Performance of GPS Stochastic Modeling for Forest Environment

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Abstract – Nacrtak

The Global Positioning System (GPS) now makes it possible to define forest boundaries using double differenced carrier phase observables. They are mostly processed with algorithms based on the Least-Squares Estimation (LSE). Although GPS was completely developed for outdoor navigation, sometimes it can be used in near/under tree or building shading. In such a case, before applying the LSE, both the functional and stochastic models should be properly defined in order to obtain reliable positioning. While the functional model for precise GPS positioning is sufficiently well known, realistic stochastic modeling is still a difficult task to accomplish in the case of unfavorable conditions. This paper analyzes the achievable efficiency of the stochastic modeling for the positioning near/under the forest. A static campaign was performed at two surveying sites that have been established near the effect of tree shading. The experiments show the efficiency of stochastic models depending on the forest. It is clear that sigma-ε and sigma-Δ models give optimum solutions for the sites located near the tree canopy. Moreover, weighting procedures based on the C/N0 values can successfully cope with the corruptive effects caused by the tree canopy. As a result, a proper stochastic model for carrier phase observables should be used as an important tool in parameter estimation for handling multipath effect and signal distortion caused by the forest canopy.

Keywords: GPS; forest; efficiency; stochasticity; weighting

1. Introduction – Uvod

NAVSTAR GPS (*Navigation System with Time and Ranging Global Positioning System*) was developed in 1973 by the United States Department of Defense, and it is the satellite-based positioning and time transfer system. The United States NAVSTAR GPS and the Russian *GLObal NAvigation Satellite System* (GLONASS) are fully globally operational systems, as of October 2011. China is in the process of expanding its regional Beidou navigation system into the global Compass navigation system by 2020. The European Union's Galileo positioning system is in initial deployment phase, scheduled to be fully operational by 2020 at the earliest. Generally, the satellite navigation system with global coverage may be termed a Global Navigation Satellite System (GNSS). The first purpose of establishing such a system is to provide the requirement for 24 hours of military positioning in all weather condition. It is well known that the system found for military purposes is limited to the management authority for civil users. Thanks to the GPS system, the high precise information of 3D positioning, velocity and time can be obtained in a global coordinate system. GPS system basically consists of three components: Space component, control component and a user component. The overview of the development of GPS system is given by Clarke (1994); Kaplan (1996); Rizos (1997); Kleusberg and Teunissen (1998); Hoffmann-Wellenhof et al. (2001); Leick (2004).

GPS measurements are carried out using the electromagnetic waves from satellites to receivers. For this purpose, there are the two main frequencies for a GPS satellite, L_1 and L_2. So the two GPS carried signals are used in engineering, topographic, forestry and cadastral applications. The reason for dual frequency GPS system is to serve as the backup frequency in case of interruption of one of the frequencies, and of course to model the ionospheric effect by using the dual frequency (Teunissen and Kleusberg 1998).

In the application of GPS, the baselines between the surveying sites are generally short. Since the desired accuracy is high, GPS carrier phase observables are processed by solving integer cycle ambiguity. For the GPS application, the accuracy depends strongly on the following factors: (a) Modeling of atmospheric effects and clock errors, (b) effective fixing of ambiguity parameter, (c) site environment (Rizos 1997; Hoffmann-Wellenhof et al. 2001; Leick 2004; Li et al. 2008). Atmospheric propagation on the GPS observables can be handled using well known atmospheric models (Roberts and Rizos 2001, Ibrahim and El-Rabbany 2008).

Clock errors are completely removed by double differencing. Carrier phase ambiguity determination has been an important field of investigation for 30 years. All in all, the residual errors of GPS observables are mainly due to specific effects of the site, e.g. multipath. It is clear that signal deterioration caused by the GPS site environment is still a main concern (Talbot 1988; Han 1997; Hartinger and Brunner 1998; Lau and Mok 1999; Pirti 2008).

Precision and accuracy of GPS receivers for static surveying in forest areas has been studied in detail by Naesset (2001); Hasegawa and Yoshimura (2003); Yoshimura and Hasegawa (2003); Naesset and Gjevestad (2008). In forest environment, there may be some restrictive factors that cause corruptive effects on the receiver of GPS signal, such as heavy forest canopy or steep terrain model (Danskin et al. 2009; Pirti et al. 2010). In such a case, corruptive objects may affect GPS satellite signal and make it difficult to get reliable products. Practically, the GPS receivers have to be used only on high elevation satellites when they are restricted by the skyview in a forest environment. In forestry applications, high precision GPS positioning is based on both mathematical and stochastic models. The mathematical model relates the observed quantities to unknown parameters, i.e. the phase observables and the coordinates of the GPS sites, respectively. If signal distortion and multipath errors by objects are not taken into account, the model will be misspecified and yield biased estimates. There are three ways to eliminate them: Modeling the effects mathematically, modifying stochastically and rejecting outlying observables.

The aim of this study is to investigate GPS stochastic models in the case of the GPS signal failures due to the forest environment, especially for short baselines. To do it, we used some stochastic models based on signal quality indicators and derivation of variance models that reflect the characteristics of GPS observables. Thereby, the achievable efficiency of the stochastic models can be assessed on the basis of the parameter estimation.

2. Problem Description – *Opis problema*

The processing of the GPS data is based on the Least Squares Estimation (LSE) method as well as the adjustment procedure for other geodetic networks. The establishment of a functional model and a stochastic model is required before using the LSE method in computing 3D position of GPS stations/sites. As it is known, the functional model contains the mathematical relationships between the GPS measurements (code and carrier phase measurements) and the unknown parameters (atmospheric delays, clock error, the carrier phase ambiguity and baseline components). The stochastic model defined by a variance-covariance matrix, reflects the basic statistical properties of GPS observations, and it is very important in terms of data quality. In order to achieve high accuracy, both models should be correctly identified. In the case of accurately establishing the functional and stochastic model, the residuals obtained by the LSE have normal distribution. Although the functional model is created strictly, the stochastic model is still a fundamental concern for processing GPS phase observables. Estimation of the unknown parameter can provide good solutions if and only if the stochastic model of the observables is formed realistically. The stochastic model is described by the Variance-Covariance Matrix (VCM) that accounts for the variances of the GPS observables and their correlations. As it is well known, there are two possible ways to obtain the VCM: With the estimation of variance and covariance values for the observables, using an a priori variance model.

As with all known observing techniques, the GPS code measurements and carrier phase also include random errors (Satirapod et al. 2000; Tiberius and Kenselaar 2000). While running under ideal conditions and with a sufficient observing period, it is expected that the residuals from LSE method will be of the same character as the true errors. Up to present day, many statistical techniques based on LSE method have been successfully developed and used in order to achieve the desired high accuracy (Rao 1971; Ziqiang 1991). Satellite orbital errors, satellite and receiver clock errors have been completely eliminated in the step of creating a functional model since the principle of relative point positioning by GPS is a difference processing algorithm (Rizos 1997; Teunissen and Kleusberg 1998; Hoffmann-Wellenhof et al. 2001; Leick 2004). However, the residuals and parameters estimated by the LSE will be unfavorably affected due to the existing functionally unmodeled errors and noise, such as the tropospheric delay, multipath and signal dispersion. Several studies have been done related to such effects to develop the stochastic models for increasing the sensitivity of GPS technique (Han 1997; Barnes et al. 1998; Wang 1999; Satirapod 2002). The delay effect due to the refraction of troposphere layer can be eliminated using appropriate models based on the atmospheric profiles.

Multipath is the major site dependent error because it depends on environment around the GPS antenna, especially for the application with short baselines. For example, the electromagnetic wave may be achieved from the satellite to receiver in more than one way due to the multipath reflectors around the GPS site, such as tree or building shading. This effect is modeled using the techniques developed to reduce the multipath effect. The effects of multipath and signal dispersion can be reduced using the stochastic models developed in the GPS data processing, and accuracy of the parameter estimation is thereby increased.

A priori and a posteriori variance is not equal to each other because all systematic and random errors cannot be modeled by using the double differenced observable equations. Moreover, these errors cause the correlations between the observables in the differencing step. All in all, the stochastic models that describe the character of the GPS observables affected by these errors, must be used (Tiberius et al. 1999; Pachter and Nguyen 2007). For this purpose, the appropriate processing models should be used, as well as the definitions of observables.

