UDC 528.2:629.78

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MODIFIED ALGORITHM OF SMOOTHING/FILTERING THE DIFFERENTIAL GNSS OBSERVATIONS IN THE KINEMATIC POSITIONING MODE

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Abstract. *The results of GNSS differential measurements code-phase smoothing/filtering modified algorithm development and validation have been presented for the mobile objects kinematic positioning. It is shown that the updated algorithm allows considerable increasing of the positioning accuracy and obtaining a glide coordinate solution in comparison with the analogs.*

Keywords: accuracy estimation; global navigation satellite systems (GNSS); differential mode; kinematic positioning; smoothing/filtering.

1. Introduction

For the positioning accuracy improvement in global navigation satellite systems (GNSS), such as GPS, GLONASS etc., during the measured parameters processing (in post-processing or real time mode) the smoothing (or filtering if in real time mode) of code measurements is carried out using high precision phase measurements [1-3]. This allows not only the effective decreasing of code observations errors caused by noise and multipath, but also forming rather precision initial solutions for the reliable carrier-phase ambiguity resolution (CPAR) [4]. The procedures of smoothing/filtering are based on proximity of slowly changing error of code and carrier-phase observations (or their linear combinations) with uncertainty of the initial carrier-phase ambiguity. In case of absence of carrier-phase cycle slips the task is obtaining the optimum estimation of carrier-phase observations level relatively the code ones. After that it is performed the «replacement» of code observations by carrier-phase observations corrected to this value [1-3]. Smoothing/filtering accuracy is determined by the accuracy of carrier-phase level estimation relatively code pseudoranges and considerably depends on the level of code multipath, and also on the volume of the sample of observations (interval of averaging) [1, 2]. In paper [3] it was proposed and researched the original «leveling»–algorithm of smoothing the differential code observations (carrier-smoothed code algorithm) which in contrast to the well-known analogs takes into account the influence of variations of the ionosphere delays (in dual-frequency case) and so-called «wind-up»–effect [1]. This effect is inherent only to carrier-phase measurements and caused by the receiving antenna rotation during the evolution of currently controlled object.

The results of single-frequency code measurements smoothing/filtering modified algorithm development and validation have been presented. The algorithm is notable for the additional observations use, namely the increments of the mobile object current coordinates estimations obtained from the continuous phase measurements increments. The given two-stage approach using at the first stage the results of processing by algorithm [3], as it is shown in the given paper, allows significant increasing of smoothing/filtering accuracy and obtaining of smooth (glide) coordinate solution – significant decrease of coordinate variations and eliminates jumps caused by change of the working constellation of satellites and the appropriate changes of the geometric dilution of precision (GDOP) [1].

2. Initial «levelling»-algorithm of single-frequency code-carrier smoothing

Further it will be given a brief succession of actions when smoothing code GNSS observations by use of «leveling»–algorithm described in paper [3]. The given algorithm assumes that in code and carrier-phase observations the anomalies are excluded, and carrier-phase cycle slips are excluded and continuity of observations is recovered [2].

The initial system of observation equations may be given as:

$$\begin{cases} \Delta\hat{S}^j(t_k) = \Delta R^j(t_k) + \eta_S + \Delta Tr^j(t_k) + \\ +\Delta I^j(t_k) + \delta\Delta S^j(t_k) \\ \Delta\hat{L}^j(t_k) = \Delta R^j(t_k) + \eta_L + \Delta Tr^j(t_k) + \\ +\Delta I^j(t_k) - \Delta N^j \cdot \lambda_1 + w(t_k) + \delta\Delta L^j(t_k) \end{cases}, \quad (1)$$

where $\Delta\hat{S}^j(t_k), \Delta\hat{L}^j(t_k)$ – single differences of code and carrier phase observations accordingly; $\Delta R^j(t_k)$ – single difference of ranges; η_S, η_L – variables involving time scales divergences between the receivers and the difference of delays in the channels of receivers; $\Delta Tr^j(t_k)$ – difference of tropospheric delays; $\Delta I^j(t_k)$ – difference of ionospheric delays; ΔN^j – single differences of carrier-phase ambiguities; $w(t_k)$ – error due to «wind-up» effect («wind-up» effects due to repeating rotations of GNSS satellites antennas are excluded in the differential observations); $\delta\Delta S^j(t_k)$, $\delta\Delta L^j(t_k)$ – multipath and noise error components of the suitable observations.

