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Information and Electronic Systems of Transport"

PERFORMANCE STUDIES OF SATELLITE NAVIGATION SYSTEMS USING PHASE MEASUREMENTS

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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The defense of the Doctoral Thesis will take place in the public meeting on 7 July 2016 at 2 p.m., at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Azenes Street, Room 2-38.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Science is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Ingus Mitrofanovs ……………………………. (Signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It contains introduction, 5 chapters, conclusion and bibliography with 80 reference sources. It has been illustrated by 58 figures and 38 tables. The volume of the present Thesis is 149 pages.

CONTENTS

GENERAL DESCRIPTION OF THE PRESENT RESEARCH

Topicality of the Research

Nowadays GNSS receivers together with reference systems are used more commonly and in a wider area of economics [6], [16]. The main fields, where these systems are used, are the ones, where the highest accuracy of positioning is necessary, for example, geodetic measurements, cartography and monitoring. Accuracy in the amplitude of 1–3m, which can be achieved with standard GNSS receivers, is too low for these fields [9], [14], [15]. In comparison with classical methods of measuring and monitoring, GNSS reference system provides considerably faster work execution, as fewer human resources are necessary [6].

During the process of monitoring of some important buildings, for example, water dam, the most important ability of GNSS RTK receiver is to repeatedly detect its position, and the ability of GNSS RTK receiver to make precise coordination towards another coordination system in such cases is less important. In such a way everyone can provide higher accuracy and respectively can find application for different and specific tasks, for example, some derived system (RTU DTET re-reference system) to define a precise position.

The above-mentioned examples of application, which refer to measurements in static conditions, can be performed with a stationary GNSS RTK receiver and repeated several times that technically makes it significantly easier to reach the defined high accuracy of measurements. Nowadays, GNSS RTK receivers can be used not only in static assignments, but also in a kind, which is related to the movement, for example, computerized guidance of specific agriculture or road construction machinery. In cases, when measurements with GNSS RTK receivers are made in dynamic conditions, it becomes more complex to solve cycle ambiguities [10]. Taking into consideration the high costs to create such kind of reference systems, it is important that it could be used more widely, but there is a need to obtain measurements and test its accuracy reliably, so that it could be surely used in dynamic conditions. Unlike static measurements, dynamic measurements have no reference value towards which accuracy control can be made, and that is why a new method for doing and processing measurements with reliable results has been developed in order to solve this problem.

In a situation, when there is a need to recover or reduce expenses on maintaining such an expensive infrastructure, it is important to optimize expenses by locating available base stations in the most rational way that provides a wider operational area as well as the customer base. Nowadays, the mobile internet can be widely used because of the data transmission speed, which can provide the necessary data flow speed that reduces expenses for the internet services and increases possible variants of the base station locations because everything that is needed is the electricity outlet.

The Goals of the Research

1. To study performance of GNSS receivers, which measure phase of carrier frequency:
    a. In static measurement conditions,
    b. In dynamic measurement conditions.
2. To make recommendations on:
    a. Reference system *EUPOS®-RIGA* area of operation extension,
    b. Reducing the reference system *EUPOS®-RIGA* maintenance costs.

The Objectives of the Research

1. To investigate the theoretical possible level of accuracy of GNSS receivers, which use signal correction implementation in real time measurements.
2. To perform measurements in static conditions according to the recommendations for reaching the maximum possible accuracy level of measurements. To repeat such measurements with scattering in time.
3. To develop the method of performing and processing measurements in dynamic conditions, which provide reliability of results and opportunity to adequately evaluate measurement accuracy in dynamic conditions.
4. To perform measurements in dynamic conditions and evaluate the accuracy of results.
5. On the basis of the available information, to evaluate *EUPOS®-RIGA* network rebuilding effect on provided accuracy and to propose the solution in order to optimize the network;
6. To appreciate the load on the communication channels between the server and the base stations, evaluate and offer an opportunity to optimize expenditures on the subscription of communication channels.

Methodology of the Research

To reach the goals of the research and accomplish the objectives, the author of the present Thesis used a quantitative research method – mathematically statistical. To conduct the experimental research properly, geodetic class GNSS RTK receivers TOPCON GRS-1, TOPCON Hiper+, LEICA 1200 and TRIMBLE R8 were used. To solve the tasks and graphically present the results, the following software was used: *Bentley Power Map*, *Topcon Tools, Bernese, Microsoft Excel, GPS Visualizer*.

Scientific Novelty

Studies show that GNSS reference system provides a higher accuracy, if used in free coordinate space, thereby monitoring can be done with a higher accuracy than performing measurements in a local coordinate system.

By processing the data collected from the reference system with a postprocessing method, it is proved that the Earth surface geodynamic movement is going on and it can be observed by using GNSS.

An original method has been developed to carry out measurements in dynamic conditions and process these data. This method provides high reliability results and verifies the possibility of using GNSS RTK in dynamic conditions with high accuracy.

Results of the Research

1. Research has been conducted on GNSS receivers' performance in static measurement conditions and the conclusion has been made that the reference system provides a higher accuracy if it is used without attracting it to physical geodetic points thereby the root mean squared error of mathematical average value does not exceed 10 mm if measurements are performed in a relatively free coordination space.
2. *EUPOS®-RIGA* reference system area of operation enlargement plan has been developed, which allows enlarging system area of the operation by 20 % with no effects on the provided accuracy of measurements.
3. The operation of RTU TET department re-reference system receiving antenna has been coordinated and checked, providing a precise complex establishment for carrying out laboratory works and scientific research.
4. After the processing of *EUPOS®-RIGA* reference system data, a constant Earth's surface geodynamic movement has been found in the northwest direction at a speed of 1–3mm a year.
5. A reliable method to estimate accuracy of measurements made in dynamic conditions has been developed.
6. During the process of measurements, it has been proven that GNSS RTK receivers can work in dynamic measurement conditions and at a speed up to 30 km/h, in 80 % of cases it provides measurements with the root mean squared error less than 10 mm, if the cycle ambiguities are solved.
7. The analysis of *EUPOS®-RIGA* reference system communication channel usage shows that the maximum amount of data sent from the base station to the server a month does not exceed 1.2 GB. On the basis of these results, a solution on how to reduce maintenance costs up to ~15 times has been proposed.

