: Epoch by epoch ordinary code DD solution and true value (straight line)

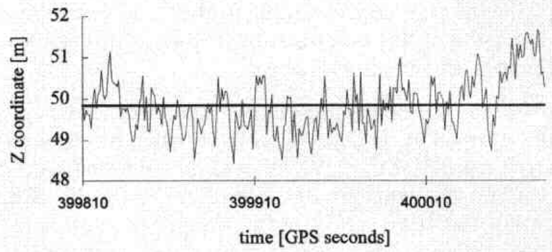

Figure 10: Epoch by epoch advanced code DD solution and true value (straight line)

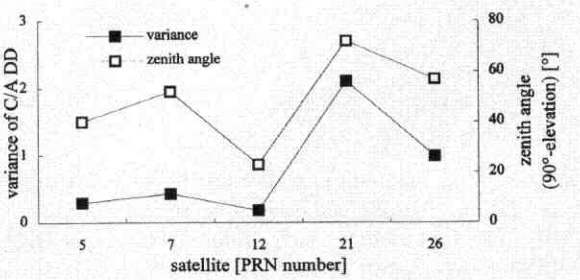

Figure 11: Dependence of noise level of code DD on elevation.

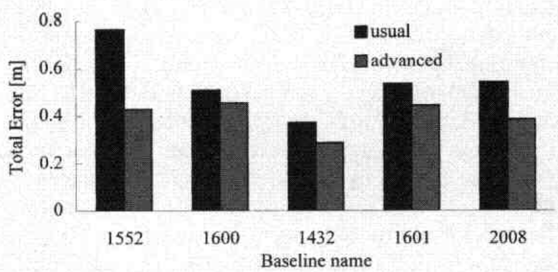

Figure 12: Comparison between ordinary and advanced adjustment of code DDs

proves the effectiveness of the proposed approach also for good quality data. The explanation is that measurements to satellites with low elevation are always worse than that to satellites with high elevation. For the baseline 2008 the variances of the code DD lay between 0.022 and 0.069 m^2. It should also be mentioned that the difference in Total Error between the ordinary solution of our Institute's software and that of Bernese software is generally in the order of few centimeters.

In order to compare the proposed method with other ones for noise reduction, a phasesmoothed code solution [HOFMANN-WELLENHOF et. al, 1992] is computed for the data of figures (9) and (10). Figure (13) illustrates the obtained results, as well as those of ordinary and advanced adjustment. The weighting factor is reduced by 0.01 each epoch. Thus, the raw pseudoranges were not taken into account after the first 100 seconds (the sampling rate was 1sec). This time is not enough for minimizing the bias of the solution, because of the enhanced measurement noise. It would be more appropriate to extent the smoothing time to – at least – 200 seconds. But for rapid static and OTF applications this is not suitable.

3.2 Phase static measurements

Extensive data analysis has shown that code and phase noise are strongly correlated. Of course the effect of noise on carrier phases is sufficiently smaller compared to that of code pseudoranges, but it must be considered when subcentimeter accuracy is required. The method described in 2.2 is used to compute a phase DD solution for the session of figures (9) and (10). Figure (14) gives the Total Error of advanced and ordinary adjustment for several numbers of used epochs. There is a substantial improvement of accuracy even for the two-minutes solutions. As the number of used epochs decreases the difference becomes more and more important.

Clearly, the observation time plays a critical role for the achieved accuracy, especially for noisy data. The proposed method seems to overcome this problem to a very large extent, a fact that makes it important for On-The-Fly applications. The only problem for kinematic applications is the computation of the covariance matrix as described in paragraph 2.2. For that reason, the measurement noise obtained from equation (3) is compared with the Signal-to-Noise Ratio (SNR), that is supplied by the receiver also in a real-time environment. The SNR values for the data of the figures (1)-(4) are given in figure (15). Obviously, there is a strong dependence between the detected noise and these values. The determination of the functional relationship between them requires further investigations.

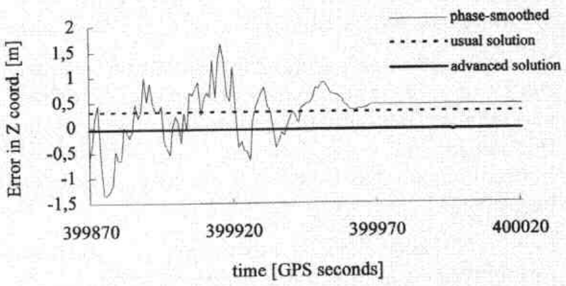

Figure 13: Phase-smoothed code DDs in comparison with ordinary and advanced adjustment

