Scientific and Engineering Approaches of Study Courses Based on The GNSS-RTK/PPP Technology in Russia

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SUMMARY

Global Navigation Satellite Systems (GNSS) are the basis for determining the coordinates of objects of various classes and purposes. Modern multi-system, multi-frequency equipment operating with the use of GLONASS, GPS, GALILEO, BEIDOU, QZSS, IRNSS signals, SBAS wide-gap add-ons (SDCM, WAAS, EGNOS, MSAS, GAGAN) provide post-processing positioning with the accuracy of 2.5 mm + 0.5 ppm and up centimeter accuracy in Real Time Kinematic mode. The prospect of further development of spatial coordinate support using orbital satellite constellations is an intensively developing method of high-precision autonomous coordinate positioning of objects using precise ephemeris and time-frequency parameter corrections (FDPs) of time scales (PPP). Over time, the above method has proven to be a powerful tool for geodetic and geodynamic applications. Although the accuracy obtained as a result of its application is quite similar to that got in the static mode of the relative method of satellite geodesy, the results of the method can be improved by using the technique of the phase ambiguity integer resolution.

In recent years, GNSS and satellite based augmentation systems (SBAS) have widely been applied in the land survey areas, such as engineering, cadastre, resources management, urban planning, landscape construction, high precision agriculture, monitoring and so on. Such intensive implementation of new technologies and improvement of the equipment defined a new level of requirements for training of the specialists in geodesy.

Keeping up with the times, the Moscow State University of Geodesy and Cartography focused onto providing the high-class specialists in these areas.

Starting from last decade, GNSS positioning had become one of the main subjects of higher educational study courses thanks to the rapid development of satellite-based positioning and to the appearance of GNSS mass-market receivers and antennas.

This article describes the progress on application of new GNSS-RTK/PPP technology study courses in Russian Moscow State University of Geodesy and Cartography, which are focused on cadastral, field mobile worker and precision agriculture areas. During the study, the students get not only additional knowledge in application of single-base Real-Time Kinematic (RTK), Network Real-Time Kinematic (NRTK) and PPP methodologies of GNSS measurements, but also moderate practical skills in cross-disciplinary subjects.

During the GNSS course study, students are welcome for participation in scientific researches within the GNSS technology area application. The newest trends, such as moving base, ionosphere modeling, GNSS/IMU and PPP methods for high-precision positioning, are

utilizing capabilities of modern hi-tech equipment of the university giving the best start for student to become not only qualified engineer but young scientist as well.

In summary, the work shows the feasibility and practicality of the courses diversification applied.

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1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have revolutionized consumer product industries and their applications have become irreplaceable in today's society. In the near future, more satellites and constellations, more broadcast frequencies, more advanced signal structures[1], and better ability to take into account the impact of the earth's upper atmosphere will allow unprecedented accuracy and open the door to even more uses. Currently operational GNSS constellations include the United States' Global Positioning System (GPS) and the Russian Federation's Global Navigation Satellite System (GLONASS). Two other global GNSS systems are expected to be fully operational in 2020: the European Union / European Space Agency satellite navigation system (Galileo) and China's global navigation satellite system (BeiDou/BDS). India and Japan are in the process of developing regional navigation systems, NAVIC and QZSS respectively[2]. Once all these global and regional systems are fully functional, the GNSS technology will provide a user with access to positioning, navigation and timing signals from more than 100 satellites. The impact of the new capabilities will extend from basic science to more practical engineering and technology including geophysical exploration, airline and spacecraft tracking, surveying and cadastre, precision agriculture, and unmanned vehicles[3]. As a result, a growing number of employers are seeking hires with understanding and experience of GNSS. The emerging nexus between education, research, and industry in this critical area presents an opportunity for a joint effort to help prepare the next generation of engineers advanced in GNSS science and technology. A relatively broad range of engineering and science disciplines is required to understand the GNSS-associated technologies that enable this spectrum of applications. These include celestial mechanics, signal processing and communication system theory, computational mathematics, statistics, radio wave propagation, upper atmospheric space physics, and even relativity theory.

