Application of the Automated Control System for Reference GNSS Station Network in the Transport Sector

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Abstract. Achieving high accuracy by GNSS (Global Navigation Satellite System) positioning is in demand in many industries, including transport, where ensuring the positioning of moving vehicles with an accuracy of 1-3 meters is an essential condition in the development of intelligent systems for monitoring and optimization of road traffic. In this case, the task should be solved in such a way as to be accessible to a wide range of users, and thus be simple and cheap. In this paper, in order to achieve accurate GNSS positioning of a moving car is considered the use of a smartphone, as the most popular navigation device of a typical user, raw data of which is processed by differential correction using the Automated Control System for Reference GNSS Station Network. Positions obtained by smartphone is compared with data obtained by the u-blox receiver. The experiment is conducted in an urban area typical for Kazakhstan. It is shown that using a smartphone as a navigation aid with a further differential correction from one reference station allows positioning with accuracies at least of 1.4 meters.

Keywords: High accuracy positioning; Lane-level positioning; Vehicle navigation; Software.

1. Introduction
Developed and implemented in the second half of the last century, GNSS (Global Navigation Satellite System) GPS (Global Positioning System) and GLONASS (GLObal NAvigation Satellite System), as well as the later Beidou and Galileo systems, nowadays solve a wide range of tasks of navigation and coordinate time support. To determine the location of objects, satellite navigation systems use two types of positioning: absolute and relative (differential), which use data from both code and more accurate phase measurements. Differential positioning, which consists in processing (differential correction) of GNSS signals using reference stations with known coordinates, is characterized by higher accuracy [1]. Among the technologies providing high accuracy of navigation, determinations are considered technologies of navigation of dynamic objects RTK (Real Time Kinematic) and NRTK (Network Real Time Kinematic) described in details by [2] and static objects PPP (Precise Point Positioning) examined in [3, 4], the use of which can provide accuracy at the level of decimeters and centimeters, and sometimes even millimeters.

High-accuracy positioning technologies developed by GNSS have opened up new possibilities, being amply applied in such applications as surveying, e.g. creation of geodesic networks, levelling works and study of geodynamic processes [5, 6], mapping, e.g. land management and cadastres [7], precision agriculture, e.g., soil sampling, yield monitoring and chemical and fertilizer application [8, 9], environment monitoring [10, 11]. In addition, GNSS solves many transport tasks, the most striking example of which is personal vehicle navigation. The application of high accuracy GNSS considerably expands the available possibilities, for example, it makes it possible to develop systems of remote control and monitoring of unmanned vehicles (self-driving cars) and aircraft (drones), so-called
unmanned ground vehicles (UGV) and unmanned aerial vehicles (UAV) studied by [12, 13], as well as intelligent transport systems for various purposes according to [14, 15].

Different transport tasks require different levels of accuracy. For example, 15 m accuracy provided by cheap receivers is quite enough for creating the route from point A to point B, and expensive navigation sensors and controlled operation conditions are necessary for the implementation of unmanned systems as pointed out by [16]. At the same time, there are intermediate tasks as defined in [17], e.g. control and navigation of transport at lane-level, which requires submeter-accurate positioning. In particular, lane-level vehicle positioning requires the accuracy of navigation determinations at the level of 1-3 m as per [16, 18].

The relevance of developing lane-level positioning of vehicle technologies lies in providing drivers of vehicles with information that will allow them to optimize the traffic route. In particular, the application of lane-level positioning will make it possible to assess the congestion of individual road lanes, to predict changes in the situation on individual road lanes and to prevent collisions with obstacles in a certain lane as also noticed by [16, 18]. Such information is particularly important in order to improve the efficiency of emergency service vehicles to get to the right place as quickly as possible, but will also be used by ordinary users. Moreover, such information will make it possible to control dedicated public transport lanes and public transport itself. Thus, the widespread of lane-level positioning will make it possible to significantly improve the existing geo-information systems, which currently provide information on traffic congestion by dividing them only by traffic directions.