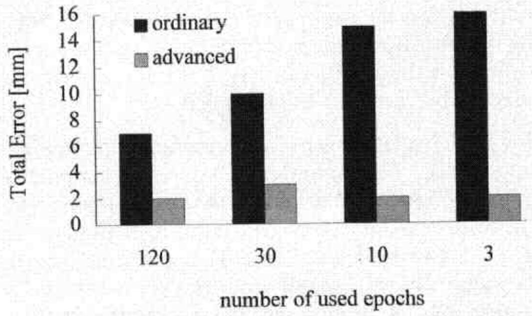

Figure 14: Differences between ordinary and advanced adjustment of phase DD

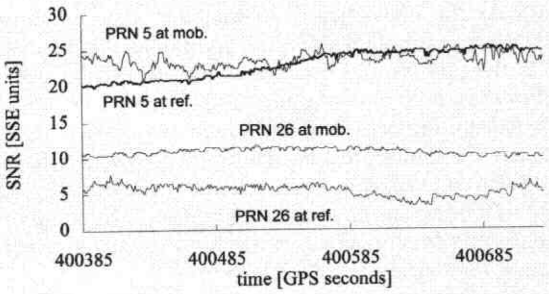

Figure 15: SNR values for good and noisy measurements

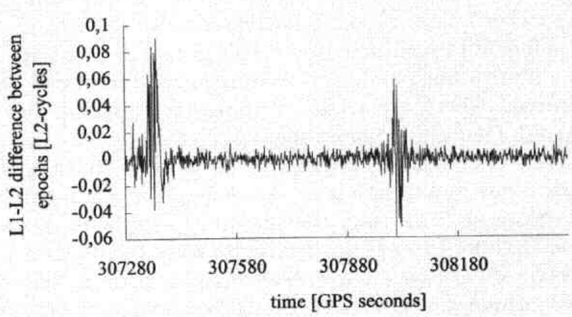

Figure 16: Strong distortion of the L1-L2 relation at a stationary receiver

3.3 Kinematic measurements

As explained in paragraph 2.3 the relation between the L1 and L2 frequency is a critical aspect for fast and reliable ambiguity resolution. Distortions of this relationship for static data are rather exceptional. For that reason only a case of static measurements is here given.

Figure (16) shows the L1-L2 distortion obtained from formula (5) without summation (n = 1). Figure (17) demonstrates how easy it is to detect such disturbances by means of the SNR values. The same effect on PRN 21 is observed at the reference station located 7 km away with a time delay of about 20 seconds. This indicates that the cause cannot be a receiver or satellite malfunction, but rather a propagation effect. Moreover, the stability of L1-SNR denotes that this effect influences only the L2 signal.

The L1-L2 relation is even more interesting in kinematic mode. The paragraph 2.3 gave an example of its behaviour for measurements with a moving van. The following data are collected during a flight test in May 1994 in Munich, Germany. Figure (18) shows the values for the quantity of formula (5) for the reference and the mobile receiver for satellite PRN 7. The trajectory of the airplane is illustrated in figure (19). The numbers mark points of direction or dynamic changes. Note the consistency between the two curves as long as the airplane is not in motion (point 0). As the plane begins to roll, the corresponding curve takes another slope and additionally fluctuates. At the turn No. 7 a jump of about one cycle occurs. For the whole time of figure (18) the SSE gave not a cycle-slip indicator for PRN 7. Similar effects took place for the reference satellite PRN 9. Thus, these effects cancel out to some extent by the building of the DDs, as can be seen in figure (20). The jump of one cycle does not concern the reference satellite and thus, remains even in the DDs!

The distortion of the L1/L2 relation has a substantial impact on the ambiguity resolution. To demonstrate this, the OTF algorithm has been started at several epochs. Where the L1/L2 relation is not disturbed, ambiguities were resolved within 3 epochs. On the contrary, much more epochs were needed for the intervals where the L1/L2 relation does not strictly hold. Figure (21) shows these points, as well as the number of needed epochs. In order to verify the ambiguities found each time, a comparison was done with those of the static time before the airplane started rolling. This was possible, as for some satellites no cycle-slips occurred. It should be mentioned that the algorithm was started at the times when the L1/L2 relationship is sufficiently distorted. The expected inefficiency of the algorithm to resolve ambiguities was

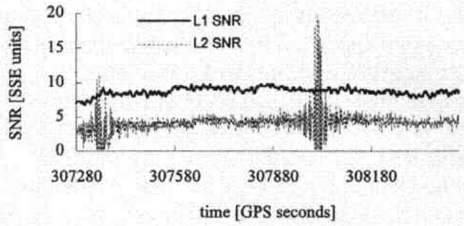

Figure 17: SNR values for the data of figure (16)

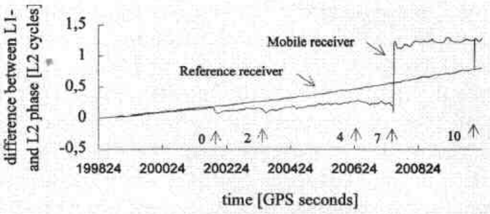

Figure 18: Relation between L1 and L2 at the reference and the mobile receiver (satellite: PRN 7).

