High Accuracy Positioning of Backbone Network Infrastructure and Mobile Objects

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Abstract: *This article deals with the system of high accuracy positioning of backbone railway network infrastructure and mobile objects of the Republic of Kazakhstan. Using the developments of high accuracy satellite positioning systems and backbone geodetic networks for creating the system of high accuracy positioning in the railway field will allow determining coordinates of backbone network infrastructure and mobile objects and sites of defects revealed with high accuracy and, moreover, will possess the high degree of reliability of conducted measurements of railway infrastructure elements. High accuracy positioning can be provided by the implementation of reference GNSS stations along the backbone railways. The relevance of the study is that the project implementation will allow providing the high accuracy monitoring of defects and/or deviations of the rail track elements from design parameters, movement speed increase and railway transportation safety increase.*

Key Words: *navigation system, control system, GNSS stations, reference station network, backbone network, rail track defects*

1. INTRODUCTION

For the Republic of Kazakhstan, with its enormous territory (the area of 2 724 902 km²) and low density of settlements, production and use of surface facilities on the entire territory, as well as railway development and modernization are important. Kazakhstan has a multiple railway circuit with the total mileage of approximately 16 614,3 kilometers. According to statistics, over 47 % of all cargo circulation and over 57 % of intercity passenger circulation of the country accounted for railways. Considering the long standing appearance of the first rail tracks and almost permanent operation of railways, safety of technical means and technological processes, and health and life safety of railway employees and passengers should be maintained. For this, the repair in effective conditions should be provided together with the scheduled repair.

For the time being, on backbone rail tracks on the territory of Kazakhstan, modern systems of monitoring of infrastructure and rail track elements are implemented, such as defect detection, laser scanning of rail tracks, contact lines and the other elements of railway infrastructure, the use of georadars, etc. These works can be conducted at high speeds of railway rolling stock movement.

As noted in the study by Durazo-Cardenas et al. [1], during the development and implementation of automated systems for detecting the railway infrastructure objects condition and train movement automation system, the systems of high accuracy positioning are of paramount importance. The basic condition of the railway transportation quality and speed increase is the development of technical and operating interoperability of railway corridors based on the implementation of digital technologies and compliance with the following requirements the following requirements:

- Development and implementation of the unified intelligent system for management and automation of production processes on railway transport;
- Reliable system of high accuracy positioning of cargo, wagons, containers in real time on their actual and predicted location in the railway network;
- Operative system of revealing and high accuracy detection of defect location or inadmissible deviation from design provisions on rail tracks with the purpose to increase the railway transportation safety.

2. REVIEW OF LITERATURE

Judging from the experience of foreign countries in the field of railway transport innovative development, high accuracy positioning requires solving tasks in creating a backbone geodetic network and a reference GNSS station network on railways. Solving a task in creating a backbone geodetic network is related to the current issue of the absence of a state geodetic network in the Republic of Kazakhstan that would allow using modern satellite methods of geodetic provision of different works [2].

For the time being, the unified national system of coordinates, heights, gravimetric and satellite measurements and the succeeding scales of state topographic maps and plans SK-42, implemented as early as since 1942 are still in use on the entire territory of the Republic of Kazakhstan [3], [4]. With regard of the fact that for the time being, 90 % of SK-42 geodetic points are lost, the conduct of geodetic works for objects located along the geographical longitude in this system has large errors and cannot apply satellite navigation technologies.

The absence of the state system of coordinates meeting the requirements of modern satellite technologies does not allow automating geodetic work and submitting guaranteed and reliable coordinate-time and navigation services on the territory of the Republic of Kazakhstan. For modernization and development of the system of determining geodetic coordinates and heights, the system of determining gravity acceleration, the system of differential correction with maximally possible accuracy on the entire territory of the country, a backbone geodetic network should be implemeneted. The backbone geodetic network with the error of units of centimeters should be implemented with the use of GNSS augmentation as the reference GNSS station network and differential correction methods.

So far, reference GNSS station networks are deployed in all developed and developing countries of the world. Since the early 1990s and until now, the USA constantly performs modernization of the state coordinate provision system with the purpose of maximal satisfaction of growing consumer needs. National Geodetic Survey (NGS) as part of National Oceanic and Atmospheric Agency (NOAA) carries out work on development and maintenance of national geodetic base in the USA [5]. Considering the experience of the USA in the issues of creating and providing satellite geodetic networks, the national network of permanently operating reference stations CORS with the number of stations exceeding 2000, should be mentioned. NGS collects data from the CORS network, controls the integrity of GNSS data: GNSS data of code and carrier phase measurements for positioning on the entire territory of the USA and some foreign countries, RINEX files with the registration period from 1 to 30 seconds, current data and data for the archive period.

