A Database Method to Mitigate the NLOS Error in Mobile Phone Positioning

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***Abstract*-Non line of sight (NLOS) error is well known to be a major source of error in mobile phone positioning. It is simply caused by the dense buildings blocking the line of sight (LOS) propagation of RF signal. Hence mobile station (MS) appears further away from the base transceiver station (BTS) than it actually is. To mitigate the effect of NLOS error, a basic method is to generate the NLOS error correction map, and then use the correction map to correct the measurements. Therefore, a more accurate MS location can be estimated. How to efficiently generate the correction map is a major problem of this approach. A method based on the spatial correlation is proposed in this paper. An experiment was carried out in a typical suburban area to verify this idea. The test result shows the proposed method based on universal kriging can improve the accuracy of position estimate using time difference of arrival technique.**

I. INTRODUCTION

Utilizing mobile phone networks for positioning has been a hot research topic since the end of 1990's. To meet most of the requirements for applications in location-based services (LBS), much attention has been focused on the signal time delay and angle of arrival measurements. Generally, approaches based on time-of-arrival (TOA) or time-difference-of-arrival (TDOA) and angle-of-arrival (AOA) measurement can greatly improve the accuracy of position determination. Unfortunately the main shortcoming of these methods is that they require line of sight (LOS) propagation for accurate location estimates. However, non line of sight (NLOS) error is the dominant error in location estimation in urban or suburban area where people are more interested in the mobile user's (MU) location [1]. When direct signal paths between handset and base transceiver station (BTS) are mostly obstructed by buildings and other structures, alternate, reflected paths dominate. These paths are longer, affecting TDOA and TOA methods, and arrive from a different direction, affecting AOA. TDOA and TOA NLOS errors are always positive, i.e. the path is longer, but range from a small number to thousands of meters [2] [3], depending on the propagation environment. Reference [4] studied the effect of NLOS error on the performance of AOA technique in position estimation. The study shows when a NLOS condition is presented for only one BTS, the estimation error of AOA technique increases 10 times or so. This is not surprising because in the worst case, an AOA error of 180˚ is possible.

To mitigate position estimates from NLOS error corruption, different approaches have been investigated. In [5], the authors used an algorithm based on the probability density function (pdf) model to reduce the NLOS error. However, it is difficult to formulate the pdf, and this function should vary with the changing environment. A general method used to mitigate the NLOS error is error identification and reconstruction. Reference [6] explained, by using the time history of the range measurements in a simple hypothesis test, and exploiting the knowledge of the standard deviation of the standard measurement noise, one can determine if the measurements correspond to a LOS or NLOS environment. A two-step LOS reconstruction was proposed. First the data was smoothed by N^{th} order polynomial fit, then the knowledge of the standard measurement noise was utilized to correct the NLOS error. Similarly, reference [3] identify the NLOS from the range characteristic and reconstruct the LOS ranging using a Kalman filter. While in [7], the NLOS BTS detection was based on an assumption that if a large NLOS error exists for a particular BTS, on the average the residual will be large in magnitude. This requires redundant measurements. Furthermore, in [8], two approaches were proposed to detect the NLOS error depending on how much a priori information is available. An NLOS State Estimation algorithm could be used with some prior information on NLOS errors available from an empirical database. In the case with no knowledge of NLOS, an improved residual algorithm could be applied to detect a small number of NLOS BTSs (treating NLOS corrupted measurements as outliers and rely solely on the knowledge of Gaussian measurement noise). Another approach consists of exploiting the redundant information present in the measurements to detect and reject the NLOS errors. The main contribution in this direction was presented in [9] where the problem was formulated in terms of hypotheses, where each hypothesis corresponded to a set of BTS considered under NLOS scenarios. The algorithm presented there was based on a weighted combination of the partial position estimates associated to each hypothesis. A well-known category of NLOS error mitigation method is constrained optimization method. This method is to exploit the property that the NLOS errors are always positive errors, then to search the true position by adding some constraints such as penalty function [1] [10]. In [11], mathematical programming is used to find the ML (maximum-likelihood) estimate of the source position in the restricted domain defined by the inequalities induced due to NLOS propagation.

Unfortunately, none of these methods can solve the NLOS problem adequately, since too many elements affect the signal propagation, and the propagation environment varies from place to place. Especially in urban or suburban areas, NLOS propagation is common for radio frequency (RF) signal. Often, only 1 or 2, even none of the signals from BTSs (or MS) can propagate in LOS scenario. The NLOS error mitigation is a classic problem, which could be solved using a basic database method.

