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Effect of Supervising GPS Code Smoothing Process on the Positional Accuracy

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Abstract— GPS smoothed codes merge the advantages of both phase and code measurements as it is based on using the high accurate phase measurements in smoothing the unambiguous code measurements. However, the resulted smoothed codes are suffering from two main problems. First, it is contaminated by relatively high biases. Also, such biases are not similar at all stations as in the classical approaches of code smoothing the process starts at the epoch of satellite rise which differs among different stations. This resulted in non-similar positional errors at different stations.

In this paper, new approach of code smoothing was introduced to overcome the non-similarity between positional errors at different stations. This approach is based on the supervision of the smoothing process by synchronizing its start, for the same satellites, at all stations. This is to achieve the highest possible convergence between the resulted positional errors. So, with the existence of only one pre-coordinated station, the entire network can be accurately solved using supervised smoothed codes. To judge the convergence among the resulted positional errors, a new indicator was introduced. This indicator, which was named Error Stability Indicator (E.S.I.), is established as the mean of the absolute values of the differences between the mean coordinate discrepancy of all stations and the coordinate discrepancy at each station. Such coordinate discrepancies are computed as the reference coordinates (computed using phases) and the coordinates produced using supervised smoothed codes.

By applying the proposed approach it was found that, by increasing the number of satellites involved by the supervised smoothing process, better convergence between coordinate discrepancies (lower E.S.I.) can be obtained. By involving all visible satellites, E.S.I. values less than 4 cm were obtained. Finally, and as a validation for the proposed approach, its efficiency was tested by varying both the length of the used session and the time of observation within the day. Results showed that neither the session length nor the observation time affects the performance of the proposed approach. With the existence of one pre-coordinated point for the entire network, supervised code smoothing can achieve positional accuracy better than 4 cm using session length of only 5 minutes.

Index Terms—Supervised code smoothing, Error Stability Indicator (E.S.I.), positional accuracy, session length.

1 INTRODUCTION

GPS positions derived from phase measurements are much more precise than that derived using code observations [1]. Unfortunately, GPS phase solutions should imply the determination of the phase ambiguity which is computation-intensive and time-consuming task [2]. Rapid and reliable phase ambiguity resolution becomes more and more difficult when the inter-receiver distance grows longer [3]. Recently, several ambiguity resolution methods have been explored and developed. However, it still takes a few tens of minutes to obtain reliable values for the phase ambiguity [4].

To overcome the above-mentioned drawbacks of the process of ambiguity resolution, without degrading positional accuracy using code observations, the code smoothing scenario is thought to be an ideal solution. The main idea of code smoothing using phase measurements is based on using the relatively accurate phase measurements in the smoothing of the unambiguous code measurements to increase its accuracy [5]. Such smoothed codes can be used directly to derive the 3-D coordinates without the need to resolve the ambiguity. This implies a combination between the advantages of both carrier and code measurements [6].

Smoothing of GPS codes results in smoother values for the ranges between the receiver and satellites. However, such smoothed codes are biased. Previous works investigated the behavior of such biases [5, 7 and 8]. In such works, the smoothed codes are computed (using different weighting functions) and then the accuracy of the resulted positions was investigated. Recently, an accuracy of few decimeters is achieved [7, 8]. Such moderate accuracy can be referenced to the differential biases, resulted by the smoothing process, at different stations with respect to different used satellites. This phenomenon is directly linked to the different epochs of satellite rising and setting at different sites.

In this paper, the behavior of the positional errors, resulted from the application of smoothed codes, is investigated carefully. Then, an attempt will be done to unify such positional errors at all the considered stations, or at least achieve the maximum possible closeness among them. This trial will be performed through supervising the process of code smoothing. If such goal is achieved, higher positional accuracy can be reached using smoothed codes with significant reduction in the required occupation time. This high accuracy can be reached simply by involving only one pre-coordinated station in the considered network.

2 Description and Validation of the Used Data

A GPS network was established in New Cairo City, 5th settlement district. Such network consists of 7 stations, with inter-distances ranges from 1.3 km to 5.1 km (figure 1). These 7 points were occupied by GPS dual frequency receivers for one complete day of observations, with a sampling rate of 15 seconds. These data were collected on August 2015.