The Practical Application of the Research Results

1. During the process of static measurements an acknowledgement has been gained that it is possible to provide measurements, the root mean squared error of which is less than 10 mm, measurement standard deviation less than 20 mm, if the homogeneous and optimal distance between the reference system base stations is kept.
2. Observation of accuracy provided by *EUPOS®-RIGA* reference systems after rebuilding the network has shown that the measurement accuracy has not worsened, and, therefore, a new variant of the network further optimization has been developed, which would provide widening of the working zone by 20 % with maintaining the measurement accuracy.
3. The re-reference system, which is created at RTU TET department, has been coordinated and evaluated in such a way creating modern laboratory equipment for the student practical studies and scientific experiments.
4. The analysis of *EUPOS®-RIGA* data has proven that this reference system possesses a high stability and its results can be used to monitor the Earth surface geodynamic movement.
5. Experiments in dynamic measurement conditions have proven that GNSS RTK receivers can provide 80 % of measurements with the root mean squared error less than 10 mm and measurement standard deviation is less than 15 mm, if the speed is less than 30 km/h. This has led to the acknowledgement that such receivers can be used for managing the automated agriculture machinery. These results are used to reach the goals of RTU project No. ZP-2008/15 "Algorithm Design to Recognize and Position Hidden Objects" and the state research program project "Innovative Signal Processing Technology to Create Smart and Effective Electronic Systems".
6. After the analysis of the theoretical and practical data flow capacity, a solution has been found on how to reduce reference system expenditures up to ~15 times, at the same time providing necessary communication channel capacity.

Thesis Statements to Be Defended

1. Theoretical and practical research has proven that using *EUPOS®-RIGA* reference system in combination with carrier phase measurements it is possible to determine the location of objects in static and dynamic mode with accuracy of 10 mm.

2. Original method has been developed for taking and processing measurements in dynamic mode, which allows estimating accuracy with reliability equivalent to measurements in static mode.
3. Usage of *EUPOS®-RIGA* reference system and post-processing method has determined that the Earth surface in Riga region has geodynamical movement with explicit trend for plane coordinates. High accuracy GNSS signal retransmission laboratory has been developed.

The Approbation of the Research Results

The main research results have been presented in the following conferences:

1. Silabriedis G., Mitrofanovs I., Plotņikovs S. EUPOS-RĪGA gatavība GOCE misijai, 48th International Scientific Conference of Riga Technical University. Riga, Latvia, 12 October, 2007.
2. Silabriedis G., Mitrofanovs I., Plotņikovs S., Ratkus B., Želinska E. EUPOS-RĪGA antenu piesaiste augstākās klases līmetņošanas tīkliem Rīgā. 48th International Scientific Conference of Riga Technical University. Riga, Latvia, 12 October, 2007.
3. Caunīte M., Mitrofanovs I., Plotņikovs S., Ratkus B., Želinska E. EUPOS-IRC iespaidi Vācijā. 48th International Scientific Conference of Riga Technical University. Riga, Latvia, 12 October, 2007.
4. Silabriedis G., Mitrofanovs I. EUPOS-RĪGA gada ekspluatācijas pieredze. 66th Scientific Conference of University of Latvia, Astronomy and Geodesy section, 2nd session, Riga, Latvia, 7 February, 2008.
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7. Mitrofanovs I. GPS atbalsta tīkla EUPOS-RIGA® precizitātes pētījumi reālajā laikā. 50th International Scientific Conference of Riga Technical University. Riga, Latvia, 15 October, 2009.
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9. Mitrofanovs I. GPS ar fāžu mērījumiem precizitātes izpēte reālā laikā. 68th Scientific Conference of University of Latvia, Astronomy and Geodesy section, 2nd session, Riga, Latvia, 19 February, 2010.
10. Balodis J., Balodis K., Janpaule I., Kaminskis J., Normand M., Mitrofanovs I., Plotņikovs S., Rubans A., Silabriedis G., Zvirgzds J. On road of "EUPOS® Contribution to GOCE Mission". International Symposium on Global Navigation Satellite Systems, Space-based and Ground-based Augmentation Systems and Applications. Brussels, Belgium, 28–29 November 2010.
11. Balodis J., Mitrofanovs I., Morozova K., Normand M., Silabriedis G. EUPOS – Rīga tīkla modifikācija 2011. Gadā. 52nd International Scientific Conference of Riga Technical University. Riga, Latvia, 11 October, 2011.
12. Kluga A., Kluga J., Bricis A., Mitrofanovs I. Multiple Frequencies Precise GNSS RTK System Research in Dynamic Mode. IFAC/IEEE PDeS 2013 conference, 12th conference on programmable devices and embedded systems, Velke Karlovice, Czech Republic, 25–27 September, 2013.
13. Balodis J., Haritonova D., Janpaule I., Jumare I., Normand M., Silabriedis G., Zvirgzds J., Mitrofanovs I., Zariņš A. GNSS staciju koordinātu izmaiņu vektori laika gaitā. 72nd Scientific Conference of University of Latvia, Astronomy and Geodesy section, Riga, Latvia, 5 February, 2014.
14. Mitrofanovs I. GPS ar fāžu mērījumiem precizitātes izpēte dinamiskajā režīmā, izmantojot divus instrumentus. 73rd Scientific Conference of University of Latvia, Astronomy and Geodesy section, Riga, Latvia, 11 February, 2015.
15. Silabriedis G., Balodis J., Kaļinka M., Liepiņš I., Rubans A., Balodis K., Mitrofanovs I. Ģeoīda modeļa projekta izpildes gaita. 73rd Scientific Conference of University of Latvia, Astronomy and Geodesy section, Riga, Latvia, 11 February, 2015.
16. Balodis J., Morozova K., Mitrofanovs I. General Concept of Geoid Model Determination and Its Verification Using RTK. The FOTONIKA-LV conference "Achievements and Future prospects", Riga, Latvia, 23–24 April, 2015.
17. Mitrofanovs I. Performance Studies of the GNSS Receivers with Carrier Phase Measuring in Dynamic Mode. ICG Experts meeting: Global Navigation Satellite Systems Services, Vienna, Austria, 14–18 December 2015.
18. Morozova K., Silabriedis G., Balodis J., Baltmane I., Balodis K., Kaļinka M., Jumare I., Haritonova D., Mitrofanovs I. Viena cm precizitātes ģeoīda modelis. 74th Scientific Conference of University of Latvia, Geodesy and Geoinformatics section, Riga, Latvia, 11 February, 2016.
19. Mitrofanovs I., Klūga J., Klūga A., Bricis A. GNSS RTK mērījumi ātrgaitas kustībā. 74th Scientific Conference of University of Latvia, Geodesy and Geoinformatics section, Riga, Latvia, 11 February, 2016.