The elements of the weight matrix define stochastic model, and it provides information on how each GPS observation can contribute to the solution. A kind of weight modification can be recommended for a high-accurate result. For example, a weight reduction and accession for the observables can be affected more and less than the others (Teunissen et al. 1998). Because of the relationship between the weights and variance-covariance matrix, it is important to know the realistic stochastic properties of the observables. For stochastic modeling of GPS observables, some signal quality criteria are widely used (Tiberius et al. 1999). Many studies based on signal quality criteria have been done. For example, the comparison of different GPS data for modeled residuals (Satirapod 2006; Satirapod and Luansang 2008), the determination of minimum shifting using a weighting based on the ionosphere (Jong and Teunissen 2000), the implementation of artificial neural networks approach (Jwo 2007), internal and external reliability of the GPS method (Kuusniemi et al. 2004). There have been some investigations on the effects of the mathematical correlations that arise from differencing of GPS observables (Yang et al. 2002; Ding et al. 2004). In addition, using weighting models derived from C/N_0 values, the effect of multipath reflection has been modeled for the short baselines (Wieser and Brunner 2000, 2002; Özlüdemir and Ayan 2003). Some GPS receiver manufacturers have developed receivers integrated with pre-assessment software in order to eliminate these effects.

3. GPS Processing Models – *Modeli obrade GPS-ovih podataka*

In the case that the baseline length is less than 20 km for GPS application, the geometry based mathematical models can be easily generated using the technique of double differencing of the GPS observations. The processing models for GPS observables have been studied most extensively in the literature, and many contributions on the subject are available, e.g. Teunissen et al. (1998); Teunissen et al. (2000); Hoffmann-Wellenhof et al. (2001); Odijk et al. (2002); Odijk 2003; Leick (2004); Verhagen (2004). The functional and stochastic models for double differenced code and carrier phase observations can be established as follows:

$$E\{y_{\mathrm{GPS}}\} = A_{\mathrm{GPS}} a_{\mathrm{GPS}} + B_{\mathrm{GPS}} b \tag{1}$$

$$\Sigma\{y\} = \sigma_0^2 Q_{\mathrm{y}}^{\mathrm{GPS}} \tag{2}$$

where y_{GPS} is the vector of double differenced code and carrier phase observables, a_{GPS} is the vector of carrier phase ambiguity, b is the vector of coordinate unknowns, A_{GPS} is the coefficient matrix of the vector of a, B_{GPS} is the coefficient matrix of the vector of b, Σ is the covariance matrix of the observables of y, Q_{y} is the cofactor matrix of the observables of y and σ_0^2 is the variance of the observation with a priori weight.

In some applications, GPS cannot provide accurate results due to undesired errors (Teunissen and Kleusberg 1998). Especially in the case of signal distortion and mutlipath effects, some criteria should be used in creating stochastic models. These are based on the power of a GPS signal. In the following subsections, we will give the models of variance that are widely used for weighting double differenced observations.

3.1 Equal Variance Weighting Model – *Model ponderiranih jednakih varijanci*

In the step of processing GPS data, the simplest approach for weighting observables is to assume that all observables have equal variances. This general approach has been used as standard stochastic model, especially in cases of ideal environmental conditions. For example, there is a panel of the standard stochastic model in the Bernese v.5.0 software (Dach et al. 2007). However, under unfavorable observing conditions, 70% of the data can be successfully modeled in stochastic terms at most. Especially in the case of signal distortion or multipath, this rate reduced even more. Although some improvements have arisen mainly with increasing of satellite elevation angle, the volume of data collected decreased. For these reasons, it is recommended to avoid using the models of equal variance weighting for high-precision GPS applications (Hartinger and Brunner 1999).

3.2 Variance Model based on Satellite Elevation Angle – *Model varijanci zasnovan na kutu nagiba satelita*

As an alternative to equal variance weighting, a large number of stochastic models are proposed, defined by a function of the elevation angles (Wang et al. 1998; Collins and Langley 1999). An example for this approach is the cosine weighting based on a cosine function of elevation angle for related satellite (Rothacher et al. 1997). In the developed stochastic model, variance of carrier phase observable can be shown as:

$$\sigma_{\phi}^{2}=\frac{\sigma_{90^{\circ}}^{2}}{cos^{2}z}, \tag{3}$$

$$z=90^{\circ}-h, \tag{4}$$

where σ_{ϕ}^{2} is the variance of carrier phase, σ_{90}^{2} is the variance of carrier phase in zenith direction, z is zenith angle of satellite, h is satellite elevation angle. σ_{90}^{2} can be estimated experimentally. In this way, covariance matrix is formed for double differenced GPS observables.

3.3 Variance Models based on Signal to Noise Ratio – *Model varijanci zasnovanih na odnosu signala i šuma*

As mentioned above, various weight functions based on Signal to Noise Ratio (SNR) have been developed in order to model the effects of multipath and signal distortion, and to reduce their corruptive effects on parameter estimation (Lau and Mok 1999; Hartinger and Brunner 1998; Tiberius and Kenselaar 2000; Schön and Brunner 2008). An example of these studies is the approach that uses stochastic models depending on SNR value regarded as a quality indicator for the GPS observations (Spilker 1996). The relationship between the values of SNR and variance of the observables will be established as follows:

$$\sigma_{\phi}^{2}\cong\frac{1}{SNR}, \tag{5}$$

where SNR is Signal to Noise Ratio and σ_{ϕ}^{2} is variance of carrier phase.

3.4 Variance Models based on Carrier to Noise Power Density Ratio – *Model varijanci zasnovan na odnosu prijamnika i snage gustoće šuma*

For establishing stochastic models reflecting the characteristics of the carrier phase observables, some weighting models are available as a function of the C/N_0 models. Contribution of these models to the solution is the use of more realistic models that reflect signal quality instead of standard models. In addition, corruptive effects can be reduced using C/N_0 models in the case of low satellite elevation angles. One of the models developed as a function of the C/N_0 values is sigma-ε (Hartinger and Brunner 1999; Özlüdemir and Ayan 2003). For the variance model proposed, the relationship between C/N_0 of the carrier phase and C_i model parameter can be expressed as follows:

$$\sigma_{\phi}^{2}=C_{i}\,10^{-\frac{C/No}{10}} \tag{6}$$

where σ_{ϕ}^{2} is variance of carrier phase. The parameter C_i is taken as 1.61×10^{-4} mm^2 (Brunner et al. 1999). The variances are estimated for each observation epoch. As a result, covariance matrices are computed for double differenced (DD) phase observables using the rules of error propagation. (Brunner et al. 1999; Koch 1999). Thus DD observables can be statistically modeled as required by the characteristic structure of the signal.

At each GPS site/station, C/N_0 values may vary depending on the type of antenna and receiver as well as on environmental conditions. Since the sigma-ε model derives different values of variance for each station, the stochastic modeling may not always be effective against signal distortion. As is known, the C/N_0 values of GPS signal corrupted by various reasons are lower than the ones of the others that have the same elevation angle. Considering this corruption effect, the equation (6) is transformed as follows:

$$\sigma_{\phi}^{2}=C_{i}\,10^{-\frac{C/No-\gamma\Delta}{10}}, \tag{7}$$

$$\Delta=\left|C/N_{0\text{template}}-C/N_{0\text{observed}}\right|, \tag{8}$$

where σ_{ϕ}^{2} is variance of carrier phase, C_i and γ are parameters of model, Δ is difference between existing C/N_0 value and C/N_0 in template model. This model is called sigma-Δ model because of the term Δ. In determining of template model, the largest possible values of C/N_0 for signals received by GPS sites were recorded. In case that a signal is not corrupted, the difference of Δ is small.

4. Case Study Fieldwork – *Terensko istraživanje*

The biases in the parameter estimation can be anticipated at the centimeter level for the GPS applications in multipath environment such as forest boundaries. If observables are contaminated by systematic errors due to environmental objects, there will be some troubles in ambiguity solution and baseline estimation. The purpose was to investigate the effectiveness of stochastic models in estimating the parameters in the case of GPS sites near the forest environment. In this study, we performed a carefully designed experiment that includes signal distortion and multipath effects due to tree shading. Thereby, the effect of signal distortion in using stochastic modeling in post processing of GPS observables can be investigated in detail. The experiments were carried out in the Samandira region of Istanbul, Turkey, see Fig. 1.

A basic geodetic baseline consisting of two sites was surveyed using the GPS surveying method. The baseline length was 20,000 m with a height difference of 1.970 m. The aim of this study was to compare the performance of the GPS stochastic models under the effects of signal diffraction. In order to create the multipath environment, one of the static GPS sites, the site T_1, was situated far from the forest obstruction. Data with signal distortion effects was collected at the site T_2 located at the forest boundary. In forest areas, GPS signal diffraction effect may occur due to diffuse obstacles such as bushes, branches and trees. Herein we designed the example including the multipath error, see Fig.2.

The static observables were taken on May 27, 2006 (Day of Year, DOY: 147). Data were collected at these two sites for 6 hours between 04:30–10:30 UT with a sample rate of 30 seconds. Therefore, 720 observations were obtained during one day of field data collection. Satellite elevation angle was assumed to be 5 degrees. Magellan Thales Z-Max receivers with internal antennas were used at all sites. Table 1 shows the basic information of the dataset.