In the following sections, a database method based on universal kriging (UK) is discussed first. Then wireless signal map matching (WSMM) is introduced. After the introduction and discussion of an experiment in a typical suburban area, the concluding remarks are given.

II. DATABASE METHOD

Before the discussion of database method, it is necessary to investigate the measurement will be used in this research. As mentioned previously, AOA, TOA or TDOA etc. can all be used for mobile phone positioning. To obtain the AOA measurement, expensive receiving antenna arrays are needed [12]. Hence, researchers are more interested in TOA or TDOA measurements at this stage (the situation could be changed after the third generation networks have been deployed). Using TDOA does not require the signal transmission time from the handset, so there is no need to synchronize handset with the BTSs very accurately. Therefore TDOA measurements are more convenient than TOA measurements. In this research, the NLOS error for TDOA measurements is utilized; it can be easily extend to other measurements.

TDOA measurement multiplying speed of light gives the range difference measurement. The range difference measurement determines a hyperbola with the two BTSs as foci. Generally, two TDOA measurements, which need at least three BTSs, can determine the transmitter's location, that is, the intersection of the two hyperbolas. Fig. 1 depicts the principle of location determination using TDOA measurements where BTS0 is the reference. Many algorithms have been proposed to calculate the MU's position such as Taylor-series method [13], Friedlander's method [14] and Chan's method [15]. Taylor-series method is an iterative algorithm, starts with an initial guess, and improves the estimate at each step using least-squares. This method can provide a precise position estimate at reasonable noise levels. In this research, the TDOA measurements are always contaminated by NLOS error which are from few meters to hundred meters. Hence Taylor-series method was chosen although it sometimes has the risk of divergence during the processing (tuning is necessary in this case).

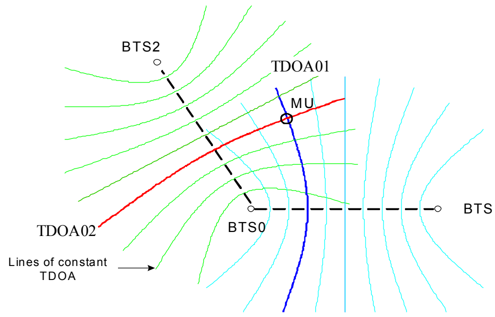


Fig. 1. Location determination using TDOA measurements

The principle of database method is simple. Assuming there are several reference points (RP) with known coordinates, the NLOS error can be directly extracted from the reference measurements at the RPs, and logged in a database for further usage (generate the correction map). Reference [16] describe methods for collecting data to create the database. But the data collection and database maintenance is quite a costly and laborious process. Generally, more reference points can help to generate a database that can describe the real situation more precisely. But despite the number of reference points being measured, the area of interest cannot be completely covered. On the other hand, to make the data collection and database maintenance easier, less data are preferred during the collection stage. *Is it possible to using small amount of data (NLOS error correction) to describe the profile of the whole area of interest? If the answer is yes, how can we efficiently solve the problem?* Hence, the basic hypothesis is that the NLOS error has a spatial correlation (it is further discussed later).

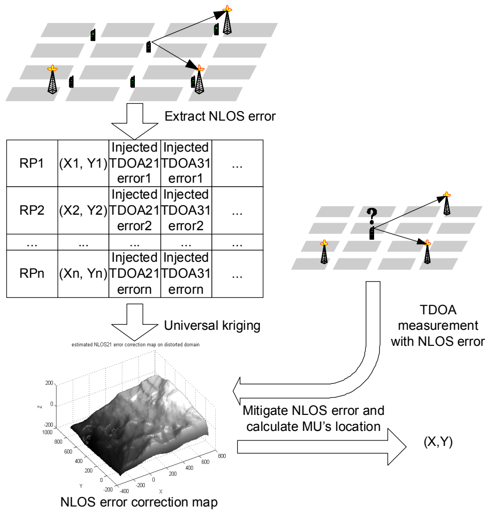


Fig. 2. The procedure of database method: first, the NLOS error correction map is generated, and then the TDOA measurements of MU can be corrected.

