Surveying for geophysical exploration, using a single-frequency global navigation satellite system receiver capable of 30 cm horizontal kinematical positioning uncertainty

Uporaba enofrekvenčnega sprejemnika GNSS s 30 cm negotovostjo v kinematičnem načinu dela za terenske geofizikalne preiskave

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Abstract: Some preliminary tests of various types of inexpensive Global positioning system (GPS) receivers were performed in order to assess the utility of the technique to geophysical surveying conditions. A 30 cm basic kinematical accuracy of the fixes was sought. Different sources of positioning errors are analyzed under different, realistic conditions in the field (multipath, satellite obscuration, etc) and the influence of the sampling rate and phase data processing on the relative accuracy for static and kinematical positioning analyzed. It is demonstrated that under favorable conditions a 30 cm relative uncertainty of the kinematical positioning is achievable and that under conditions where a degradation of the GPS fixes occurs during the scans, it is possible to a certain extent, by post-processing of the measurement data, to compensate for the errors and to refine the positioning results.

Izvleček: V članku so predstavljeni začetni preizkusi različnih vrst cenejših sprejemnikov GPS, opravljenih z namenom ugotoviti uporabnost radionavigacijske satelitske tehnike za geofizikalne preiskave. Preizkuse smo začeli z namenom ugotavljanja, če je natančnost določitve položaja 30 cm dosegljiva. Na terenih smo analizirali različne vzroke napak (večpotje, zastrtost satelitov) in vpliv pogostnosti odčitavanja in obdelave faze na relativno natančnost statičnih in kinematičnih preizkusov. Pokazali smo, da je v dobrih pogojih relativna natančnost 30 cm dosegljiva in da je v določenih pogojih možno z naknadno obdelavo odčitkov (kompenzacijo napak) rezultate popraviti.

Scientific paper

Key words: GPS tracking, kinematic measurements, geophysical exploration
Ključne besede: sledenje z GPS, kinematične meritve, geofizikalne raziskave

INTRODUCTION

The idea behind the construction of an inexpensive single frequency GPS system that is simple to use arises from the need for flexibility and effectiveness of geophysical surveys. A sufficient degree of flexibility can only be assured by the complete autonomy of the team in the planning and executing of fieldwork through the positioning of identified anomalous areas. This is the data layer in integral bases, which in archaeo-geophysical prospection represents the basis for the planning of further systematic and detailed geophysical research on identified sites through the application of the multi-method approach (see: MUŠIČ & HORVAT, 2007; MUŠIČ et al., 2008).

GPS equipment (receivers) is relatively cheap, is easily portable, offers real-time fixes and thus makes kinematical positioning possible (WANG et al., 2002). Neither does its application require specialist skills. It makes GPS positioning technology well suited for autonomous geophysical prospection (GAFFNEY, 2003), in particular in large-scale evaluation projects, where total detailed survey is not as important as establishing background levels and acquiring a good understanding of the effects of the geology and pedology. Its efficient application is of crucial importance for surveys in the regions where geodetic fixed points for terestrial position meaurements are not accessible. The nominal accuracy of the GPS positioning can be greatly improved by advanced signal processing and post processing, which means that a 30 cm accuracy of kinematical relative positioning (VAN SICKLE, 2001), deemed sufficient for the autonomous use of the GPS for geophysical prospection, is attainable.

It is characteristic of GPS positioning methods that the accuracy of relative positions fixes is usually considerably better than the accuracy of absolute position fixes. After a comprehensive post-processing efforts a very accurate static positioning by single frequency GPS receiver it is also possible (BERAN, 2007). We have thus attempted to improve the performance of relatively inexpensive GPS receivers by use of reference points of known position in the field. We were concerned solely with horizontal positioning, which is of primary importance, leaving the more difficult problem of vertical positioning to a future project. In the autonomous mode with a single frequency receiver, the position of a reference point is first measured as accurately as possible. A roving receiver then continuously corrects its position outputs by calculating its pseudo range by using single pseudo range differences (DGPS) obtained from a nearby monitoring static GNSS station on a known location, from a network of such stations, or from geostationary satellites known also as SBAS (VAN SICKLE, 2001).

Kinematical sub-meter accuracy as determined by a single receiver was also studied. This requires time triggering and/or event triggering of the logging process, and a synchronization of the process with position output acquisition. In the kinematical acquisition mode, if there is insufficient time for the settlement of the position outputs, the positioning device must still ensure sufficient continuous accuracy. When settlement of geophysical results takes minutes, instead of seconds, semi-kinematical positioning is possible. This requires the surveyor to return to a reference measurement point after a certain period of time.

Positioning and accuracy of positioning by GPS

When at least four satellites are in view of the receiver, it is possible to calculate a three dimensional position from the received data. The computation of position is influenced by the propagation of the signals from the satellites through the atmosphere, and stability of the satellite clocks. Weak satellite signals, coded for higher accuracies, are distinguished from the noise with correlation techniques. In addition to time signals, the GPS receiver also receives

Table 1. Some of the frequently used abbreviations
Tabela 1. Seznam pogosteje uporabljanih kratic

CP	Carrier phase. A phase of a signal that carries the information
DGPS	An augmentation system whereby radionavigation signals are monitored at a known position and the corrections so determined are transmitted to users in the coverage area.
DOP	A dimensionless number that accounts for the contribution of relative satellite geometry to errors in position determination.
GNSS	Generic term for satellite navigation systems. GNSS-1 covers GPS and GLONASS augmented with additional ranging, differential and integrity signals (eg EGNOS, MSAS, WAAS).
GPR	Ground Penetrating Radar
HDOP	The factor by which a two-dimensional fix in a horizontal plane is degraded by geometrical considerations.
RMS	The variability of a measurement such as a single line of position in one dimension; with no bias also an estimate of the standard deviation of the errors.
2DRMS	Twice the root-mean-square of the radial distances from the true position to the observed positions obtained from a number of trials Should contain 95% of observed positions.
TPS	Total positioning station
UERE	User equivalent range error. Any error contributing to the error budget of a stand-alone satellite navigation receiver, expressed as an equivalent error in the range between the user's receiver and satellite. Total UERE is the root sum square of the individual errors.
UTM	Universal Transverse Mercator, a projection whereby a meridian as line of contact between projection plane and Earth surface are used
VDOP	The factor by which the one-dimensional vertical accuracy of a fix is degraded by geometrical considerations.

navigation signals comprising positions of satellites and their operational status. Receivers can operate in an autonomous mode or as rovers. Higher accuracies can normally be achieved by also taking into account the corrections transmitted by a primary positioning receiver station, located at a known position. Single, double and triple difference methods diminish some of the errors generated either by the primary station and/or the rover and the satellites (VAN SICKLE, 2001).

Equipment manufacturers normally state the accuracy of positioning of their products with respect to certain conditions (signal to noise ratio) of reception, and this is considered as the greatest possible absolute accuracy that can be achieved by a device. However, nominal accuracy does not depend solely on the stated conditions, but to a much larger extent on processing and post processing of the satellite data available to the receiver. In satellite positioning it is impossible to completely exclude all the environmental factors that may influence the results. They result in an accuracy interval, which is related to the experimental standard deviation (estimated position error, also known as (d)RMS error) (USM, 1999). Since more variables (dimensions) are observed, the accuracy is noted in each dimension separately. Two dimensional (2DdRMS) is calculated for two variables. The compound error of positioning is the result of all the contributing factors: inaccurate satellite ephemeris data and inaccurate clock corrections sent, changes of propagation delays due to ionosphere density fluctuations with solar or geomagnetic activity and signals reflected from highly conductive surfaces resulting in multipath signals at the receiver position, disturbing the processing of the directly received signals and receiver thermal noise. Processing methods (phase averaging, estimation filter scenarios) of the raw signals also influence the accuracy of the results.

Reducing the influence of the limited receiver view of satellite constellation (dilution of precision, DOP: HDOP – horizontal DOP, VDOP – vertical DOP) during signal processing yields the final positioning error, the so called "user equivalent range error" (UERE) (DE JONG et al., 2001). The precision of a position measurement output (known as the fix) depends both upon the measurement geometry, as represented by the DOP values, and range errors caused by signal strength, ionospheric effects, and multipath errors. The latter depend upon physical surroundings of the measuring point, i.e. to terrain relief, near-by buildings or other highly reflective surfaces (water bodies), or foliage plants (LACHAPELLE at al., 1994). Multipath errors cause systematic variations of GPS fixes, while other sources of errors cause random, chaotic or bias type of variations. Overall uncertainty of positioning of a point is thus calculated as a product of the accuracy (experimental deviation of the measurements) and DOP (VAN SICKLE, 2001).