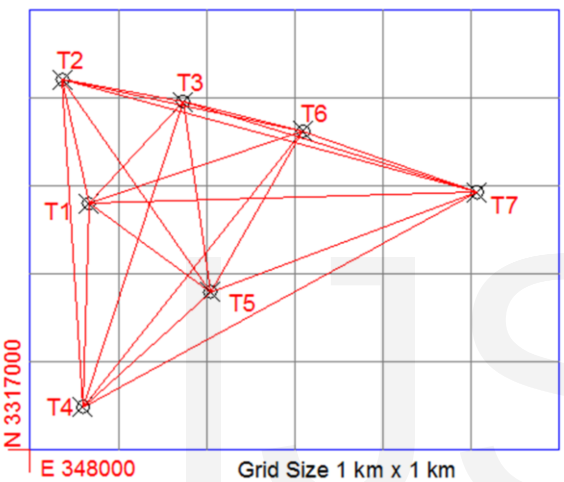

Fig.1. Established GPS Network

The collected GPS data were divided into 12 equal sessions, each of them with duration of 2 hours. Then, the whole network is adjusted and solved using Leica Geo-Office Package. In all the 12 performed solution, the point T_1 was assigned as the reference point. Final grid coordinates are derived (for each of the 12 sessions) with respect to the UTM system. These adjusted coordinates of the involved 7 points will be considered as the reference coordinates in all the following steps.

Before going through any smoothing process for the measured codes, it was of great importance to check the existence of any cycle slips in the phase data. This is due to the fact that any smoothing algorithm will certainly fail if any cycle slips occurred [5]. So, existence of cycle slips in the collected data was checked. This check was done using the Difference between Change in Phase and Code (DCPC) values as a test quantity. Such test quantity can be computed as [9]:

$$DCPC = \Delta P_{12} - \Delta\phi_{12} \qquad (1)$$

Where:

DCPC	Used test quantity
ΔP_{12}	Change in the measured codes between the two consecutive epochs t_1 and t_2
$\Delta\phi_{12}$	Change in the measured phases between the two consecutive epochs t_1 and t_2

DCPC values and its changes between each two consecutive epochs are computed (for both carriers L_1 and L_2). Also, changes in DCPC values are drafted against time for both carriers. This was done for the collected data at all the considered network stations. Any cycle slip (even with a value of only one cycle) will be reflected as a sudden change (spark) on the DCPC – time graph [9]. Concerning the used data, no sparks were observed. So, the used data are all free of any cycle slips. More details concerning the detection of cycle slips using DCPC can be found in [9].

3 Assessment of Positional Accuracy Using Both Raw and Smoothed Codes

To explore the achievable positional accuracy using code measurements, both the original raw codes and the classically smoothed codes are tested. Here, the classical smoothing of codes was performed by applying the original Hatch filter, using weight increment of 0.01 [10]. This implies a full weight for the phase measurements after 100 epochs (25 minutes).

In the current assessment process, only one session is used (from 8:00 pm to 10:00 pm). Concerning the smoothing of the codes, a MATLAB program was prepared to apply the smoothing algorithm. All visible satellites, at each station, are smoothed. The smoothing process started at the epoch of the satellite rising. This implies different smoothing start times for the same satellite at different stations.

For each of the two performed solutions, absolute coordinate discrepancies are computed at each of the considered 7 stations as:

$$\delta E_i = |E_{R.S.} - E_{T.S.}| \qquad (2)$$

$$\delta N_i = |N_{R.S.} - N_{T.S.}| \qquad (3)$$

Where:

δE, δN	Coordinate discrepancies
R.S.	Reference Solution (Using phases)
T.S.	Tested Solution (raw and smoothed codes)
i	Considered station (i = 1, 2, …7)

Equations (2) and (3) were applied twice, at the considered 7 stations, using both raw and smoothed codes. The resulted discrepancies are drafted in figures (2) and (3), for Easting and Northing discrepancies, respectively.

