Assessment of the errors in single point positioning

BENCE TAKÁCS

Budapest University of Technology and Economics, Department of Geodesy and Surveying
bence@agt.bme.hu

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After turning off Selective Availability (SA) a new chapter began in the GPS-technique. The performance of GPS standard single point positioning technique was discussed in details [4]. It was stated, that in favourable conditions accuracy of several meters is achievable. Recently the number of GPS users has impressively increased; turning off SA has clearly played an important role in the propagation of GPS technique. Turning off SA is considered as a key point not only for the practice, but also for scientific researchers. It is well known, that compared to the artificial degradation of GPS accuracy, the effect of systematic and random errors on single point positioning is practically negligible. Some of the receivers do not take into account some systematic effects, because of the order of magnitude of SA error. Formerly errors on single point measurements could be invetigated only with limited efficiency. Turning off SA offers an opportunity to assess all the systematic and random effects in details; this paper will summarize the most important results of these investigations.

According to the GPS system operators the horizontal positioning error at 95% level of probability is around 13 m, the vertical error is around 22 m [2]. There are two possibilities to increase the achievable accuracy:

- Relative positioning instead of single point positioning, this is widely used in surveying and geoinformatics; or
- Using more effective models for taking into account the systematic errors.

The second method is also known as *precise single point positioning*. In a rigorous sense neither in this case one mention single point positioning, since modeling the systematic errors can be derived from special processing of permanent GPS stations' measurements. Major part of the users, because of convenience and practical aspects prefer to operate only one receiver. Hence this kind of relative technique is often represented as a single point positioning technique, since the user is not aware of using relative positioning.

Thanks primary to the activity of the International GPS Service (IGS), most of the systematic errors can be taken into account using precise models in post-processing. As a result of scientific processing of data from permanent GPS stations, satellite orbits are known to a few centimeter accuracy, the effect of satellite and receiver clock offsets (after converting them into distance) can be determined with the same accuracy. Finally, accurate maps of the Earth's ionosphere may contribute to the precise single point positioning.

The paper deals with the most important effects on single point positioning measurements. Algorithms and methods will be presented how to refine upon common models using products of permanent GPS stations, decreasing positioning errors to submeter level or even better.

Ionospheric effect

For the simplicity of computations, it is conventional to suppose that the electromagnetic waves on their whole paths have the same propagation velocity as in vacuum. Since GPS satellites orbit is around 20.000 km above the Earth's surface, signals travel in vacuum much part of their path, but before reaching the receiver antenna they have to cross the Earth's atmosphere, meanwhile their speed is modified significantly.

For the aspect of a decimeter radio signals, the atmosphere may be divided into two, totally different layers: the ionosphere and the troposphere. In the higher (between 40 km and 1000 km) ionospheric layer, particularly due to the ultraviolet radiation of the Sun, there are particles with electric charge. These particles modify the velocity of signals according to the signal frequency. So the ionosphere, from the point of a decimeter electromagnetic signals is a dispersive medium, its refractive index depends also on the signal frequency.

The effect of ionosphere could be taken into account using several methods. From the point of practice, two methods should be highlighted:

– with computations, using ionospheric models; or
– with elimination using dual frequency receivers, exploiting the properties of frequency dependency.

Now only the modeling method is discussed, since dual frequency receivers are used only in high precision scientific projects. In modeling it is supposed, that free electrons in the ionosphere are pressed into a single layer (also called a thin-shell model). The models can describe the Total Electron Content (TEC) of each point in the single layer.

Most frequently the effect of the ionosphere is taken into account using the Klobuchar-model with the parameters broadcast in the satellite navigation mes-