The positioning accuracy of a moving receiver (rover) is in general not equal to the uncertainty of a stationary fix and should at a certain areas be determined separately. For this purpose a reference trajectory (charted path, on-site measured distances) is established and marked on the measurement site. Deviations of fixes from the reference trajectory are measured while taking the velocity of the rover into account. Uncertainty of kinematical positioning is defined (USM, 1999) as the standard deviation from the mean value or the true value if known. It has been calculated in our work from the distances of fixes against a reference trajectory marked on the ground.

GNSS accuracy required for geophysical purposes

A basic requirement of geophysics is determined as a 30 cm uncertainty in kinematical positioning. A positioning system should satisfy the demands of geophysical fieldwork, such as real-time position output acquisition with the specified accuracy. A special concern in geophysical field work is the accuracy with which the user can return to an already measured position with the same navigation system. In evaluating the positioning results, it should be understood that accurate static positioning does not necessarily lead to accurate kinematical positioning. Obstacles obscuring or reflecting the signals from satellites, and the pattern of positions of obstacles in the field, often change the conditions of reception along the positioning trajectory, causing multipath errors.

When using a low-cost GPS receiver, measurement errors, i.e. multipath and antenna variations in carrier phase, are much more likely to cause problems than with high performance receivers. Kinematical accuracy is determined from the root mean square differences between the position outputs and the nearest point on the reference trajectory. It strongly depends on the velocity of the roving receiver and capabilities of

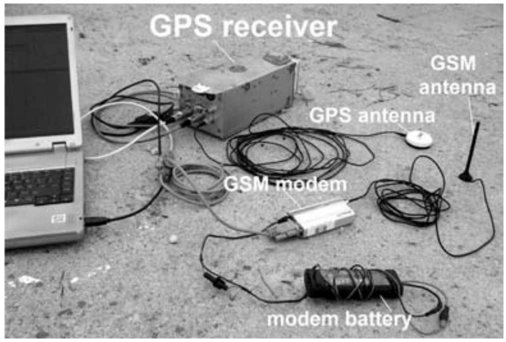


Figure 1. Test GPS equipment
Slika 1. GPS oprema za preizkusne meritve

the GPS software. In our work velocities up to 3 m/s have been considered.

In testing the viability of a GPS based positioning sytem for geophysical fieldwork the following equipment was used (see Figure 1):

- Single frequency GPS receivers: R1 Allstar (12 channels, 1 Hz), R2 Allstar (12 channels, 5 Hz), Novatel , R3 GPSmap C60, Garmin,
- antenna: Aero AT 575-70, (gain: 26 dB), Canadian Marconi Company,
- total station: TPS 1100 (Leica),
- GSM modem: Fastrack M1206B-on, Wavecom,
- logger: laptop computer,
- log software: Starview,
- processing data: Matlab (Mathworks), in case of more than one geodetic point available, a transformation from GPS data to local geodetic system was used.

For the comparison reasons two more GPS receivers which were not involved in the fieldwork are also taken into consideration: R4 FlexPak-V1, NovaTel and R5 SR 20, Leica Geosystems. The lowest RMS can be achieved by the R5 (0.3 m, after CP post-

Table 2. Test sites with brief descriptions
Tabela 2. Oznake preizkusnih terenov s kratkimi opisi

Site label	Description
S1	sports field, predefined geometry
S2	archaeological site Veselov Cvinger, near Stična
S3	a car park in front of a building in Ankaran
S4	the surroundings of the geodetic point at Malija
S5	an archaeological site Dolge njive, near Vrhnika
S6	an archaeological site Tanagra, Greece

processing) whereas the highest 2DRMS is get by the commercial R3 (static 2.5 m). Under good receiving conditions the experimentally observed RMS values might become very similar, however in atmosphere changing conditions for example a benefits of R5 would result in lower RMS as of R3. Comparison of the prices to the price of R3 as the etalon price (1 EP) gives the following sequence: R2 as already obsolete device (1.9 EP), R4 (5 EP) and R5 (from 10 EP up to 13 EP).

RESULTS AND DISCUSSION

Test sites and equipment types

In order to test the positioning capabilities and accuracy of a GPS system, several types of equipment were tested at 5 different and well defined testing areas: the Adria sports field at Ankaran (site S1), an archaeological site at Veselov Cvinger, near Stična (site S2), a car park in front of a building in Ankaran (site S3), the surroundings of the geodetic point at Malija (site S4), and an archaeological site of Nauportus at Dolge njive, near Vrhnika (site S5) (see: MUŠIČ & HORVAT, 2007; MUŠIČ et al. 2008). The third archaeological site is Tanagra (Greece) (site S6) (see: BINTLIFF et al., 2000, 2002; BILC, 2003; MUŠIČ et al., 2004). The different locations have considerably different topological and signal propagation characteristics: Site S1 (a sports field) has simple geometry and is topologically well defined, site S2 is an exposed location on a ridge, signals at site S3 are especially prone to multipath errors and signal losses due to obscuration, site S4 (geodetic reference point of the 1st degree) has a well defined position and low multipath variations, however it is exposed to interference and other errors, and site S5 is an archaeological site close to a river.

A summary of the static positioning measurement results on the sites is given in Table 3. It can be seen that uncertainty of fixes is decreased by the absence of multipath errors as well as open sky, and by the use of DGPS. Uncertainty was calculated for three locations: Site S2 where moderate multipath error was observed (point No. 1, was used further as a reference point at this site, as it is also a geodetic point), a location at site S3 with obvious multipath errors, and a location at site S4, again with moderate multipath errors and additional sources of error, whose effects can only partially be resolved by data analysis. Variations of HDOP strongly influence the uncertainty. Average HDOP of experiment No. 2 was 1.24 while for experiment No. 3

Table 3. Statistical parameters of static measurements
Tabela 3. Statistične značilnosti statičnega določanja položaja

Exp. No.	Site	Receiver	Mode	No. of fixes	Absolute static uncertainty (m)
1	S2	R2	DGPS	7201	1.2
2	S3	R2	GPS	438855	4.5
3	S3	R2	GPS	1921488	3.4
4	S4	R3	GPS	3903	2.3
5	S4	R2	GPS	12148	2.1
6	S4	R2	DGPS	7739	1.7

it was 1.12. In the absence of loss of data due to cycle slips, the numbers of fixes is simply the product of measurement time (in seconds), and the data acquisition rate (number of fixes per second, 1 for R3 and 5 for R2).

Static positioning measurements

The measurements of static positioning at sites S2 and S3 are presented in Figure 2. Measurements were performed continuously for 5 consecutive days at S3 (Figure 2.a). Accuracy was determined as dRMS and was 2.96 m. The details of transformed angle/length ratio resolution are shown around a geodetic point, chosen as (0,0) position. The repeatability of observations at S2 with receiver R2 (DGPS) are shown in Figure 2.b. Measurements were performed over two days, separated by 42 days. Repeatability of positioning at points No. 2, No. 3 and No. 4 from the reference point (No. 1, with relative position 0 m) is shown. The relative experimental standard deviation of distances for points No. 2, No. 3, and No. 4 are 23 cm, 30 cm and 29 cm respectively, with a standard deviation of the reference point from its true position of 32 cm. It should be pointed out, that the large excursions of data in Figure 2.b do not represent settling times of the measurements, but real excursions of the instrument fixes from the points under consideration, caused by the movement of the experimenter from one point to another. The largest source of the uncertainties in this case are not the multipath errors, but the unfavourable position of the sites chosen (S2, S3), which have a reduced view of the satellites, not insuring optimal number of satellites in view. Data in Figure 2.b demonstrate that fixes, relative to a reference point, under unfavourable measuring conditions (obscuration of satellites) do not satisfy the accuracy requirements. However, even under such conditions the average accuracy of fixes is 8 cm from the requirement. These results cannot be directly compared to uncertainties presented in Table 3, as the relation between accuracy and uncertainty involves the variable HDOP.