List of the Scientific Publications on the Topic of the Doctoral Thesis

1. Abele M., Balodis J., Balodis K., Normand M., Janpaule I., Mitrofanovs I., Rubans A., Silabriedis G., Zarins A. Implementation of New Positioning System in Riga. International Symposium EUREF – 2008, 18–20 June, 2008, Brussels, Belgium, 2008, pp. 2–6.
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3. Balodis J., Silabriedis G., Caunite M., Janpaule I., Balodis K., Rubans A., Aleksejenko I., Otto R., Ratkus B., Reiniks M., Mitrofanovs I., Plotnikovs S., Zvirgzds J. *EUPOS®-RIGA* Network Elevation Analyses. International Symposium on Global Navigation Satellite Systems, Space-Based and Ground-Based Augmentation Systems and Applications, Berlin, Germany, 30 November – 2 December 2009; Conference Proceedings. Senate Department for Urban Development, Berlin, Germany 2010, pp. 68–72. ISBN 978-3-938373-93-4.
4. Balodis J., Balodis K., Janpaule I., Kaminskis J., Normanda M., Mitrofanovs I., Plotnikovs S., Rubans A., Silabriedis G., Zvirgzds. On Road of "EUPOS® Contribution to GOCE Mission". International Symposium on Global Navigation Satellite Systems, Space-Based and Ground-Based Augmentation Systems and Applications: Conference Proceedings, Belgium, Brussels, 29–30 November, 2010. Berlin: Senate Department for Urban Development, 2011, pp. 47–50. ISBN 978-3-938373-94-1.
5. Kluga A., Kluga J., Mitrofanovs I. GPS Receiver with Phase Measuring Precision Estimation. Proceedings of 13th Biennial Baltic Electronics Conference (BEC2012), Estonia, Tallinn, 3–5 October, 2012. Tallinn: Tallinn University of Technology, 2012, pp. 169–172. ISBN 978-1-4673-2772-5.
6. Kluga A., Kluga J., Bricis A., Mitrofanovs I. Multiple Frequencies Precise GNSS RTK System Research in Dynamic Mode. Programmable Devices and Embedded Systems: 12th IFAC Conference on Programmable Devices and Embedded Systems. Vol.12, Part 1, Czech Republic, Velké Karlovice, 25–27 September, 2013. Velké Karlovice: International Federation of Automatic Control, 2013, pp.95-98. ISBN 978-3-902823-53-3.
7. Kluga A., Mitrofanovs I., Kluga J., Jeralovics V. State and Dynamic Precision Research Using Two GPS Receivers with RTK. Proceedings of the 14th Biennial Baltic Electronics Conference, Tallinn, Estonia, 6–8 October, 2014. Tallinn University of Technology, 2014, pp. 141–144. ISBN 978-9949-23-672-5.

8. Balodis J., Morozova K., Mitrofanovs I. General Concept of Geoid Model Determination and its Verification using RTK. The FOTONIKA-LV conference “Achievements and Future Prospects”, 23–24 April, 2015, Riga, Latvia. Book of Abstracts, p. 60. ISBN 978-9984-45-993-6.
9. Balodis J., Silabriedis G., Haritonova D., Kaļinka M., Janpaule I., Morozova K., Jumāre I., Mitrofanovs I., Zvirgzds J., Kaminskis J., Liepiņš I. Development of the One Centimeter Accuracy Geoid Model of Latvia for GNSS Measurements. IOP Conference Series: Materials Science and Engineering (MSE) Volume 96, 30 September – 2 October, 2015, Riga, Latvia, pp. 1–8. ISNN 1757-8981.
10. Mitrofanovs I. Performance Studies of the GNSS Receivers with Carrier Phase Measuring in Dynamic Mode. International Committee on Global Navigation Satellite Systems Experts Meeting on Global Navigation Satellite Systems (GNSS) Services: Abstracts, 14–18 December, 2015, Vienna, Austria, p. 26.

The Structure and Volume of the Doctoral Thesis

The Doctoral Thesis is an independent scientific research and it contains an introduction, 5 chapters, conclusions and bibliography comprising 80 reference sources. The total volume of the Thesis is 149 pages. It has been illustrated by 58 figures and 38 tables.

CONTENT OF THE DOCTORAL THESIS

The introduction of the Doctoral Thesis substantiates topicality of the research, states goals and objectives, as well as determines the scientific novelty, practical application of the research results and the thesis statements promoted for defense.

Chapter 1
GLOBAL NAVIGATION SATELLITE SYSTEMS

The author has examined factors influencing GNSS accuracy. The main sources, which cause errors in measurements, are:

- Errors in the performance of the satellite apparatus and changes in satellite orbits;
- Errors in radio signal diffusion (influence of atmosphere and multipath);
- Errors in the users’ apparatus operation;
- Errors which occur because of the satellite location or the geometric factor.

Accuracy provided by GNSS has been examined using standard (C/A) and precise (P) code receivers [14], [15]. For comparison purposes, the author has described what kind of the measurement accuracy improvement is expected, if measurements are carried out using carrier phase measurements combined with ground-based reference stations or networks (reference systems) [20]. Operational principles of a typical carrier phase measurement reference system are pictured in Fig. 1.1.

The first chapter also contains a review of mathematic models of measurements for both measurement methods which are possible, using GNSS signals:

- The code pseudorange (distance between satellite and receiver [11]) measurements;
- The carrier phase measurements.

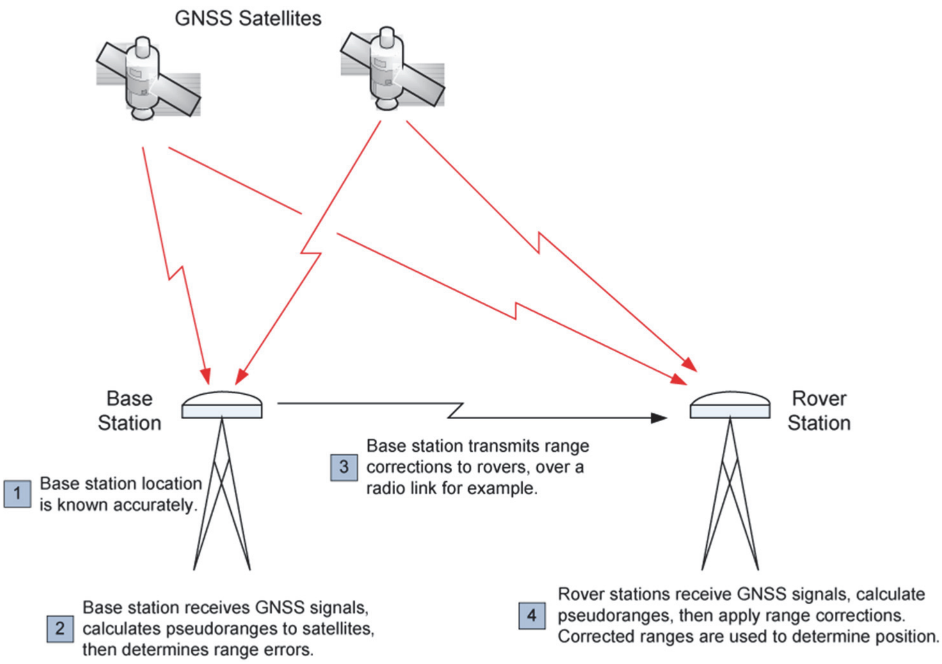

Fig. 1.1. Typical reference system principles.