Not only has GNSS revolutionized modern technology, it has begun to be used effectively for a broad range of educational purposes. Moscow State University of Geodesy and Cartography educational courses on GNSS have been developed to teach fundamental science and engineering concepts, the principles of engineering design, and the impact of modern technology on society.

The training of engineering students at the undergraduate level in GNSS technology, the general subject of this report, has seen a variety of teaching approaches. These have often been based on application training within specific engineering disciplines rather than acquisition of detailed first principles understanding. The training is often provided as needed in a module within the offering of a core course. For instance, in Civil and Environmental Engineering, GNSS technology is incorporated into construction engineering for training students to use spatial construction data for various applications that include surveying, construction planning, and scheduling. Aerospace Engineering curricula place emphasis on technology applications related to air and space navigation, traffic control, and pilotless aircraft and aerospace technologies, such as atomic clocks, that enable GNSS. In general, undergraduates appreciate applications of GNSS and design projects that are effective in giving some insight into fundamental GNSS principles. These approaches, however, do not address learning GNSS from first principles and so do not convey the depth of understanding that is necessary to work with a broad spectrum of GPS technologies and to design new applications.

Educational approaches that utilize GNSS signals collected at the raw level and which replicate the detailed computations performed inside actual GNSS receivers have begun to be more commonplace. This latter approach is very effective at teaching fundamental principles and is considered in the following discussion. We report on our experience in teaching a laboratory and field practical GNSS courses on GNSS theory and design applications. The course has been taught for the past 10 years at Applied Geodesy department of Moscow State University of Geodesy and Cartography and has evolved with advances in GNSS technology and on-going assessment of instructional effectiveness. The range of technical disciplines associated with GNSS provides a rich interdisciplinary educational experience that can be used to effectively train a broad range of engineering students. The GNSS learning experience brings together fundamental concepts utilized in many lower division engineering courses and therefore strengthen the students' understanding of working on real world engineering problems and systems that require multiple disciplines. The courses have benefited a broad cross-section of students from a number of engineering departments outside of Survey Faculty that include aerophotogrammetry, cadastre and adjacent specialists. It consists of a theoretical component that explains the inner workings of GNSS and an innovative hands-on laboratory and field practical component that uses modern equipment to give students practical training and the opportunity to work on more extensive design projects. Students are trained in how to operate GNSS receivers, decode data and to into getting necessary practical skills, as described below.

2. MAIN COURSE CONTENT

As previously described, competencies over a relatively broad range of engineering and science topics are required for understanding GNSS. The course contents are listed in Table 1 for a fourteen-week semester course. The theory of GNSS is presented during lectures that occur one to three times a week depending on specialization chosen, for 90 minutes at a time. A seminars with laboratory or field practical work take place each week that reinforces understanding of the theory. During the seminars in-class discussion are the key point. The laboratory component is open-access with on-site tutorial help available. Each student team (generally consisting of three students) is assigned a personal job with their own GNSS equipment for the duration of the semester.

	Subject
1	Fundamental Concepts, Coordinate and Time Systems
2	Space Geodesy
3	Satellite Orbit Theory
4	Concept of Ranging and GNSS Observables Determination
5	Navigation Solution Calculation
6	Error Sources and Accuracy Determination
7	Atmospheric Effects and Associated Scientific Measurements
8	Signal and Communication System Theory
9	Differential GNSS (e.g., SDCM/WAAS/EGNOS/MSAS/GAGAN)
10	GNSS Modernization

Table 1. Standard GNSS course contents

It can easily be seen that the conceptual basis of the course extends over many engineering and science topics including vector analysis, linear algebra and matrix theory, probability and statistics, Kepler orbit theory, radio wave propagation and electromagnetics, and signal and communication system theory. Concepts of atmospheric science (ionosphere and troposphere) are also discussed and applied including Total Electron Content (TEC), scintillations ($S4$, $\sigma\phi$), and occultation[4]. Typically few undergraduate students, even upper level ones, have strong capabilities across all these disciplines. For instance, aerophotogrametry engineers may have a solid understanding of satellite orbit theory but not electromagnetics or signal theory while electrical engineering students may have contrasting skills. Some students may have competencies in vectorial and matrix mathematics but not in probability and statistics theory. We have found that teaching GNSS using a first principles approach is highly effective for imparting functional competencies across this broad range of topics for both upper level undergraduates and beginning graduate students.
Once students are close to finalize the main course of GNSS, both laboratory practical classes and the specialized courses start.

