GPS for Vehicle Navigation - A System using Differential Corrections or Raw Observation Data for Precise Position Determination

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ABSTRACT

In today's traffic, that will be more and more growing in the coming years, it is important for the individual as well as the public traffic to locate and navigate the vehicles. Therefore, systems have to be installed controlling the traffic and helping to find navigation solutions for the driver. But all these problems can only be solved if you know your exact location. One possibility is the use of DGPS. With it's help you are able to get precise position data in real-time.

In most cases it is sufficient to use corrected data. But for positioning with a very high accuracy, you have to use carrier phase observations. In the paper a precise positioning system to locate a vehicle by means of GPS carrier phases will be presented. With respect to the on-line aspect this will be one of the future methods in vehicle navigation. Further it is imaginable to use these systems for auto-pilot systems. Using DGPS to solve the problems of on-line positioning we have not to forget the real-time aspect of such a system. It is necessary to use algorithms which allow a fast and secure computation of the received data for ambiguity resolution and position determination.

1. INTRODUCTION

Talking about today's requirements for land vehicle navigation systems, accuracies of several meters are sufficient for the majority of applications. Only some special tasks need positions in the decimeter level and even better. But in the near future, as the traffic will be more and more growing, the road user must be able to determine its position as accurate as possible. Furthermore, for every navigation system the real-time concept is mandatory. This is, especially for GPS algorithms, not an easy task to accomplish and therefore one of the main aspects of the paper.

The system presented in the paper is able to compute the positions of a roving GPS receiver with accuracies of some centimeters at a very high level of reliability and in real-time. The availability of these results depends not on the observation time but on the number of tracked satellites. This means on the one hand, that as soon as at least five satellites are tracked on both frequencies the ambiguities will be solved instantaneously. But on the other hand this illustrates, that every GPS-based positioning system depends on the tracking-situation. In urban areas there can be large gaps in the observation data, which do not allow a position computation by means of GPS measurements. The system described here focuses on position determination within the time spans where a good receipt of the satellite signals is possible. It is obvious that GPS could not be a stand-alone land vehicle navigation system, especially if accuracies of some meters and better are required.

2. BASICS OF DIFFERENTIAL GPS-POSITIONING

Here, the basic algorithms for kinematic positioning by means of GPS code pseudorange and carrier phase observations, that are implemented in the real-time system, are outlined. In order to improve the poor single-point position accuracy of GPS (> 100m), that is influenced by a lot of natural, technical, and intended errors and the kind of observables,

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differencing techniques - and so at least one GPS reference station - are mandatory. Besides a certain accuracy level, all algorithms must allow an epoch-by-epoch positioning. In contrast to static GPS-observations, this means that only the observations of one epoch can be used for the computation of a position. For phase-smoothing of code pseudoranges and ambiguity resolution additional information of preceding epochs can be used. The adaptation of these algorithms to a real-time system and their practical implementation are shown in chapter 4.

All following considerations are limited to short baselines not exceeding 10 kilometers and suppose that only the positions and related results, like velocity, azimuth etc., are stored at the roving site.

2.1 LOW ACCURACY

This class of accuracy means that the vehicle position is determined within 0.5-5 meters. In principle, there are three different approaches to obtain this accuracy: differential position corrections, differential code pseudorange corrections and double differenced code pseudorange solutions.

Differential position corrections:
Using this model, the reference site computes its time-dependent coordinates $XYZ_R(t)$ based on code pseudorange observations corrected for atmospheric influences. The differences between these coordinates and the time-independent known position XYZ are the differential position corrections $DCor_{Pos}$:

$$DCor_{Pos,i}(t) = XYZ_i - XYZ_{R,i}(t) \tag{1}$$

where i denotes the three position-components X,Y, and Z (cartesian) or Latitude, Longitude, and Height (ellipsoidal), respectively. The consideration of $DCor_{Pos}$ at the roving receiver results in accuracies in the range of several meters. Due to some disadvantages, mainly the possible different satellite constellations at reference and roving site, these corrections are often replaced by differential code pseudorange corrections. But one advantage still remains: In case of a real-time system where the roving site cannot receive the broadcasted messages of the reference station over a longer time span and computes inaccurate single-point coordinates, the offline improvement of these coordinates with the recorded data of the reference site will be possible.