Assesment of kinematic uncertainty

The results of assessment of kinematical uncertainty, relative to reference lines of 30.00 m and 41.30 m lengths, marked on the ground, are presented in Figure 3 and Figure 4 respectively. Measurements were performed by two receivers R1 and R2 on three different sites S1, S4 and S6. It can be observed from Figure 3 that in all cases

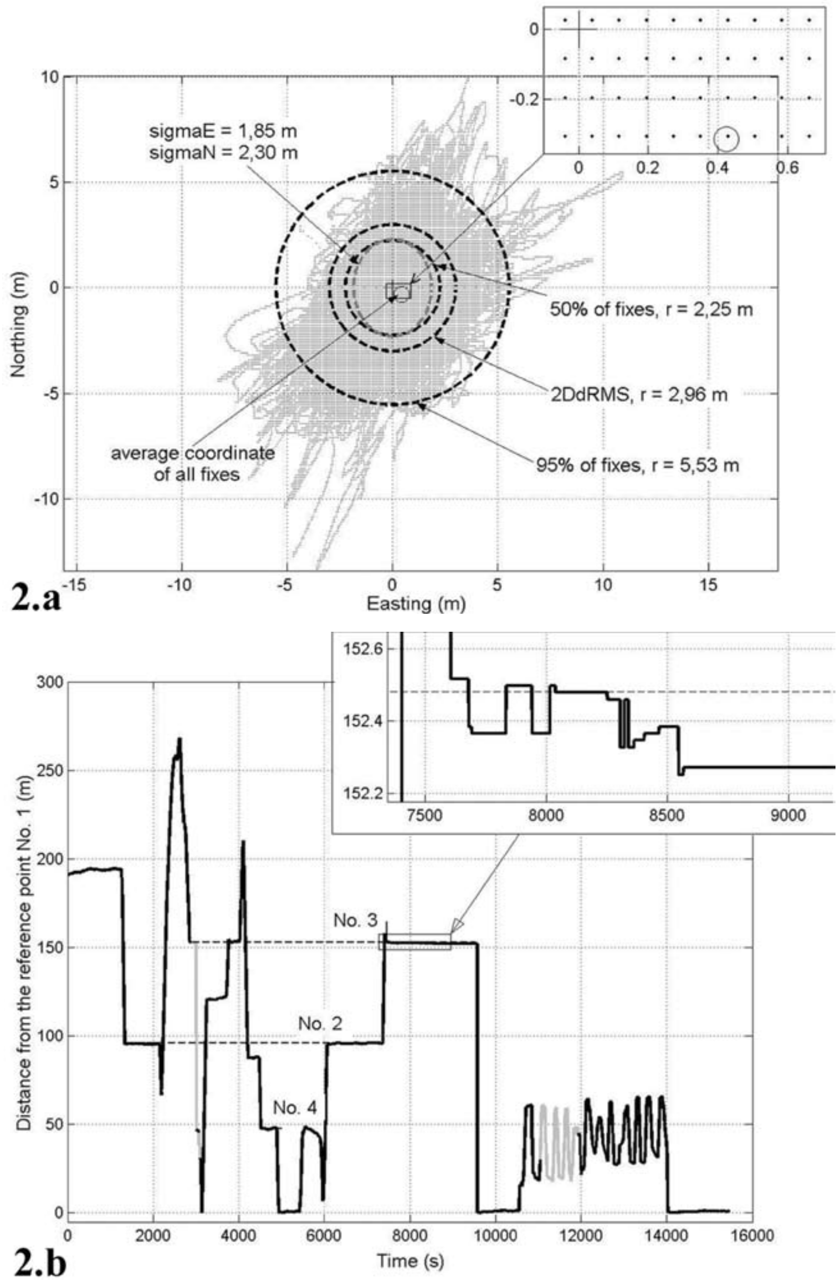


Figure 2. Results of static positioning at S3, centered with geodetic procedure (2.a) and repeatability of a distance from the reference point during fieldwork at S2 (2.b)

Slika 2. Rezultati določanja položaja točke na terenu S3, osredinjeni z geodetsko izmero (2.a) in ponovljivosti določanja razdalje do referenčne točke na terenu S2 (2.b)

Table 4. Statistical parameters of the 'line following' kinematical measurements on sites S1, S4 and on archaeological site S6

Tabela 4. Statistične značilnosti kinematičnih preizkusov sledenja ravni črti na terenih S1, S4 in arheološkem najdišču S6

Site	Conditions	Receiver	No. of fixes	No. of walks	Relative kinematical uncertainty (cm)
S1	Multipath	R1	3475	101	- 6 ± 317
S1	Multipath	R2	24551	132	5 ± 104
S4	higher HDOP	R2	10790	50	1 ± 41
S4	lower HDOP	R2	10755	50	1 ± 26
S4	moderate HDOP, DGPS	R2	6867	36	2 ± 29
S6	moderate HDOP	R2	6919	18	-15 ± 41

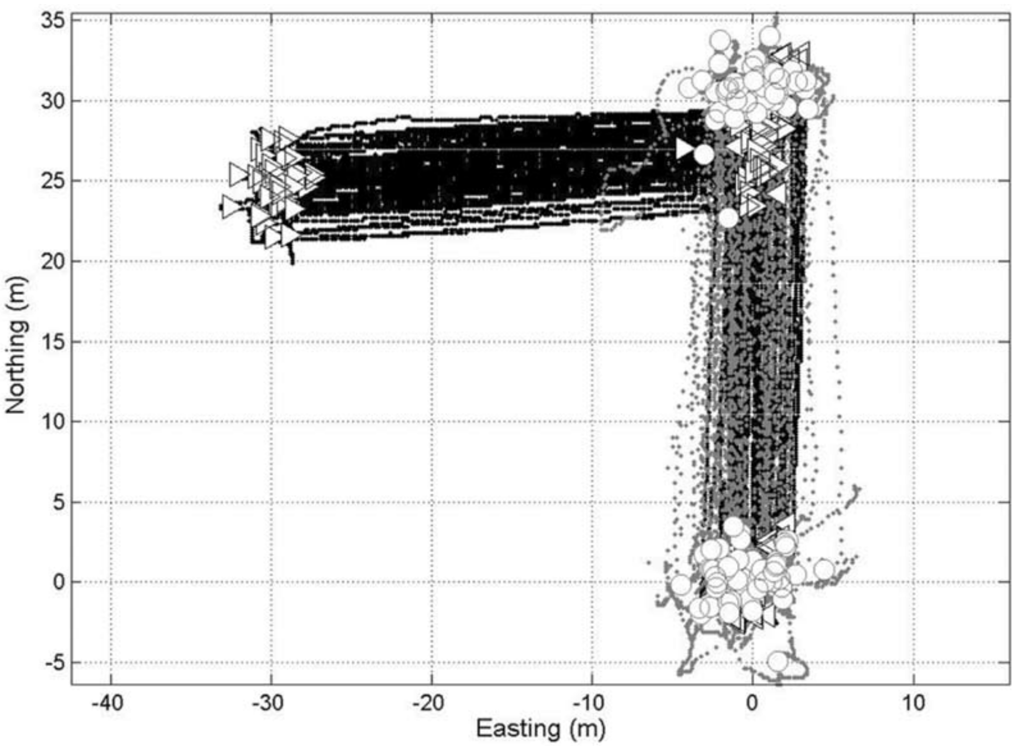


Figure 3. Fixes obtained by walking along a 30.0 m line on Site 1 with two receivers (R1 grey, R2 black). Extreme positions after two minutes of measurements are marked with circles (R1) and triangles (R2).

Slika 3. Sledi hoje ob ravni črti, dolgi 30,0 m na terenu S1 z dvema različnima sprejemnikoma (R1 siva, R2 črna). Srednje vrednosti odčitkov, zabeleženih ob dvominutnih stanjih na skrajnih točkah so označene s krogi (R1) in trikotniki (R2).

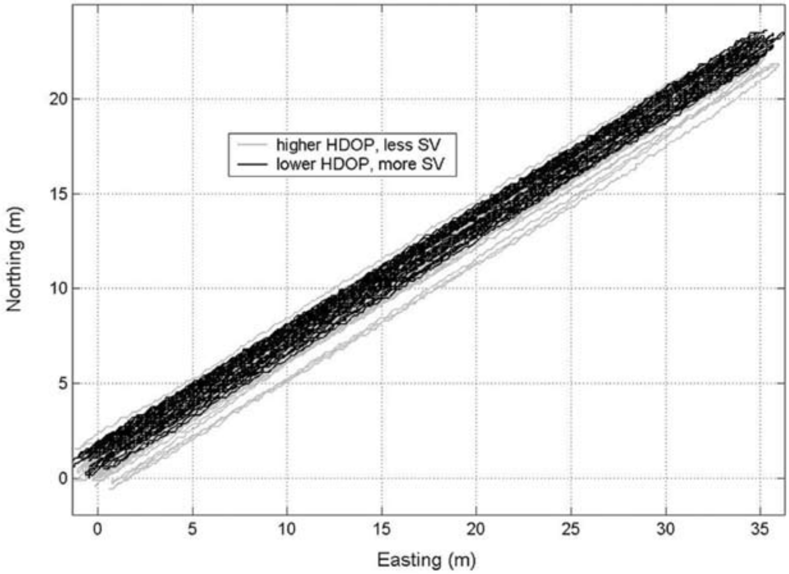


Figure 4. Fixes obtained by walking along a 41.3 m line on Site 4 with receiver R2 in two experiments, each under different conditions. The receiver was held on for up to 20 seconds only in extreme positions.
Slika 4. Zabeleženi dve sledi hoje z istim sprejemnikom (R2) ob ravni črti, dolgi 41,3 m na terenu S4 v različnih pogojih opazovanja. Stanja na skrajnih točkah niso presegala 20 s.

the worst case absolute accuracy of the following of the lines by receiver R2 is 2.50 m. However, the measured trajectories are highly parallel to the reference lines, resulting in a up to 40 cm relative accuracy in positioning, taking one of the end points of the lines as the reference point. This experiment demonstrates the considerable difference between the absolute and the relative positioning accuracies and indicates the necessity of taking the reference point positions into account in determining the fixes in the field. Obviously, in this way it is also possible to correct and improve the absolute accuracy of the positioning. The overall accuracy is then determined by the relative accuracy of the kinematical data and the absolute accuracies of the reference point fixes. As the distribution of uncertainty of fixes also incorporates the highly variable HDOP values, the width of the distribution does not reflect the accuracy that can be obtained under more favourable conditions. Even within low multipath conditions, as on site S4, changes of HDOP exert considerable influence on accuracy (Figure 4). A distribution of fixes for the determination of the uncertainty of all kinematical results from site S4 is shown on the Figure 5. The improvement of accuracy due to the smaller multipath errors is negligible with the DGPS technique. The numerical values of statistical parameters are given in Table 4.