3. LABORATORY SCIENTIFIC RESEARCH

In order to provide practical exercise on use of GNSS, it is necessary to provide GNSS receivers to each student. Typically, a group of three students get one one high-class modern multifrequency GNSS smart antenna to work with.
University has local Base-Station Network used for research purposes and conducting local high-accuracy RTK surveys.
In laboratories students learn to work with base stations and process the data collected.
RTK and PPP measurements are conducted at the inner university campus at Moscow territory and two counrtyside campuses.
Besides the practical skills in engineering areas students get oportunity to participate in scientific laboratory researches. Currently, there are seven research directions in focus of this laboratory. Brief description for each of them is given below.

3.1. Experimental Studies of a Dynamic Real-Time Mode Relative to a Moving Base Station

Moving Base RTK differs from conventional RTK positioning by allowing both the reference and rover receivers to be moving while calculating heading solution which is required by some geodesy applications[5].

Constant expansion of the capabilities of global navigation systems provided for consumers allows geodetic methods of positioning to develop intensively. One of the promising methods of positioning in the field of geodesy and navigation is the Moving Base method. The purpose of the research is to obtain experimentally and estimate the relative positioning accuracy of that method. Within the framework of the research, an experiment is conducted to determine the accuracy of relative positioning in the Moving Base mode. To estimate the accuracy during the experiment, the results of processing GNSS measurements performed on a special measuring stand based on a metrological accurate rigid basis as well as two multi-frequency GNSS smart antennas as main equipment for the experimental measurements were used. The measurements are carried out, both in the fixed position, and during the movement of the basis. The results of the experiment are processed, as well as for visualization done of all the obtained values.

To solve some navigational and geodetic tasks, a centimeter accuracy coordinates of an object are often required, as well as elements of object orientation.

Classic RTK positioning technology allows to solve the first problem when a rover receiver is operating in relation to a fixed reference station “base” or network. To solve the second problem, you can apply the dynamic mode of kinematics in real time - Moving Base RTK mode, when the reference station is installed at a short distance and acts as a moving base station.

3.2. Orbital Method Evolution by Precise Point Positioning Technology Development

Global Navigation Satellite Systems (GNSS) are the basis for determining the coordinates of objects of various classes and purposes. Modern multi-system, multi-frequency equipment operating with the use of GLONASS, GPS, GALILEO, BEIDOU, QZSS, IRNSS signals, SBAS wide-gap add-ons (SDCM, WAAS, EGNOS, MSAS, GAGAN) provide post-processing positioning with the high accuracy and in Real Time Kinamatic mode[6][7]. The prospect of further development of spatial coordinate support using orbital satellite constellations is an intensively developing method of high-precision autonomous coordinate positioning of objects using precise ephemeris and time-frequency parameter corrections of time scales. Over time, the above method has proven to be a powerful tool for geodetic and geodynamic applications. Although the accuracy obtained as a result of its application is quite similar to that got in the static mode of the relative method of satellite geodesy, the results of the method can be improved by using the technique of the phase ambiguity integer resolution.

Research focuses the accuracy and the robustness of the technology compared to RTK technique.

3.3. Operational Monitoring of the Parameters of the Ionosphere in the Local Area Using the Results of Multi-frequency GNSS-Measurements