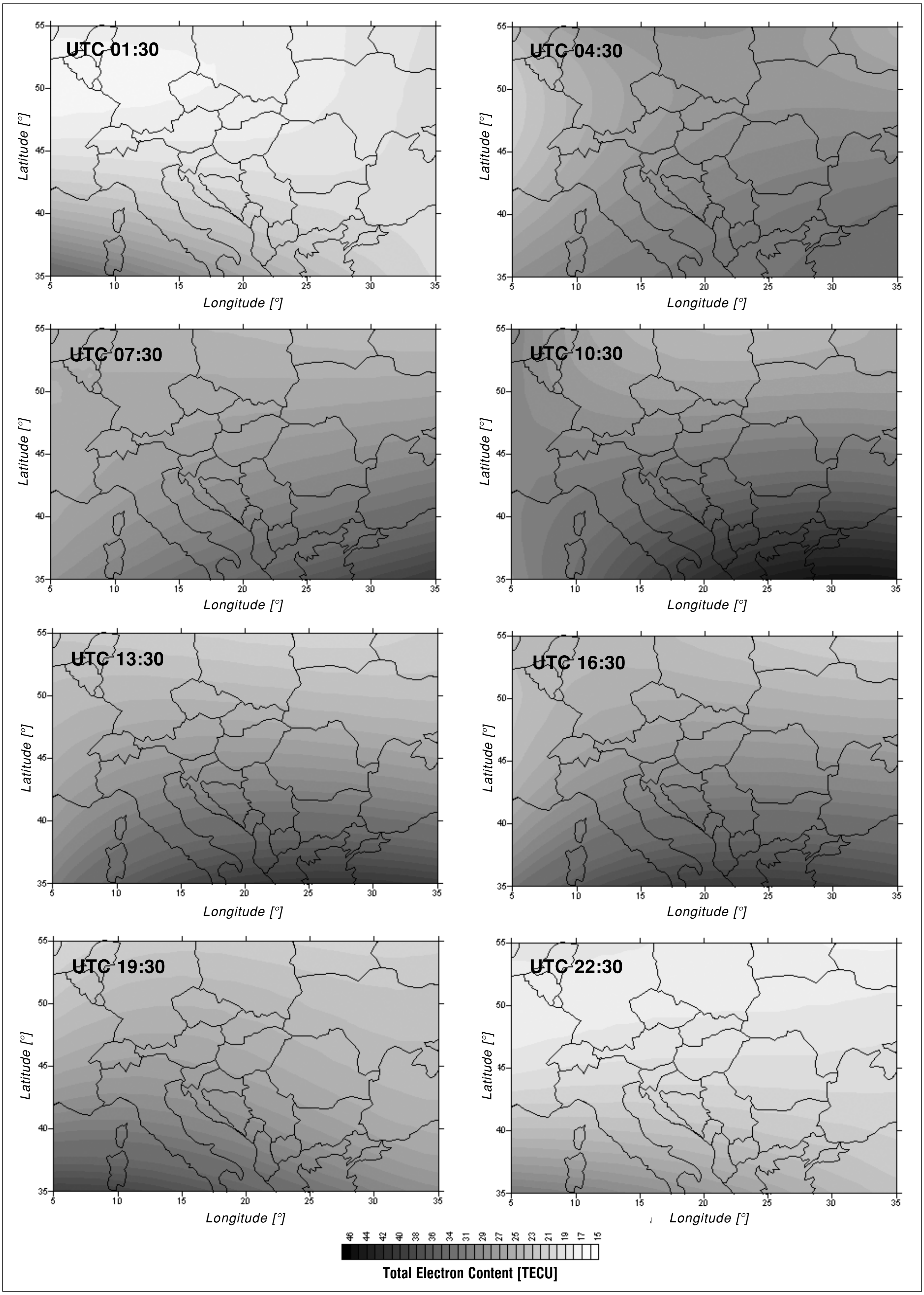


Fig. 1. Ionosphere maps from local models above Hungary and the neighbouring countries (16th June, 2002)

sage. This model is a simple cosine function, a more detailed description can be found for example in [3]. The most important advantage of the Klobuchar-model is that its parameters are transmitted in real-time by the GPS satellites themselves; hence for the positioning there is no need for external data. Its disadvantage is that the Klobuchar-model describes the ionospheric effect only with limited performance, according to the experiences with 50-60%.

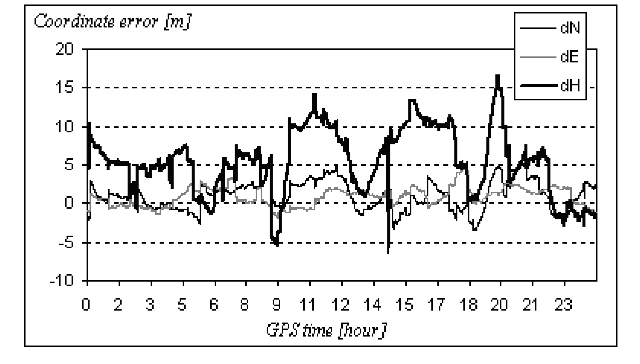
The ionosphere can be modeled more effectively, using so called local ionosphere models or global ionosphere maps. In the first case the single layer is described with low degree Taylor series, in the second one with harmonic spherical functions. The formulas can be found in the manual of the scientific post-processing software, BERNESE [1].