Our database method is based on the spatial correlation, and utilizing interpolation technique to generate the NLOS error correction map. Fig. 2 describes the procedure of this method. As NLOS error is environmental related error, if the environment doesn't change or doesn't change significantly, once the correction map has been generated, it can be used for a long period. And the map can also be updated since the RPs information can be updated. The key aspect of this method is the NLOS error correction map generation.

To efficiently yield the correction map, UK is utilized as it has a lot of advantages. Kriging is based on well-developed statistical theory for geospatial analysis and was first used in mining industry. The basic tool, the variogram, is used to quantify spatial correlations between observations [17].

The NLOS error sampled at location x can be expressed as

$$Z(x) = f_0(x)\beta_0 + f_1(x)\beta_1 + \ldots + f_p(x)\beta_p + \delta(x) \tag{1}$$

where $\beta_0,\ldots, \beta_p$ are unknown parameters; $\delta(x)$ is intrinsic and $E[\delta(x)] = 0$. In matrix notation, the above expression can be written as

$$Z = X\beta + \delta \tag{2}$$

To predict $Z(x_0)$ the UK predictor is a linear combination of values of the sample $Z(x_i)$

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{3}$$

where λ_i is the weighting factor. After a series of deduction, a linear equation can be obtained

$$\begin{bmatrix} \Gamma & X \\ X^T & 0 \end{bmatrix} \begin{bmatrix} \lambda \\ m \end{bmatrix} = \begin{bmatrix} \gamma \\ f \end{bmatrix} \tag{4}$$

where m consists of the Lagrange multipliers and

$$\Gamma = \begin{bmatrix} \gamma(x_1 - x_1) & \cdots & \gamma(x_1 - x_n) \\ \vdots & \gamma(x_i - x_j) & \vdots \\ \gamma(x_n - x_1) & \cdots & \gamma(x_n - x_n) \end{bmatrix}$$

$$X = \begin{bmatrix} 1 & f_1(x_1) & \cdots & f_p(x_1) \\ \vdots & \vdots & f_i(x_j) & \vdots \\ 1 & f_1(x_n) & \cdots & f_p(x_n) \end{bmatrix}$$

$$\gamma = [\gamma(x_0 - x_1) \quad \cdots \quad \gamma(x_0 - x_n)]^T$$

$$f = [1 \quad f_1(x_0) \quad \cdots \quad f_n(x_0)]^T$$

$$\gamma(h) = \frac{1}{2} Var[Z(x+h) - Z(x)] : \text{variogram}$$

So, the result is

$$\lambda^T = \left[\gamma + X\left(X^T\Gamma^{-1}X\right)^{-1}\left(f - X^T\Gamma^{-1}\gamma\right)\right]^T \Gamma^{-1} \tag{5}$$

γ (variogram) is basic tool in kriging, the details of it can be found in [18]. In [19], the variogram of injected TDOA NLOS error was discussed and a simulation of NLOS mitigation can be found.

After the generation of the correction map, the rest work is straightforward. When MU requests his position, the TDOA measurements with NLOS error are obtained by location center. Then the correction map is used to mitigate the NLOS error. Eventually, the MU's location is estimated based on the corrected TDOA measurement. Finally, the MU's position is sent to the user.

III. WIRELESS SIGNAL MAP MATCHING

Obtaining the reference points and their measurements is prerequisite in our database method. A survey can be carried out in the area of interest, and the coordinate of the RPs, the TDOA measurements can be acquired. However, special instruments and extensive labor are required to get sufficient measurement. To eliminate the need for expensive outdoor surveying, a new wireless signal map matching (WSMM) concept was recently introduced [20].

The key idea of the WSMM is the automatic extraction of the RPs based on the relationship between an electronic map (ideal map) and the fully populated anonymous user distribution (distorted map). A prerequisite of WSMM is the large amount of the TDOA measurements.