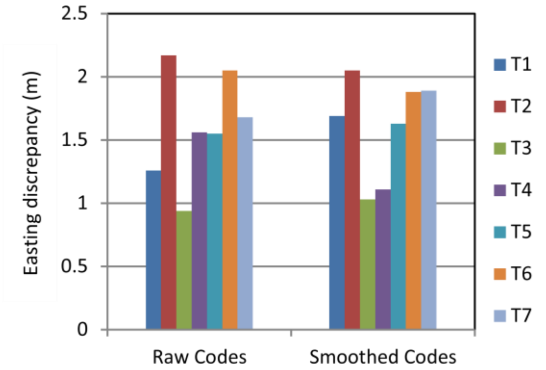

Fig. 2. Easting discrepancies using raw and smoothed codes

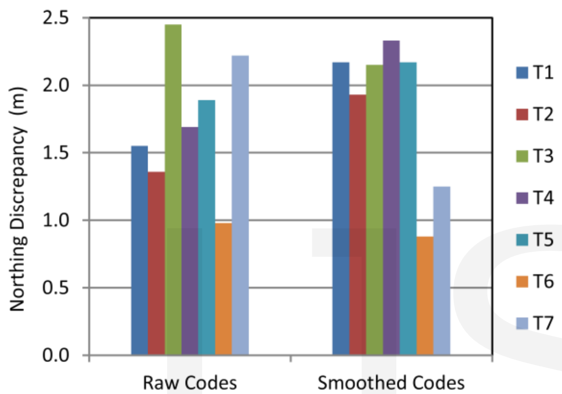

Fig. 3. Northing discrepancies using raw and smoothed codes

As mentioned before, the main target of this paper is to achieve the highest possible convergence between the resulted positional discrepancies, at different stations, using smoothed codes. Although this convergence can be checked visually by observing the fluctuations of each 7 bars in figures (2 and 3), it is of great importance to express this convergence numerically. So, a new numerical indicator is established in this paper to achieve this goal. Such indicator is named Error Stability Indicator and will be denoted as (E.S.I.).

Error stability indicator (E.S.I.) is established as the mean of the absolute values of the differences between the mean coordinate discrepancy of all stations and the coordinate discrepancy at each station (computed using equations 2 and 3). Such indicator is computed individually for both E and N coordinates. Mathematically, the Error Stability Indicator (E.S.I.) can be expressed as:

$$E.S.I._E = \frac{\sum_{i=7}^{i=1} \left| \frac{\Sigma \delta E_i}{i} - \delta E_i \right|}{i} \qquad (4)$$

$$E.S.I._N = \frac{\sum_{i=7}^{i=1} \left| \frac{\Sigma \delta N_i}{i} - \delta N_i \right|}{i} \qquad (5)$$

Where:

$E.S.I._E$ Error Stability Indicator in East direction
$E.S.I._N$ Error Stability Indicator in North direction
δE_i Discrepancy in E direction, computed at station (i)
δN_i Discrepancy in N direction, computed at station (i)

Equations (4) and (5) were applied for both raw and smoothed code solutions. The resulted E.S.I. values, in both E and N directions, are plotted in figure (4).

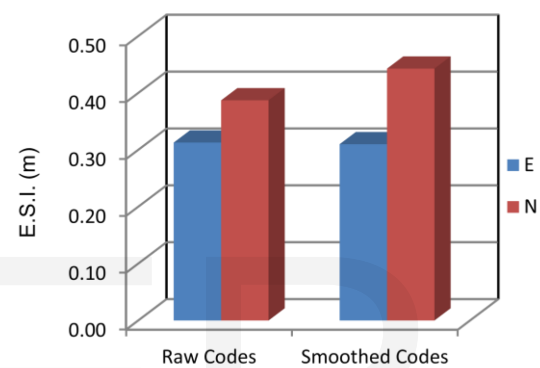

Fig. 4. Resulted E.S.I. for both raw and smoothed codes

By noticing figure (4) it is very obvious that neither raw nor smoothed codes yielded any convergence in the positional errors. This is reflected by the relatively high values of the resulted E.S.I. Moreover, the application of the smoothed codes degrades such thought convergence as its E.S.I. values are higher than that of the raw codes.