As an obstacle, the trees at the forest boundary mainly caused shading of satellites during the experiment. Fig. 3 shows the skyplots prepared for the sites T_1 and T_2. It is clear from the satellite distribution that there are some differences between the satellite visibilities between the sites. From the skyplot, we can see that the receiver at the site T_1 tracked more satellites continuously than the other, as some satellites were shaded by trees. At the site T_2, the receiver recorded less data from some satellites, e.g. PRN 4, PRN 15, PRN 18, PRN 19 and PRN 22. It can be seen that the

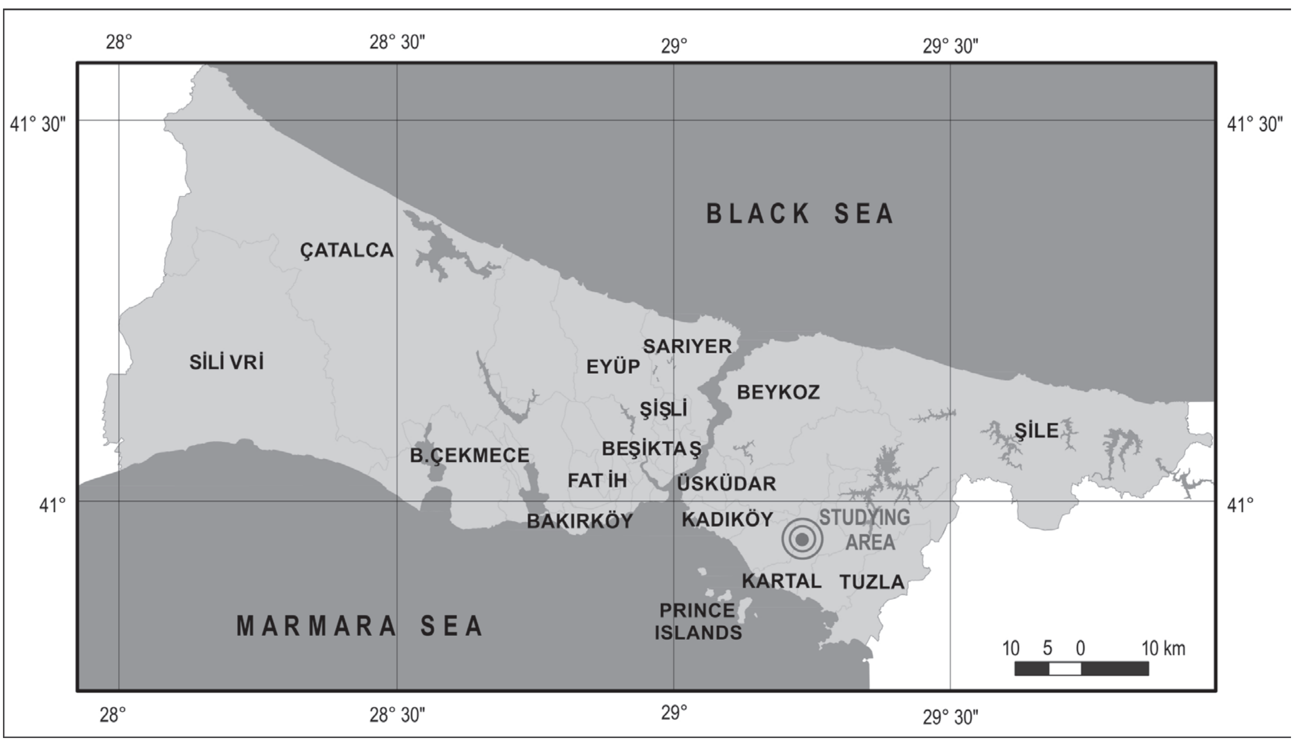

Fig. 1 Study area in Istanbul

Slika 1. *Područje istraživanja u Istanbulu*

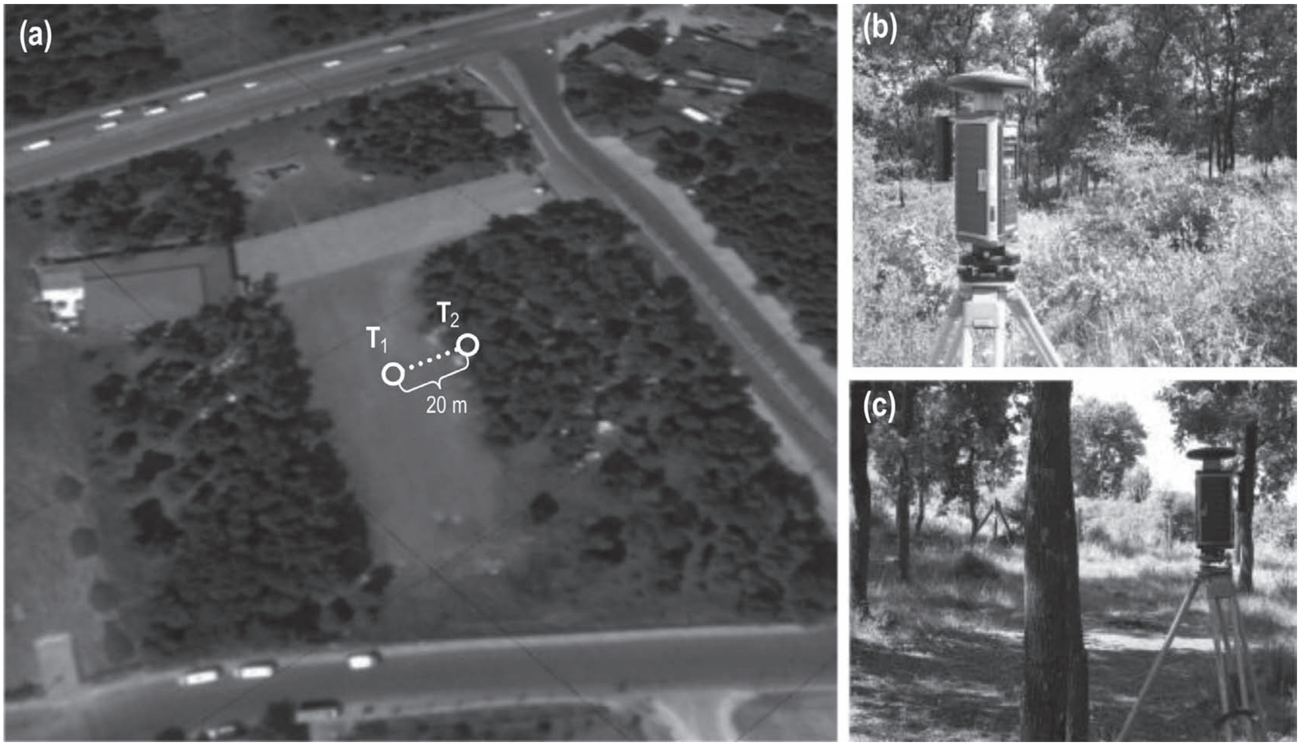

Fig. 2 Study area, (a): GPS sites and forest area, (b): Site T_1 far from the trees, (c): Site T_2 at the forest border
Slika 2. *Područje istraživanja, (a): pozicije GPS-a i šumsko područje, (b): mjesto* T_1 *udaljeno od stabala, (c): mjesto* T_2 *na granici šume*

Table 1 Basic information about the experiment
Tablica 1. *Osnovne informacije o pokusu*

Date/Hour – *Datum/Vrijeme*	27.05.2006 / 04:30–10:30 UTC
Session type – *Način rada*	Static
Receiver type – *Vrsta prijamnika*	Magellan Thales Z-Max Receiver
Antenna type – *Vrsta antene*	Internal Antenna
GPS observables – *Opažanja GPS-om*	C1, P2, L1, L2, S1, S2
Data sampling rate – *Frekvencija prikupljanja podataka*	30 seconds
Satellite elevation angle – *Kut nagiba satelita*	5°
Baseline length – *Duljina osnovne linije*	20.000 m
Height difference – *Visinska razlika*	1.970 m
Site coordinates – *Koordinate mjesta pokusa*	T_1: 40° 58' 28''.75 N, 29° 13' 14''.87 E T_2: 40° 58' 29''.36 N, 29° 13' 15''.16 E
Satellite orbit file – *Datoteka orbite satelita*	igs13766.eph
Explanation – *Dodatna pojašnjenja*	T_1 : At a distance of 20 m from forest boundary T_2 : At the forest boundary

trees shaded PRN 15 above 20° at the site T_2, see Fig. 3 (right). The strong signal interruption and distortion may therefore be expected since 50% of the sky is obstructed by the trees at the site T_2 mounted at the forest boundary. It is clear that the coordinates of the site T_1 were less affected by forest environment than the other site. Therefore, the coordinates of the site T_1 should be fixed in the static processing.