Test on followed trajectories

The persistence of straightness and shape of the followed trajectory was tested on Site

S1 with instruments R1 and R2. Results were collected without use of the DGPS. In the absence of known geodetic points a direct transformation from degrees into meters was performed, the two orthogonal coefficients being obtained from a comparison of the physical distance of the 30.0 m line and the mean distance of position outputs on the line edges. The results are presented in Figure 6. Figure 6.a demonstrates the effects of stopping at each of the 6 reference points for two minutes. The excursions of fixes are due to changing measuring conditions. A continuous scan (without stopping) shows a qualitatively different result (Figure 6.b: the straightness of parallel lines of the trajectory is demonstrated, with a shift error occurring only during the two minutes stop between scans.

A test somewhat similar to the one described above, using R2 attached to an instrument with a different function, but in realistic field conditions (Site S2), is shown in Figure 7. The surveyor followed straight lines, parallel to each other and displaced by 50 cm, to scan the whole area of the field. As the GPS antenna was not mounted in the middle of the carrier instrument (see Figure 8, equidistance between lines was not expected.

Figure 9 shows the results of a kinematical GPS scan at the archeological site S5, compared to data obtained from a TPS scan. The GPS antenna and geodetic prism (fixed as on Figure 8) both simultaneously traveled the same route. The GPS results were transformed into the D48 system. A

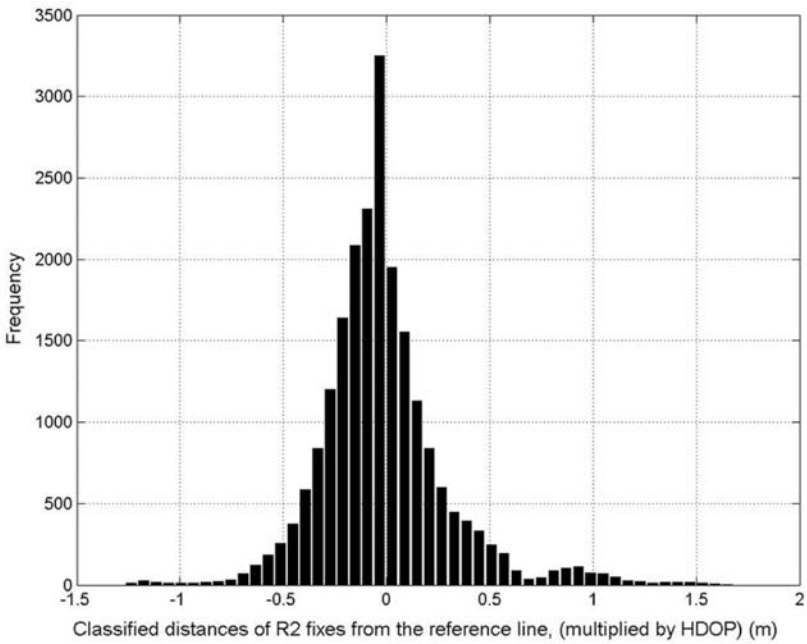
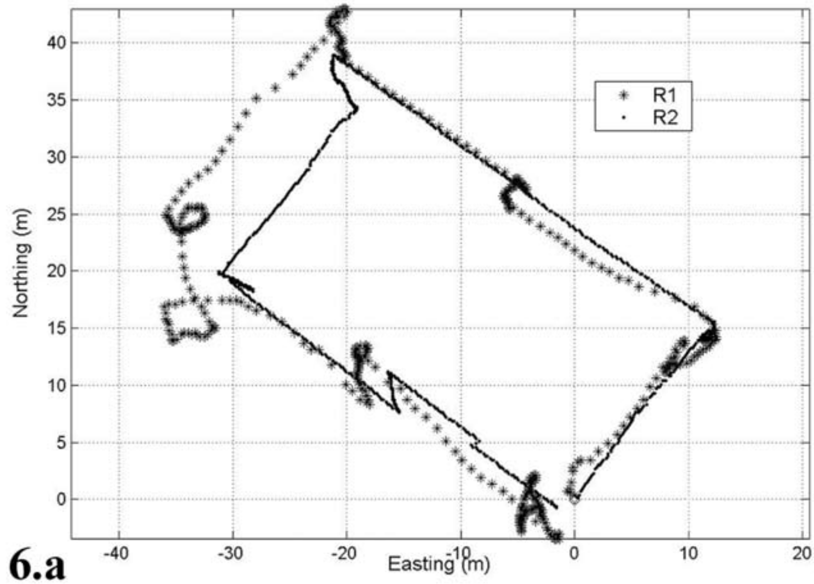


Figure 5. A distribution of fixes for the determination of the uncertainty of all kinematical results from site S4.

Slika 5. Porazdelitev odčitkov za določitev negotovosti vseh kinematičnih preizkusov na terenu S4.



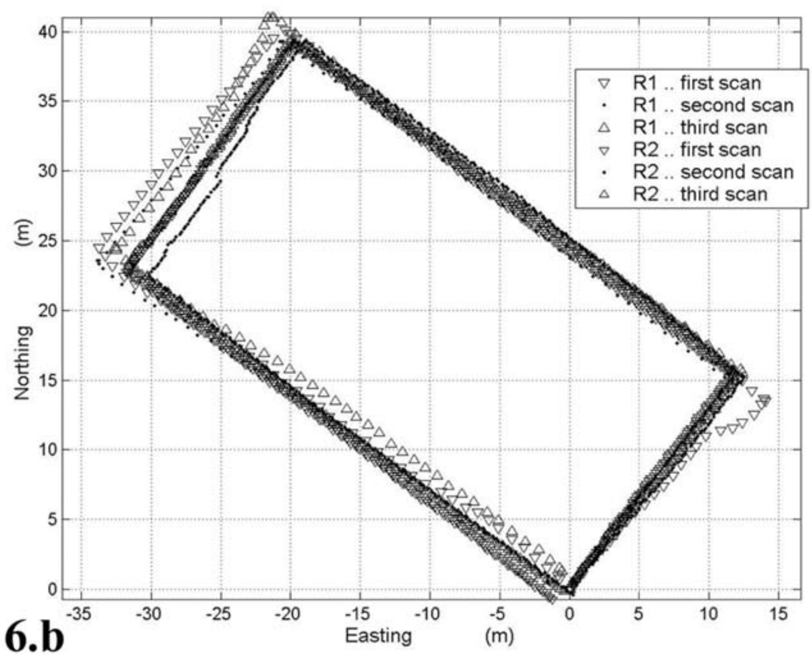


Figure 6. The starting point of scans is at coordinates (0, 0). The transformation parameters are the same for figures 6.a and 6.b. Scan around the sports field with two minute stops at reference points (6.a) and scan without stops (6.b).
Slika 6. Začetna točka sledi je premaknjena v (0,0). Transformacijski parametri so enaki na slikah 6.a in 6.b. Sled hoje okoli športnega igrišča z dvominutnimi postanki na ogliščih (6.a) in sledi, dobljene s hojo brez postankov (6.b).