The main advantages of the local ionosphere models are that models, valid for a few thousands of square kilometers can be determined from measurements of a few permanent GPS stations, even in real-time using simple mathematical tools. At the same time global ionosphere maps are valid for the Earth, they are more precise but for the completeness of calculations the parameters could be determined only with some delay in time. For more details about global ionosphere maps, refer to the website of the IGS processing centre Berne (http://www.aiub.unibe.ch/ionosphere.html).

In a former paper [5] local ionosphere models valid for Hungary and the neighbouring countries were introduced. For the computations self-developed software was used. Without presenting the details, some maps demonstrating the total electron content for a given day are shown on the *Fig. 1.*

Henceforward the accuracy of single point positioning using different ionosphere models are presented. It is well known, that after turning off SA, the effect of the ionosphere became the largest impact [3]. For the analysis, 24-hour measurements from the permanent station of Budapest University of Technology and Economics were processed applying different ionosphere models and the position errors were compared. Self-developed software was used for the computations.

Fig. 2.
Errors of single point positioning at BUTE station (16th June, 2002, ionosphere: Klobuchar-model with broadcast parameters)



In the first case the Klobuchar-model with parameters from the navigation message was used. Most of the conventional GPS receivers use this method. According to *Fig. 2.* coordinate errors can reach 15 meters.

Then the ionosphere was taken into account using the local models shown on the *Fig. 1.* The improvement of the coordinate errors is clear on *Fig. 3.* especially in vertical sense. While the standard deviations of all the three components have been decreased equally with about 30%, the average systematic error in vertical sense has been decreased with 80%!

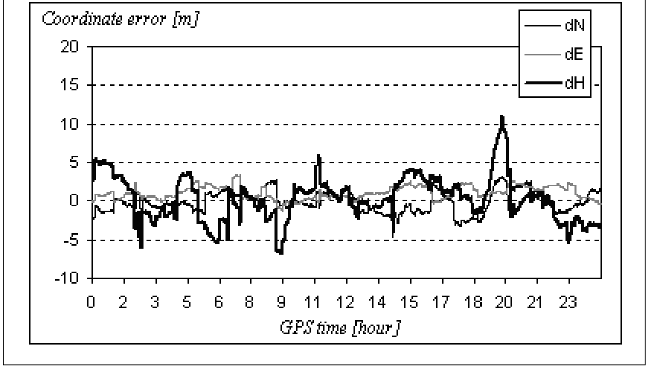
Orbits and satellite clocks

For GPS positioning it is essential to know the satellite orbits. The most conventional way to compute satellite positions is to use the broadcast ephemeris. The most important advantage of this technique is that the necessary information is broadcast by the GPS satellites, so external data sources are not required. Its most important disadvantage is that the broadcast satellite orbits are only a couple of meters accurate, so this technique is not precise enough for all kinds of applications. The accuracy may be improved using the so called precise satellite orbits based on the special processing of permanent GPS stations' data.

The different kinds of orbits can be compared with Bernese software. According to two data series the software can compute the differences of the satellite positions. In practice an orbital coordinate system consists of radial, tangential and out-of-the-plane components *(Fig. 4)*.

GPS is a passive positioning system, users do not transmit only receive signals from the satellites. Satellite-receiver distance determination is based on measuring the propagation time of signals from satellites to the user receiver. As a consequence it is necessary to have a clock both at the satellite and at the receiver side. These clocks have an individual offset from the so called GPS system time. The effect of satellite clock offset can be decreased significantly using a quadratic function with parameters taken from the navigation message.

Fig. 3.
Errors of single point positioning at BUTE station (16th June, 2002, local ionosphere models)



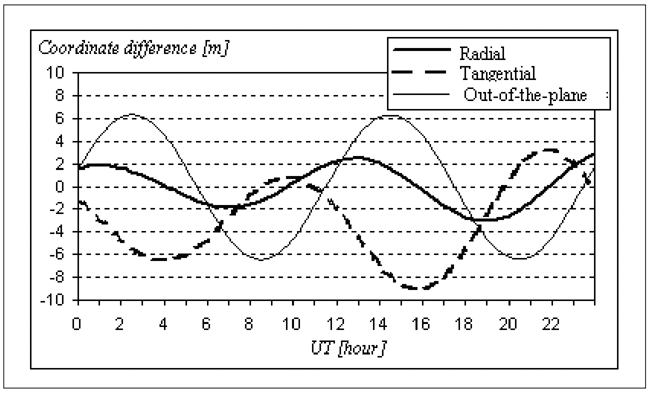


Fig. 4.
Differences of the satellite coordinates computed from the broadcast ephemeris and the IGS precise orbits (16th June, 2002, PRN: 08)