During the processing of observations the following corrections are taken into account:

– calculated ranges «satellites–receiver of the reference station»; it is assumed that the coordinates of the phase center of the receiving antenna are known with centimeter/millimeter accuracy;

– corrections to signal delays in the troposphere and ionosphere calculated by use of the well-known models.

After observation equations linearization and correction for the troposphere and ionosphere effects the measurements single differences processing for the chosen reference satellite is performed as a following:

$$\Phi^1(t_k) = \Delta \overset{*}{S}{}^1(t_k) - \Delta \overset{*}{L}{}^1(t_k). \quad (2)$$

For the obtained difference $\Phi^1(t_k)$ it is done the estimation of the average value $\overline{\Phi}^1$ and is formed the result of code-carrier smoothing for the reference satellite:

$$\Delta\tilde{S}^1(t_k) = \Delta \overset{*}{L}{}^1(t_k) - \overline{\Phi}^1. \quad (3)$$

Then the dual code-carrier differences are formed for all the satellites of the current working constellation relatively the reference one where the «wind-up» effect is absent (excluded) due to probable rotation of the receiving antenna:

$$\Phi^{j1}(t_k) = \nabla\Delta \overset{*}{S}{}^{j1}(t_k) - \nabla\Delta \overset{*}{L}{}^{j1}(t_k). \quad (4)$$

For every linear combination $\Phi^{j1}(t_k)$ it is estimated its average value. The obtained estimations $\overline{\Phi}^{j1}$ allow forming the result (5) of code-carrier smoothing of dual differences of observations:

$$\nabla\Delta\tilde{S}^{j1}(t_k) = \nabla\Delta \overset{*}{L}{}^{j1}(t_k) + \overline{\Phi}^{j1}. \quad (5)$$

After obtaining of sets of data $\Delta\tilde{S}^1(t_k)$ (3) и $\nabla\Delta\tilde{S}^{j1}(t_k)$ (5) we will return (by means of linear transformations) to the equations of single differences of observations:

$$\begin{cases} \Delta\tilde{S}^1(t_k) = \left\| a^1_{\vec{X}}(t_k) \right\| \Delta\vec{X}(t_k) + \tilde{\eta}_{SL}(t_k) + \\ +\delta\tilde{f}^1(t_k) + \delta\Delta L^1(t_k) \\ \Delta\tilde{S}^2(t_k) = \left\| a^2_{\vec{X}}(t_k) \right\| \Delta\vec{X}(t_k) + \tilde{\eta}_{SL}(t_k) + \\ +\delta\tilde{f}^2(t_k) + \delta\Delta L^2(t_k) \\ \ldots \\ \Delta\tilde{S}^m(t_k) = \left\| a^m_{\vec{X}}(t_k) \right\| \Delta\vec{X}(t_k) + \tilde{\eta}_{SL}(t_k) + \\ +\delta\tilde{f}^m(t_k) + \delta\Delta L^m(t_k) \end{cases}, \quad (6)$$

where $\Delta\vec{X}(t_k)$ – vector of currently estimated corrections to a priori set values of the unknown coordinates; $\tilde{\eta}_{SL}(t_k)$ – divergence of the receiver and the reference station time scales;

$\underset{(j=\overline{1,m})}{\delta\tilde{f}^j}(t_k)$ – slowly varying residual error components; $\underset{(j=\overline{1,m})}{\delta\Delta L^j}(t_k)$ – errors of carrier-phase pseudo ranges caused by multipath effects and by noise.

The estimation of parameters $\Delta\vec{X}(t_k)$ and $\tilde{\eta}_{SL}(t_k)$ is carried out by the least-squares method.

3. Updating (modification) of the algorithm of GNSS observations smoothing/filtering

The modified «leveling»–algorithm of smoothing of single-frequency code GNSS observations described below is based on using the additional information – estimations of increments of the mobile object current coordinates. The estimations are obtained by the increments of continuous carrier-phase observations in time. The combination of estimations of the smoothed solution of the first stage of processing by algorithm [3] and the given additional information allowed achieving a new more effective solution of the assigned task.