Recently, much attention is given to problems of ionospheric agitations influence on GNSS signals worldwide. The reason of such influence is increasing solar activity, expansion of GNSS application area, the emergence of new satellite systems, and introduction of new frequencies, etc. Research that is dedicated to the equatorial and polar zones ionosphere being conducted along with electron density distribution dynamics, the abnormal effects and their impact on GNSS positioning signals.
This research focuses the organization of operational monitoring of the ionospheric parameters in a local region using the results of multi-frequency GNSS-measurements. The purpose of monitoring is to determine the critical frequency of the F2 layer and the height of the maximum of the F2 layer in real time. The refined by using the measured values of the total electron content IRI ionosphere model has been used to calculate the values of the critical frequency of the F2 layer and the height of the F2 layer maximum. Total electron content is obtained by phase GNSS measurements taking into account the effect of both GNSS receiver and satellites inter-channel delays. Refining the IRI model is done by calculating the refined values of the solar activity index for each moment of time[8][9]. The considered approach of the ionospheric parameters operational monitoring organization in a local area has been implemented in the hardware and software solution. Verification of the obtained values of the F2 layer critical frequency and maximum height is carried out by synchronous measurements of the hardware and software solution for monitoring the ionospheric parameters and the vertical sensing ionosonde.

3.4. Development of Architecture Survey GNSS Receiver Based on Client-Server Architecture

Client-server architecture is a distributed computing model where client applications request services from server processes. Client and server usually run on different devices that are connected to each other using a computer network. Client-server based solutions architecture is widely applicable in the field of geodesy and, in particular, in positioning using signals from Global Navigation Satellite Systems (GNSS).
This research covers the problems of using client-server architecture for survey GNSS receivers. The theoretical justification of the possibility to use this architecture is given, and its practical advantages during the designing and operating the equipment phases are considered. The research focuses the engineering of the survey GNSS receiver prototype based on the use of client-server architecture. Special attention is given to use of the opportunities of the Internet and separate various network resources to expand and improve the functionality of the designed survey GNSS receiver in context of constructing it on the basis of client-server architecture.
Further research and development in this area has moved to the use of cloud technologies instead of client-server architecture.

3.5. Developing the Algorithm to Analyze the Navigation Signal Reflections with the Purpose to Study the Effect of Multipath at the GNSS Measurements

There are a number of techniques to mitigate the effects of multipath at the GNSS-measurements on hardware and software level instrumentation. Thus from the perspective of the observation approach to minimize the effect of multipath in difficult conditions is not developed. The research is dedicated to the development of an algorithm to calculate the coordinates of the navigation signal reflection point on an arbitrary surface, in order to study the impact of multipath effects on GNSS-measurements from a viewpoint of geometry and the development of methods of weakening the organization at the stage of observations.

3.6. A Model of Portable Multisystem GNSS Receiver With Precise Positioning Capability Based on PPP And Differential Correction Methods

The researchers aim is to design a mobile GNSS receiver model on the base of public multisystem chips for current mobile platforms, with the support of a PPP method for precise positioning objects and GIS. The implementation of this method will allow to reach a new technological level of high-precision satellite equipment and expand the area of its application in different industries. A related challenge is the development of software designed for the required characteristics of GNSS receiver. The test platform for the implementation of hardware and software features of the model is Arduino — a set of technical tools for the automation systems and robotics construction.

3.7. Estimation of The Combined INS/GNSS System Positioning Accuracy When The Breaking of Navigation Signals Reception

The use of measurement methods such as airborne laser scanning, mobile laser scanning, aerial photography, bathymetric survey using echo sounders requires the kinematic determination of the coordinates of the object and its spatial orientation. Technologies of combining inertial navigation systems (INS) and global navigation satellite systems (GNSS) are used to solve this problem.

These technologies are also actively used to create unmanned solutions, since, in addition to determining the orientation of an object in space, the use of an INS makes it possible to determine its coordinates in cases when they cannot be obtained from processing measurements using GNSS signals. Such situations arise when obstacles along a certain section of the route prevent a sufficient number of GNSS satellites from being observed. This problem is relevant when using mobile laser scanning technology, since the carrier is located on the surface of the earth and can get into areas with difficult visibility of GNSS satellites in the process of passing the route.

The research focuses on assessing the positioning accuracy of a combined INS/GNSS system with discontinuities in the reception of navigation signals.

4. SPECIAL COURSES CONTENT

4.1. Precision Agriculture module

Applying GNSS technology to crop production through mechanization, fertilizers, crop protection chemistry, genetics, and other innovations has resulted in multiple-fold gains in productivity and efficiency. Now, the application of information technology to crop production, known as precision agriculture, has transformed many aspects of crop production and promises even more.