Differential code pseudorange corrections:
The second method to apply differential corrections is the code pseudorange correction. There, the corrections will be computed directly for the observed code pseudoranges instead for the computed coordinates. By doing this, the dependence of the position on the constellation will be avoided. In accordance to [7] the code pseudorange correction PRCor(t) will be computed by building the difference between measured code pseudorange PRM(t) and the computed distance between satellite and station PRComp. It reads:

$$PRC(t) = PRComp - PRM(t)\,. \tag{2}$$

Applying this correction to the measured code pseudoranges at the roving site, the position error decreases to several meters, too.

Double differenced code pseudorange solution:
In this model we use no longer corrections but the raw (undifferenced) observations. Building a code pseudorange double difference as in (3), the errors of satellite and receiver clocks, selective availability, and atmospheric influences are reduced. Neglecting all remaining error influences, the code pseudorange double difference R between the two stations A, B and the two satellites j, k reads [6]:

$$R_{AB}^{jk}(t) = PRM_B^k(t) - PRM_B^j(t) - PRM_A^k(t) + PRM_A^j(t)\,. \qquad (3)$$

If there are at least the same four satellites in view at the reference and the roving station, this approach leads to accuracies of 1-5 meters. In order to improve this by a factor of 2 or 3 and to reduce the noise of the code pseudorange positions, the combination with the second GPS-observable, the carrier phase, is possible. Here, the carrier phase measurements Φ with a noise of a few millimeters are used to smooth the code pseudorange observations. And thus, the position computation based on (3), but using smoothed pseudoranges PR_{sm} instead of the raw ones, leads to less noisy and more accurate solutions. Here, the improvement of the position accuracy is strictly correlated with the observation time and the start time of the smoothing process, respectively. This becomes clear if we look at a very simple algorithm that can be found in [4]:

$$PR(t_i)_{sm} = \omega PR(t_i) + (1-\omega)\left[PR(t_{i-1)})_{sm} + \lambda(\Phi(t_i) - \Phi(t_{i-1}))\right] \qquad (4)$$

with *i* the actual and *i*-1 the last epoch, λ the wavelength and ω the time-dependent weight factor. The weight of the raw code pseudoranges at the beginning of the smoothing process will be set very high (ω = 1) and will be reduced more and more in time, whereas the weight of the carrier phase observations increases as expected. Of course, errors in the carrier phase measurements, such as cycle slips, must be detected but it is not necessary to correct them.

2.2 HIGH ACCURACY

The position computation with accuracies in the order of a decimeter and better requires the use of the carrier phase observations. Because of the ambiguous nature of these observables, the unknown integer ambiguities have to be computed. The mathematical model widely used is the carrier phase double difference PH. It is build in accordance to (3) but extended by the double difference ambiguity value N [6]:

$$PH_{AB}^{jk}(t) = \lambda(\Phi_B^k(t) - \Phi_B^j(t) - \Phi_A^k(t) + \Phi_A^j(t)) + N_{AB}^{jk} = \lambda\Phi_{AB}^{jk}(t) + N_{AB}^{jk}\,. \qquad (5)$$

The basic search algorithm for solving the unknown ambiguity values N within a couple of epochs can be found in [8], and its important improvements in [5]. This algorithm uses carrier phase measurements on two frequencies and code pseudorange observations on at least one frequency. It is able to solve for the unknown integer ambiguities within a couple of seconds if at least the same five satellites are tracked at the reference and roving site. It is suited for static as well as kinematic applications. Once the ambiguities are correctly solved, a position computation with accuracies beyond one decimeter becomes possible. The crucial point of the use of carrier phase observations is the required continuous tracking of the satellites. If the signal will be interrupted by obstacles like trees or buildings, the corresponding ambiguity changes and must be re-calculated. If the receiver cannot keep the lock to at least four satellites, the position accuracy decreases to the above mentioned code pseudorange one and the ambiguity resolution must be started again.

3. CONSIDERATION OF THE DATA QUALITY

The accuracy of the code double difference solution is important not only for differential code positioning but also for carrier phase positioning. The reason for that is that the searching interval around the float ambiguities is proportional to the accuracy of the code solution. In other words, the better the code coordinates the less ambiguities should be tested and consequently the faster the ambiguity search algorithm will be.

Besides the used method of differential code positioning the accuracy of the solution depends also on the performance of the receiver. Code measurements can be obtained from a handheld up to a geodetic receiver, but there are enormous differences in their quality. A powerful processing software must consider the quality of the input data. For the case of an ‘On-The-Fly (OTF)’ algorithm, this point is given in full details in [2]. Here, this aspect will be discussed for code positioning.