The illustrating block-diagram of processing the GNSS observations according to the modified algorithm is given in Fig. 1. The proposed algorithm of processing uses the following equations of observations as the initial ones:

$$\begin{cases}\Delta\hat{L}^j(t_k)=\Delta R^j(t_k)+\eta_L+\Delta Tr^j(t_k)-\\ -\Delta I^j(t_k)-\Delta N^j\cdot\lambda_1+w(t_k)+\delta\Delta L^j(t_k),\\ \hat{\vec{X}}(t_k)=\vec{X}(t_k)+\delta\vec{X}(t_k)\end{cases} \qquad (7)$$

where $\Delta\hat{L}^j(t_k)$ – single differences of carrier-phase observations; $\hat{\vec{X}}(t_k)$ – vector of the current estimations of the mobile object coordinates; the estimations are obtained by use of «leveling»–algorithm; $\vec{X}(t_k)$ – vector of the unknown coordinates; $\delta\vec{X}(t_k)$ – errors vector of the coordinate estimations obtained by use of the «leveling»–algorithm.

During the processing we form the increments of carrier-phase observations in time:

$$\begin{aligned}&d\Delta\hat{L}^j(t_{k,k-1})=\Delta\hat{L}^j(t_k)-\Delta\hat{L}^j(t_{k-1}),\\ &k=2...n\end{aligned} \qquad (8)$$

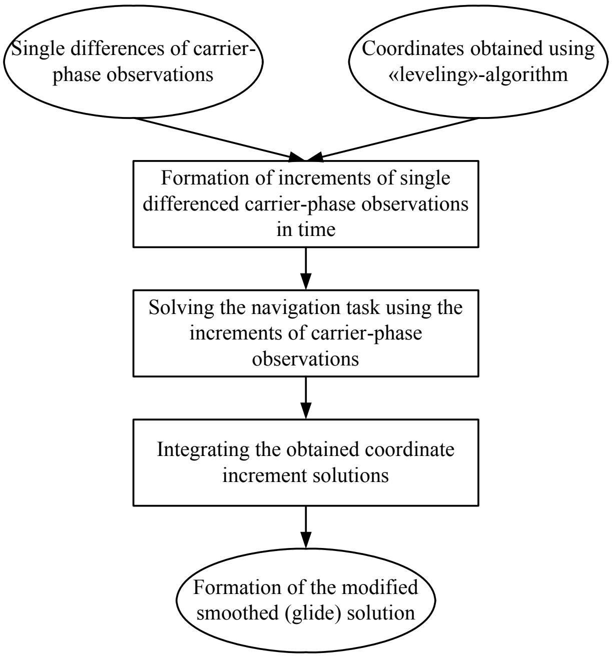
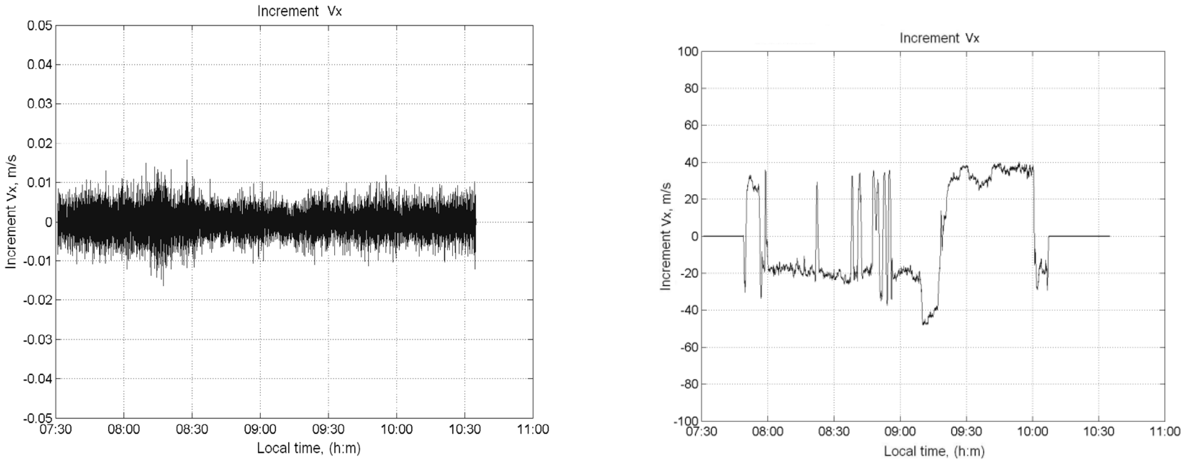


Fig. 1. Block-diagram of GNSS observations processing

After that we will carry out the estimation of coordinate increments ($d\Delta\hat{\vec{X}}(t_{k,k-1})$) using the increments of carrier-phase pseudo ranges in time. It is important to emphasize that using carrier-phase increments does not require the solution of the difficult and sophisticated task – carrier-phase ambiguity resolution. Fig. 2 illustrates, as an example, the estimated increments of coordinates in time (equivalent of velocity changes at 1 Hz sample rate).