4 Supervised Code Smoothing

As shown in the previous trial, there is a clear divergence among the positional errors deduced by using smoothed codes. Such divergence is reflected by the large computed E.S.I. values. Also, the resulted divergence among the positional errors increased by applying smoothed codes than that in the case of applying raw codes. This expected result can be simply referred to the well-known fact that smoothed codes are biased with different values. This is due to the different degree of smoothing, for the same satellite, at different stations. In other words, the smoothing process started for any satellite at its rising epoch, which differs among stations (figure 5). This is the basic motivation behind the thought concept of supervised code smoothing.

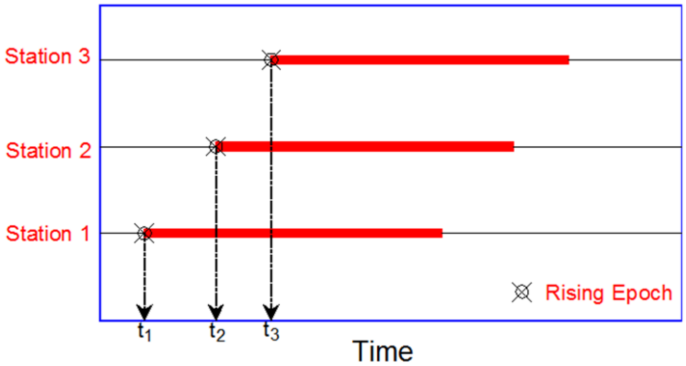

Fig. 5 Concept of supervised code smoothing

The main idea of supervising the code smoothing process is based on unifying the starting epoch of the smoothing process at all stations. Referring to figure (5) it can be seen that, the same satellite rises at different times with respect to different stations. This yields different weight factors for the phases at these stations. Consequently, smoothing bias will be different, for the same satellite, at different stations. Instead of this classical scenario, the smoothing process is proposed to start at the last rising epoch among all stations (which is t_3 according to figure 5). This idea grantees the same weight for the phases at all stations, which will certainly be reflected as similar values for the biases in the smoothed codes.

5 Application of the Supervised Code Smoothing

To study the effect of supervising the code smoothing process, many trials were performed. In each trial, the number of supervised satellites is changed, whereas raw codes at the remaining un-supervised satellites are used. Here, the same previously used 2 hours session is used (from 8:00 pm to 10:00 pm). In this session, there were 7 common satellites among the considered 7 stations. In the first trial, supervised code smoothing was applied to only one satellite and the remaining 6 satellites are entered to the solution using their raw codes. In all subsequent trials, the number of supervised smoothed satellites is increased by one till reaching the supervised smoothing of all the 7 common satellites. Classical Hatch filter was applied, with a weight increment value of 1% [10]. A MATLAB program was prepared for performing all the required computations. Table (1) summarizes the properties of the performed 7 supervision processes.

Table 1
Properties of the tested supervision processes

Trial No.	No. of Supervised Satellites	Supervision Action: No. of modified smoothing starting epochs	Supervision Action: Delay of smoothing starting epoch (minutes)
1	1	-------	-------
2	2	1	0.75
3	3	2	0.75, 1.00
4	4	2	0.75, 1.00
5	5	2	0.75, 1.00
6	6	3	0.75, 1.00, 1.50
7	7	4	0.75, 1.00, 1.50, 1.75

For the seven performed trials, the resulted codes from the supervised smoothing process are entered in the network solution (besides the raw codes of the unsmoothed satellites). In each solution, coordinate discrepancies are computed using equations (2) and (3). Statistics of the resulted discrepancies at the seven points are listed in table (2).

Table 2
Statistics of the resulted coordinate discrepancies using different supervision trials

Solution	Coordinate discrepancies (m) Easting Max.	Easting Min.	Northing Max.	Northing Min.
Trial 1	2.01	1.01	1.91	0.89
Trial 2	2.11	1.17	2.04	1.15
Trial 3	2.12	1.46	1.88	1.02
Trial 4	2.11	1.56	1.78	0.99
Trial 5	1.68	1.22	1.31	0.77
Trial 6	2.26	1.99	1.36	1.25
Trial 7	2.89	2.81	1.74	1.68

To better recognize the behavior of the resulted positional discrepancies in the performed supervised smoothing trials, the corresponding E.S.I. values are computed for the seven performed trials (using equations 4 and 5). Results are depicted in figure (6).