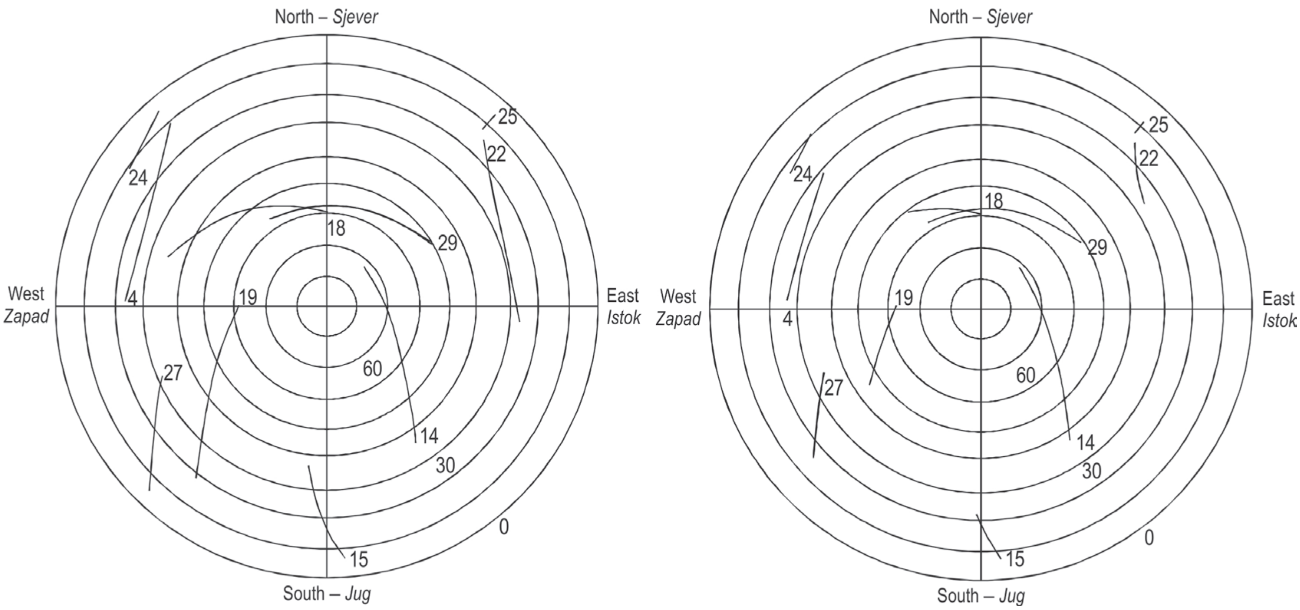

Fig. 3 Skyplot of sites T_1 (left) and T_2 (right), 04:30–10:30 with heavy obstruction by trees
Slika 3. *Skica satelita na nebu na mjestima:* T_1 *(lijevo) i* T_2 *(desno) s velikim smetnjama od stabala (04:30–10:30)*

In this study, the data were processed using the BERNESE v. 5.0, MATLAB v. 7.0 and some complementary tools (URL1, URL2). The computation scheme is shown in Fig. 4. The UNAVCO TEQC Software converts the data from BINARY format into RINEX files (URL3, URL4). In addition, TEQC is employed to obtain Signal to Noise Ratio (SNR) to be used in stochastic models later on. The pole data and CODE orbits are processed in the BERNESE in order to reconstruct the satellite orbits. In processing scheme, we used broadcast orbits for the short baselines because they provide enough accuracy (Teunissen and Kleusberg 1998). Preprocessing of data is performed by the BERNESE software. The functional and stochastic models for the data are also generated via the GPSEST module of the BERNESE, i.e. the double differenced observables, the design matrix, the cofactor matrix and so on.

For the other variance models, a complementary tool is used in order to obtain C/N_0 values. The corresponding programs make a transformation from SNR into C/N_0 values. Finally, the MATLAB software imports all functional and stochastic models, and processes static GPS sessions.

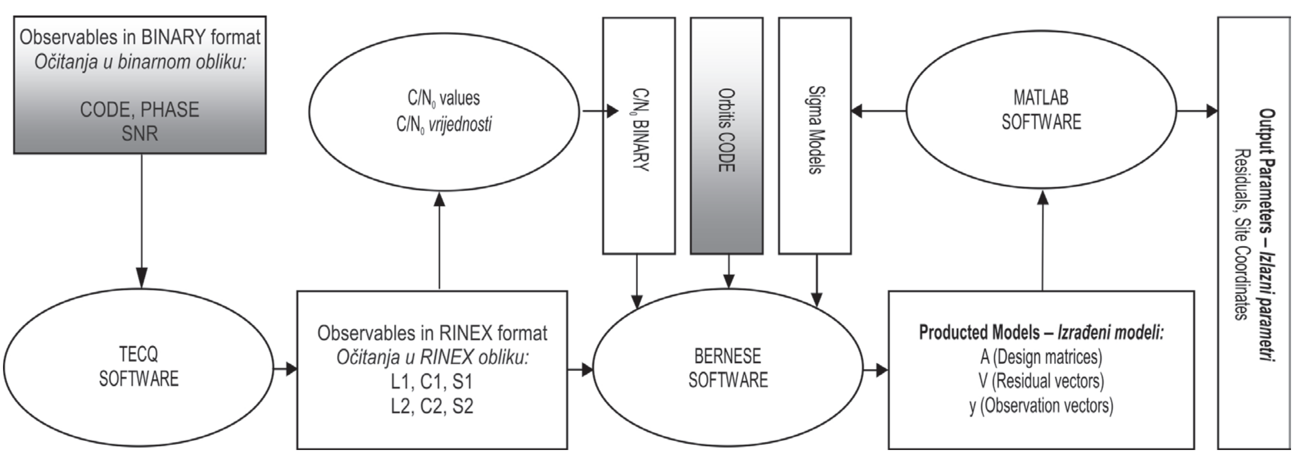

Fig. 4 Computing scheme: Inputs, algorithms, software programs and outputs
Slika 4. *Plan načina izračuna: ulazni podaci, algoritmi, računalni programi i izlazni podaci*

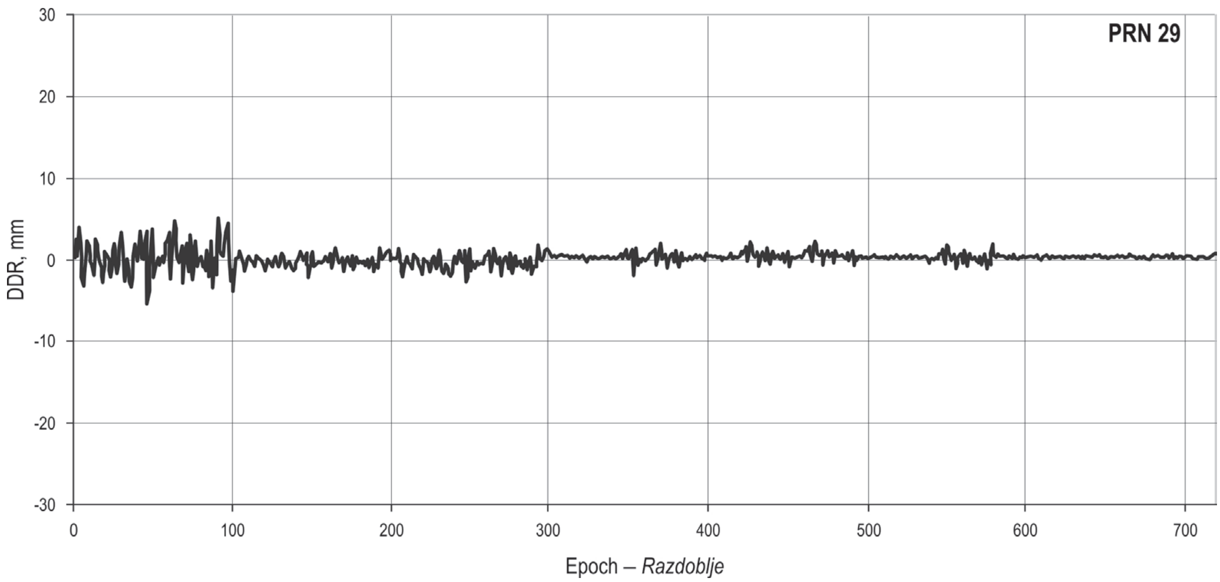

Fig. 5 Double difference residuals of PRN 29 for the baseline T_1–T_2
Slika 5. *Dvostruki diferencijalni ostaci od PRN 29 za osnovnu liniju* T_1–T_2