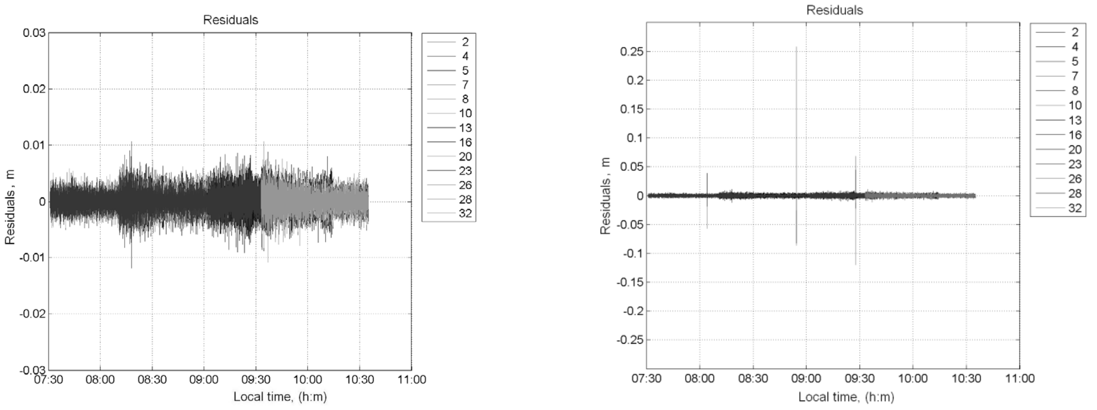


a *b*

Fig. 2. Examples of estimation of the object current coordinate «x» increments
a – static object; *b* – kinematic object (helicopter flight)

This information may be also useful for determination of stops and motion passes, for example, during the realization of the algorithms «stop&go» [1].

The important positive factor of high precision increment coordinate solution using carrier-phase observations is the possibility of the reliable detection (and next following estimation and exclusion) of phase slips from the analysis of the solution residuals. For identification of slips (to which satellite they refer) and estimation of its value it requires a separate procedure, in particular, the procedure described in [5]. Fig. 3 shows the examples illustrating this possibility. The figure displays the solution residuals (differences between the measured and estimated values).



a *b*

Fig. 3. Coordinate solution residuals: *a* – in the absence of carrier-phase slips; *b* – in the occurrence of carrier-phase slips at three epochs

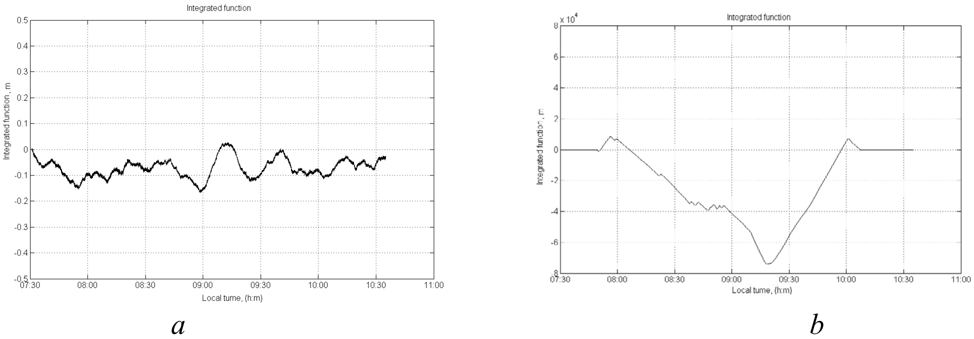
After determination of coordinate increments it is carried out their integrating:

$$\Delta\hat{\hat{X}}^{*}(t_{k,k-1}) = \sum_{i=2}^{m=k} d\Delta\hat{\hat{X}}(t_i)\,. \qquad (9)$$