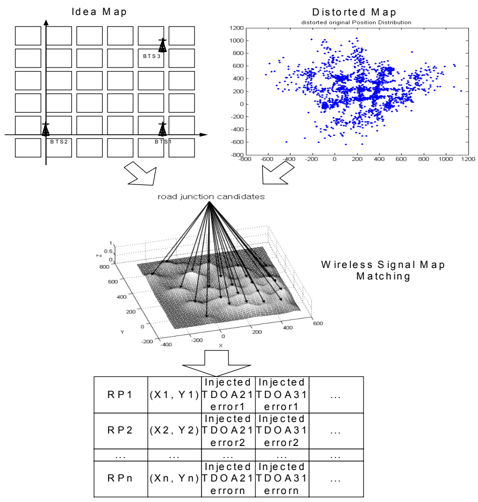


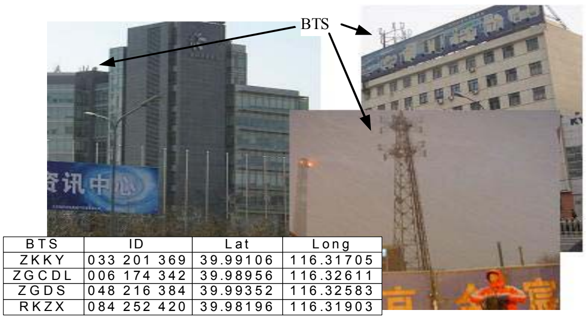
Fig. 3. Extraction of the RPs in WSMM, the candidates of RPs are the intersections, the points close to the BTS etc.

The simulation of WSMM can be found in [20]. The difficulty to verify this idea is the acquisition of large amount of the measurements.

IV. EXPERIMENT

To verify the proposed database method, an experiment was carried out using a CDMA (Code Division Multiple Access) network in a typical suburban environment in Beijing, China (see Fig. 4). In such an environment, NLOS propagation can be expected. The test area is about 1km by 2km and in total there are 4 BTSs. At least 8 BTSs are located in the adjacent areas. To simplify the experiment, the test area is further divided into 2 small areas (partly overlapped), named area A and area B. In each small area, 3 BTSs are distributed evenly. As we know, a typical BTS has 3 sectors and each sector has a unique ID. Hence each sector (antenna) can provide a TDOA measurement. However, the 3 sectors are part of one BTS, so they have the same or very similar location. From the trilateration positioning point of view, the 3 sectors can be only used as one base station because the measurements must come from spatially diverse locations. The coordinates of these BTS are prerequisite. Fig. 5 shows some BTSs and also gives the coordinates of these four BTSs. A standard CDMA2000 1x handset was used to collect data. A normal GPS receiver was used to provide the 'true' location of MU.

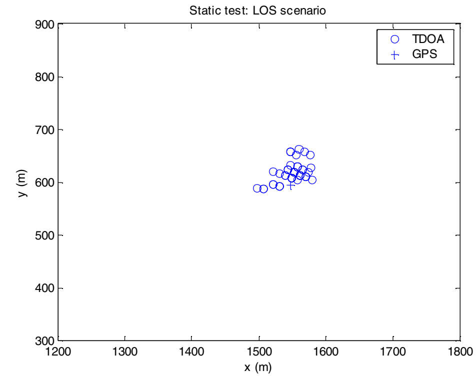
Fig. 4. A typical suburban area in Beijing where the experiment was carried out in



BTS	ID	Lat	Long
ZKKY	033 201 369	39.99106	116.31705
ZGCDL	006 174 342	39.98956	116.32611
ZGDS	048 216 384	39.99352	116.32583
RKZX	084 252 420	39.98196	116.31903

Fig. 5. Some BTSs used in the test

First, a static experiment was carried out. The test points were chosen carefully: at one test point, the handset could receive more than 3 LOS signals, while at the other test point, the handset could only receive NLOS signals. TDOA measurements of three LOS BTSs (for the first test point) or NLOS BTSs (for the second test point) with good geometric distribution were utilized to compute the position of the test points. Fig. 6 shows the results of this test. One can see, in the NLOS scenario, the noise level increases significantly comparing with the LOS scenario. Using GPS solution as the 'true' value, Table 1 summarizes the experiment results. The standard deviation in x direction increases from 20m to 44m, and that in y direction change from 19m to 90m. In the NLOS scenario, the magnitude of noise is very large, hence the effect of NLOS propagation can hardly be detected only use few measurement. To reduce the noise effect, the more measurements collected at one point the better. The results also depict the effect of NLOS error (precisely, other errors, such as the error of the position of BTSs, the error caused by ignoring the effect of the height of the BTSs etc., are considered as part of the NLOS error), there is a evident offset between the true position (using GPS) and the calculated position based on TDOA measurements in the NLOS scenario.