Studies on the theoretically possible accuracy provided by GNSS have revealed that the only variant to reach centimeter level accuracy is the usage of GNSS RTK receivers with receiving real time corrections based on calculations of the phase difference [6], [10]. For a high accuracy GNSS with phase measurements first, second and third order phase difference equations are used, which are written as follows:

$$\Phi_{AB}^{j}(t) = \frac{1}{\lambda}\rho_{AB}^{j}(t) + N_{AB}^{j} - f^{j}\delta_{AB}(t) \tag{1.1}$$

$$\Phi_{AB}^{jk}(t) = \frac{1}{\lambda}\rho_{AB}^{jk}(t) + N_{AB}^{jk} \tag{1.2}$$

$$\Phi_{AB}^{jk}(t_{12}) = \frac{1}{\lambda}\rho_{AB}^{jk}(t_{12}) \tag{1.3}$$

The use of the first order phase difference equation can eliminate the effect of the satellite clock shifting, second order difference equation – the receiver’s clock shifting, but the third order phase difference equation is not affected by phase cycle ambiguities.

Chapter 2
PHASE CYCLE AMBIGUITIES AND SHIFTING IN GNSS MEASUREMENTS

One of the main problems in phase measurements is the cycle ambiguity resolution or calculations on the satellite signal full wave number (number of full waves between the satellite and receiver, when the receiver starts to track the signal). In addition, another problem is that there is no information on the amount of fractional part of wave, respectively from the satellite received signal and receiver generated signal is not in the same phase; visually this problem is pictured in Fig. 2.1. The determination of the fractional part of the wave is significantly easier, as modern apparatus with direct measurements can determine it at up to 1 % accuracy of the wavelength [6], [11].

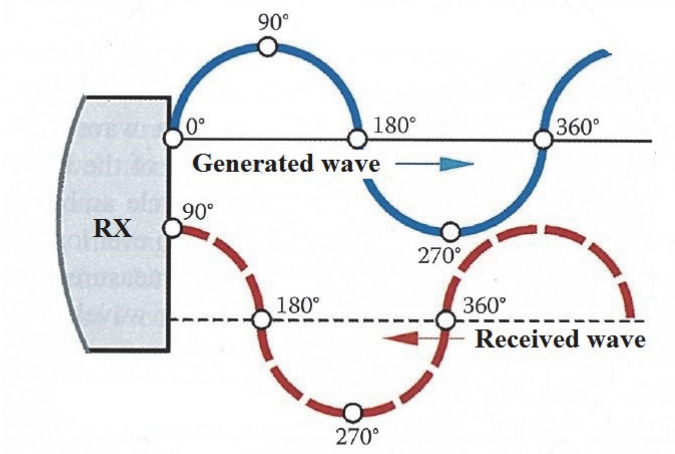

Fig. 2.1. Phase shift of generated and received wave.

Further in the chapter, the most interesting and common solution methods of phase cycle ambiguities are considered, such as:

- Determination of the phase cycle ambiguities with two-frequency phase measurements;
- Determination of the phase cycle ambiguities with multi-frequency phase measurements and code measurements, etc.

The end of the second chapter provides research on the phase cycle shift problem, which in fact is sudden jump in the observed signal phase for the whole number of cycles, which does not affect the fractional part of wave and if it is not removed (fixed) in time, it introduces a significant decrease in measurement accuracy [5], [9], [10], [11].

Chapter 3
CREATION, TESTING AND DEVELOPMENT OF HIGH ACCURACY LOCAL DIFFERENCIAL GNSS REFERENCE SYSTEM

At the beginning of the chapter, there is a short description of *EUPOS®-RIGA* reference system development process. There is an indication that this reference system is created according to EUPOS common technical standards and recommendations [1], [3].

Subsections of Chapter 3 contain summarized author's research results on GNSS performance in static measurement conditions. The measurements are made in several stages:

- Provided accuracy evaluation after the network creation;
- Provided accuracy evaluation after rebuilding the network;
- Recurrent accuracy evaluation for the network stability control.

To evaluate the possible accuracy for measurements towards the classical geodetic points, several geodetic network RG2 points were selected in all measurement sessions [17]. Each of the three measurement sessions had a different number of points. Overall depiction of the used points is demonstrated in Fig. 3.1.

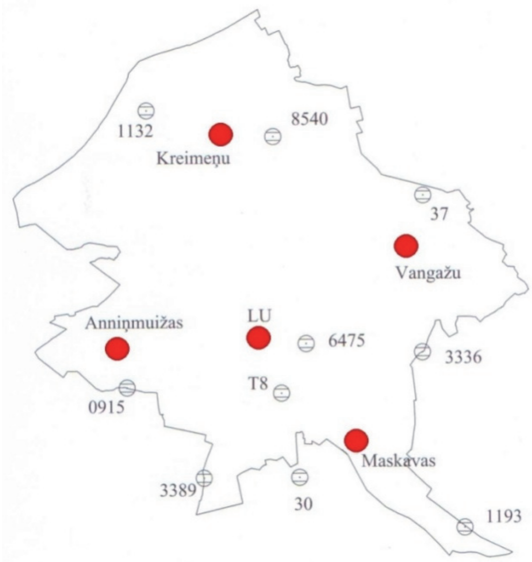

Fig. 3.1. Used RG2 points for accuracy evaluation of measurements (red – original *EUPOS®-RIGA* base station location).

Measurements were made by setting up GNSS RTK receivers on the tripod, which was centered on the point with optical centering method, in this way receiver could be set up with 1 mm accuracy (see Fig. 3.2).

Fig. 3.2. Equipment for accurate GNSS receiver setting.

During the first accuracy evaluation, three different manufacturer (TOPCON, TRIMBLE and LEICA) receivers were used, thus reducing the effect of receiver's error. It revealed that the reachable accuracy was almost the same for the results received from different receivers.

In this phase of the research, it was revealed that the summary (X and Y coordinates) root mean squared error, which was calculated using (3.1) and (3.2) was in the limits of 5 mm, which confirmed the stable system functioning and accuracy of the establishment.

$$s_x = \sqrt{\frac{\sum_{i=1}^{N}(x_i - x_{vid})^2}{N(N-1)}}, \tag{3.1}$$

$$\Sigma = \sqrt{X^2 + Y^2}, \tag{3.2}$$

The obtained results showed high system reliability, which allows using it for specific tasks, in which the required and expected accuracy was lower. *EUPOS®-RIGA* was used to coordinate and check the signal retranslation system antenna [8] created at RTU TET department (see Fig. 3.3).

Fig. 3.3. Receiving antenna of GPS signal retranslation system at RTU TET department.

The retranslation system was coordinated during the direct GNSS RTK measurements and afterwards checked, using its retranslated signals in real time measurements and with the post-processing method. Indoor results differed from the direct results by 0.8–27 mm plane coordinates and by 41–51 mm in determination of the height component.

After *EUPOS®-RIGA* rebuilding, the distance between neighboring base stations increased from maximal 13 to maximal 46 km, in that way base station operation radius increased from 6.5 to 23 km. In the network development conception, it was decided that the base station operation radius was 20 km, thus the operation area of the network increased from 400 km^2 to 2600 km^2.