This action allows obtaining the coordinate changes in time ($\Delta\hat{\hat{X}}^{*}(t_k)$) with centimetric accuracy which, however, do not contain the unknown initial values of coordinates at the first epoch. The systematic (slowly varying) errors of the coordinate changes in this case (the differential mode of measuring) are relatively small and the fluctuating errors of the adjacent phase coordinate increments are excluded and not accumulated. Therefore the errors of the integrated increments will be practically equivalent to the errors of glide carrier-phase unambiguous (i.e. the ambiguities are resolved) coordinate solution. This gives the ability of avoiding the outliers of coordinates when changing the satellite configuration. These outliers are characteristic for the smoothed (leveling) code solution obtained at the first stage of smoothing. Fig. 4 shows the examples illustrating the obtained coordinate increment solutions for Fig. 2 examples

The obtained integral functions repeat the carrier-phase coordinate solution, but along with that the initial values of the first epoch stay unknown. Now these initial values may be determined with the involvement of the smoothed code-carrier «leveling» solution. For this purpose from code-carrier solution there will be eliminated the changes of coordinates in time by use of the integrated increments (9), and the result will be averaged:

$$\hat{\hat{X}}_{sr}(t_k) = \left\langle \hat{\hat{X}}(t_k) - \Delta\hat{\hat{X}}^{*}(t_k) \right\rangle. \qquad (10)$$



a *b*

Fig. 4. Examples of the integrated coordinate increment solutions («x» coordinate):
a – static object; *b* – kinematic object (helicopter flight)

For the purpose of achieving the maximum accuracy the averaging shall be done with eliminating of the influence of probable abnormal values by means of their excluding from the sample or use to such values the suitable small weights.

Final estimations of smoothed coordinates ($\hat{\hat{X}}_{fin}(t_k)$) are calculated as a sum of integrated increments of coordinates and its average values (10):

$$\hat{\hat{X}}_{fin}(t_k) = \Delta\hat{\hat{X}}^{*}(t_k) + \hat{\hat{X}}_{sr}(t_k)\,. \qquad (11)$$

Finally, the accuracy of the modified smoothed solution (in comparison with the complete carrier-phase solution) is restricted by the errors of estimation of average values $\hat{\hat{X}}_{sr}(t_k)$.

4. Results of verification of the proposed method by use of real measurements

As an example of testing and verification of the proposed modification of the «leveling»–algorithm there are presented the results of processing the GNSS measurements obtained during the flight experiment on the airdrome «Borodyanka» (Kiev region, June 2013). The result of the experiment is obtaining the measurements onboard the unmanned aerial vehicle (UAV). In the period of the experiment it was installed on the airdrome a dual-frequency ground base station (BS) with a symbolic notation PILB.

The processing of observations was carried out in the following succession:

♦ coordinate tying of PILB station relatively GLSV reference station (IGS/EPN station, Kiev) by dual-frequency single-base carrier-phase method (baseline ~52,5 км);

♦ determination of the reference trajectory of UAV relatively PILB by use of dual-frequency single-base carrier-phase processing;

♦ comparison of UAV motion trajectories obtained by use of 1) standard DGPS algorithm (code solution), 2) initial «leveling»–algorithm and 3) modified «leveling»–algorithm with the reference trajectory obtained by dual frequency method;

♦ analysis of the processing results.

The determination of UAV reference trajectory relatively PILB station was carried out by use of dual-frequency observations. Below, in Fig. 5 and 6 it is given a graphical display of UAV motion trajectory.

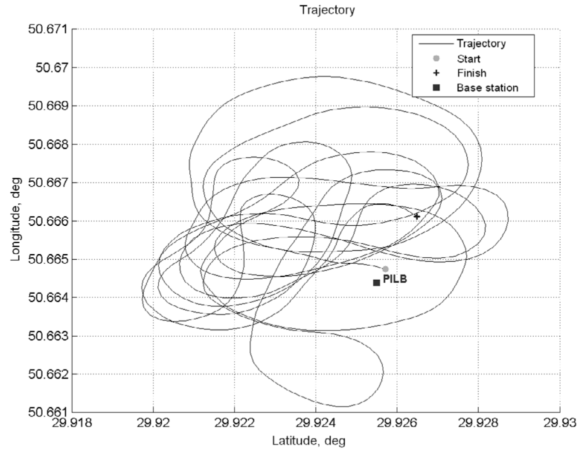


Fig. 5. Displaying of UAV motion trajectory in the map (plane coordinates)