SAPOS, the national network of basic GNSS stations of the National Geodetic Service of Germany AdV [6] contains 260 basic GNSS stations providing determination of GNSS coordinates of consumer receivers with the centimeter accuracy throughout the entire territory of Germany. The mean remoteness of basic stations is 37 km, actually, from 10 to 50 km. SAPOS provides conventional DGNSS, RTK, PP services from a single station, and network solutions. The mean square error of coordinates determination in the plane is approximately 5 mm, and for geodetic height, it is 8 mm in the unified 3-dimensial coordinate system in Europe ETRS89 (European Terrestrial Reference System 1989) [7]. The consumer connects to the service wirelessly, the software determines the user's location, and calculates network differential corrections of centimeter accuracy for the VRS network virtual basic station.

In 1993, the construction of the network of permanently operating differential stations SWEPOS was started, supported by the Swedish government. At that time, the network consisted of 21 point located at the distance of 200 km from each other and the accuracy of coordinates determination in the RTK mode was close to 1 m and in the post-processing mode, to 1 cm. For over than 20 years of its development, the SWEPOS network proved its efficiency at conducting measurements in the real time mode and for geodynamic studies. In 2014, the network included over 300 stations accepting GNSS signals, with the average distance between them of approximately 40 - 70 km. The RTK national service, allowing operation in the real time mode, was created in 2004, and had over 2000 registered users in Sweden by 2014 [8]. In 2018, the SWEPOS network included over 457 stations accepting GNSS signals, with the average distance between them of approximately 20 - 50 km.

So far, high accuracy positioning systems in Russia are at the active development stage. As of April 2017, 1035 basic GNSS stations were present in federal and regional networks of Russia. The reference GNSS station network SmartNet Russia includes over 250 stations, checking the integrity of satellite measurement data and providing their transfer to consumers [9]. SmartNet Russia offers two main products: transfer of RTK corrections in real time and RINEX files for post-processing. The industrial geodetic system HIVE unites 527 basic GNSS stations in 77 regions of Russia into a common network, it is one half of all basic Russian stations. The HIVE system uses the satellite positioning cloud technologies based on domestic software and provides consumers with satellite measurement data throughout the entire territory of Russia: RTK differential corrections and "raw" data RINEX files.

With regard to the experience of developed countries, a conclusion can be made that the creation of a backbone geodetic network on the territory of the Republic of Kazakhstan will allow, in distinction from traditional methods, solving the following important social and economic tasks with higher efficiency:

- Perform high accuracy determination of geodetic coordinates and normal heights of infrastructure and mobile objects of the backbone railway network in real time and post-processing modes;
- Apply modern methods of rail track automated diagnosing and monitoring;
- Increase accuracy in establishing coordinates of defect location on rail tracks;
- Increase efficiency in detecting deviations from design requirements at rail track modernization/upgrade;

- Increase labor efficiency (in average, by cost and time expenses, they are not less than 20% from total quantity of work);
- Increase quality and automation of service for providing spatial data of railway backbone networks;
- Study the earth surface deformation and railway platform geodynamics;
- Provide high accuracy means of location determination and orientation.

3. CONTROL SYSTEM FOR REFERENCE GNSS STATION NETWORK INFRASTRUCTURE

Analysis and generalization of characteristics of the existing foreign GNSS station networks allow forming the structure and the requirements of the reference GNSS stations network infrastructure control system. The reference GNSS stations network infrastructure control system allows controlling the processes of selection, processing and storage of data from the GNSS station network and providing corrected navigation information to consumers. The architecture of the network infrastructure control system of the reference GNSS stations is given in Figure 1 as a generalized structure chart.