To evaluate the measurement accuracy provided by the network, repeated measurements were made on 5 from all points involved in this stage and obtained results showed that the measurement root mean squared error, after rebuilding the network, was less than 5 mm in the determination of plane coordinates. In the determination of the height component root mean squared error was less than 6mm.

To make sure about the network operation stability, in 2014 repetitive measurements were made to determine accuracy. These measurements showed that the overall measurement root mean squared error for the plane coordinates was less than 3 mm, but for the height component – 2 mm. Average root mean squared error for all three dimensions was less than 4 mm.

The results showed a high accuracy in the measurement repeatability, which allowed using GNSS RTK receivers in measurements, for example, in geodesic monitoring.

At the same time, it was established how precisely results fitted with the classical geodetic measurement methods and after comparing all the three measurement sessions average results with official RG2 coordinates, results showed that difference in the plane was less than 10 mm. Hence, the system can provide measurements with subcentimeter accuracy.

EUPOS®-RIGA data processing with a post-processing method towards the stable EPN stations [12] showed that *EUPOS®-RIGA* base stations were established with a very high stability and showed the geodynamic Earth’s surface movement towards the north-west direction, which was confirmed by the information from Fig. 3.4.

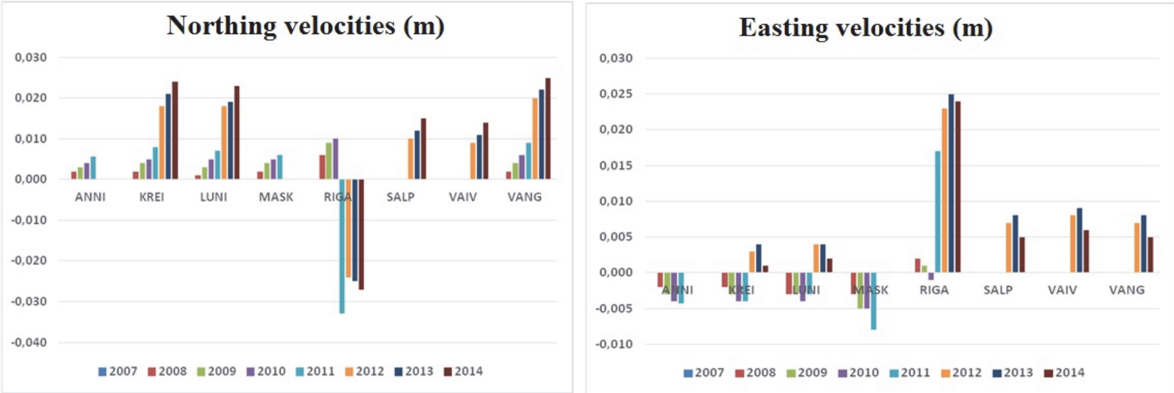

Fig. 3.4. *EUPOS®-RIGA* collected data post-processing results (in plane).

Meanwhile Fig. 3.5 shows the results on height component changes during a period of time in an analogue way. Figure 3.5 shows that in height component changes are not explicit and constant, which means that location and fastening of stations confirm system stability and ability to work reliably.

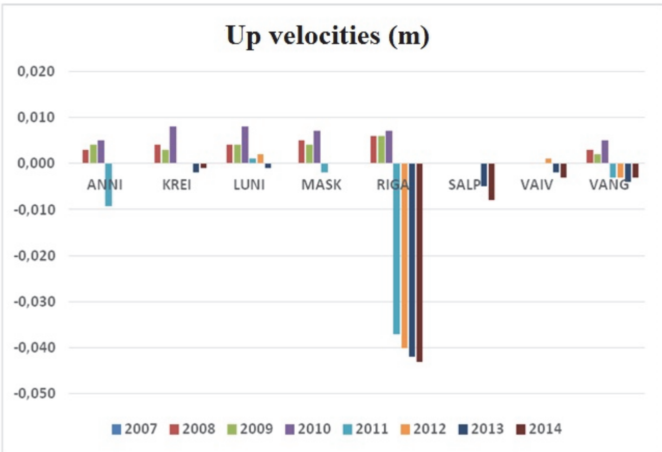

Fig. 3.5. *EUPOS®-RIGA* base station changes of height component during a period of time.

Considering *EUPOS®-RIGA* base station location conditions – the operation radius is 20 km, the author developed a proposal on how to increase the network operating zone by 20 %, noticing these conditions and without additional technical equipment. On the basis of previous measurements, new measurements were made, in which potentially movable station was disconnected. Under the author's guidance, measurements were carried out by J. Koļesņikovs, the student of RTU Faculty of Civil Engineering, Institute of Transport Structures, during the process of developing of his Bachelor Paper. In such a way it has been planned to acquire results on how the network accuracy makes changes after its possible further rebuilding [4]. The results of measurements showed that being out of the direct network operation zone in small

~15 km distance, the root mean squared error was less than 10 mm, but height component – 26 mm. During the measurements closer to the network operation zone, offered as a new place for locating base station, root mean squared error was less than 15 mm. During the measurements in the network operation zone, the difference between the measurements with the enabled and disabled Jugla base station was just 2 mm, the measurements in which Jugla base station data were not used showed a higher accuracy. The results justified that rebuilding of the *EUPOS®-RIGA* network would maintain existing accuracy and at the same time significantly increase its operation zone, which is an important aspect for attracting a larger number of users.

If *EUPOS®-RIGA* network rebuilding proposed by the author is accomplished, it will provide a more homogeneous positioning of the base stations (Figs. 3.6 and 3.7) and reduce the distance between contiguous base stations. The regular distance between base stations will ensure that the accuracy in the entire network operation zone will be regular and independent from user's geographical location in a network operation zone, because of a similar base line length.

The rebuilding proposed by the author will result in widening of the network operation zone by 565 km^2. The existing and the possible network coverage area is displayed in Fig. 3.6.

Fig. 3.6. Existing (to the left) and proposed (to the right) network coverage area.

If rebuilding proposed by the author is accomplished, the base stations location homogeneity will improve (see Fig. 3.7).