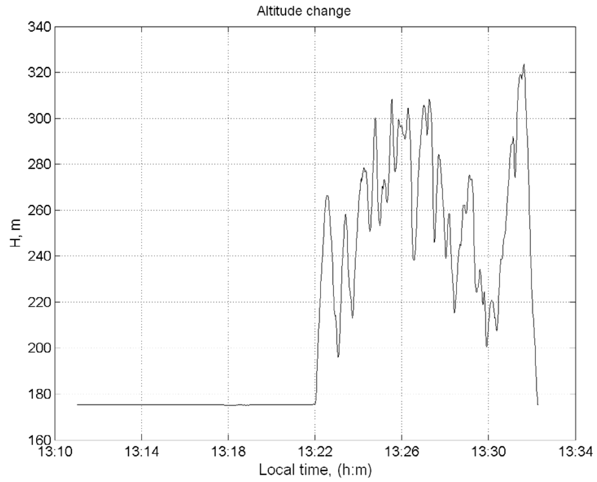
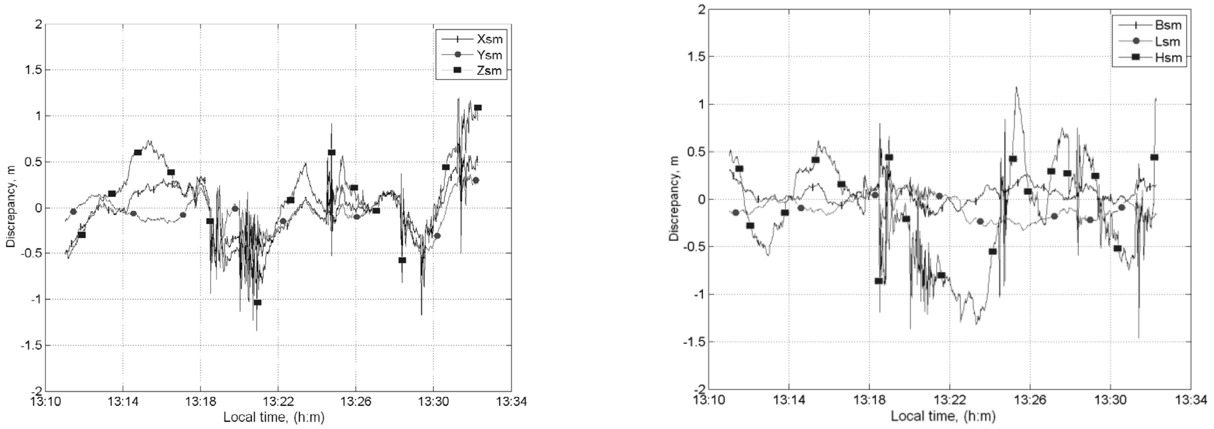


Fig. 6. UAV height variation during the experiment

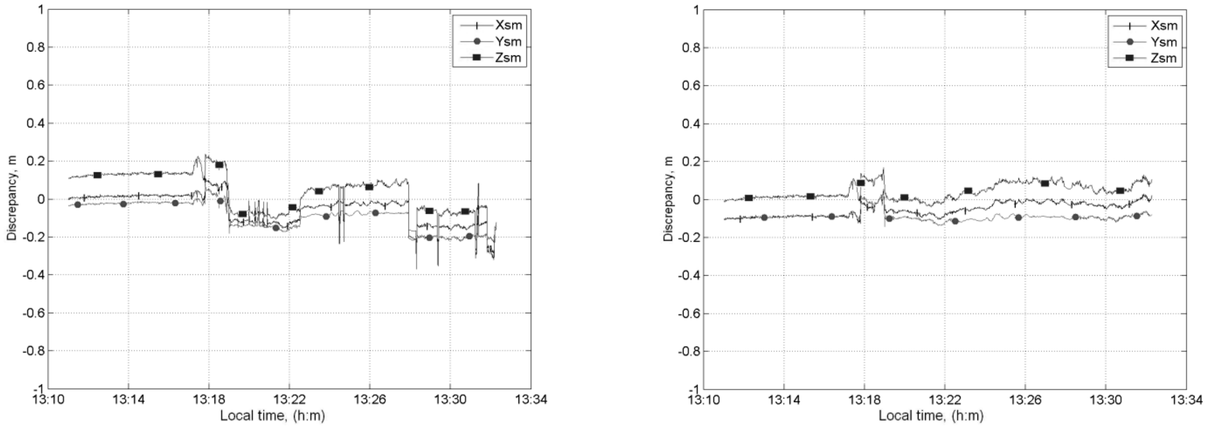
Fig. 7-9 presents the discrepancies of three solutions from the reference trajectory pointed above, and tables 1-3 give error statistical characteristics of these solutions. In the process of the experiment there were also obtained similar results for the case when the parameters of UAV motion trajectory were determined by the differential method directly relative to the remote (~52,5 km) station GLSV without using the intermediate base station.