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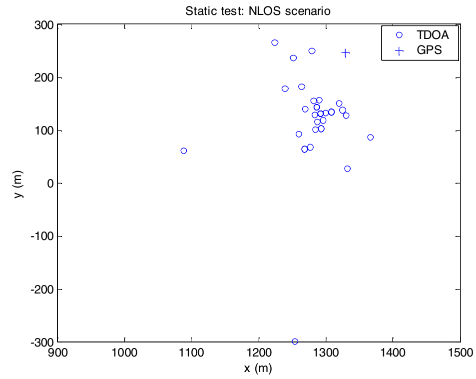


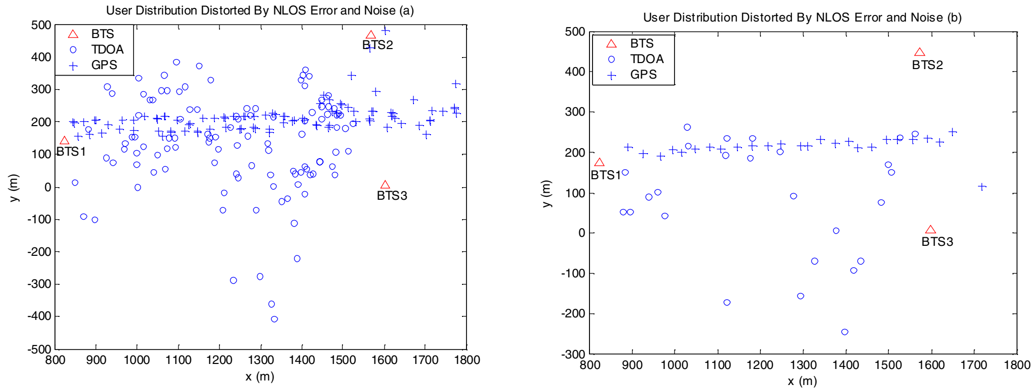
b

Fig. 6. The results of static test using TDOA measurements (GPS provide the 'true' value); (a) LOS scenario and (b) NLOS scenario

TABLE 1
RESULTS OF STATIC EXPERIMENT

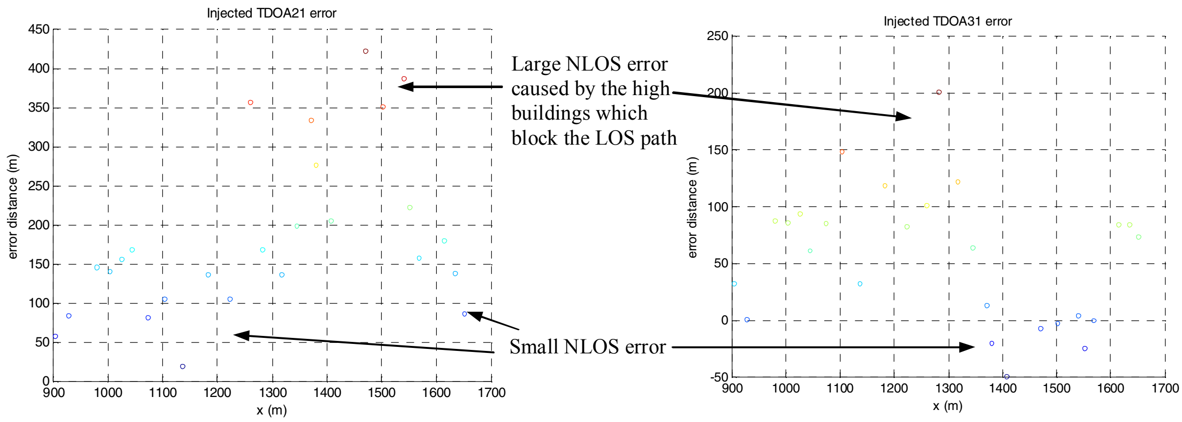
	Standard deviation (m)		Mean error (m)	
	X	Y	X	Y
LOS test	20	19	2	24
NLOS test	44	90	48	129

Then, we walked along the nearby streets, and several thousands of measurements were taken. The position provided by GPS was used as the 'truth' reference (because of the blockage of satellite's signal by the buildings, sometimes map matching was used to correct the offset). Fig. 7 depicts the test results along a main street in test area A. Part (a) is based on data collected at densely distributed test points (the average interval of the test points is about 15 m), and at each point, only 2 measurements were taken (the average of the measurements were utilized). Part (b) is based on data collected at less densely distributed test points (average interval is about 40 m), but around 30 measurements were acquired at each point. The results were distorted seriously because of the NLOS error. Part (a) also shows the effect of the noise. However, both of the two diagrams have a similar pattern. It indicates that the NLOS error has a fixed pattern along this street. Fig 8 illustrates the injected TDOA error along the main street. The street is of east-west direction (x axis). From the plots, we can see the spatial correlation of the injected TDOA21 error and that of the injected TDOA31 error.