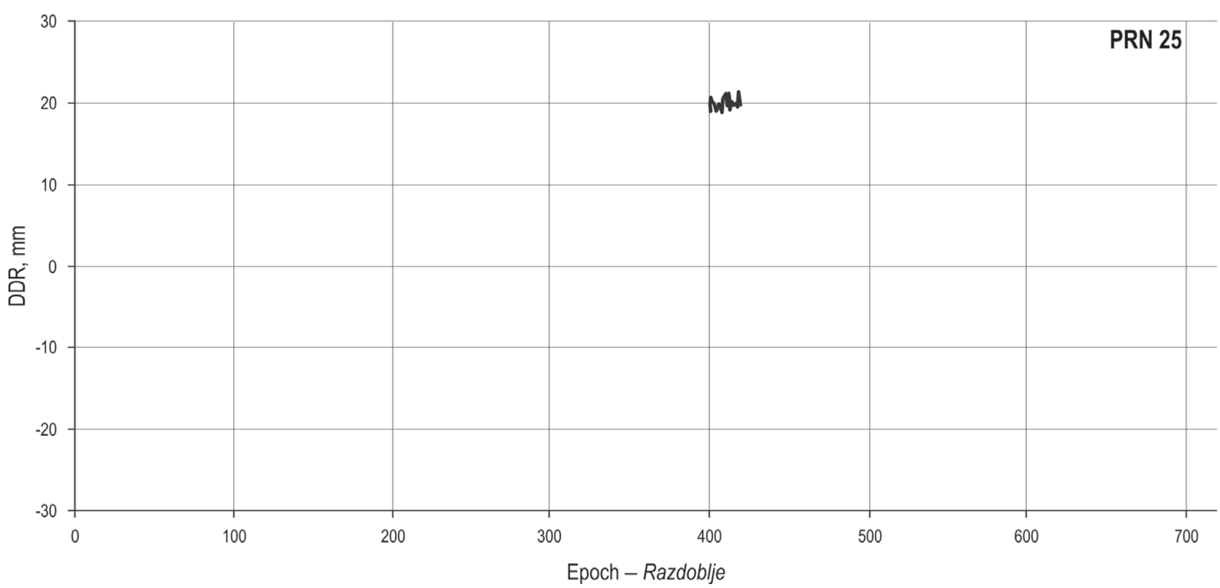

Fig. 6 Double difference residuals of PRN 25 for the baseline T_1–T_2
Slika 6. *Dvostruki diferencijalni ostaci od PRN 25 za osnovnu liniju* T_1–T_2

The ITRF2005 coordinates of the site T_1 were estimated using data from the IGS permanent station ISTA, at a distance of 20 km from the project area, and the observables recorded during the experiment. Then, the coordinates of the site T_1 were taken as known in processing of GPS experiment data including both sites. Atmospheric effects are completely eliminated by double differencing technique because of the short baseline and also low height difference for this study (Teunissen and Kleusberg 1998). Moreover, we used the same type of antenna with same orientation during the experiment in order to remove errors occurring by antenna effect.

Fig. 5 gives the double difference residuals (DDR) of PRN 29 for the baseline T_1 and T_2. These residuals mean very high data quality due to the visibility of PRN 29 only at the high elevation angle; see the sky-

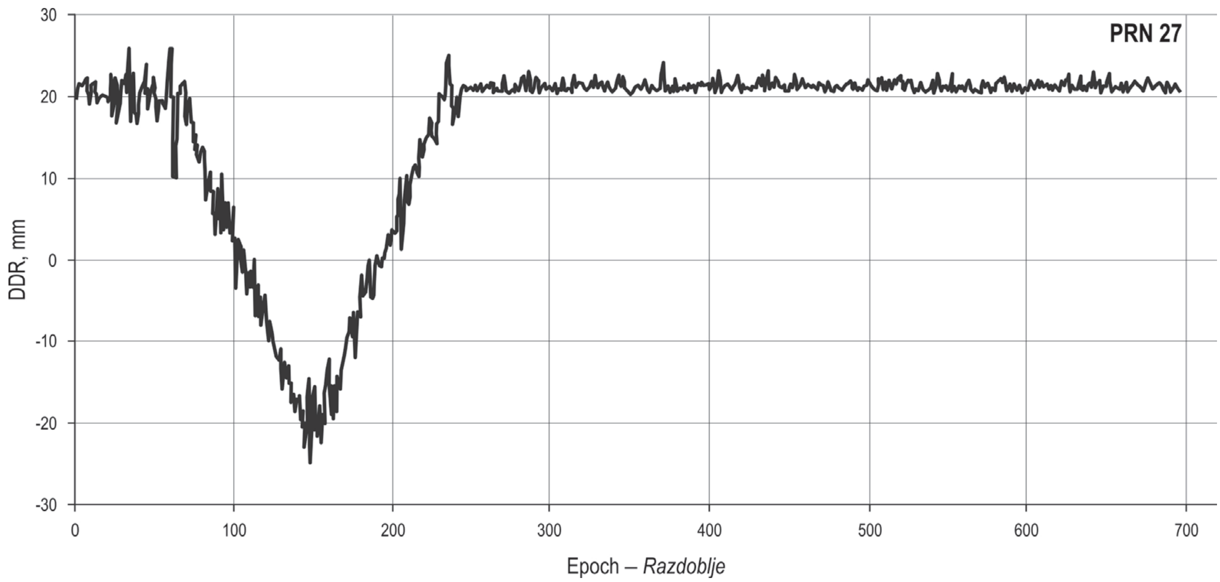

Fig. 7 Double difference residuals of PRN 27 for the baseline T_1–T_2
Slika 7. *Dvostruki diferencijalni ostaci od PRN 27 za osnovnu liniju* T_1–T_2

plot in Fig. 3. As a result, the double differenced observables are not badly affected by systematic effects due to the shading of the forest. Only some scattering effects were recorded at the first 98 epochs of observation. A possible reason can be mutual shading of PRN 18 and PRN 29.

Fig. 6 gives the DDR of PRN 25 for the same baseline. PRN 25 was only visible for a short interval of observation about the 420th epoch, due to heavy shading of trees. Although there is small scattering for the limited data of PRN 25, the average of the DDR values is about 20 mm. We can conclude that the data quality is low because of the forest canopy.

From the DDR of PRN 27 given in Fig. 7, it can be clearly seen that the spoiling effects are caused by the trees. Especially, during the first 60 epochs, non-systematic scatters attract the attention. Moreover, there are significant changes in the DDRs between the 60th and 254th observation epochs. This is because of the heavy distorting effects on the GPS signals. The bias

Table 2 Estimated baseline components and standard deviations for baseline between the sites T_1 and T_2
Tablica 2. *Predviđene osnovne sastavnice i standardne devijacije za osnovicu između mjest* T_1 *i* T_2

#	Stochastic Model *Stohastički model*	Baseline Component – *Osnovna sastavnica* (m)			Standard Deviation – *Standardna devijacija* (mm)		
		North *Sjever*	East *Istok*	Up *Visina*	North *Sjever*	East *Istok*	Up *Visina*
1	Equal variance weighting model	18.7780	6.6375	–1.2915	8.6	13.1	20.3
2	$\sigma_{90}^2 / \cos^2 z$	18.7683	6.6589	–1.2892	7.7	11.0	18.5
3	1 / SNR	18.7795	6.6439	–1.3087	7.3	8.4	10.9
4	sigma-ε	18.7727	6.6515	–1.3147	4.8	5.0	7.8
5	sigma-Δ	18.7717	6.6559	–1.3045	4.5	4.9	6.7
6	$\sin^2 h$ / *SNR*	18.7762	6.6463	–1.3075	6.1	8.8	9.5

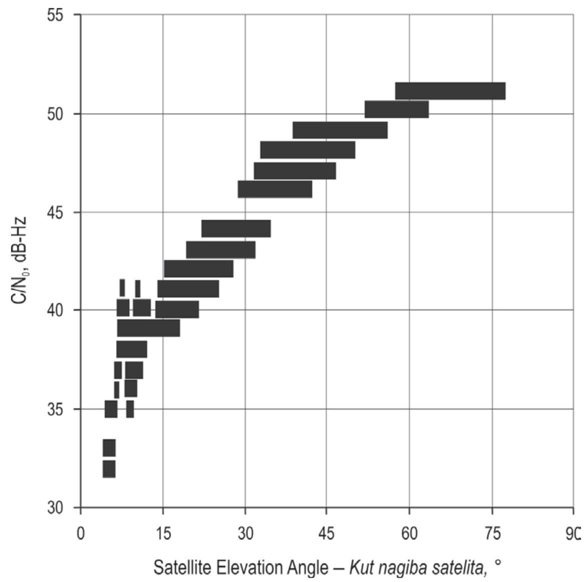

Fig. 8 C/N_0 values of $L1$ signal for the site T_1
Slika 8. *C/N_0 vrijednosti signala* L*1 za mjesto* T_1

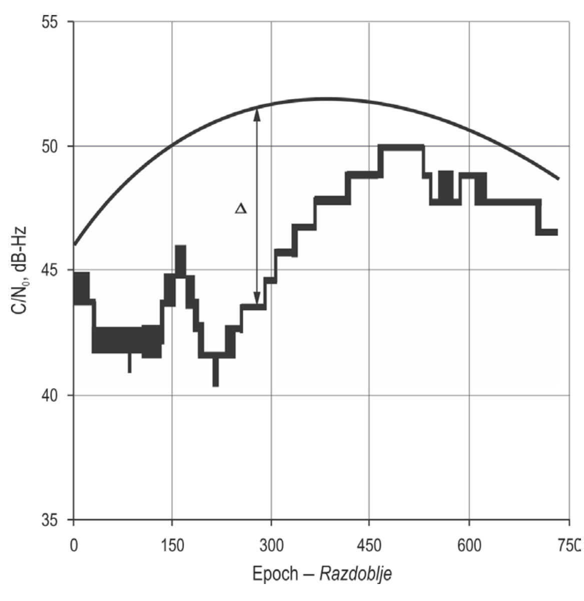

Fig. 9 C/N_0 values of $L1$ signal and template model (^) for the site T_2
Slika 9. *C/N_0 vrijednosti signala* L*1 i predloženi model (^) za mjesto* T_1

values decrease by about 40 mm. After the 254th epoch, the track of PRN 27 shaded by trees and the scatters for the DDR are significantly reduced.