The given comparative analysis of the obtained results shows that the maximum (p=95%) errors of the smoothed modified solution relatively PILB station made up ~10 cm for all the three components of coordinates. While carrying out of kinematic positioning relatively GLSV station the errors (p=95%) made up ~5 cm for plane coordinates and ~20 cm vertically.



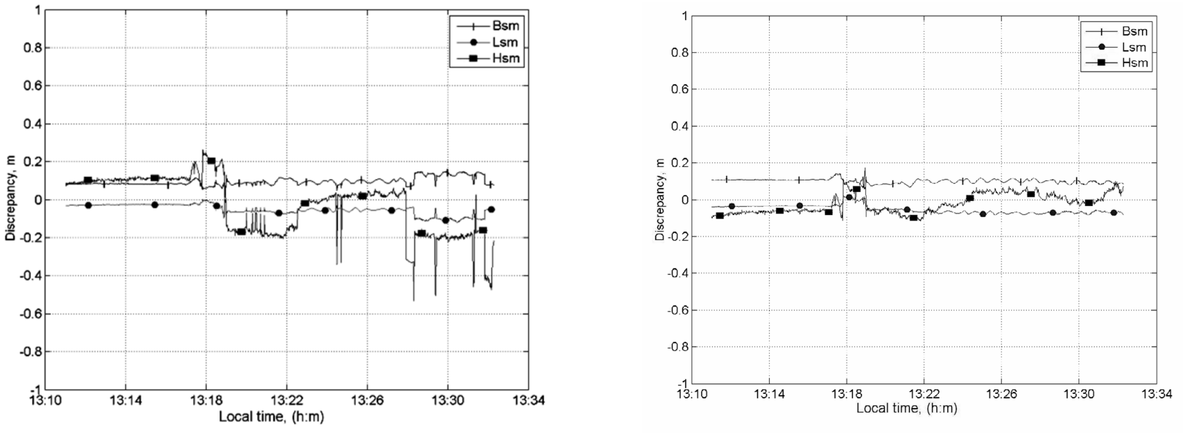
a *b*

Fig. 7. Discrepancies of standard DGPS solution and reference coordinates: *a* – for coordinates XYZ; *b* – for plane coordinates and height



a ***b***

Fig. 8. Discrepancies of «leveling»–algorithm solution (*a*), modified algorithm solution (*b*) and reference geocentric coordinates X,Y,Z



a *b*

Fig. 9. Discrepancies of «leveling»–algorithm solution (*a*), modified algorithm solution (*b*) and reference coordinates in local system of coordinates (plane coordinates B, L and height H)

Table 1

Error statistical characteristics of UAV trajectory determinationby use of DGPS-algorithm (code solution)

Coordinate errors	Average value	P = 68 % (RMS)	P = 95 %	P = 99,7 %
δ*X*, m	-0,03	0,26	0,50	0,80
δ*Y*, m	-0,07	0,16	0,45	0,70
δ*Z*, m	0,06	0,46	0,90	1,18
δ*B*, m	0,09	0,16	0,30	0,37
δ*L*, m	-0,05	0,15	0,27	0,48
δ*H*, m	0,02	0,54	1,07	1,50

Table 2

Error statistical characteristics of UAV trajectory determination by use of initial «leveling»–algorithm

Coordinate errors	Average value	P=68% (RMS)	P=95%	P=99.7%
δ*X*, m	-0,05	0,12	0,17	0,30
δ*Y*, m	-0,09	0,14	0,21	0,23
δ*Z*, m	0,04	0,13	0,22	0,34
δ*B*, m	0,10	0,10	0,14	0,15
δ*L*, m	-0,05	0,06	0,11	0,12
δ*H*, m	-0,03	0,17	0,26	0,49

Table 3

Error statistical characteristics of UAV trajectory determination by use of modified «leveling»–algorithm

Coordinate errors	Average value	P=68% (RMS)	P=95%	P=99.7%
δ*X*, m	-0,05	0,08	0,10	0,12
δ*Y*, m	-0,09	0,10	0,12	0,14
δ*Z*, m	0,04	0,07	0,11	0,14
δ*B*, m	0,10	0,11	0,12	0,14
δ*L*, m	-0,05	0,07	0,08	0,08
δ*H*, m	-0,02	0,06	0,10	0,12

The obtained results show that the proposed modified solution allows considerable increasing of smoothing/filtering accuracy and obtaining glide coordinate solution – significant decrease of coordinate variations and eliminate jumps caused by change of the working constellation of satellites and the appropriate changes of the geometric dilution of precision. Use the modified smoothing algorithm allows to reduce twice the positioning errors relatively the analog («leveling»–algorithm) and 3-4 times reducing relatively code DGPS solution on baselines up to 50 km.