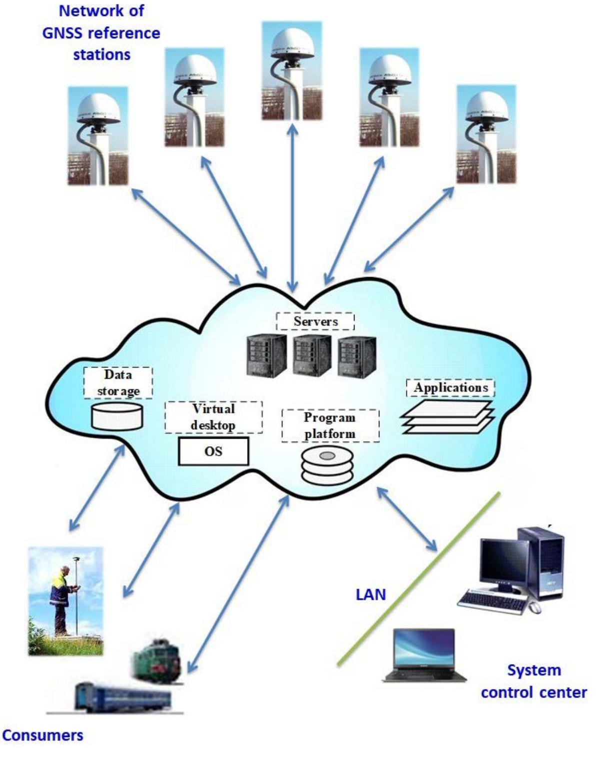

Figure 1. The architecture of the network infrastructure control system of the reference GNSS stations

The architecture of the network infrastructure control system of the reference GNSS stations is centralized and is built under the multi-beam star pattern. The reference GNSS stations network infrastructure control system includes the following main components:

- System control center;
- Computing center;
- Reference GNSS stations network;

- Communication networks;
- Consumers.

The system control center is the only control station sending control commands to control objects, network of reference GNSS stations, via data transfer channels. Software for controlling the network of reference GNSS stations should control the operation of reference GNSS stations, receive the flow of "raw" satellite data from them, upload measurement files in regular periods of time. For consumers' operation in real time mode, the server should also output differential corrections supplied to the consumers via the dedicated communication channels. In the computing center, collection, storage and processing of data received from the network reference GNSS stations are performed, and spatial coordinates of each antenna of stations, by which their spatial shifts for the certain moment of time are determined, are calculated. Communication networks ensure data and command the transfer between the system main components. Consumers connect to the system via the Web browser, pass identification and authorization on the user's personal account page. A reference GNSS station delivers the "raw" GNSS data flow to the control center at every moment of time. These data flows contain navigation information from GNSS satellites, measurements of code and carrier phase frequencies of satellite radio signals located at the given moment of time within the area of reception of base stations satellite receivers antennas. The network stations are positioned so as to enable their working zones cover the required territory and cover each other, allowing the under to work with several stations at any point of space covered by the network. The network reference GNSS station includes the GNSS receiver, a satellite antenna, an uninterruptible power supply, meteorological sensors, means of communication, inclination sensor and other devices installed at the stationary position in a designated place. Telemetry signals of reference GNSS stations allow assessing actual values of the device parameters and reveal emergency states when values of telemetry signal parameters are close to or beyond the admissible (set) boundaries. Network differential corrections allow receiving exact coordinates on vast areas, avoiding, at the same time, the increase of the error of location determination and ionosphere and troposphere modeling. Network corrections are created by the dedicated software algorithm of the network management center with regard to satellite data of several reference GNSS stations during the operation of a mobile satellite receiver. Knowing the exact coordinates of basic networks stations and using permanently received satellite signals from these stations, the management center program uses the decision algorithm for satellite phases beating cycles many-vagueness to find instantaneous coordinate discrepancies for each of the stations. Based on these data, the Kalman filter is used to build the model of errors of location determination in the network that accounts for the atmosphere instantaneous state, watch errors and orbit errors of GNSS satellites. This model is required for forming differential corrections common for all the network stations.

4. SIMULATION MODELING OF HIGH ACCURACY POSITIONING IN A BACKBONE RAILWAY NETWORK

In order to assess the efficiency of application of the system of managing the reference GNSS station network infrastructure in high accuracy positioning of backbone railway network, a simulation model was developed in C# programming language. Simulation model of high positioning in backbone railway network allows simulating the graph of errors of using navigation receivers and corrected coordinates by network differential correction method, the optimal number of he required reference GNSS stations and their location along the backbone rail track. Simulation model of high positioning in backbone railway network simulates the diagnostic movement of the car, with sensors to determine the rail track technical condition and a navigation receiver mounted on it. Using a standard navigation receiver, the mobile object location is determined with the accuracy of 12-15 m. However, in order to determine railway bed defects with the use of laser scanning, georadars, defect detection and other devices, accuracies to units of centimeters are required. The “raw” navigation data correction with the use of network differential corrections provides an error not exceeding 5 cm.