Then we investigated the C/N_0 values of the signals recorded at each site. As mentioned above, C/N_0 values provide key information about the effects of reflection and distortion of the signal. As is known, there are different C/N_0 values for $L1$ and $L2$ phases, which are designed in terms of fixing ambiguity. For the site T_1, the C/N_0 values and corresponding satellite elevation angles are given together in Fig. 8. The data collected at the site T_1 have higher frequencies of C/N_0 because the receiving signals from GPS satellites are less affected by forest canopy compared to the site T_2.

The impact of the tree canopy on the data collected at the site T_2 is clearly seen in Fig. 9. The lower C/N_0 values are the result of the signal distortion at the site T_2 caused by the tree canopy. Thus C/N_0 values of the signal recorded at the GPS receiver were significantly lower. In this study, stochastic models based on C/N_0 values were used in evaluating GPS data, as well as other criteria of signal quality.

In this study, the stochastic modeling of GPS data is used in several approaches. These are equal variance weighting model, satellite elevation angles dependent weighting model, SNR dependent weighting model, sigma-ε model, sigma-Δ model and a proposed model by the function of $\sigma_\phi^2 \cong \sin^2 h / SNR$.

Using these stochastic models, baseline components between the sites T_1 and T_2 were estimated. To do it, the data were processed by geometry-based model derived by the technique of double differencing. To obtain high precision in positioning, reliable estimates of the integer double difference ambiguities are determined in an efficient manner. In this study, we used the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method (Teunissen, 1993). For the baseline estimation of T_1 and T_2, the data is processed using six different stochastic models. Table 2 presents a number of conclusions that have been reached about the effects of stochastic models used for the parameter estimation.

Multipath effects are expected to occur especially at the site T_2. In this regard, multipath fading badly affects the performance of the 1st and 2nd stochastic model in the processing, see Table 2. For these models, standard deviations are up to the cm level. This is why the processing strategies based on the equal variance weighting and low satellite angles have resulted in poor final products. The effects of multipath and signal distortion caused by the forest canopy were not adequately modeled using the first two models, especially with the low satellite angles. Considering SNR values of the signal in stochastic modeling, the 3rd model improved the results, see Table 2. The algorithms called sigma-ε and sigma-Δ have been developed to take C/N_0 values of GPS signal into account in stochastic modeling. When looking all coordinate components and their standard deviations from epoch by epoch processing presented in Table 2, it is clear

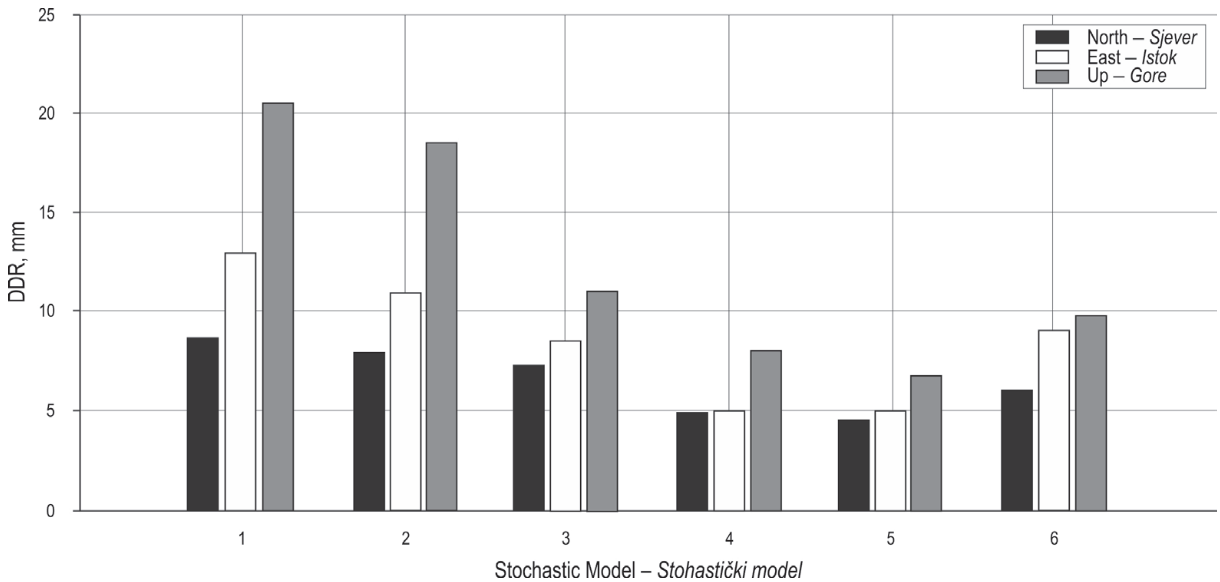

Fig. 10 Standard deviations from epoch by epoch processing of baseline T_1-T_2
Slika 10. *Standardne devijacije obrade podataka za promatrano razdoblje osnovne linije T_1-T_2*

that the sigma-ε and sigma-Δ give optimum solutions. For example, the standard deviations are at the level of 4–5 mm for the components of north and east. This is why the weighting procedure based on a signal quality indicator has successfully reduced the corruptive effects caused by the tree canopy. As is known, the elevation above ground gives worse products according to the components of north and east due to the troposphere, poor satellite geometry and reflection effects.

Finally, we proposed a new method for stochastic modeling by combining the satellite elevation angle h and SNR values. The proposed model of $\sin^2 h$/SNR provides better results compared to the ones from the 1/SNR model.

In addition, the standard deviations in baseline components from the epoch by epoch processing are presented in Fig. 10. As seen from the results, the 3rd, 4th, 5th and 6th models provide better estimates than the others. Moreover, the standard deviations of the 3rd and 6th models are almost identical for the components of North and East. For estimating the baseline T_1–T_2, the elevation was significantly improved using the model of $\sin^2 h$ / SNR. In addition, the standard deviations of sigma-ε and sigma-Δ models are close to each other. The sigma-Δ model provides a positive contribution to the elevation.

We processed GPS data to determine epoch by epoch positions as well as baseline components much more efficiently and accurately. This is why the epoch by epoch analysis becomes more and more important for studying the efficiency of the variance models discussed before. Geodetic time series were used to show the contribution of stochastic modeling by applying some functions of signal quality indicators to estimation of the baseline components between the sites T_1 and T_2. The models of equal variance, sigma-Δ and $\sin^2 h$ / SNR are used as the variance model for the reasons described above. All data are processed for epoch by epoch positioning. We obtained the components of North, East and Up for the baseline T_1–T_2. Then, the averages of baseline components were determined separately. Finally, we computed deviations between the averages and time series. The deviations computed from geodetic time series of epoch by epoch processing are shown in Figs. 11, 12 and 13 for the equal variance, sigma-Δ and $\sin^2 h$ / SNR models, respectively.

The deviations computed from the coordinates confirm that the stochastic models behave differently against the multipath and signal distortion caused by the forest canopy. The main reason is that they are totally based on various signal quality criteria. Fig. 11 indicates that the model of equal variance modeling produce less accurate solutions since it does not take quality criteria into account for stochastic modeling. The coordinate deviations have therefore the biggest scattering values.