5. Conclusions

The given paper presents the results of the development and verification of the modified «leveling»–algorithm of smoothing/filtering of code observations by use of continuous carrier-phase observations in the kinematic survey mode. The updated algorithm is characterized by using the additional information – estimations of the increments of the mobile object current coordinates. These estimations are obtained by use of the increments of continuous carrier-phase observations in time.

The proposed solution allows considerable increasing of positioning accuracy and obtaining of glide coordinate solution. In particular, the results of the experiments show that on baselines ~50 km it is possible to increase several times the positioning accuracy in comparison with the analogs and standard code differential solution.

The results given in this paper were obtained during full-scale experimental measurements carried out by the group of scientific-training center “Aerospace center” of NAU in summer 2013 within Research Work № 871-ДБ13 (state registration number 0113U000090).

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Received 10 June 2014

[1]В. М. Кондратюк, [2]О. О. Желанов, [3]І. В. Дицький, [4]Є. А. Бессонов. Модифікований алгоритм зглажування/фільтрації дифференціальних ГНСС спостережень в режимі кінематичного позиціонування

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У статті представлені результати розробки і верифікації модифікованого алгоритму кодово-фазового зглажування/фільтрації диференціальних ГНСС спостережень в задачах кінематичного позиціонування рухомих об’єктів. Запропонований підхід базується на застосуванні згладжування/фільтрації в реальному часі кодових спостережень з використанням високоточних фазових спостережень, які відрізняються використанням додаткових спостережень – оцінок приросту поточних координат рухомого об’єкту, отриманих з приросту неперервних фазових спостережень за часом. Такий підхід реалізовано з застосуванням модифікованого «leveling»–алгоритму зглажування/фільтрації кодових спостережень з використанням неперервних фазових спостережень в режимі кінематичної зйомки, що дозволяє значно підвищити точність та дозволяє отримати гладке координатне рішення яке зменшує варіації і скачки координат, викликаних зміною робочого сузір’я супутників і відповідними змінами геометричного фактору (GDOP).

Запропоноване рішення дозволяє значно підвищити точність позиціонування та отримати гладке координатне рішення. Результати експериментів показали, що на базових відстанях ~50 км можливе підвищення точності позиціонування в декілька раз в порівнянні з аналогами і стандартним кодовим диференціальним рішенням.

Ключові слова: глобальні навігаційні супутникові системи (ГНСС); GPS; диференційний режим; кінематичний режим позиціонування; згладжування/фільтрація спостережень; оцінка точності.

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В статье представлены результаты *разработки и верификации модифицированного алгоритма кодово-фазового сглаживания/фильтрации дифференциальных ГНСС наблюдений в задачах кинематического позиционирования движущихся объектов. Предложенный подход базируется на применении сглаживания/фильтрации* в реальном времени кодовых наблюдений с использованием высокоточных фазовых наблюдений, которые отличаются использованием дополнительных наблюдений – оценок прироста текущих координат подвижного объекта, полученные с прироста непрерывных фазовых наблюдений во времени. Такой подход реализовано с использованием модифицированного «leveling»–алгоритма *сглаживания/фильтрации* кодовых наблюдений с использованием непрерывных фазовых наблюдений в режиме кинематической съемки, что позволяет существенно улучшить и получить гладкое координатное решение, которое уменьшает вариации и скачки координат, вызванные изменением рабочего созвездия спутников и соответственно геометрического фактора (GDOP).

Предложенное решение позволяет существенно повысить точность позиционирования и получить гладкое координатное решение. Результаты экспериментов показали, что на базовых расстояниях ~50 км возможное повышение точности позиционирования в несколько раз по сравнению с аналогами і стандартным кодовым дифференциальным решением.

Ключевые слова: глобальные навигационные спутниковые системы (ГНСС); GPS; дифференциальный режим; кинематический режим позиционирования; сглаживание/фильтрация наблюдений; оценка точности.

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