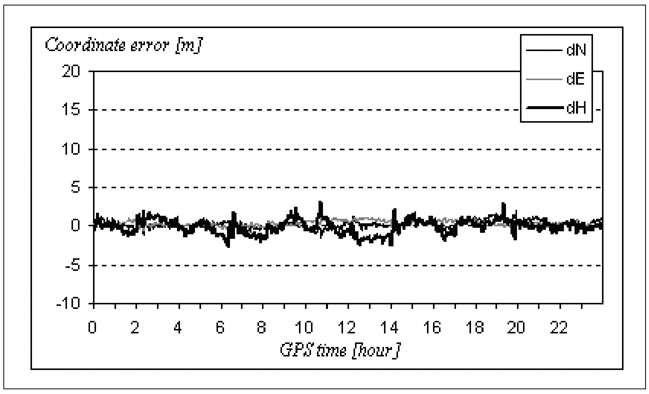
Similarly to the satellite orbits, International GPS Service determines the quasi correct satellite clock offset values based on processing permanent GPS stations, again. Using these values the accuracy of the parameters in the navigation message can be estimated and the differences can be applied as corrections *(Fig. 5)*.

It is possible to precise satellite orbits and clock offsets in the positioning. In this case the discrete values (usually given every 15 minutes) need to be interpolated using high ordered Lagrange polynomials.

From the computational point of view it is more elegant, if the differences of the precise orbits and the ones calculated from the broadcast ephemeris are taken into account as corrections. Its main advantage is that differences can be interpolated easily. The same algorithm can be used for the satellite clock offsets, as well.

On *Fig. 6.* the same measurements of the BUTE station are processed using the IGS precise orbits and satellite clock offsets. It can be clearly seen that the horizontal position errors are less than 2 m, the vertical error is less than 3 m. The average systematic error is practically the same in each component, less than 30 cm, the standard deviation is less than 1 m.

Fig. 6.
Errors of single point positioning at BUTE station (16th June, 2002, global ionosphere maps of Berne, IGS final orbits and satellite clocks)



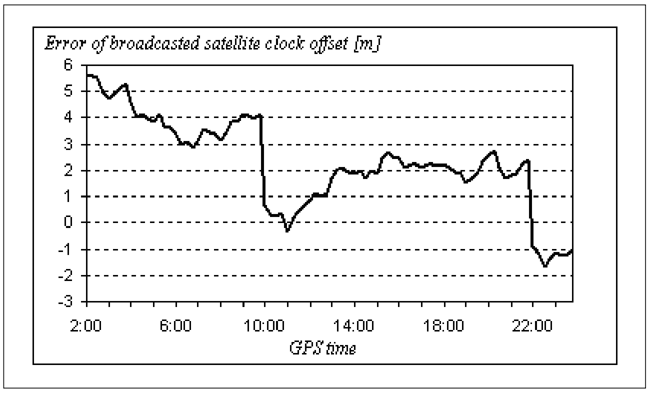


Fig. 5.
Errors of satellite clock offsets computed from the parameters of navigation message (16th June, 2002. PRN: 02)

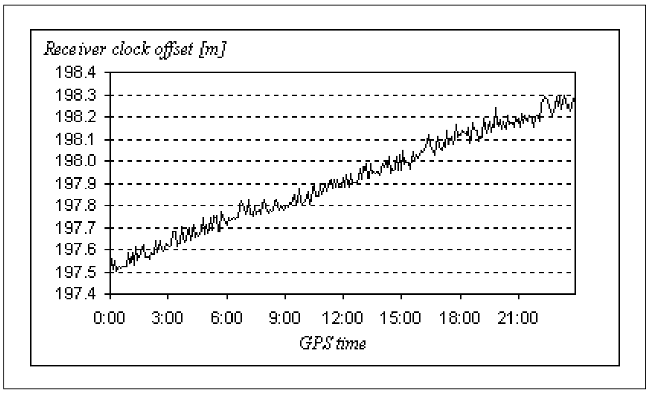
Receiver clock offset

The quartz frequency etalons in the receivers are much less accurate (with several orders of magnitude) than the atomic etalons on the satellites. In most of the cases the receiver clock offset is treated as unknown, its value is computed from the GPS measurements. That is why four satellites are required for the unambiguous three dimensional positioning, although from geometrical point of view three satellites were enough.