In general, the noise level of the measurements depends on the tracking method, the implemented filters, and the design and quality of the hardware. For a certain receiver the observation noise depends mainly on the elevation of the satellite. The modern geodetic receivers have a very good performance when tracking low satellites. So the elevation cut-off angle can be 5-10° smaller than the commonly used limit of 15°. An extensive discussion of this point and a special adjusting algorithm that considers the elevation-noise dependence can be found in [1]. Figure 1 shows the error in the Z-coordinate of the epoch-by-epoch code double difference solution, when using all satellites and only that above 20°. The reference position for the computation of the error was that from our OTF algorithm. The data have been collected with TRIMBLE 4000SSE receivers. The rover receiver was mounted on a van. It is interesting that there were seven satellites above 20°. The improvement in the first case is due to two satellites with elevations between 15° and 20°. The situation for the X- and Y- coordinates is similar. Many other tests with geodetic receivers have shown that also satellites between 5° and 15° improve the code double difference solution.

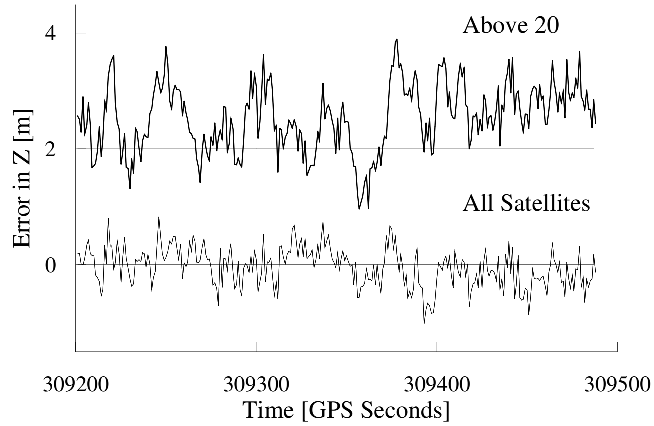

Figure 1 Differences between Code Double Difference Solution and Phase Solution (Upper Curve is Shifted by 2 Meters)

4. ASPECTS OF REAL-TIME GPS-POSITIONING

Before talking about the different aspects of GPS real-time systems, one must define the term ‘real-time’ in connection with vehicle navigation. According to [3] a possibility to define the term ‘real-time DGPS’ is: *The setup and operation of two or more GPS receivers in combination with the appropriate software in a way that allows the computation of the baseline vectors during the survey or with a time-delay that is defined by the kind of application*. For vehicle navigation and control there are maximum time-delays of some seconds for the navigation task and down to some milliseconds for the controlling task acceptable. These very short time-delays between measurements and availability of the results require highly sophisticated hard- and software components at the reference and the roving site.

The basic equipment and the main tasks of both stations are:
Reference site: In general a GPS reference site consists of a high-quality two-frequency GPS receiver, a data transmission unit, a data storage unit, and any kind of computation and control unit. There are mainly three kinds of tasks that must be executed at the same time: the data-logging, the computations, and the transceiving (transmission and receipt). The data-logging task is responsible for the receipt of the GPS measurements and other possible observations, for example meteorological data, and the recording of all data. In the computation task the observation data are prepared, some integrity checks are performed, and the correction data is calculated. The transceiving task is responsible for the transmission of the reference station’s messages, like correction data, raw observations, and integrity informations, and for the receipt of possible inquiries of roving or other reference stations. Besides the execution of these three tasks in a multitasking manner, the data security must be guaranteed for offline applications and the time-delay between receipt of the GPS observations and transmission of the data messages must be minimized to a value that makes real-time operation possible.

Roving site: The basic equipment of a roving site consists of a GPS receiver and a transceiving unit to receive the broadcasted messages of a reference site. The choose of the kind of GPS receiver depends mainly on the required accuracy. The higher the accuracy demands are the better must be the quality of the GPS receiver. To achieve centimeter accuracy in real-time at a very high level of reliability, a high-quality two-frequency GPS receiver must be used. In this case an additional computing device must be added to the equipment, that carries out all necessary computations. The main three tasks that must be carried out at the roving site at the same time are: data-logging, computations, and controlling/output. The data-logging task reads the data of the GPS receiver and the transceiving unit, and synchronizes them via the time marks. The computation unit carries out an integrity test of the received data, computes the position and the baseline, respectively, and prepares the results for further use. The controlling/output task enables the system control, stores the positions and related results, and enables the communication with the hardware for vehicle navigation and control.