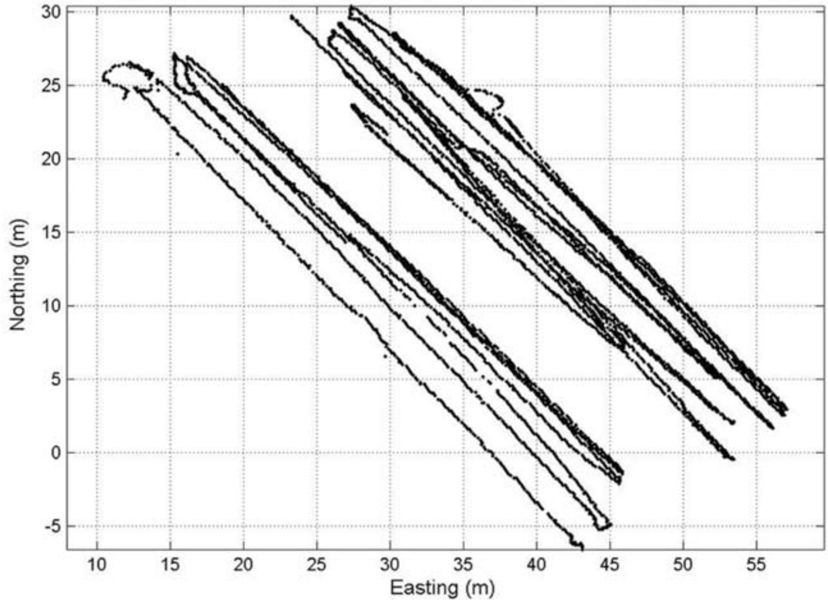


Figure 7. Following profiles with R2 in DGPS mode
Slika 7. Sledenje profilom z R2 v načinu DGPS

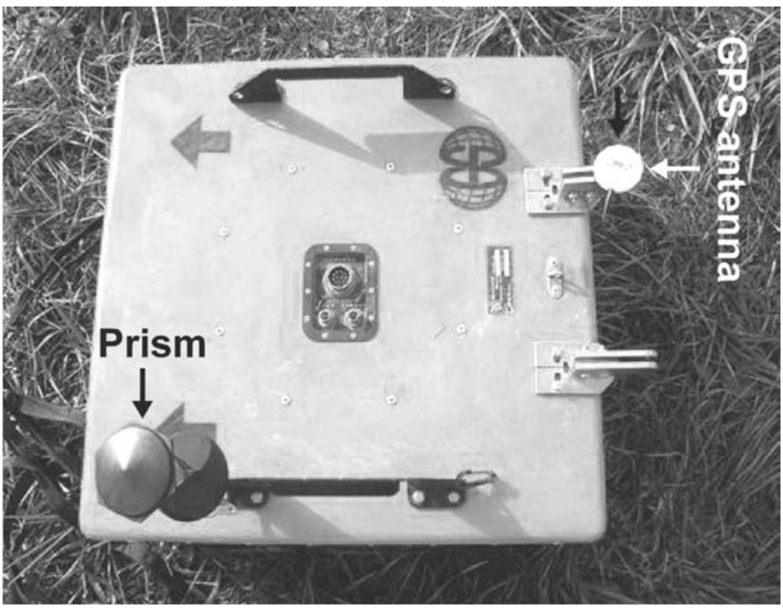


Figure 8. Positions of GPS antenna and geodetic prism for the use of TPS on the top of a 200 MHz GPR antenna
Slika 8. Namestitev antene GPS in geodetske prizme za uporabo TPS na pokrovu 200 MHz antene GPR

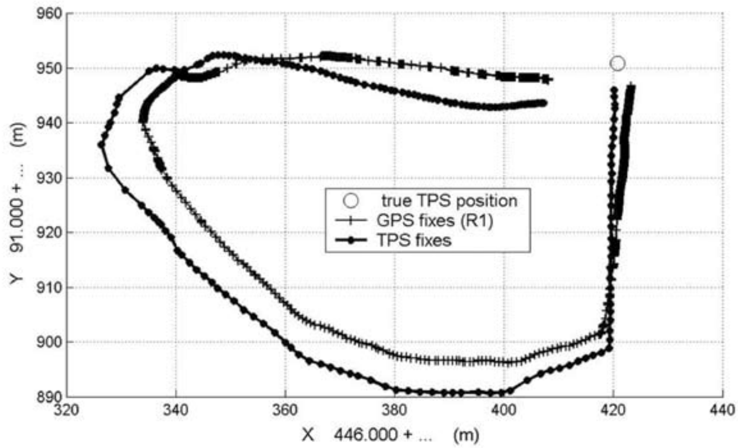


Figure 9. Comparison of R1 and TPS fixes, taken simultaneously on the same route

Slika 9. Primerjava sledi drsenja, zabeleženih sočasno s sprejemnikom R1 in TPS

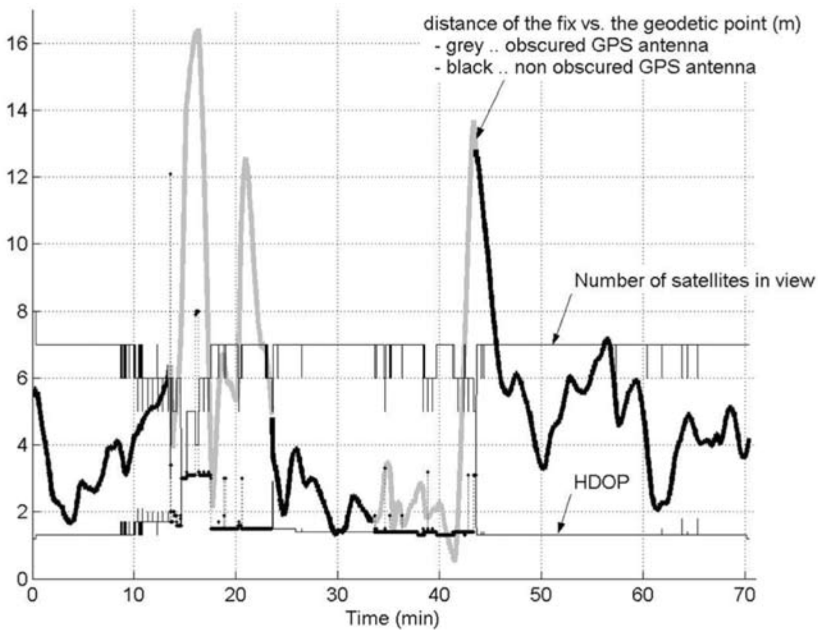


Figure 10. Static positioning with obscured antenna: how a distance from geodetic point apparently changes over time. According to the obscuring signals of less satellites are capable to reach the GPS antenna and thus HDOP and consequently the deviations arise.

Slika 10. Določanje položaja z zastrto anteno GPS: razdalja do geodetske točke se je sčasoma navidez spreminjala. Zastrto anteno dosežejo signali manjšega števila satelitov, zaradi česar se HDOP in posledično odstopanje od geodetske točke povečata.

significant displacement of the GPS fixes (up to 8 m) from the TPS trace can be observed. Also the GPS scan data do not return to the starting point after the completion of the scan. The data demonstrate that careful analysis of the GPS data is required in real situations when trajectories across the field are of a general shape (not straight lines or other favourable shapes).

Static positioning test with obscured antenna

As the obscuration of one or several satellites during measurements severely degrades the accuracy of the fixes, we attempted to quantify this by deliberately obscuring the satellites for certain time periods. To evaluate the obscuration effects on static accuracy of R2, the antenna was covered by a metal, dual-shell lid. The results are shown in Figure 10: the solid bold line represents the measured distance from a geodetic point under conditions of obscuration. It can be observed that during the obscuration (at times 13 min, 23 min, 33 min, and 43 min) the accuracy of positioning is decreased by an order of magnitude, but obscuration does not cause complete loss of data. However, as expected, obscuration in the multipath conditions leads to unpredictable behavior of the positioning system and should be avoided if possible.

The applicability of GPS system for GPR survey

The applicability of the GPS system in the GPR survey of Antique cities was tested on the archaeological site at Tanagra (Greece) (see: Bintliff et al., 2000, 2002; Bilc, 2003; Mušič et al., 2004) within the framework of geophysical survey in the Boeotia Project (http://www.nia.gr/Pharos13.htm). The starting-point of the test measurements was the recognition of archaeological features defined on aerial photographs and magnetograms by directing GPR profiles in the required direction. This information is important for the definition of the priorities of systematic geophysical survey with application of multi-method approach (see: Mušič & Horvat, 2007). GPR profiles in selected directions are a rapid means to provide data on the depth and degree of preservation of architectural remains to complement the results of geophysical mapping with resistivity and magnetic methods. Two profiles with control points in UTM projection (see Bilc, 2003) were chosen for the test measurements (Figure 11 and 12).