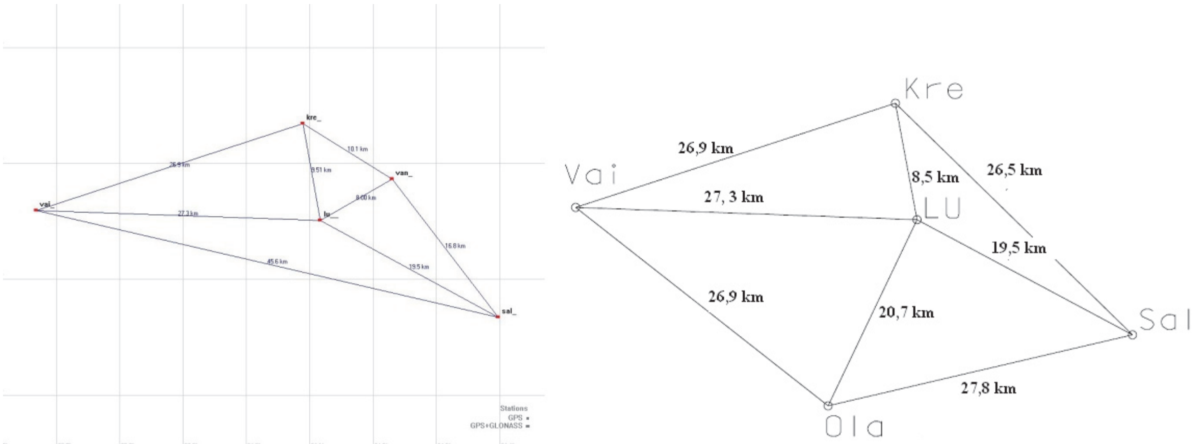

Fig. 3.7. Existing (to the left) and proposed (to the right) base station geometric location for homogeneity improvement.

Chapter 4
RESEARCH ON MEASUREMENT ACCURACY PROVIDED BY *EUPOS®-RIGA* IN REAL TIME IN DYNAMIC MEASUREMENT CONDITIONS

The main difference between measurements in dynamic and static conditions is that under dynamic conditions it is possible to make only one measurement at one location, thereby the measurement average value, which is the beast gauge to determine accuracy of measurements [2], [23], is not available. The determinative to make successful measurements in dynamic conditions is the movement speed of the meter or receiver (user). The movement speed has a direct influence on meter ability to fix the measurement within one phase track. The phase track width depends on the radio wave length and it is equal to radio wave length, or λ [24]. Taking into consideration that nowadays the carrier phase correlator can measure signal phase with 1 % accuracy, or up to 99 sc (6.22 rad) shift, it is possible to get a maximum linear movement speed, at which the object will stay in one phase track during the measurement. The maximum speed can be found as follows:

$$v_{max_{F_{1,2}}} = \frac{c\Delta\varphi_{max_{F_{1,2}}}}{\omega t_m} \quad (4.1)$$

where:

c – the speed of light;

$\Delta\varphi_{max_{F_{1,2}}}$ – the maximum possible receiver generated replica and received signal phase shift;

ω – the angular speed;

t_m – the time necessary to take measurement;

Using (4.1) we obtain the following values:

$$v_{max_{F_1}} \approx 679\ km/h;$$

$$v_{max_{F_2}} \approx 871\ km/h;$$

The acquired values show that GNSS RTK can provide high accuracy measurements for land traffic, as well as for noncommercial air traffic. Accuracy is possible in order of one radio wave length, which is approximately 19–24 cm. That urged the author to conduct research on accuracy ensured by GNSS RTK receiver under dynamic measurement conditions.

In the design of GNSS apparatus mainly first, second or third order Phase Locked Loop (PLL) is used. PLL basically is a non-linear feedback loop, which follows the signal phase. PLL order in the GNSS apparatus determines the following [7]:

- 1st order – such a PLL is sensitive to the movement;
- 2nd order – such a PLL is sensitive to the acceleration;
- 3rd order – such a PLL is sensitive to the jitter.

PLL task is to follow changes of the signal phase, which cannot exceed 15° value from wave length [22] that, in case of GPS system, for L1 frequency is 8 mm and for L2 frequency is 10 mm, with one sigma limit. In case, if this value is exceeded, the result is believed to be unreliable. Mathematically, it can be written as follows:

$$\sigma_{PLL} = \sqrt{\sigma_{tPLL}^2 + \sigma_v^2 + \sigma_A^2} + \frac{\sigma_e}{3} \leq 15° \qquad (4.2)$$

where:

σ_{tPLL} – the standard deviation of thermal noise expressed in degrees;

σ_v – the standard deviation of shift caused by oscillator instability expressed in degrees;

σ_A – the oscillator error caused by Allan variation, expressed in degrees;

σ_e – the error caused by dynamic conditions in PLL.

First half on the right side of equation (4.2) (except the error caused by dynamic conditions) according to GPS development standard IS-GPS-200 cannot exceed 5.7°. The apparatus PLL bandwidth, used in measurements, is 25Hz, assuming that the effect caused by Allan variation and oscillator vibration is similar to [22] and the used receiver integration time is 1 ms, but the signal-to-noise ratio is 51 dB-Hz [21], we acquire that right side components of equation (4.2) introduce error, which is less than 3.63° of the wavelength. Modifying the previously mentioned maximum movement speed in acceleration values, we obtain 19.4 g and 24.5 g respectively, and using these values in (4.2) we get:

$$\sigma_{PLL_{L1}} = 7.33°$$

$$\sigma_{PLL_{L2}} = 7.27°$$

The results fully satisfy requirements of (4.2), which is the main factor for successful practical measurements in dynamic conditions.

GNSS RTK receivers, which were available to the author, could perform measurements automatically with the time and distance criteria. Performing measurements with time criteria, movement speed must be fixed with high accuracy to be able to determine the distance, but GNSS RTK receivers do not fix the movement speed. Fixing the movement speed from the moving car speedometer, its value can be very approximate and it is impossible to speak about measurements with centimeter accuracy. A better situation is with measurements with the distance criteria. In this case, for example, every 7 m position is fixed and after the calculations between the coordinates, it is possible to determine the conducted road distance, the example is shown in Fig. 4.1.

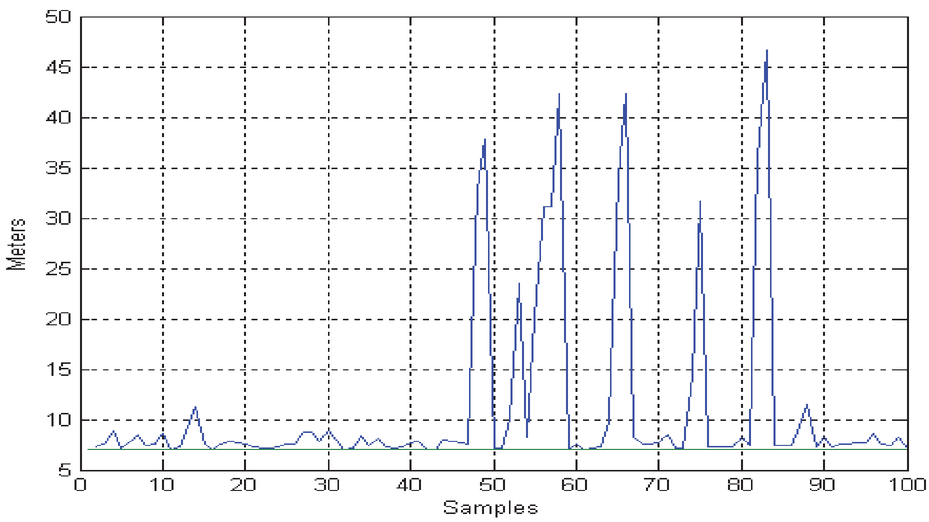

Fig. 4.1. Conducted road distances at a speed of 20 km/h.