a *b*

Fig. 7. User position distribution along a suburbans street in the presence of distorted by NLOS error and noise; (a) using dense test points but less measurements at each point and (b) using less test points but around 30 measurements at each point



a *b*

Fig. 8. Injected TDOA error along the main street; (a) TDOA21 and (b) TDOA31

After the data along the street in the test area had been collected, a distorted map was generated. Fig. 9 shows the ideal map which was based on GPS data, and the distorted map of area B as an example. The idea map was generated using GPS data. The different symbols in the distorted map indicate the different streets. Since the map has been deformed seriously, without those symbols, it is hard to find the streets. The noise and the rarity of test points made it almost impossible to find the intersections using the distorted map only. This is one of the difficulties in deploying WSMM in a real application. Assuming the intersections showing in the ideal map (indicated by circles) can be found, the proposed method can be utilized. The NLOS error can be mitigated more or less in that case. Fig. 10 compares the cumulative distance error distribution before and after using the correction map. The improvement is considerable. Before applying the correction, only 23% of the test points within 50m-distance error and close to 60% of the test points within 100m-distance error while after correction, those percentages increase to 49 and 86 respectively. One thing that must be emphasized is that only 4 reference points (the intersections) were utilized to generate the correction map. Intuitively, if more reference points were used, the result would be better. Similar improvements were also found in area A.

V. COUNCLUDING REMARKS

In this paper, a database method to mitigate the NLOS error in mobile phone positioning is discussed. The experiment verified the idea. However, from the experiment, it is observed that the noise level is much higher than what anticipated; and it gets serious in the NLOS scenario. This makes the detection of the reference points extremely complex and difficult. Apparently, this is the major problem for WSMM. As a very large number of measurements are necessary for further investigation, collaboration is needed. Future work will focus on noise reduction and reference point detection.

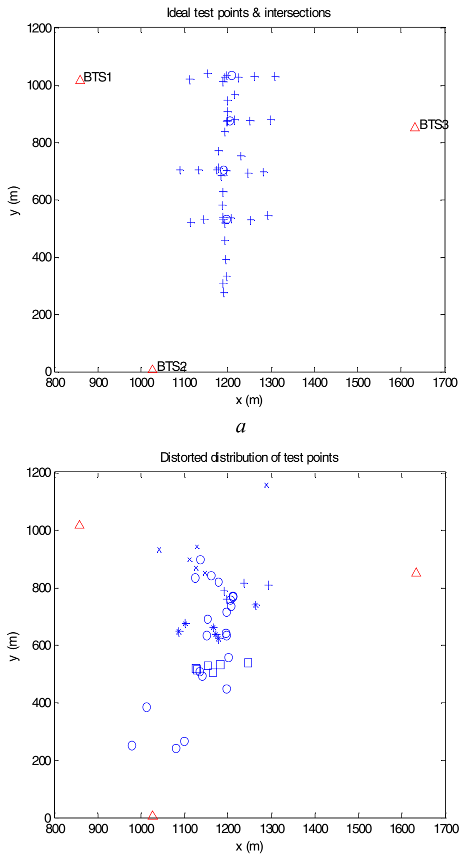


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Fig. 9. The idea map (a) and distorted map (b) of test area B. The circles in idea map indicate the intersections; the different symbols indicate the test points from different streets.

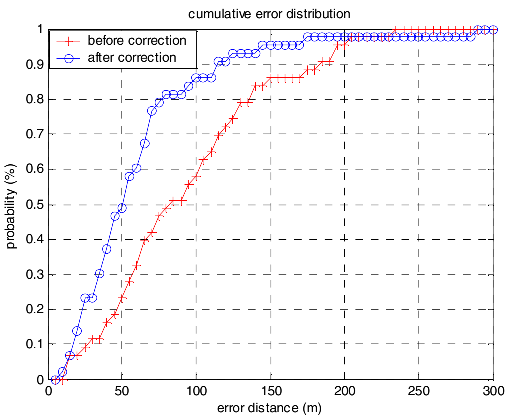

Fig. 10. Cumulative error distribution before and after applying the correction

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