The trial survey in GPR profiles was undertaken using a 200 MHz antenna. This made it possible for us to register both information on the archaeological architectural remains found at a shallow depth below the surface, and changes in the basic geology at a somewhat greater depth. This 200 MHZ GPR antenna is therefore suitable for survey, because of the appropriate ratio between resolution and attainable depth. It also has a solid construction, which guarantees sufficient antenna mobility during measurement, as well as its stability in the direction of movement. This greatly reduces background noise. Prior to the identification and classification of the echoes in categories, the GPR profiles were processed according to the following procedure (for explanation see e.g.: Conyers at al. 1997): *Background removal* (Removal of horizontal banding), *Range gain* (Recovery of lower amplitude information), *IIR – Filter* (Smoothing operators for noise

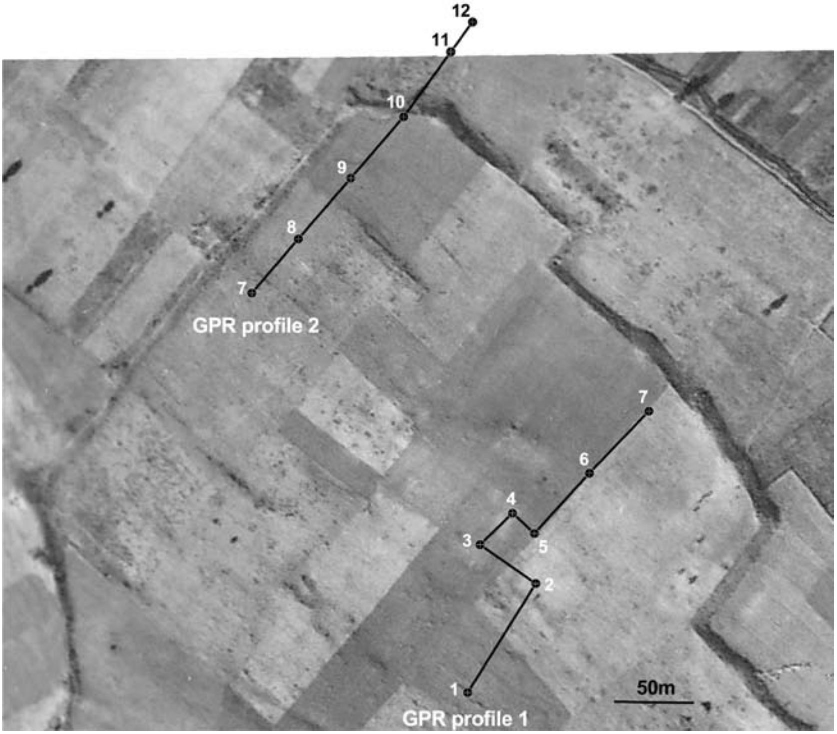


Figure 11. The northern part of Tanagra on a vertical aerial photograph (Royal Air Force, 26. Oct. 1943. Courtesy of British School in Athens) with the selected GPR profiles 1 and 2 and the control points in the direction of the profiles in the UTM system (1-12)

Slika 11. Severni del Tanagre na vertikalnem aeroposnetku (Royal Air Force, 26. Oct. 1943, z dovoljenjem britanske šole v Atenah) z izbranima GPR profiloma 1 in 2 in kontrolnimi točkami v smeri profilov v UTM sistemu (1-12)

reduction), *Migration* (Removing diffractions and correcting dipping reflectors to their true position), *Surface normalisation* (Correcting topographic position of reflectors on variable surface morphology).

It is necessary to select an appropriate standard for the marking of archaeologically significant echoes, when the single 2D GPR profiles are interpreted. Only the most typical GPR echoes that are characteristic for archaeological architectural remains are marked on the radargram (Figure 13.a). Control over the interpreted echoes and the ease of understanding of the results is established by classification of the echoes in selected, typologically defined categories. The most suitable for this purpose is the division of the echoes into 14 classes, which are precisely defined by B. BEVAN (1996, fig. B116) (Figures 13.a and 14).

The greatest deviation in the GPS measurement from the direction of the movement of the GPR antenna was determined at points 3, 4 and 5 (Figure 14), which was a result of a a sharp change in the direction of movement of the antenna at an angle to an approximate right angle. The deviations are in accordance with the established aims of the research on the level areas and correspond to the deviations, which were determined in GPR profile 2, where there was no greater change in the direction of movement. Figures 11, 14 and 15 indicate that at each change in direction the GPS measurements »returned to the right« place, but some time nevertheless passes before this happens. If the direction of movement changes too frequently and time is not taken for the GPS readings to settle down, then these errors accumulate. The deviation in the direction of movement in fourth loop in trial GPR profile 1 already amounted to almost 2 m (Figures 14.b and 15). The GPS fixes »settled down« according to the reference lines after circa 35 meters of linear movement (see the segment from point No. 3 to No. 2).

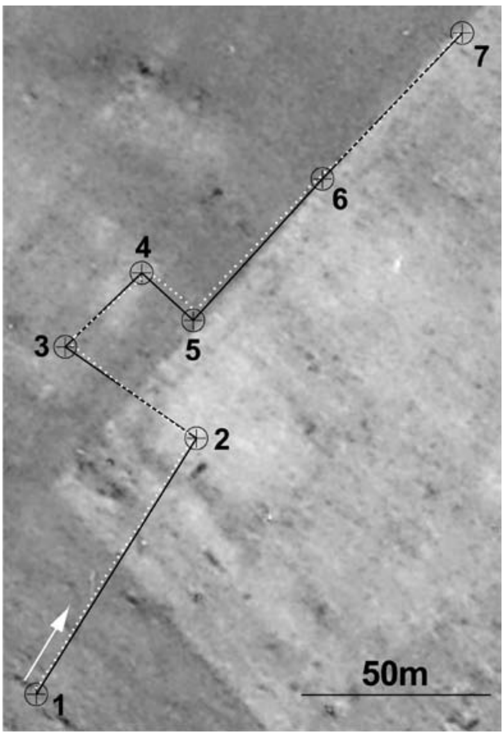


Figure 12. The GPS readings at a distance of 2 m are indicated by the white points in the direction of GPR profile 1

Slika 12. Z belimi točkami v smeri GPR profila 1 so prikazani GPS v razdalji 2 m

GPR profile 2 runs in a straight line, crosses the town wall and descends via a steep slope on the exterior of the wall at a height of 113 metres above sea level (from 122 m down to 109 m). A deviation (in the horizontal plane: average of fixes including HDOP according to the reference lines between reference points is 44 cm while 95 % of fixes lie closer than or equal to 55 cm to the reference lines) from the actual direction of movement in the particular case of linear movement due to the rapid change in height (z) was determined in this profile.

On the basis of these results it is possible to conclude that the precision of this GPS system only meets our requirements completely in the specific case of linear movement. Effective use requires the selection of a direction of movement with the least possible number of changes in direction at a greater angle. This problem can be solved by planning the prospection in long, relatively straight traverses.

The estimation of the accuracy of the location of the GPR echoes by the GPS system was also correlated in relation to the location of the magnetic anomalies, mapped by the Geometrics G-858 magnetometer (see Mušič et al., 2004), which had been georeferenced by TS measurements, using a

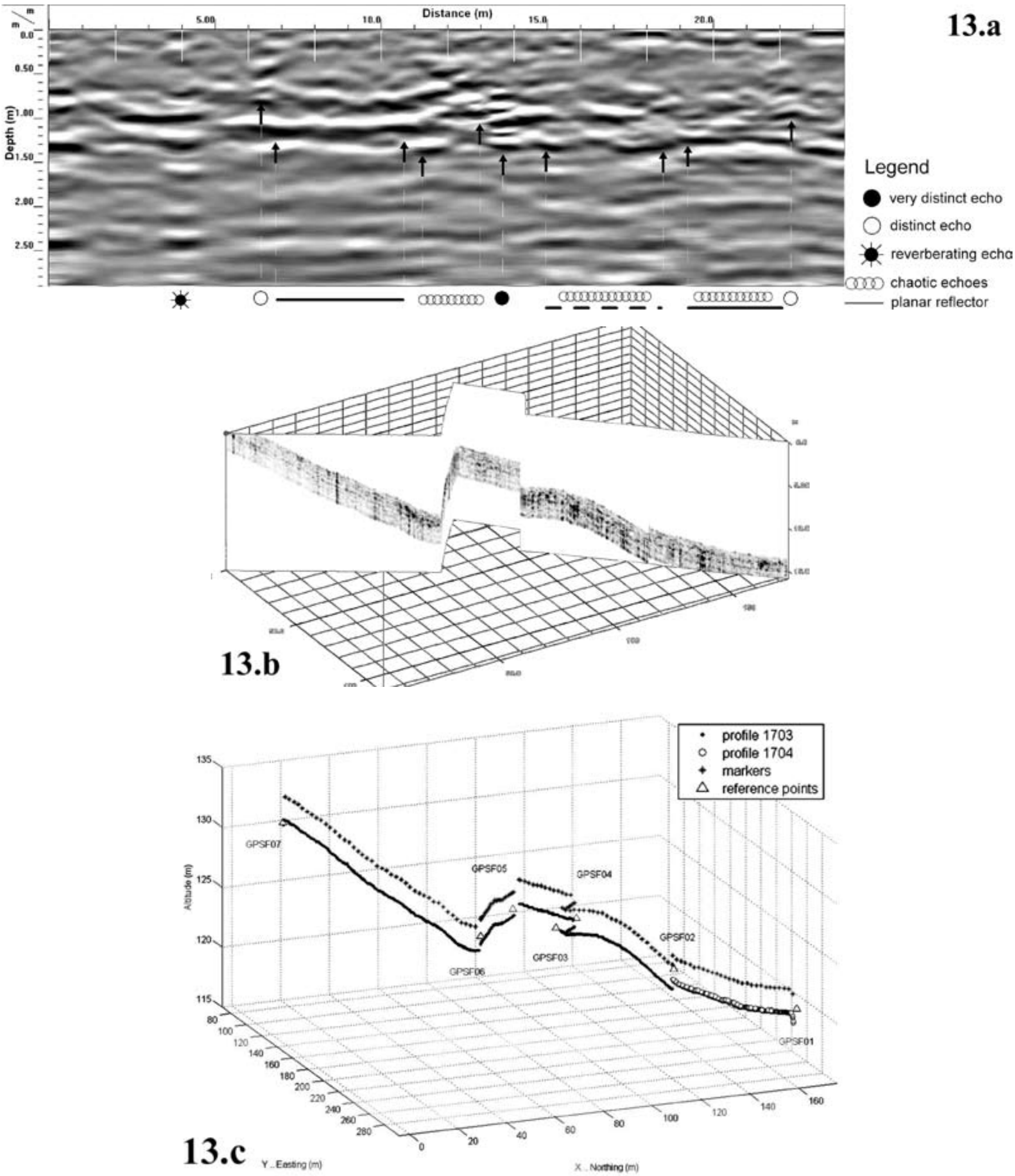
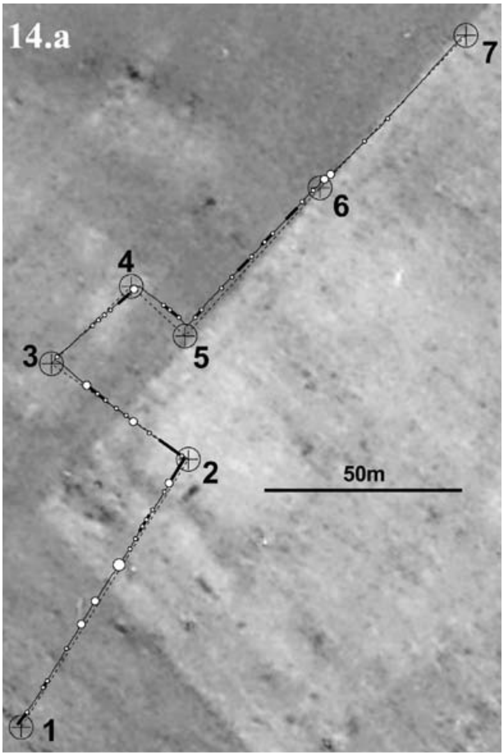