The International GPS Service beside the satellite clock offsets provides the receiver clock offsets of some permanent stations, again in discrete epochs (usually every 5 minutes). These products are available on the IGS home page (ftp://igscb.jpl.nasa.gov/pub/product/). The accuracy of these receiver clock offsets are estimated at a few centimeters level. (The receiver clock offset is treated as a time unit by nature, but for the better interpretation it is multiplied by the vacuum speed of light to get a metrical dimension.)

Unfortunately for our investigations the BUTE measurements are not usable in the followings, since BUTE is not part of the IGS network. Hence we selected another station: BRUS (Brussels, Belgium). *Fig. 7.* shows the receiver clock offsets of BRUS station according to the IGS product.

Fig. 7.
The receiver clock offset at BRUS station, according to the IGS product (16th June, 2002.)



As it can be seen on *Fig. 7.*, the clock offsets at BRUS station controlled by a hydrogen maser etalon can be modeled efficiently with e.g. linear regression. Now we present the accuracy of single point positioning if the receiver clock offset was not treated as an unknown, but as value taken from the above linear regression. Now the equation system contains only three unknowns in spite of the usual four.

On *Fig. 8.* we can see that the vertical position errors are not larger than the horizontal ones, the error of the three components is typically less than 1 m. It is worth mentioning that in “conventional” positioning the vertical position error is two times larger than the horizontal.

Two main disadvantages of the method based on the IGS receiver clock offsets are mentioned:

- it works only in the case of high precision frequency etalons, e.g. in a laboratory;
- the positioning can be carried out only with post-processing.

To encounter the second disadvantage we propose an algorithm based on Kalman-filtering. The single point positioning equation system is solved in two separate steps:

1) solving with the “conventional” conditions, using four unknowns;
2) smoothing the receiver clock offset with a Kalman-filter and solving the whole system again, but only with three unknowns.

Details are not presented because of the lack of space, but it is mentioned that this algorithm yields practically the same results as using IGS product, of course only in the case of stations with well-modeled receiver clock offsets.

Noise of code measurements

In this paper the effect of the most important systematic errors were presented. The random effects, especially the noise on code measurements have not been treated yet. It is well known that the noise on phase data is practically negligible in comparison with the code noise. In theory single point positioning can also be carried out using phase measurements only but the well known phase ambiguity problem is rather complicate in the practice. The optimal solution should be the use mixed phase and code data. The principle is to smooth the code distances with phase ones.

According to the most often used algorithm the phase ambiguity equals more or less to the difference of phase and code distance in each time epoch. Of course this value is affected by the code noise which can be decreased with simple mathematical tools, like running averaging. This algorithm is easy and efficient. One of its main disadvantages is however that using single frequency receivers the length of smoothing in time is limited, since the effect of the ionospheric delay has opposite sign on the code and phase measurements. Another disadvantage is that the quality of the smoothed data depends on every satellite, so once the smoothing has stopped at one satellite for whatever reason, it is no worth continuing the smoothing process for the other satellites either.

If we have a dual frequency receiver, the problem caused by the ionosphere can be almost totally neglected. A further advantage of the dual frequency receivers is the opportunity of cleaning the phase data from cycle slips using various types of linear combinations. This method is used in the Bernese software, too.

The effect of smoothing is presented in the case of BRUS station, using the above used data. *Fig. 9.* shows the positioning errors. The effect of systematic errors have been decreased using the most powerful algorithms presented before: ionosphere was taken into account using local ionosphere models, satellite orbits and clock offsets were modeled by the IGS final products, and receiver clock offsets were smoothed by a Kalman-filter approach.

On *Fig. 9.* it is clear that positioning error components were decreased significantly, however other systematic effects (e.g. troposphere and multipath) play still some role.