Although, in massive applications, the corrections are needed in real-time, post-proposing can also be useful, for example, to collect statistical data on the traffic load on individual lanes, which can be used to plan the repair of the roadway, to justify the need for the construction of junctions, to improve the efficiency of traffic management systems, etc.

The current trend in high precision positioning technology is the spread of high accuracy GNSS positioning on mass-market applications. The implementation of high precision positioning in the mass market involves the use of an inexpensive navigation receiver, which will be available to users without experience on professional navigation equipment. In this regard, the authors of many works were faced with the task of using inexpensive receivers for high precision GNSS positioning for various applications. For example, the authors of [19, 20] consider the possibility of using low-cost GNSS receiver for geodetic applications and geomatics, and in [21] the subject of research was the implementation of local monitoring of displacement, for example, landslides, using GNSS positioning with a low-cost GNSS receiver.

Thus, in this paper the task of studying the possibility of using a smartphone with a standard single frequency navigation receiver to determine the location of the vehicle on the lane level with an accuracy of 1-3 meters using the Automated Control System for Reference GNSS Station Network.

2. Related Studies

In general, vehicles are navigated in three types of terrain characterized by environmental conditions affecting GNSS signal propagation: open terrain (i.e. semi-urban and residential area), intermediate terrain (urban area) and difficult terrain (urban canyons), that is characterized by densely constructed buildings and densely planted trees.

There are two problems, when there are too many obstacles to the spread of the GNSS signal. The first problem is the ability to block the signals of significant number of satellite, resulting in too few visible satellites to accurately calculate trilateration. The second problem is that there are many reflecting surfaces that reflect GNSS signals, which contributes to the determination of pseudo-range and thus position. When reflecting GNSS signals, the end-user receives either only reflected signals (non-line-of-sight reception) or both direct and reflected signals at the same time, resulting in multipath interference at the receiving location [17, 22, 23]. An error of location associated with these effects could reach from several tens to 100 or more meters as it is shown in [23, 24].

The problems of non-line-of-sight reception and multipath interference are mostly evident in urban canyons characterized by the close proximity of skyscrapers. There are a lot of experimental and theoretical works considering different vehicle navigation in urban canyon approaches. Under these conditions, high accuracy positioning can only be achieved using GNSS data along with additional
information, because the usage of differential correction only does not produce effective results. For example, [17, 23] propose to improve the accuracy of GNSS positioning by taking into account the tall buildings using a 3D map of the city buildings, which allows taking into account the spread of GNSS signals. It is shown that the navigation of the vehicle using a method that combines GNSS data and 3D maps is performed with an error of up to several meters. In addition, for navigation tasks in urban canyons, methods using a combination of GNSS with various sensors, such as gyroscopes, accelerometers, odometers, etc., and supplemented with 3D map data are considered, e.g., in [25]. At the same time, in the case of open and intermediate terrain (i.e. semi-urban and residential, urban areas), precision positioning error is less affected by non-line-of-sight reception and multipath interference. Therefore, in these areas, as a rule, high-precision positioning is implemented with the use of GNSS receiver and differential correction technologies [26, 27, 28, 29]. Often, for transport purposes, researchers consider as a rover high-priced professional receivers that provide accurate positioning at the level of centimeters and millimeters. For example, in [26] it was used an expensive GNSS receiver of geodesic class Trimble R10 and as a result of kinematic measurements in a residential area it was shown that multi-constellation GNSS in the selection of the optimal mask angle and data processing using RTK technology allows achieving accuracy at the level of a few centimeters in harsh environments with tree canopies. In [27] Topcon HyperPro+ was used as a rover and, having integrated the obtained results with odometry data, the accuracy of positions was also obtained at centimeter-level. Such solutions are relevant for navigation of unmanned moving objects (i.e. UAV and UGV), however, for lane-positioning there is no need in centimeter accuracy, and the use of high-precision professional navigation equipment will not allow introducing a massive application. So the positioning of transport in an urban terrain is an urgent task that requires an effective low-cost solution available to a large number of users is necessary.