Figure 13. Detail of the filtered GPR profile in the direction of GPR profile 1 (13.a) with the arrangement of the GPR echoes in categories (BEVAN, 1997) and the 3D representation of the radargram with topographic correction in the direction of GPR profile 1 (13.b) accompanied with the GPS observation of the profile route (13.c)

Slika 13. Detajl filtriranega georadarskega profila v smeri GPR profila 1 (13.a) in tridimenzionalna predstavitev radarskega diagrama s topografsko korekcijo po smeri profila 1 GPR (13.b), izdelano po zebeleženi sledi opazovanja z GPS na isti poti (13.c)



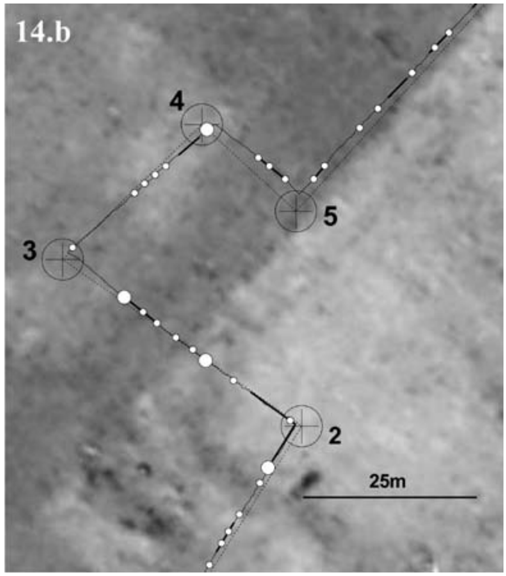


Figure 14. The significant GPR echoes are classified in the two basic categories: small and distinct echoes and long echo pattern found along a traverse (Bevan, 1996) in the direction of GPR profile 1 (14.a) and a detail of the same profile (14.b)

Slika 14. Značilni georadarski odboji so razvrščeni v dve osnovni kategoriji: majhni in izraziti odbji in dolge sledi vzdolž profilov (Bevan, 1996) v smeri GPR profila 1 (14.a) in detajl istega profila (14.b).

reference point in UTM projection (Bilc, 2003). The magnetogram (Figure 15) shows the streets of Ancient Tanagra, the building blocks and the division of space within the blocks. GPR profile 1 was, thus, located in the area, where it was reasonable to expect numerous GPR echoes from various types of architectural remains. The results of the magnetic method led us in general to expect marked individual echoes from walls (distinct echoes-small and compact echoes) and echoes from horizontal reflectors or roads (planar reflectors-long echo pattern found along a traverse). Figure 15 shows that the entire survey process with the GPR/GPS system, in accordance with the method of GPR profile evaluation explained above, was successful in terms of rapid assessment of archaeological potential. By planning surveys in radial or parallel located linear traverses, it is possible to avoid errors in defining the position of GPR echoes from GPS measurements, which are the result of frequent changes in direction. These are visible on Figure 15 between fixed points 5 and 6. It is possible to conclude from this test that such a GPR/GPS system is useful for the rapid evalu-

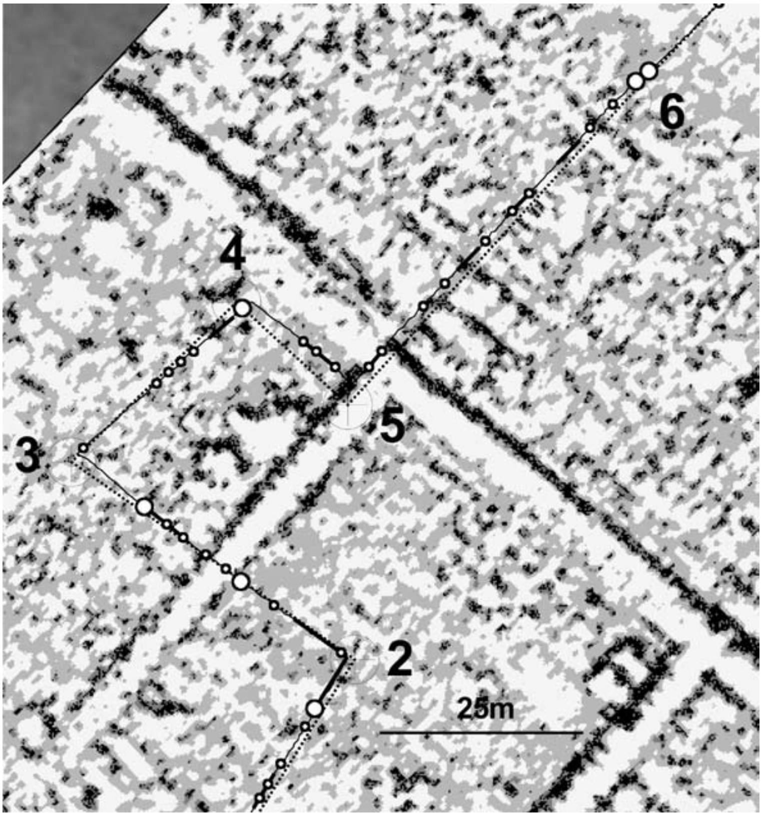


Figure 15. Detail of the magnetogram with the interpretation of GPR profile 1
Slika 15. Detajl magnetograma z interpretacijo GPR profila 1

ation of the degree of preservation of architectural remains, the extent of sites, as well as for geological mapping etc. It is especially useful where fieldwork is subject to temporal constraints and effective prospection urgently requires autonomy in the operation of the geophysical team.

CONCLUSIONS

As expected, according to the use of (L1) carrier wave, we were able to obtain a positioning resolution up to one wavelength (19 cm, see Figure 2.a). This resolution is better than our initial goal, i.e. 30 cm relative uncertainty of positioning, however, the desired 30 cm uncertainty could only be achieved under favourable conditions (ODIJK, 2002). In order to extend the positioning capabilities of the type of equipment used to less favourable conditions, further post-processing, especially concerning the influence and reduction of multipath errors is necessary (CANNON et al., 1993). Under conditions where a degradation of the GPS fixes occured during the scans, we were able to compensate for this and to refine the positioning results by taking the real-time radio link or archived fixes from the nearest reference station into account. As described in the literature (Van Sickle, 2001; Saka et al., 2004), a dual frequency receiver enables faster real time kinematical positioning than single frequency receiver, eliminating some of the multipath and receiver noise errors. In order to describe positioning conditions the processing of the carrier phase (CP), based on smoothing the pseudo ranges, should also be considered (Ford, 2003). The techniques described are not adequate for archaeological work in extreme conditions, e.g. underground caves or urban environments, where navigation satellite signals are obscured from the receiver. A hybrid positioning technology, involving relative positioning by wideband carrier waves or by some other types of sensors (Mezentsev et al., 2004) would be recommended in such circumstances. It is now well known that many of the positioning problems investigated in our work will be solved by better basic accuracy in new satellite positioning technologies, based on a new satellite network that is now under the new satellite networks that are now under construction (Galileo, GLONASS, CNSS, GAGAN). As the new system still seems to be several years from becoming operational, the necessary experience in the geophysical fieldwork using satellite positioning can be obtained by utilizing the existing, though barely adequate GPS system. Nevertheless, the vulnerability of the satellite navigation systems due to intentioned jamming and the rate of errors due to the observation conditions, lead to the implementation of a complementary sensor.