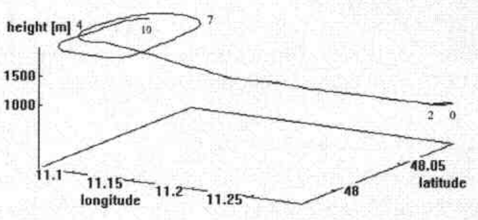

Figure 19: Trajectory of the airplane

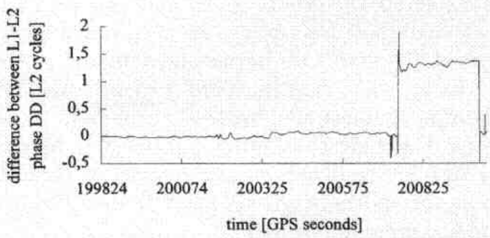

Figure 20: Difference between L1 and L2 phase DD for satellite PRN 7 (reference PRN 9)

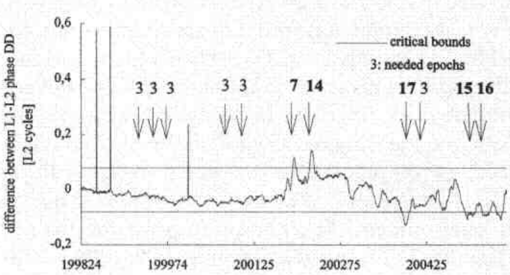

Figure 21: Difference between L1 and L2 phase DD for satellite PRN 26 (reference PRN 9) and epochs needed for ambiguity fixing

verified. This means that a preprocessing of the data permits to judge if instantaneous ambiguity fixing is possible or not.

4. Discussion

4.1 Noise of static measurements

The analysis of many code and phase static measurements verified the principle of paragraph 2.1 for accessing the measurement noise. The noise level obtained from formula (1) is in accordance with several noise indications such as: Frequent loss of lock, big observation residuals by the adjustment and signal-to-noise ratio.

In order to separate by the noise estimation the effects that cancel out in the double difference level, the formula (3) is introduced. It's importance is obvious, especially for the phase DDs. Here, the phase of the incoming signal is measured with a high precision (a few millimeters) with respect to the signal generated in receiver. But this is in no case the accuracy of the phase pseudorange, which variates strongly due to Selective Availability and receiver oscillator instabilities.

The double differences (phase or code) within a session are characterized by different noise levels. Extensive data analysis showed that this is rather the case than the exception. Even in a region with outstanding signal reception, there is a noticeable dependence of measurement quality on elevation. Therefore, a method is developed, which considers this fact in the adjustment of DDs. It is based on a data preprocessing, in which a variance for every observation is computed. The non-diagonal elements of the covariance matrix are equal and correspond to the single difference for the reference satellite.

This approach proved to be more realistic than the uniform weighting of all observations. But there is a point that must be discussed. The building of the covariance matrix in the proposed way does not obey the variance-covariance propagation. There is no guarantee that the matrix is positive definite. So, one could obtain a negative definite matrix. This problem was faced at an early stage of the method's development, when some other ways were tested. For the procedure described in paragraph 2.3, the problem did never occur. The possibility of a singular weight matrix is being further investigated as well as a way to build the matrix by means of the SNR using variance-covariance propagation. Another fact that verifies the reliability of the computed co- variance matrix is the a-posteriori variance of the weighting unit. The suggested method results in values closer to the unit than the ordinary adjustment. Furthermore, the closeness of the advanced solution to the true values proves also that the introduced covariance matrix is realistic.

The importance of the new method becomes greater as the number of used epochs decreases. This is demonstrated in paragraph 3.1, where the epoch by epoch and over the whole time advanced solution is compared with the usual one. By uniform weighting, the noisy observations cause coordinate errors bigger than two meters at some epochs. On the contrary, the reduction of their weight leads to an accuracy of about one meter. This corresponds almost to the standard code DD performance of the Trimble SEE receivers. To demonstrate the importance of this improvement let us consider the case of kinematic survey with an accuracy requirement of 1.5 meters. In a noisy environment this could not be guaranteed for all epochs. So, the surveyor has to use a more accurate method and in case of GPS that means the phase measurements. But this makes the situation much more complicated. First, the phase tracking is more susceptible to noise and second, the needed software for the processing is quite complicated. The suggested method permits the use of code DD without a serious performance degradation.