In this regard, options for high-precision positioning of moving vehicles in urban environment are being studied, where a rover can be an ordinary smartphone [28, 29, 30], which is currently the most common navigation device for typical users. At the same time, an important fact is that the use of a smartphone not only allows users to significantly reduce the financial cost of using a system of lane-level positioning, but also does not require experience in working with complex navigation equipment. However, vehicle navigation in dynamic mode in an urban environment with a smartphone with standard positioning technique is carried out with an accuracy of 10-15 m [30]. High precision positioning using a smartphone is difficult without any external hardware and data correction, which is also noticed by [31]. For lane-level vehicle positioning, the differential correction relative to one reference station is effective. For example, in the works [28, 29] by processing raw observations obtained with a smartphone by RTK technology has reduced the error of positioning of a moving object in an urban environment to 1 m. Thus, the task of positioning transport in urban terrain is particularly relevant, as many cities are much less developed than urban canyons.

3. Correction Algorithm of Smartphone Location Using Reference Station Data

For solving the problem of increasing the accuracy of the location of a smartphone with a standard single frequency navigation receiver are used DGPS methods, the essence of which is to amend the initial data of the rover relative to the reference station. There are two known methods for implementing the DGPS method [32]: block shift and range corrections. Range corrections require the observables (pseudorange, carrier phase), which cannot be provided by the smartphone. At the same time, block shift method can be applied to already calculated coordinates.

Therefore, the accuracy of position data of rover, including smartphones, can be improved using based on block shift method DGPS-CP method, which is based on comparing a known reference station position and computing the corrected position [33].

For implementing the DGPS-CP method are used followings: data of the reference station; NMEA-0183 message data of the smartphone, which is located at a distance of no more than 30 km from the reference station; the Automated Control System for Reference GNSS Station Network (hereinafter referred to as the System) developed by the authors of this paper.

The main elements of the System are the control center and computing center, which are connected via the communication network to GNSS reference stations and system users. The computing center
receives input data from GNSS reference stations via communication network for processing and storage (i.e. data integrity control, calculation of navigation solutions, archiving) and NMEA-0183 message data of rover to apply differential corrections according to DGPS-CP method. Output data (i.e. corrected position of the rover) is provided to users connected to the System via a web browser in the screen form of a personal account on the information portal of the System after passing the identification, authentication and authorization. The algorithm for calculating corrections to raw data based on the DGPS-CP method is presented in figure 1.

The System operates raw data from the reference station (ephemeris, range correction) and data from the smartphone in a form of NMEA-0183 message via communication channels. Using ephemeris obtained from the reference station, and PRN (Pseudo-Random Noise) numbers of the satellites being used in the current solution and the Dilution of Position (DOP) from GPGSA sentence of NMEA data of the smartphone, the approximate position of current satellites is calculated.

Then the Pseudo Range Correction (PRC) $\delta \hat{\rho}$ for the satellite constellation is calculate using range correction data obtained from the reference station, and GPGSA data in the NMEA format of the smartphone. The calculated approximate position of satellites and current position fix data $x$ from GPGGA of NMEA allow defining observation matrix $H$. After that position-domain correction $\delta \vec{x}$ can be calculated using equation (1):

$$\delta \vec{x} = - (H^T H)^{-1} H^T \delta \hat{\rho}$$

where: $-(H^T H)^{-1} H^T$ – projection matrix, $\delta \hat{\rho}$ – PRC for the satellite constellation.

Then corrected position $x_{DGPS}$ of smartphone defines using calculated position-domain correction $\delta \vec{x}$ and position of the smartphone $x$ from GPGGA of NMEA using equation (2):

$$x_{DGPS} = x + \delta \vec{x}$$

Figure 1. The algorithm for calculating corrections to NMEA-0183 message data of rover based on the DGPS-CP method implemented in the computing center of the Automated Control System for Reference GNSS Station Network.
where: $x$ – current position fix data from GPGGA of NMEA, $\delta x$ – position-correction domain.