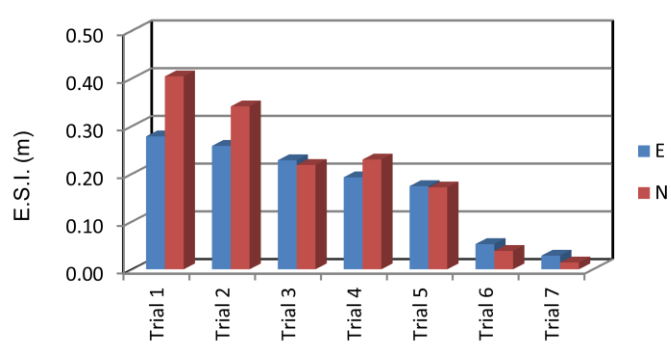

Fig. 6 E.S.I. values for the performed supervised smoothing trials

Referring to table (2) it is evident that the resulted discrepancies are fluctuating up and down (in both directions) with increasing the number of supervised smoothed satellites. On the other hand, figure (6) shows very clearly that a great convergence among the resulted discrepancies can be achieved by increasing the number of supervised smoothed satellites. This is reflected by the rapid degradation of the E.S.I. values in figure (6). So, it can be said that the proposed supervised code smoothing approach is very useful in maintaining very similar values of coordinate discrepancies at all stations regardless the value of such discrepancies. By maintaining these discrepancies almost the same at all stations, the occupation of only one pre-positioned station can be considered as an ideal solution.

6 Effect of Reducing the Length of the Used Session

As mentioned before, one of the main objectives of this paper is the reduction of the required relatively long sessions implied by phase solution. So, after introducing and testing the approach of supervised code smoothing, it is of great importance to study the ability of using this approach using sessions shorter than the used two hours session. To achieve this goal, six different session lengths were tried. These sessions started with clear 5 minutes session (after applying the supervised smoothing concept shown in figure 5) up to the previously applied 2 hours session. Of course, all sessions shorter than 25 minutes were not sufficient to reach the full weight of phases. So, phase weight increment (which was 0.01 in the previous trial) was modified in some sessions. Characteristics of the tested session lengths are summarized in table (3).

Table 3
Characteristics of the tested session lengths

Clear time (min.)	Original time (min.)	Phase weight increment	Time to reach full weight for phases (min.)
5	6.75	0.10	2.50
10	11.75	0.04	6.25
15	16.75	0.02	12.50
30	31.75	0.01	25.00
60	61.75	0.01	25.00
120	121.75	0.01	25.00

In all the tested sessions, the concept of supervised smoothing was applied to all the visible satellites and the whole network was solved using smoothed codes. The resulted coordinates are compared to the reference coordinates (phase solution) and the corresponding discrepancies are computed. The resulted discrepancies exhibited very significant tendency to increase with decreasing the session length. However, the main factor in the proposed approach is the degree of convergence of the coordinate discrepancies among the different stations not the values of the discrepancies. So, the E.S.I. values are computed for the tested six sessions. Results are given in figure (7).

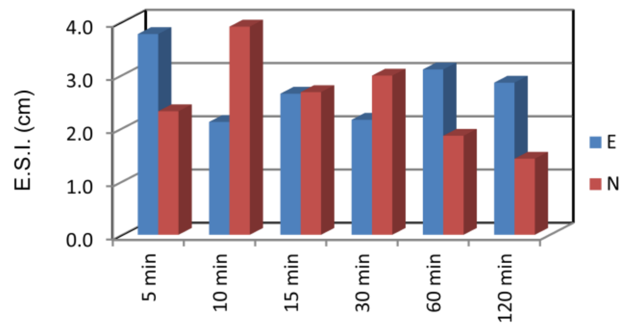

Fig. 7 Resulted E.S.I. values for different session lengths

Based on figure (7) it can be shown that the resulted E.S.I. values are fluctuating randomly up and down with changing the length of the used session. In addition, even with a session length of only 5 minutes, E.S.I. values less than 4 cm can be obtained for both coordinate components. So, a great saving of occupation time can be achieved by applying the proposed concept of supervised code smoothing.