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Povzetek

Uporaba enofrekvenčnega sprejemnika GNSS s 30 cm negotovostjo v kinematičnem načinu dela za terenske geofizikalne preiskave

Zamisel o izdelavi cenenega, enofrekvenčnega GPS sistema, ki je preprost za upravljanje izhaja iz potrebe po večji fleksibilnosti in učinkovitosti terenskega dela pri geofizikalnih raziskavah. Zadostno fleksibilnost zagotavlja le popolna avtonomija ekipe pri načrtovanju in izvajanju terenskih postopkov pri natančnem prostorskem umeščanju ugotovljenih anomalnih območij.

Uveljavljeni geodetski terenski postopki, tudi s pomočjo satelitske navigacijske tehnike, so pogosto dolgotrajni, cenovno predragi in za našo rabo pogosto tudi preveč natančni. Z žrtvovanjem visoke natančnosti bi skrajšali čas pridobivanja dovolj zanesljivih podatkov o položaju merilnih instrumentov z uporabo enofrekvenčnih (L1) sprejemnikov GPS srednjega razreda.

Preizkusni tereni obravnavani v članku so enaki realnim situacijam in imajo napake določanja položaja s satelitskim sistemom enake vzroke: zastrtost, večpotje, spremenljivost ionosfere. Vplivov spremenljivosti ionosfere na rezultate v predstavljenih primerih še nismo opazovali.

V pogojih večpotja je raztros rezultatov (Slika 2a), izmerjen s preprosto GPS anteno (glej sliki 1 in 8), pričakovano prevelik. Pri geofizikalnih raziskavah je pomembna tudi zanesljiva ponovljivost določanja položaja, kadar je potrebno meritve ponoviti pri drugačnih nastavitvah geofizikalnega instrumenta ipd. Z določanjem razdalje do referenčne točke s statičnimi preizkusi (Slika 2b) smo dokazali, da je v dobrih pogojih oz. pri majhni zastrtosti satelitov, ponovljivost rezultatov položaja ustrezna. V tabeli 3 vidimo, da imajo na negotovost meritev pričakovano večji vpliv okoliščine in izbira sprejemnika kot način opazovanja (samostojni GPS, diferencialni - DGPS). Vpliv izbire naprave na rezultate kinematičnih preizkusov je razviden iz tabele 4: v enakih pogojih je negotovost precej manjša, v pogojih z malo večpotja je negotovost ustrezna. Sliki 3 in 4 prikazujeta rezultate z dveh terenov: v pogojih nezanemarljivega večpotja smo preizkušali različna sprejemnika (Slika 3), ob različnih razporeditvah satelitov nad obzorjem (HDOP) smo na terenu z malo večpotja in zastrtosti preizkušali isti sprejemnik. Ponovljivost oblike sledi smo v različnih režimih hoje opazovali v enakih pogojih večpotja (Slika 6a in 6b). Sledenje ravnim profilom ob znatnem večpotju je razvidno s slike 7. Sočasno določanje položaja s sprejemnikom GPS in teodolitom (TPS) na sliki 9 kaže odstopanja, pričakovana v slabših pogojih sprejema. Namerno zastiranje mirujoče antene GPS (Slika 10) povzroča velika nihanja rezultatov položaja oziroma navidezne premike. Na arheološkem terenu (Slika 11) smo zaznali odstopanja od referenčne črte, ki so naključno (glej Slika 5) naraščala z oddaljevanjem od oglišča, v katerem smo začeli hojo. Z določitvijo parametrov odstopanja ob upoštevanju vpliva HDOP in kvantitativne ocene večpotja na določenem terenu, je odstopanja možno kompenzirati.

Testno rekognosciranje v georadarskih profilih smo izvajali z 200 MHz anteno, s katero poleg informacij o arheoloških arhitekturnih ostalinah, ki se nahajajo plitvo pod površjem, registriramo tudi spremembe v geološki podlagi na nekoliko večjih globinah. Ta GPR antena je ustrezna za rekognosciranje zaradi ustreznega razmerja med ločljivostjo in globino dosega ter masivne konstrukcije, ki ob zadostni mobilnosti antene med meritvami zagotavljajo tudi njeno stabilnost v smeri gibanja, kar bistveno zmanjšuje šum.

Največja odstopanja GPS meritev od smeri gibanja GPR antene so bila ugotovljena v točkah 3, 4 in 5 (glej sliki 14b in 15), kjer smo naglo spreminjali smer gibanja antene, dejanske spremembe smeri so približno ustrezale pravemu kotu. Na ravnih odsekih so odstopanja v skladu z zastavljenimi cilji raziskave in ustrezajo odstopanjem, ki so bila ugotovljena v GPR profilu 2, kjer večjih sprememb v smeri gibanja ni bilo. Na istih slikah vidimo, da se pri vsaki spremembi smeri odčitki GPS »vrnejo na pravo« mesto vendar vmes vselej preteče nekaj časa. Če smer gibanja spreminjamo pogosto in ne počakamo, da se odčitki GPS ustalijo, se te napake akumulirajo. Na osnovi te ugotovitve lahko zaključimo, da natančnost tega GPS sistema popolnoma odgovarja našim zahtevam samo v posebnem primeru premočrtnega gibanja. Za učinkovito rabo moramo izbirati smeri gibanja z najmanjšim možnim številom sprememb smeri pod večjimi koti. Ta problem rešimo tako, da prospekcijo načrtujemo v dolgih, približno ravnih prečnicah.

Oceno natančnosti pozicioniranja georadarskih odbojev z GPS smo preverjali tudi v odnosu do položaja magnetnih anomalij, kartiranih z magnetometrom Geometrics G-858 (Mušič et al., 2004), ki so bile georeferencirane z zemeljskimi meritvami z uporabo referenčnih točk v UTM projekciji (Bilc, 2003). Na magnetogramu (slika 15a) vidimo ulice antične Tanagre, stavbne bloke in razdelitve prostorov znotraj blokov. GPR profil 1 je bil torej izbran na območju, kjer smo lahko pričakovali številne radarske odboje od različnih tipov arhitekturnih ostalin. Glede na rezultate magnetne metode smo v splošnem pričakovali izrazite posamične odboje od zidov in odboje od horizontalnih reflektorjev oziroma cest. Iz slike 15 je razvidno, da je celoten postopek rekognosciranja z GPR/GPS sistemom v skladu z obrazloženim načinom vrednotenja radarskih profilov učinkovit v smislu hitre ocene arheološkega potenciala. Z načrtovanjem pregledov v radialno oziroma vzporedno zastavljenih ravnih prečnicah se izognemo napakam v določanju položaja radarskih odbojev iz opazovanj z GPS, ki so posledica pogostega spreminjanja smeri in so vidne na sliki 15 med točkama 5 in 6.

Iz rezultatov statičnih in kinematičnih primerjalnih preizkusov različnih vrst preprostejših sprejemnikov GPS vidimo, da imajo preprostejše naprave pričakovano širši interval zaupanja. Kakovost obdelave satelitskih signalov namreč v večji meri zagotavljajo zmogljivejša elektronska vezja.

Možnost kompenziranja napak z naknadno obdelavo izmerjenih odčitkov sprejemnikov GPS obstaja, če zadosti dobro poznamo vzroke napak oziroma pogoje, v katerih izvajamo terenske raziskave. Pričakovanja od novih sistemov satelitske navigacije (Galileo - Evropa, GLONASS - Rusija, CNSS - Kitajska, GAGAN - Indija) in posodobitve obstoječega (GPS - ZDA) so zaradi raznih nedorečenosti še v domeni prihodnosti. Dva splošna pojava zmanjšujeta zanesljivost določanja položaja satelitskih navigacijskih sistemov: že omenjene napake zaradi okoliščin na terenu in neodpornost na namerno radiofrekvenčno motenje (*jamming*). Eden od ustreznih odgovorov za zagotovitev zahtevane zanesljivosti GPS meritev z enofrekvenčnim sprejemnikom je vključevanje dodatnih komplementarnih senzorjev (npr. pospeškometer pri kinematičnih meritvah) v odvisnosti od narave motenj.

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