Currently, in the System post-processing of NMEA-0183 message data is realized. Providing real-time processing is the subject of further work, during which it is necessary to solve the task of exchanging data between smartphone and the System in real time, for example, through an application.

4. Experimental Part

To verify the possibility of lane positioning of vehicles using a smartphone with further differential correction of raw observations by the System, an experiment described below was conducted.

To experiment, the following items were used: the u-blox 6 receiver with an antenna, the smartphone Xiaomi Redmi Note 4X with NMEA Tools application installed in advance, the Trimble BD930 receiver with an antenna, the Automated Control System for Reference GNSS Station Network.

The u-blox 6 receiver is a dual-frequency navigation receiver that operates only on GPS signals and is characterized by 2.5 m positioning accuracy. The Xiaomi Redmi Note 4X smartphone's GNSS receiver receives signals from multiple GNSS (GPS+GLONASS+BeiDou+A-GPS). Other information about the navigation module characteristics in the smartphone is not provided by the manufacturer, but it is known that it belongs to the group of code receivers as defined in [30] with accuracy only at meters' level. The Trimble BD930 receiver is a dual-frequency receiver that supports GLONASS, GPS, BeiDou and Galileo signals and provides high accuracy (2-3 cm).

The smartphone and u-blox 6 receiver served as a rover and were installed inside the car for the duration of the experiment in order to study the possibility of using the system in real operating conditions. The Trimble BD930 receiver acted as a reference GNSS station and was installed on the roof of the Institute of Space Technique and Technologies in Almaty, Kazakhstan.

Raw data (ephemeris, range correction) from the Trimble BD930 receiver continuously collected in the System storage (the geographical coordinates of the Trimble BD930 receiver referenced to the WGS-84 datum are 43° 15.3047’ N, 76° 51.3976’ E, 727.675 m height).

The experiment consists of the following: the smartphone and receiver installed inside the car simultaneously record data in NMEA format when the car is moving in the middle of one lane on three types of roads at different distances from the reference station in Almaty. The city of Almaty is the most densely populated and built-up city on the territory of Kazakhstan, which however cannot be categorized as the urban canyon, but rather to the urban terrain with open areas. So it is assumed that the successful use of the considered method of navigation of vehicles in Almaty is obviously determined that this method will be equally effective in other cities of Kazakhstan and cities with similar development. The roads selected for the experiment reflect the main types of roads in Almaty and their surrounding area, characterized in table 1.

The recorded GNSS signals from the smartphone were post-processed by the System using DGPS-CP method relative to one GNSS reference station, and the positions from u-blox 6 were left raw (unprocessed) to compare the results, assuming that the accuracy it provided should be sufficient for lane-level purposes. The results were presented by map-matching on a Google Earth map and determined whether the lane determined from GNSS data corresponded to the real one. The decision to use Google Earth map to display tracks on the map, despite the known error, was made to conduct preliminary studies and consider the possibility of using these maps in the future in the development of low-cost solutions to the problem. The accuracy of positioning was assessed relative to the middle of the traffic lane using the least-squares method.


Table 1. Main experimental conditions.

| Parameter                  | Track number |
|----------------------------|--------------|
|                            | 1            | 2                        | 3                        |
| road width                 | two-lane road (one line in each direction) | eight-lane road (four lanes in each direction) | six-lane road (three lanes in each direction) |
| track length, km           | 2.4          | 7.0                      | 5.2                      |
| surrounding area           | buildings no higher than two floors, densely planted trees | five-storey residential buildings, few trees | open terrain |
| speed of car, km/h         | 30–40        | 40–50                    | 40                       |
| distance to the reference station, km | 0.5–1        | 1-3                      | > 4                      |

5. Results

The experiment resulted in real-time positioning from the u-blox receiver, real-time positioning from the smartphone and post-processed NMEA-0183 message data (i.e. GPGSA and GPGGA) from the smartphone using the System and one reference station on three road types. Figure 2 shows the trajectories of the car, obtained from raw data from the u-blox receiver and smartphone, as well as post-processed by DGPS-CP method smartphone data.