Fig. 8.
Errors of single point positioning at BRUS station (16th June, 2002, receiver clock offset modeled by linear regression of the IGS product)

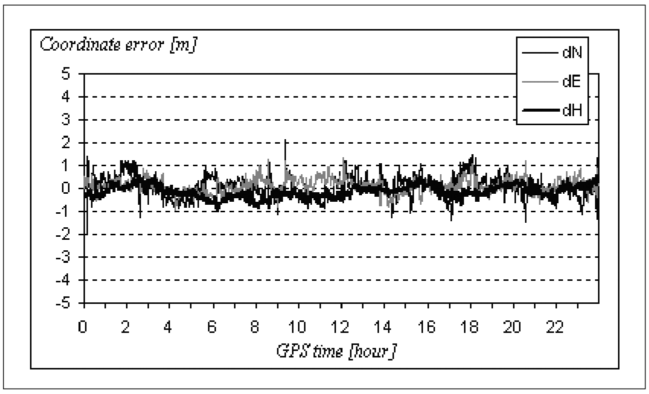
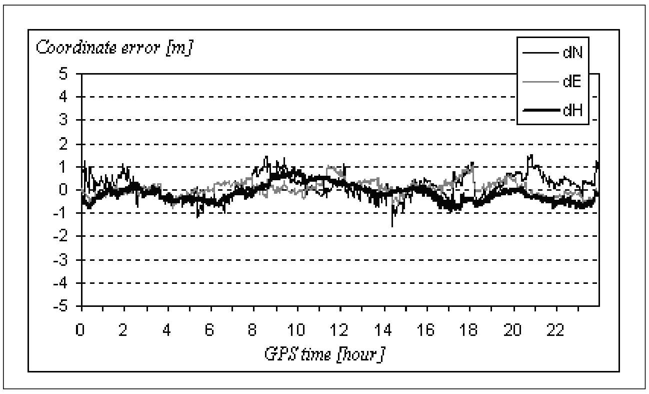


Fig. 9.
Errors of single point positioning at BRUS station (16th June, 2002, code distances are smoothed with phase data, carried out by Bernese)



Summary

The motivation of the investigations, presented in this paper was to develop the necessary algorithms for the one-meter-accurate, real-time GPS single point positioning. The method and results of the local ionosphere modeling were introduced. It was presented that with the precise IGS orbits and satellite clock offsets the standard deviation of the positions can be decreased below one meter, even in real-time. Further improvement in accuracy can be reached with receiver clock offset modeling and with smoothing code distances with phase data. Using dual frequency, high precision geodetic receivers controlled by atomic etalons the position error components are less than one meter.

It is worth mentioning that so called augmentation systems (EGNOS in Europe) have started their operation. Currently EGNOS is working in a test phase, but its results are well promising. The augmentation systems, beside so many other processes, use similar algorithms and models as presented in this paper. The corrections are transmitted from geostationary satellites and via Internet to the users.

In the newest generation of GPS infrastructure to get a homogenous corrections set for a region or a country, the corrections from the individual stations need to be co-ordinated. These algorithms are based again on similar methods, as presented in this paper.

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News

ComArch takes telecommunications forward with OSS&BSS solutions supporting the technology of the future EDGE and UMTS and expands the possibilities of implementing new types of services for customers and gives new wide business opportunities for telecom operators and content providers. ComArch TYTAN Billing Platform and InsightNet Network Management Platform enable information and communication service providers to deploy, then effectively use 3G networks, and allow for the extension of their current functionalities within 2,5G networks.

The accounting of new type of UMTS services requires open and flexible billing systems to handle huge amount of data, new complex types of services and multiple service and content providers. The fully integrated TYTAN Billing Platform enables operators rapidly develop new revenue streams, handle new services and share the revenue with whole chain of service providers. Its real-time capability allows full prepaid and postpaid convergence. TYTAN Data Processing Server (DPS), as the kernel of the platform, is a very efficient rule-based rating engine, that has been benchmarked on major hardware platform to process the volume of data that UMTS will generate. TYTAN IneterPartner Billing component uses the DPS to respond to the new market requirements i.e. quick implementation and configuration of various revenue sharing scenarios.

ECI Telecom is presenting its Hi-FOCuS MiniRAM Outdoor Unit (ODU). The MiniRAM ODU is the first system with ADSL2+ capability and Gigabit Ethernet interface that is specifically designed to support triple play services. ECI´s MiniRAM ODU is a self-contained unit for installation in any outdoor location. This lowers service providers´ deployment costs and enables them to reach new triple play customers. In urban and suburban areas, the MiniRAM ODU enables Telcos deliver the higher bandwidth required for triple play. ECI´s MiniRAM ODU provides solution where existing remote network facilities, such as street cabinets, do not have sufficient space or conditions for broadband equipment.

The MiniRAM ODU can be equipped with various interfaces including T1 IMA, OC-3, and Gigabit Ethernet and provides 32 or 48 ADSL/2/2+ or 24 VDSL lines. A range of Hi-FOCuS products are available to fit a variety of applications, such as Remote Terminal and DLC cabinets, MTU/MDU and more.