The above mentioned tasks and the appropriate hardware must be controlled by the 'heart' of the real-time system: the software kernel. One of the basic requirements for this kernel is to carry out different tasks at the same time, i.e. a multitasking capability. A sequential program execution would tend to decrease the time resources of the system and thus to lose or damage observation data or to shut down the whole system. Talking about system resources, the aspect of time-consumption of the calculating functions must be taken into account. The more an algorithm is blown up and the more disadvantageous programmed, the slower will be its execution. Therefore, the goal must be a compact and compressed source code with only the essentials in it. Another important requirement for GPS real-time software is the capability to detect and indicate possible errors instantaneously at a very high level of reliability. Therefore, different error detection strategies have to be implemented in the software kernel.

5. EXEMPLARY SYSTEM

The realization of our system is outlined in figures 2 and 3. There, one can see the arrangement of the chosen hardware and the several tasks of the software. We use two-frequency Trimble 4000SSi GPS receivers with geodetic L1/L2 antennas. The data transceiving unit is a 6-watts Philips FM 1100 radio data modem with 9600 bit/sec at a frequency of about 460 MHz. This frequency allows a high transmission rate but, due to the short wavelength of 65 centimeters, it has some disadvantages regarding the signal interruption by large obstacles. Nevertheless, for the transceiving of raw dual-frequency observation data we need this high transmission rate. The data flow is interrupt-driven and realized via RS232 ports.

The computing and storage device at the reference site (figure 2) is a 486/33 personal computer. This machine is sufficient for the management and transceiving of all data. The time-delay between the receipt of the GPS measurements and the transmission of the prepared data is below 1/100 of a second. At the roving site a mobile computing device has to be used. We decided to use a Husky FC486/50, a portable notepad with a build-in keyboard. Besides a very long battery living of more than 8 hours, the computational power we need to solve for the unknown ambiguities in real-time is given by this notepad. For ambiguity resolution and position determination we need less than 0.1 second. Adding the time-delay caused by the data transmission from the reference site, we are able to produce results 0.3-0.5 seconds after the GPS measurements. As stated above, the ambiguity resolution is instantaneously possible within a couple of seconds. Figure 4 shows the roving station mounted on a backpack and on a van. A detailed description of the system and its performance can be found in [6] and [5].

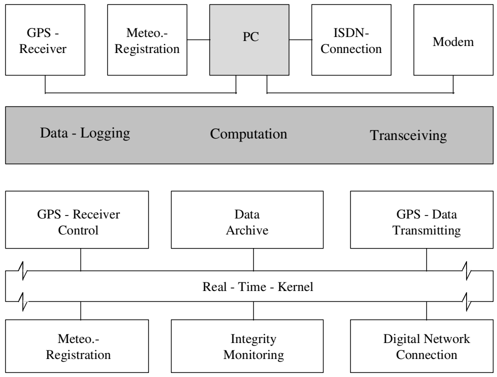

Figure 2 Setup of Reference Site

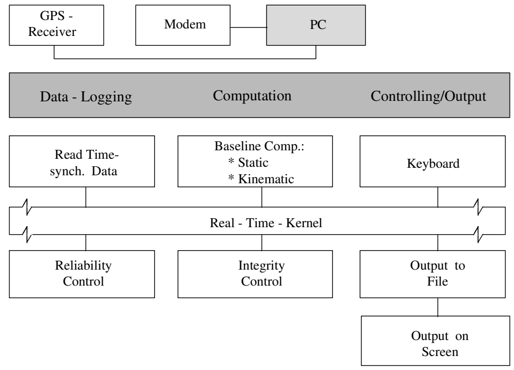

Figure 3 Setup of Roving Site

6. CONCLUSION AND OUTLOOK

The paper shows the development of a powerful GPS real-time system based on algorithms developed at the Institute of Physical Geodesy. It shows that an instantaneous ambiguity resolution in connection with a precise position computation in the range of 2-3 centimeters even in real-time is possible and reliable. Today, many applications exist for such systems and lots more will arise in the future, also in the field of vehicle navigation.

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Figure 4 Roving Site Mounted on a Backpack and on a Van