The trajectories of the car, received according to the data of u-blox receiver, pass through the traffic lanes, on which the car actually moved in case of all three investigated road types. In this case, the surrounding roads 1 and 2 trees and buildings did not affect the result of positioning by the u-blox receiver. For the u-blox receiver, the observed positioning accuracy corresponds to the specification. However, despite the fact that its accuracy provided by the manufacturer is sufficient for lane-level vehicle positioning issue, equipping a large number of private vehicles in practice will be difficult and will be a significant problem in attempting to implement automated transport systems for various purposes that require lane-level vehicle positioning. In addition, the u-blox 6 receiver only accepts data from the GPS constellation, which is also a limitation, for example, in the case of GPS suffer from prolonged outages.

At the same time, the trajectories obtained from a raw smartphone data in all three cases do not represent reality, but pass through the neighbouring lanes (roads 2 and 3) or roadside (road 1), therefore the accuracy of the smartphone's real-time positioning is not sufficient to implement lane-level vehicle positioning.

The observed greater accuracy of the u-blox receiver, which uses only GPS signals, compared to the accuracy of a smartphone, can be explained by the fact that the u-blox receiver is a dual-frequency receiver that has been specifically designed to pacify the signal problems caused by the interference in the ionosphere, signal blocking due to large physical structures such as mountains, and highly urbanized area with tall buildings.

As a result of post-processing obtained from a smartphone data relative to one reference station located within no more than 5 km from the receiver, for the studied road types were obtained trajectories of the car that slightly differ from the data from the receiver u-blox and correctly represent the movement of the car within the traffic lane.

Determination of accuracy of the vehicle positioning obtained by post-processing relative to one GNSS reference station smartphone NMEA-0183 message data showed that the positioning accuracy does not change significantly with increasing distance between the receivers and the reference station in the studied distance range (up to 5 km). In this case, according to the results of the calculation (table 2) the smallest positioning error of 0.5 m is observed on multi-lane roads (tracks 2 and 3), passing through both open terrain and urban areas, while the car positioning error on a two-lane road (track 1) is 2.8 times higher. However, the positioning accuracy is of 1.4 m is still sufficient for lane-level vehicle positioning.
Figure 2. Comparison of map-matched trajectories (Images: Google, Maxar Technologies). Red line is the map-matched smartphone provided trajectory, orange line with square dots is the map-matched u-blox provided trajectory, green line with circular dots is the map-matched trajectory obtained by correction of smartphone coordinates. The lane in which the car was moving is enclosed between white solid lines.

Table 2. Positioning error data for corrected smartphone data.

| Parameter                  | Track number |
|----------------------------|--------------|
| maximum position error, m | 3.0 1.2 2.1  |
| minimum position error, m  | 0 0 0.3      |
| average position error, m  | 1.4 0.5 0.5  |

Thus, as a result of the experiment, it has been shown, that the post-processing of NMEA-0183 message data obtained using smartphone allows for the positioning of transport at lane-level, and one reference station for the conditions typical for the Almaty city is enough to cover an area of 10 km in diameter.

6. Conclusion

The necessity to provide a large number of users with intermediate accuracy positioning between the geodesic-class GNSS receivers and a conventional smartphone makes the development of low-cost and easy-to-use solutions relevant. This paper shows the possibility of using a smartphone to determine the location of vehicles in the urban area at lane-level using post-processing of NMEA-0183 message data of the smartphone. The implementation of post-processing of NMEA-0183 message data of the smartphone was carried out from one reference station using the System using DGPS-CP method. An experimental study showed that this method of navigation of a vehicle has a satisfactory result and allows positioning the vehicle at lane-level with an error of 1.4 m. In urban conditions typical for Almaty, increasing the distance from the reference station does not significantly affect the accuracy of positioning in the studied range and one reference station covers an area at least of 10 km in diameter. The proposed approach can be applied in cities with similar urban conditions to Almaty.

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