Here, another aspect should be mentioned. In chapter 3 the Total Error is mainly used for comparison purposes. This quantity indicates the position error in all three coordinates. When the Total Error of the advanced method is smaller than that of the ordinary one, that means not that the error of every coordinate is smaller and actually, this is not the case. Generally, two of the coordinates become better and the third one worse. But this is not a disadvantage as the third coordinate is that with the smallest error. To explain this let us consider the mentioned measurements in Darmstadt. For its geographical position the X and Z coordinates are the most sensitive as they correspond to the ellipsoidal height. The Y coordinate is almost independent from the height and thus it is always the best one. The low satellites introduce an error in height, but at the same time (under consideration of a uniform distribution) they allow a good estimation of Y. Thus, the reduction of the their weights improves X and Z and degrades the Y. In practice, this is not a problem at all. The degradation is much smaller than the improvement of the other coordinates so that the Total Error is always smaller than that of the ordinary solution. At least, to avoid misunderstandings, this method does not completely overcome the general problem of bad height determination with GPS. It overcomes only the problem of noise in – mainly – the height determination. A bias due to incomplete DD modeling is not eliminated.

Even more interesting is the application of the proposed method to the phase processing. Here, the achieved accuracy is already very high and thus, the improvement cannot be so great as by the code measurements. But for subcentimeter demands it is considerable. For noisy observations there is a significant improvement even for observation times of two minutes. For shorter times this is true also for data of good quality. One can think that this is not important, because for rapid-static the recommended time is 5–10 minutes. Actually, modern algorithms are able to re- solve the ambiguities within a few seconds, e.g. [MATHES and GIANNIOU 1994]. After the fixing of ambiguities, more epochs are needed only for accuracy improvement using a sequential adjustment. Some tests indicated that the proposed method can achieve in 10 seconds the accuracy that the ordinary adjustment yields using 120 seconds. Further investigations are programmed in order to generalize this conclusion.

As the needed occupation time decreases the situation becomes more and more similar to the OTF method. Here, the antenna is moving and every epoch refers to a different position. It would be very helpful if the presented method could be applied to OTF applications. The difficulty is that the method described in paragraph 2.2 cannot be used when the receiver is in motion. In this case, variations in the formula (3) are due to the velocity and direction changes and not due to noise. A possibility would be to use the SNR values for the building of the covariance matrix. The relation between noise level obtained with the described method and SNR was outlined. Further investigations are in progress in order to found a functional relationship between SNR values and noise level of the double differences.

Of course, the suggested method of phase adjustment can be used only if the ambiguities are correctly resolved. The relation between L1 and L2 phase is widely exploited for robust ambiguity resolving. Distortions of this relationship make the ambiguity fixing difficult or even impossible. Interfering frequencies, receiver hardware imperfections and propagation effects (e.g. ionospheric influence) cause sometimes such problems. Formulas (5) and (6) allow the detection and quantification of these distortions. If they exceed some limits, ambiguities cannot be resolved or the algorithm must be modified to consider such distortions.

4.2 Kinematic measurements

In kinematic mode the situation is much more interesting. Many researchers have faced the case, where the OTF algorithm needs more epochs when started at certain times of a measurement. The figure (21) proves that sometimes the reason for that is the disturbed relation between the L1 and L2 phase. By this time, it is not clear if both phases are affected or only the L2. This can be found out by a rail surveying. Jumps like that of figure (18) result in jumps in phase pseudorange in the order of 30 cm. When the trajectory is known, they can be easily detected. To do this, a solution must be computed for every phase. If only the L2 phase is disturbed, then the L1 solution will yield correct results while the L2 trajectory will not coincide with the rails.

Conclusions

The proposed method for noise detection has been verified by analyzing field data. Observations at low elevations (e.g. below 35 degrees) or in the presence of interferences are sufficiently degraded. Taking this into account by means of the proposed method leads to increased accuracy and precision of the code and phase DD solutions.

The first results showed that a certain level of accuracy can be achieved using less observation time as by uniform weighting of the observations. This is of particular interest for kinematic applications. In order to extend the approach for kinematic mode the strong relation between the observation quality and the SNR values is verified. The case of building the observation covariance matrix considering these quantities will be further investigated.

The question of data quality has been treated also from point of view of ambiguity resolution. The analysis showed that in kinematic environment the relation between the L1 and L2 phase is distorted. This proved to be sometimes the reason for ambiguity resolution inefficiency.

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