Figs. 12 and 13 show that sigma-Δ and $\sin^2 h$ / SNR models yield higher standard deviations for all coor-

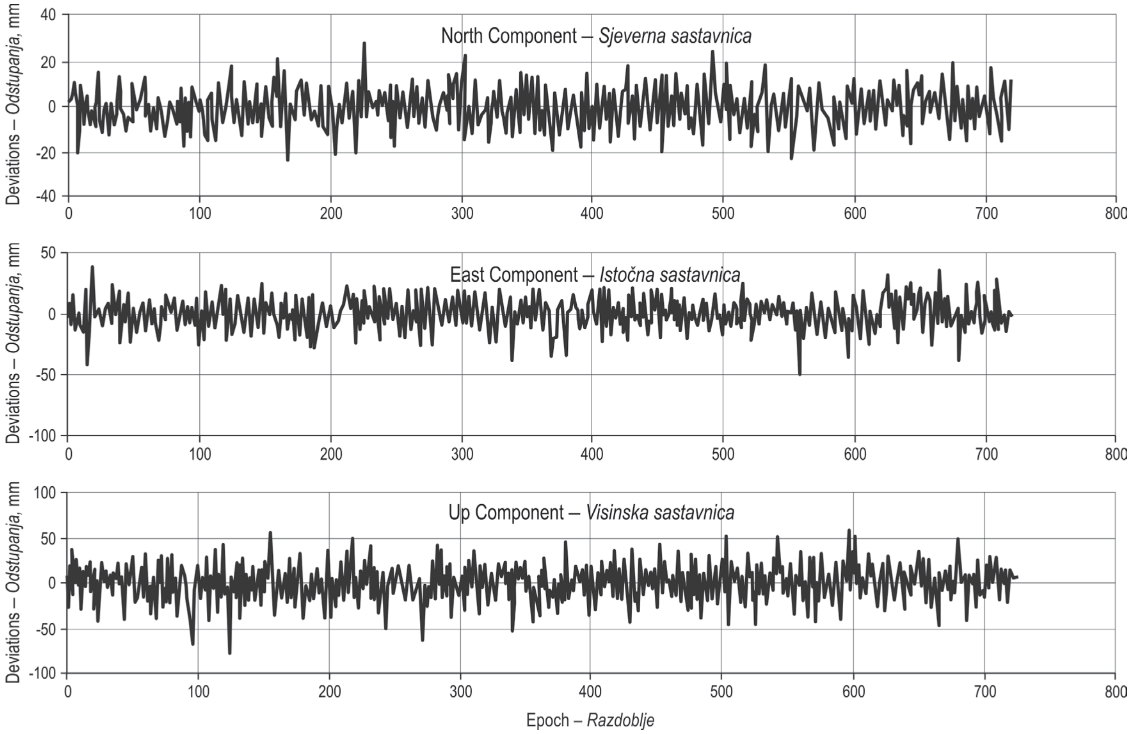

Fig. 11 Deviations of the components from averages for the equal variance modeling
Slika 11. *Odstupanja sastavnicâ od prosjeka za model jednakih varijanci*

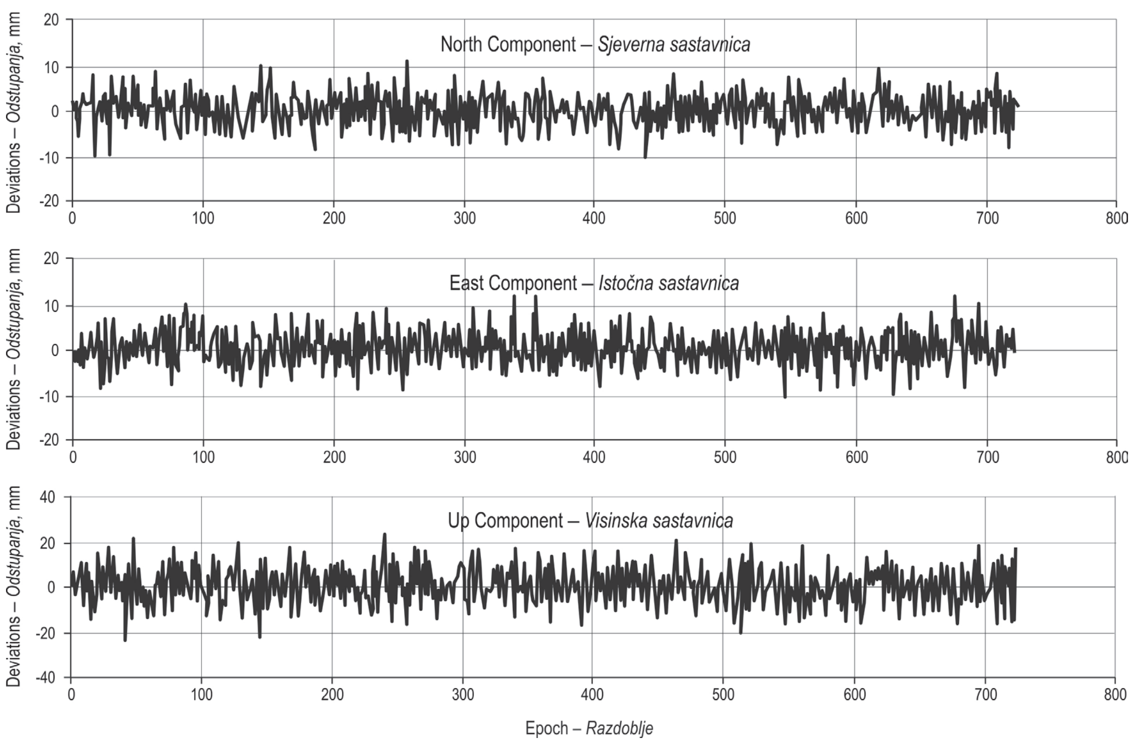

Fig. 12 Deviations of the components from averages for the sigma-Δ modeling
Slika 12. *Odstupanja sastavnicâ od prosjeka za model sigma-Δ*

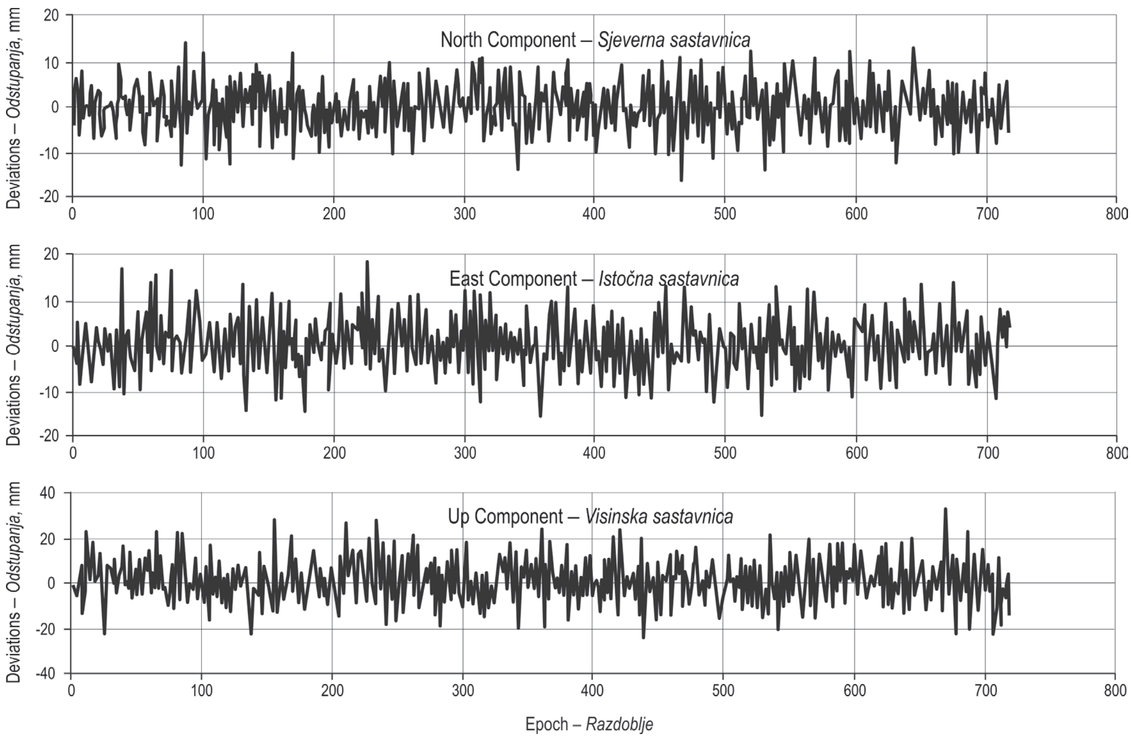

Fig. 13 Deviations of the components from averages for the $\sin^2 h$/SNR modeling
Slika 13. *Odstupanja sastavnicâ od prosjeka za model* $\sin^2$h/*SNR*

dinate components than the model of equal variance modeling. This is why the basic signal quality indicator, like C/N_0, SNR and h, provide a positive contribution to the coordinate component reducing bad effects caused by the forest canopy. So they allow for successful positioning of the data.

5. Conclusions – *Zaključci*

Engineering, topographic, forestry and cadastral applications using data are commonly performed for short baseline, short observing time and also high accuracy demands. However, the site cannot be established to ideal conditions for accurate positioning. In other words, natural or artificial obstacles close to an antenna cannot be avoided. In such a case, the GPS observables will be spoiled by the effects of multipath and signal distortions.