All telemetry and navigation data of the mobile diagnostic complex are delivered to the computing center where they are checked for integrity and recorded into the archive of the specific length. The integrity of input data packets is checked by Cyclic Redundancy Check (CRC) method. Corre3ct input data are delivered to the navigation solution computing subsystem and the data storage subsystem. Moreover, the calculation of the differential corrections of the navigation receiver data based on reference GNSS station network data is also performed in the computing center. The calculation of the differential corrections is performed through RTK, MAX, VRS, FKP technologies in real time, in the required CMR, CMRx, RTCM 2.x, RTCM 3.x formats [10]. At the simulation model launch, it is required to specify railway diagnostic complex movement route: departure and destination points. As an example, we selected the most frequent route in Kazakhstan, between the large cities of Almaty and Nur-Sultan. The diagnostic complex movement route is built on the basis of the actual railway map of the Republic of Kazakhstan (Figure 2). After the diagnostic complex movement route introduction, it is required to establish the high accuracy positioning system parameters, such as maximal distance between two neighboring reference GNSS stations and the maximal distance from any rail track point on the selected route to the closest reference GNSS stations. Simulation model determines the optimal number and location of permanently operating reference GNSS stations meeting all the necessary requirements (Figure 3).

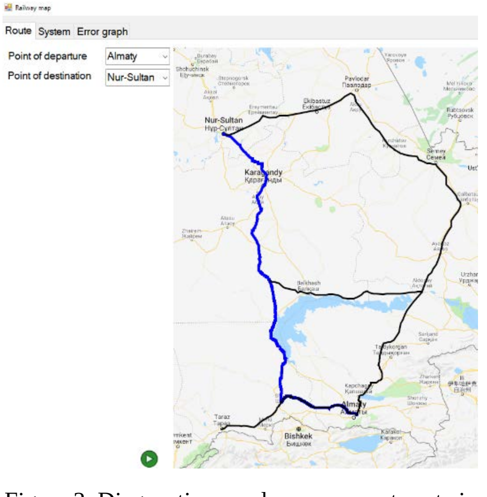

Figure 2. Diagnostic complex movement route in the simulation model

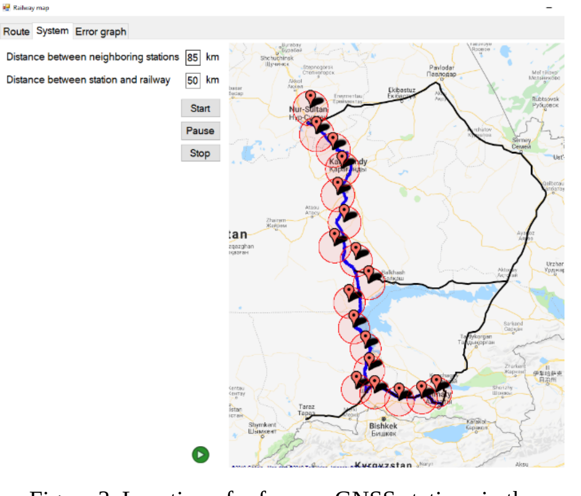

Figure 3. Location of reference GNSS stations in the simulation model

Reference GNSS stations, the zone of action of which includes passable sections by diagnostic complex, will be involved for high accuracy positioning of the mobile navigation receiver (Figure 4).

In the process of simulation modeling, the diagnostic complex movement trajectory is built based on “raw” navigation data (red points) of the mobile navigation receiver and corrected data (green points) by differential correction method (Figure 5). It can be seen on the map that the diagnostic complex movement trajectory based on corrected data almost coincides with the actual rail track.