7 Assessment of the Efficiency of the Proposed Approach During Different Times of the Day

It is well known that most of GPS biases are varying along the day especially both tropospheric and ionospheric errors. Also, all the previous tests were performed in the same site conditions (from 8:00 pm to 10:00 pm). So, it is of great importance to check the stability of positional errors at different times along the day. This is to validate the obtained results at any conditions, and hence, the proposed approach of supervised code smoothing can then be generalized.

As mentioned before, data were collected for one complete day at all the seven considered stations. To check the validity of the proposed approach during different times of the day, these 24 hours of data were divided into six equal 4 hours sessions. At the middle of each session, a sample of 5 minutes was picked out. This yields six different data samples representing the whole day. Although it was decided to pick out the data samples at the middle of each session, some slight backward and forward shifts were done during picking the six samples. This was done to unify the number of common satellites, at all stations, in all the tested samples. Characteristics of the selected six samples are given in table (4).

Table (4)
Characteristics of the assigned samples along one day

Sample No.	Session Time		Sample Start Time
	From	To	
1	00:00 am	04:00 am	02:00:45 am
2	04:00 am	08:00 am	06:01:00 am
3	08:00 am	12:00 pm	10:00:00 am
4	00:00 pm	04:00 pm	02:01:45 pm
5	04:00 pm	08:00 pm	06:00:00 pm
6	08:00 pm	00:00 am	10:02:00 pm

For all the selected six samples, phase weight increment of 0.1 was used. Also, the supervised code smoothing approach was applied for all the common satellites (particularly 7 satellites). For each sample, coordinate discrepancies were computed using equations (2) and (3). Of course, such discrepancies exhibited significant variations along the same day. However, and referring to the main idea of the proposed approach, this will not affect the efficiency of the proposed approach which is based only on the degree of error convergence. So, E.S.I. values are computed for all the tested 6 samples. Results are summarized in figure (8).

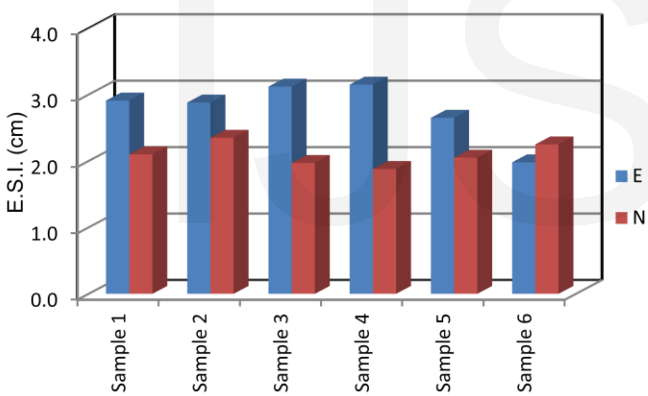

Fig. 8 Resulted E.S.I. values along the day

Based on the obtained results in figure (8) it can be said that the time of observation do not affect the convergence degree of the resulted coordinate discrepancies. This is reflected by the random fluctuations in the resulted E.S.I. values in figure (8). So, the proposed approach of supervised code smoothing can be applied successfully at any time within the day.

8 Conclusions

Based on the performed tests and the obtained results, many important conclusions can be extracted concerning the efficiency of the proposed approach which is based on the supervised smoothing of code measurements. Such conclusions can be summarized as:

- Classical smoothing of code measurements led to very significant positional errors. These errors can exceed the errors produced by raw codes.
- Supervising the code smoothing process by synchronizing its start for all the involved satellites leads to more similarity among positional error at different stations (lower E.S.I. values) regardless the value of such errors.
- Application of the supervised code smoothing to larger number of the involved satellites increases the convergence among the resulted positional errors.
- Length of the used session does not affect the resulted E.S.I. values. This means that error convergence is independent on the session length.
- E.S.I. values are independent on the observation time within the day.
- Great time saving can be achieved by applying supervised code smoothing approach.
- For medium GPS networks (up to 5km spacing), and with the existence of only one old control point, positional accuracy of better than 4 cm can be achieved by applying the proposed approach of supervised code smoothing.

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