While the capabilities of precision agriculture have progressed dramatically in recent years, the inability to understand and apply these to benefit crop production can greatly limit utility. Precision Agriculture is a special course that provides specific knowledge to better understand the science of site-specific.

Subject	Description
Introduction to Precision Agriculture	Scope and overview of the technologies and their applications
Differential Correction	Ground-based and space-based correction systems, levels of accuracy, manual guidance and autoguidance Network Real-Time Kinematic (NRTK), Precise Point Positioning technologies
Sensors	Satellite, aerial, UAV, and proximal sensing platforms; active vs. passive sensing; spectral, spatial and temporal resolution; soil, crop and weather sensors
Geographic Information Systems	GIS coordinate systems, map scales and standards, capture, storage, editing, analysis, display, image classification
Automation	Implement steering, VRT seeding, planter unit controllers, variable hybrid/ variety planting, spray boom and nozzle controllers, boom leveling
Data Analysis	Experimental design, data quality, compatibility, privacy, interpretation and correlation, product comparisons
Precision Farming Economics and Adoption	Cost effectiveness of guidance systems, section controllers, site-specific management in various crops, regions, situations

Table 2. Precision Agriculture module outline

4.2. Cadastre module

Many GNSS methods are applied to the cadastral survey after the rapid development of satellite-based positioning. These methods are reported to give efficiency, speed and economy compared to the conventional ones. It is clear that the GNSS based methods achieve high. In addition, the robust criteria appear to be a fast, effective and objective method to compare the results, especially for the height component. This course is aimed to comprehensively teach student of the most commonly used GNSS methods for cadastral survey.

Subject	Description
Introduction to Cadastre GNSS positioning	Scope and overview of the technologies and their applications
Differential Correction	Ground-based and space-based correction systems, levels of accuracy Network Real-Time Kinematic (NRTK), Precise Point Positioning technologies
Sensors	Satellite, aerial, UAV, and proximal sensing platforms; active vs. passive sensing; spectral, spatial and temporal resolution
Geographic Information Systems	GIS coordinate systems, map scales and standards, capture, storage, editing, analysis, display, image classification
Automation	Software applications for GNSS controllers in cadastre

Data Analysis	Experimental design, data quality, compatibility, privacy, interpretation and correlation, product comparisons
Cadastre GNSS positioning technology Economics	Cost effectiveness of RTK/PPP equipment, section controllers

Table 3. Cadastre module outline

5. CONCLUSION

Opportunities will continue to grow for well-trained engineers and researchers in the area of GNSS design and application of GNSS technology for the foreseeable future. Here, we have described a comprehensive course for senior undergraduates and beginning graduate students that integrates theory and laboratory instruction to promote first-principles understanding of GNSS and competencies in related technical areas and in GNSS analysis and design. As described here, a state-of-the-art laboratory component greatly enhances the instructional value of such a course.

The ongoing modernization of GNSS includes the development of a number of new satellites constellations and their accompanying frequency bands and signal structures. This will require an even broader scope of training involving large, international engineering systems. Teaching programs will need to expand to take into account the new GNSS constellations and the applications associated with the expanded services. The new opportunities and teaching requirements will encompass K12 education as well as education and training at the university level. In summary, just as GNSS has revolutionized our society through technological advances over the past few decades, the future is bright for instructors and students to transform education and research experiences with GNSS.

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BIOGRAPHICAL NOTES

ANDREY KUPRIYANOV – PhD, professor, Chief of the Applied Geodesy Department of the Moscow State University of Geodesy and Cartography (MIIGAiK), Russia. His areas of the professional interest and research are the issues of high-precision spatial orientation, including azimuth and latitude definitions, automation of astronometric observations, use of the orbital methods of space geodesy and satellite systems for solving problems of navigation and geodesy. He works on the theoretical and experimental solution of the problems of high-precision spatial orientation, automation of the processes of high-precision observations for coordinate support of space navigation, as well as the Global Navigation Satellite Systems and technologies development and practical application.

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