Figure 4.1 shows that only the measurements at the beginning of the trip are approaching the set measurement interval, but starting from the middle, distance intervals are up to 47 m. At a speed of 20 km/h, a vehicle does 5.55 m a second that means it is smaller than the set criteria and the GNSS receiver should be able to fix the position as it is set, every 7 m. Increasing the speed up to 40 km/h and 60 km/h, the situation worsens and the measured intervals for the set criteria are approached just at the beginning of distance and in the middle, which is justified with a smaller starting speed and smaller speed in the middle of the distance, where a turn is made to drive in the opposite direction.

To understand whether the fixed position shifts in several directions or just in the radial movement direction, the visual evaluation of car movement route was made using the website http://www.gpsvisualizer.com. The results are shown in Fig. 4.2.

Fig. 4.2. The visual evaluation of car movement route.

In Fig. 4.2, where the car movement route during the process of doing measurements is marked in pink lines, one can see that there is no shift, which can be up to 20 m, as lines lie over the road. It suggests that the shift, which was even more than 40 m, is observed only in the direction of the radial movement and is related to the movement speed or technical performance of the measurements. Processing the results of the movement at a speed of 40 km/h and 60 km/h, a similar situation was revealed: there was no route line scattering (Fig. 4.2). Carrying out additional measurements, in which movement was on foot along smaller constructions and in several directions, it turned out that measurements remained within 50 cm limit.

Since the results showed the opportunity to reach at least 50 cm accuracy, an original measurement realization and processing method was developed. It is not necessary to set the conducted distance intervals to apply this method. The method is based on the usage of two equal accuracy class receivers, which remain in a stationary distance from each other during the period of measurements, thereby providing a reference value to which it is possible to check accuracy, similarly as it is in the static measurements.

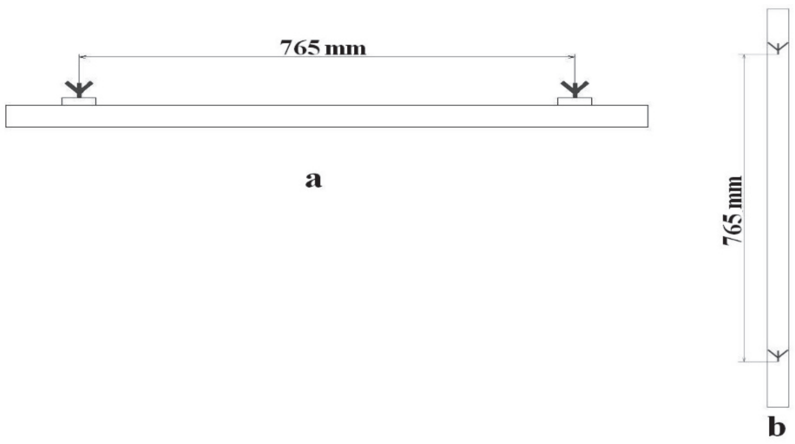

Fig. 4.3. Receiver placement for the measurements in dynamic conditions.

Figure 4.3 shows GNSS RTK receiver placement during the measurements.

- In variant “a”, the measurement results form two parallel lines, between which determination of the distance is possible with a high accuracy, using Bentley PowerMap software;
- In variant “b”, the measurement results form a cloud of points, among which there must be the distance, which is physically between the receivers. In this variant, the same Bentley PowerMap software was used.

Variant “a” receiver placement allows to avert time synchronization, between receivers, effect on the measurement results.

The route lines, which were formed in variant “a” measurements, and the distance readouts between them are shown in Fig. 4.4.

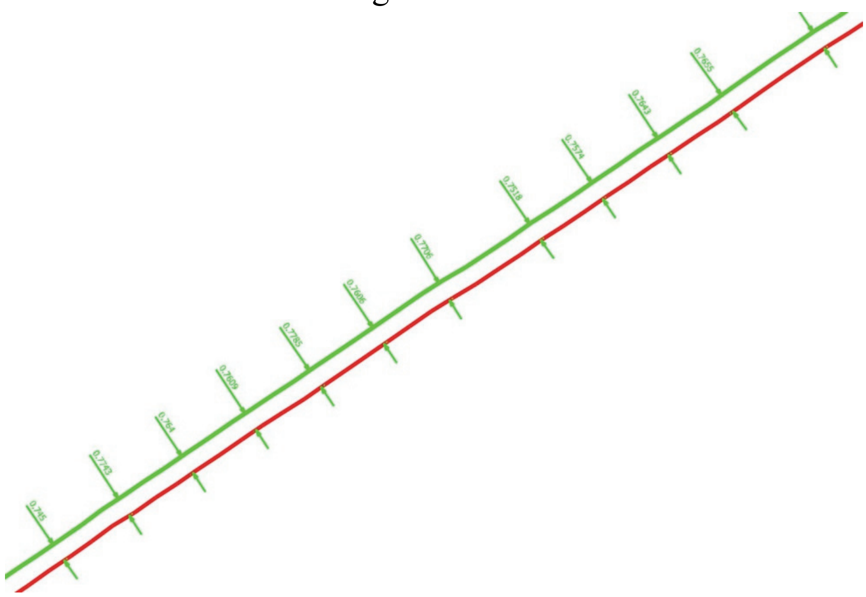

Fig. 4.4. The route lines and the distance readouts between them.

In this way 81 measurement results were acquired, in which the movement was on foot, and 179 measurement results, in which the movement was by car at an approximate speed of 30 km/h. The overall measurement results, in which phase cycle ambiguities remained solved, are shown in Tables 4.1 and 4.2.

Table 4.1

Measurement Summary for the Session, Moving on Foot

Number of measurements	81
Measurement average value, m	0.765
Measurement absolute error, m	$-0.0201 \leq x \leq 0.0335$
Measurement standard deviation, m	0.0045
Root mean squared error, m	0.0005

Table 4.2

Measurement Summary for the Session, Moving by Car

Number of measurements	179
Measurement average value, m	0.7661
Measurement absolute error, m	$-0.0619 \leq x \leq 0.088$
Measurement standard deviation, m	0.0096
Mean squared error, m	0.0007

The results shows that the measurements made during movement on foot display a higher accuracy, or the error in measurements is lower than in measurements with the movement by car, which proves that if speed rises, accuracy becomes lower [19].

The measurements have shown that at the movement speed up to 30 km/h GNSS RTK receivers provide measurements with the absolute error less than 10 mm at least in 80 % of the cases.