This paper concluded that forest canopy has a great effect on the stochastic modeling for processing the GPS observables. Many disturbing effects can be modeled functionally and/or removed by the technique of double differencing. In addition, the carrier phase observables should be modeled stochastically against effects of multipath and diffraction caused by the forest, using appropriate variance functions that reflect quality characteristics of GPS signal. Thereby, the influence of signal distortion will be reduced on the parameter estimation, i.e. fixing of carrier phase ambiguity and estimation of baseline components. The experiments also showed that the models of sigma-ε and sigma-Δ give optimum solutions for the sites located near the tree canopy. The weighting procedure based on the C/N_0 values can successfully cope with the corruptive effects caused by the tree canopy. In addition, we presented a new method $\sin^2 h$/SNR by combining the satellite elevation angle h and SNR values. According to the results, the proposed model gives better results compared to the ones from the 1/SNR model.

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Sažetak

Svojstva stohastičkoga modeliranja GPS-ovih podataka u šumskim područjima

*NAVSTAR GPS (*Navigation System with Time and Ranging Global Positioning System*) u današnje vrijeme omogućuje utvrđivanje šumskih granica uz pomoć dvostruko diferencijalnoga prijenosnoga prijamnika. U primjeni GPS-a udaljenost je između mjestâ izmjere mala. Kako je željena visoka točnost, podaci opažanja GPS-om obrađivani su rješavanjem dvoznačnih cjelobrojnih ciklusa.*

U šumskom području mogu se pojaviti ograničavajući čimbenici koji uzrokuju negativne utjecaje na signal GPS-a, na primjer guste krošnje stabala ili veliki nagibi terena (Danskin i dr. 2009; Pirti i dr. 2010). U takvu slučaju

navedene prepreke mogu utjecati na slab signal GPS-ovih satelita te prouzročiti teškoće pri izradi krajnjih proizvoda ovoga procesa, odnosno pouzdanih prostornih karata. To je zato što se obrada podataka koje šalje GPS zasniva na metodi najmanjih kvadratnih odstupanja (metoda LSE). Cilj je ovoga rada istražiti stohastičke GPS-ove modele u slučajevima gubitka signala zbog šumskoga okoliša, posebice za kratke udaljenosti. Da bi se to postiglo, uporabljeni su statistički modeli zasnovani na kvalitetnim pokazateljima signala i derivacijama razlike modela koji ukazuju na prijam i prepoznavanje GPS-ova signala.

Utjecaj višestrukih putova (višestazja) i raspršenosti signala može se smanjiti pomoću stohastičkih modela razvijenih pri obradi podataka, pa je točnost proračunskih parametara time povećana. U ovom je istraživanju upotrijebljena varijanca modelâ koji su korišteni u dosadašnjim istraživanjima za utvrđivanje jačine dvostrukih diferencijalnih opažanja. To su model jednakih varijanci (Hartinger i Brunner 1999), modeli zasnovani na kutnom nagibu satelita (Wang i dr. 1998; Collins i Langley 1999), modeli odnosa signala i raspršenosti (Schön i Brunner 2008) i modeli varijanci temeljeni na odnosu prijamnika i snage raspršenosti gustoće signala (Brunner 1999).

Primjenom određenih postupaka proveden je precizno dizajniran pokus koji uzima u obzir iskrivljavanje signala i učinke višestazja zbog sjene drveća. Pokusi su bili obavljeni u regiji Samandira, Istanbul (Turska). Temeljna je linija bila spoj dviju nepomičnih lokacija, T_1 i T_2, a mjerenja su provedena na svakoj od njih pomoću GPS-ovih prijamnika. Cilj je pokusa bio usporediti svojstva stohastičkoga GPS-ova modela pod utjecajem raspršivanja signala. U šumskim je područjima očekivano bilo raspršivanje signala zbog prepreka, kao što su grmlje, grane drveća i sama stabla. Da bi se osigurala višestazna okolina, mjesto T_1 nalazilo se daleko od zapreke koju radi šuma. Podaci sa signalnim iskrivljavanjem bili su skupljani na mjestu T_2 lociranom na granici šume. Iz rasporeda satelita vidljivo je da postoje neke razlike između vidljivosti satelita između mjestâ istraživanja. Postojao je pažljivo dizajniran primjer uključujući pogrešku višestazja. Temeljna je linija bila 20 m duga s visinskom razlikom od 1,970 m. Podaci su bili skupljani na spomenute dvije lokacije tijekom 6 sati između 4:30 i 10:30 sati svakih 30 sekundi. Tako je prikupljeno 720 opažanja tijekom jednoga dana terenskoga rada. Tijekom pokusa korišten je isti tip antene na obje lokacije identične orijentacije da bi se uklonile pogreške uzrokovane eventualnim utjecajem antena.

Podaci su bili obrađivani pomoću programa BERNESE v. 5.0 i drugih prikladnih alata. Za razliku između modelâ korišten je komplementarni alat da bi se dobila C/N_0 vrijednost. Odgovarajući programi preveli su vrijednost SNR-a u C/N_0. Naposljetku, u program MATLAB v. 7.0 uneseni su svi funkcionalni i stohastički modeli te obrađeni podaci nepomičnoga GPS-a. Atmosferski učinci sasvim su uklonjeni dvostruko diferencijalnom tehnikom zbog kratke osnovne linije, ali i niske visinske razlike (Teunissen i Kleusberg 1998).

Dvostruki diferencijalni ostatak (DDR) satelita jasno daje informacije o kakvoći podataka. Na primjer, DDR od PRN 29 ukazuje na vrlo visoku kvalitetu s obzirom na vidljivost PRN 29 samo kod visokoga kuta nagiba satelita. S druge strane, DDR od PRN 25 ima nižu razinu kvalitete podataka zbog sjene koju čini šuma.

Vrijednosti C/N_0 signala zabilježene su na istraživanim lokacijama. Kao što je rečeno, C/N_0 vrijednosti pružaju ključne informacije o utjecajima odraza i iskrivljavanja signala. Rezultati pokazuju da podaci skupljani na mjestu T_1 imaju višu frekvenciju C/N_0 zato što primanje signala GPS-ovih satelita nije bilo pod utjecajem krošanja stabala, kao što je to bio slučaj na mjestu T_2.

Pomoću stohastičkih modela bila je utvrđena osnovna linija između mjesta T_1 i T_2. Da bi se to postiglo, podaci su obrađivani geometrijski zasnovanim modelom dobivenom tehnikom dvostrukoga diferenciranja. Za visoku točnost pozicioniranja učinjene su pouzdane procjene cjelobrojne dvostruke razlike dvoznačnosti. U ovoj je studiji primijenjena metoda najmanjih kvadrata dvoznačnosti dekorelacijske prilagodbe (LAMBDA Teunissen 1993). Podaci sa T_1 i T_2 analizirani su pomoću šest različitih stohastičkih modela. Rezultati upućuju na nekoliko zaključaka koji su doneseni pod utjecajem stohastičkih modela korištenih za procjenu parametara. U ovom je istraživanju primijenjeno stohastičko modeliranje GPS-ovih podataka. To su model jednakih težinskih varijanci, model ovisnosti kuta nagiba satelita, model SNR, sigma-ε model, sigma-Δ model i model predložene funkcije. Po rezultatima je očito da modeli sigma-ε i sigma-Δ daju optimalna rješenja. Na primjer, standardne su devijacije na razini od 4 do 5 mm za sjeveru i istočnu sastavnicu. To je zato što je procedura ponderirane procjene zasnovane na kakvoći signala uspješno smanjila negativne utjecaje krošanja stabala. Naposljetku, predložena je nova metoda stohastičkoga modeliranja kombiniranjem satelitskoga elevacijskoga kuta h i SNR vrijednosti. Predloženi model $\sin^2 h/SNR$ pruža bolje rezultate usporedbom s bilo kojim modelom 1/SNR.

Zaključak je ovoga rada da krošnje stabala imaju velik utjecaj pri stohastičkom modeliranju u procesiranju GPS-ovih podataka. Mnogi ograničavajući čimbenici mogu se funkcionalno oblikovati i/ili izbjeći tehnikom dvostrukoga diferenciranja. Nadalje, očitanja prijenosnika mogu se modelirati stohastički usprkos utjecaju višestazja i rapršivanja signala koji se pojavljuju u šumi primjenom prikladnih funkcija, što se ogleda u kakvoći prijma signala GPS-a. Utjecaj raspršenosti signala može biti smanjen parametarskom procjenom, odnosno podešavanjem dvoznačnosti prijamnika i procjenom temeljnih sastavnica. Eksperimenti su također pokazali da modeli sima-ε i sigma-Δ daju optimalna

rješenja za lokacije ispod zastora krošanja drveća. Postupak ponderiranja zasnovan na vrijednostima C/N_0 može uspješno premostiti negativan utjecaj krošanja stabala. Sukladno tomu, predstavljena je nova metoda sin^2h/SNR kombiniranjem nagiba kuta satelita h i SNR vrijednosti. Predloženi model daje bolje rezultate u usporedbi s modelima 1/SNR.

Ključne riječi: GPS, šuma, učinkovitost, stohastički, ponderiranje

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