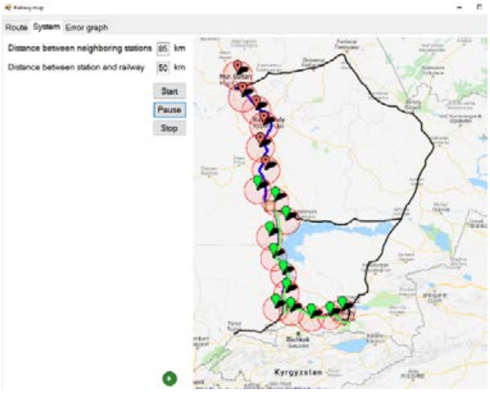

Figure 4. Movement of diagnostic complex in the simulation model

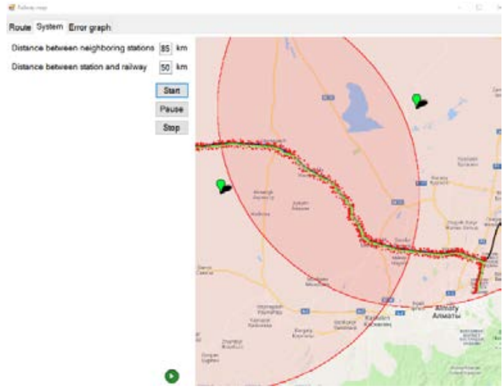

Figure 5. Movement trajectories of diagnostic complex in the simulation model

Figure 6 represents the error graph of coordinates of the diagnostic complex mobile navigation receiver in the simulation model based on “raw” navigation data. Figure 7 represents the error graph of coordinates of the diagnostic complex mobile navigation receiver in the simulation model based on corrected data by the differential correction method.

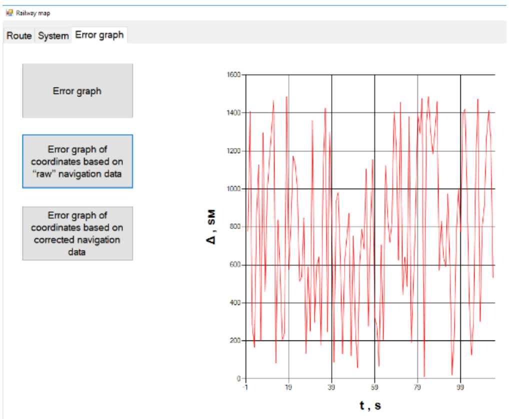

Figure 6. Error graph of coordinates of the diagnostic complex mobile navigation receiver in the simulation model based on “raw” navigation data

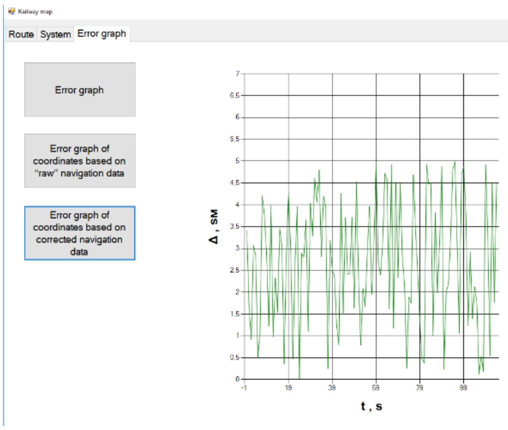

Figure 7. Error graph of coordinates of the diagnostic complex mobile navigation receiver in the simulation model based on corrected data by differential correction method

It can be seen from the error graphs that the use of the high accuracy positioning system considerably increases the accuracy of detecting the rail track defect coordinates and inadmissible deviations. The high accuracy positioning in work with the use of track measuring equipment, the complex of straightening-lining machines, automation and telecommunications laboratory cars, track measuring carriages reduces time and material costs for engineering surveys, design, construction, repair and operation of the backbone railway network infrastructure objects by 20 %.

Implementation of the high accuracy positioning system can be applied as a basis for forming the system of train movement interval adjustment where high accuracy satellite navigation data on the train location, movement speed and length will allow going to the implementation of safe methods of ensuring train movement without traffic guide lights, and further to unmanned train driving.

5. CONCLUSIONS

Work conducted for the purpose of development and implementation of intelligent, communication, navigation technologies into the railway infrastructure of Kazakhstan coincides with the railway transport strategic development vector in the world where key trends of the railway industry development, along with innovative power- and resource-efficient systems for rolling stock and infrastructure, is the creation of an “intelligent” railway. The use of the system of high accuracy positioning of backbone network mobile objects based on up-to-date satellite methods and technologies of positioning will allow increasing the railway infrastructure operation safety, which, in the long run, will allow increasing the speed of train movement via backbone railway networks and automating processes of control and management of the railway infrastructure of Kazakhstan.

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