Chapter 5
THE NECESSARY COMMUNICATION CHANNEL CAPACITY TO ENSURE GNSS REFERENCE SYSTEM OPERATION

When the GNSS reference system is being developed, it is necessary to know the data amount that is broadcasted from the base stations. In such a way, it is possible to avoid communication channel overload, by choosing communication channel capacity between the base stations and server rationally, and reference system maintenance costs can be reduced. In addition, the reference system users need to know what kind of data flow they need to be able to receive corrections. Taking into consideration the mobile operator tariff specification, it is important to choose an appropriate tariff, which best satisfies user needs to avoid additional expenditures, or not to choose a tariff, which is not fully used.

Standardized messages are used to broadcast corrections from the server to users, approved by the special radio technical committee RTCM SC-104 (*Radio Technical Committee for Maritime Special Committee No.104*), and a detailed message description of version 2.x can be found in [13], [18].

EUPOS®-RIGA provides users with corrections, using RTCM2.3 and RTCM3.0 standards and DGPS corrections, which contain information only on the corrections for one frequency. There are correction services, which contain corrections only for GPS satellites and for GPS and GLONASS satellites.

This chapter presents research, according to EUPOS®-RIGA configuration, on the theoretical possible amount of the data flow and the comparison with the actually registered data flow to gain the average characteristics of one connection, according to which the user could calculate the data flow necessary exactly for him / her.

Tables 5.1 and 5.2 show respectively the theoretically broadcasted amount of data with a different visible satellite number and the average amount of actually registered broadcasted data in one second.

Table 5.1

Theoretically Broadcasted Data Amount in Bytes

	Number of visible satellites		
Correction service	**8**	**10**	**14**
EUPOS_DGPS	114	138	187
FKP01	576	696	935
PRS01	291	351	471
PRS02	286	351	478
PRS03	576	696	935
PRS_5Hz	2856	3456	4656

Table 5.2

Average Amount of Actually Registered Broadcasted Data

Correction service	**Broadcasted data amount (bytes)**
EUPOS_DGPS	136
FKP01	899
PRS01	463
PRS02	316
PRS03	868
PRS_5Hz	3364

System register shows that the average number of observed satellites is 19.1 at base stations. With such a number of satellites, the theoretical transferable data amount would exceed actual transferred data by 150–2800B, which can be explained by the fact that in the user position visible satellite number is smaller than in the base station position. User receives corrections only for the satellites, which are visible to both user and the reference system base station at the same time [6], [10].

Having performed a deeper analysis of average time of one connection, the author has come to a conclusion that in most cases users perform several measurements during one connection, which are close to each other and do not switch off *EUPOS®-RIGA* reference system correction service channel, which by its specifics corresponds to the topographical survey conducting.

Unlike the user's channel load evaluation, the system channel load cannot be evaluated using the same principles, as there is no registration of the data flow. There is no overall standard, based on which the data flow is broadcasted from the reference base stations to the central server, to calculate the corrections. Broadcasted data flow depends on the number of visible satellites and on each manufacturer of apparatus individual technological solutions. The author has not had access to the respective base station manufacturer standards; therefore, the channel load evaluation is based only on practically broadcasted data amount. For channel evaluation of such a system, the author has developed parallel untitled data flows from reference base stations to the server. Development of the virtual data flows allowed registering the broadcasted data amount from the base stations. Results of this data process are showed in Table 5.3.

Table 5.3

Amount of Data Flow from Reference Base Stations

Reference station	**Broadcasted data amount (bytes/s)**
KRE_	317
LU__	328
SAL_	307
VAI_	313
VAN_	332

Results show that the incoming internet capacity must be at least 13 kbit/s, but each reference station must have the internet connection at a speed of at least 3 kbit/s.

Knowing the broadcasted data amount and using (5.1), we get that the maximum broadcasted data amount is less than 1.2 GB a month.

$$DA_{m_{max}} = DA_{d_{max}} \times 31 \qquad (5.1)$$

These results and the telecommunication market availability for the mobile internet subscription show that it is possible to reduce the costs from approximately 100 € to approximately 6 € for each communication channel per month, which is approximately 15 times less and is a significant saving. Information published by the mobile internet service providers shows that the provided transmission speed is at least 9.7 kbit/s, which is enough to provide data transmission from the base stations to the server without any interferences.

Conclusions

The research deals with performance of the satellite systems with phase measurements. It is based on the GNSS *EUPOS®-RIGA* reference system, which allows evaluating the measurement accuracy, which exploits data from the phase measurement corrections, both in static and dynamic measurement conditions. The Thesis contains calculations and recommendations based on the practical experiments for the *EUPOS®-RIGA* system operation zone widening and reducing the maintenance costs.

Results of the static measurements show that usage of *EUPOS®-RIGA* reference system, where the base stations are located taking into account optimal distance between them and homogeneous geographic location, together with the GNSS RTK receivers provides the measurements with root mean squared error of 10 mm or less, but standard deviation of the measurement is not larger than 20 mm.

In case of distance enlargement between the base stations from 10–15 km to 25–30 km, accuracy of the measurements remains the same with root mean squared error of less than 10 mm. On the basis of the research, the author proposes options for the reference system optimization, which would allow increasing coverage by 20 %. Repeated measurements show that *EUPOS®-RIGA* reference system is a stable and reliable GNSS augmentation system and can be used for the high accuracy measurements and accomplishment of specific tasks.

Coordination and evaluation of the RTU TET department satellite signal retranslation system (re-reference system) is based on the results of static measurements. Currently the system is being used in the student teaching process for practical studies, scientific papers and research. The system plane coordinates are set with accuracy of ±27 mm, but height component with ±51 mm.

EUPOS®-RIGA data processing with the postprocessing method towards the EPN stations shows that in Riga region the Earth surface does geodynamical movement to north and west directions at a speed of 1–3mm a year. There is no similar tendency with the height component, showing that the base station antennas are stable in vertical plane.

Using the original measurement realization and processing method with two GNSS RTK receivers has shown that in 80 % of the object localization cases in dynamic conditions at a speed of up to 30 km/h root mean squared error is at the level of less than 10 mm, but standard deviation of the measurements is less than 15 mm. If the cycle ambiguities in dynamic measurement conditions are not solved, the measurement root mean squared error exceeds 80 mm, but the standard deviation – 400 mm boundary.

Theoretical exploration of the RTCM standard message size shows that the transmitted data amount with *EUPOS®-RIGA* correction service configuration and 14 visible satellites produces 935 bytes, if the corrections are transmitted once a second, which corresponds to data transmission speed of 7.48 kbit/s. Such a speed can be provided with 2G standard mobile data transmission. Research on the amount of practically transmitted data shows that average correction data amount, which is transmitted to the user once a second, does not exceed 900 bytes, but maximum – 1030 bytes, which corresponds to 8.24 kbit/s.

Research of the communication channel load between the base stations and central server shows that the maximum data amount transmitted per second does not exceed 460 bytes; consequently, the maximum data amount does not exceed 1.2 GB per month. Choosing appropriate mobile data plan could reduce current expenses on the data transmission services by approximately 15 times.

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