Development of High Precision Differential GPS System in Kazakhstan

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Abstract

Objectives: This article describes design and classification of a variety of states and events that form the basis for information model of the local system of differential correction in the post-processing mode. Methods: The article introduces computational methods of differential correction that employ measurements from single-frequency GPS receivers. Experimental results confirmed estimation accuracy of the methods in post-processing mode, which proved that the developed differential GPS system demonstrated appropriate performance when compared with the existing analogous systems in the world. Findings: The research reveals a set of states and events fundamental for developing an LSDC information model in post-processing mode. A GPS-based system of differential correction is one of the main alternatives in solving problems of high-precision satellite navigation. In future, this system under development will be able to operate in real time and post-processing modes, static and dynamic modes, as well in the mode of a thick client (rover coordinates are computed using the mobile station) and a thin client (rover coordinates are computed using the base station). The composition and structure of the model in post-processing mode are examined. As a result of this research, a systematic project of the LSDC GPS was developed. These designs were made using Unified Modeling Language (UML), which represents functional requirements and appropriate system diagrams of mathematical provision, LSDC hardware and software. High accuracy and precision of the developed system are verified by experimental results shown in the paper. Applications/Improvements: The GPS system should be developed further to be able to cover other modes of operation.

Keywords: GPS, High Precision Satellite Navigation, Local System of Differential Correction, Post-Processing Mode

1. Introduction

High-precision satellite navigation systems exist in the world for a long time and keep developing, for example, such as EGNOS (European Geostationary Navigation Overlay Service), WAAS (Wide Area Augmentation System), EUPOS (European Position Determination System) and MSAS (MTSAT Satellite Augmentation System). In the Republic of Kazakhstan products have recently emerged developed by ALSI, SCOUT, Bassar Electronics and other companies, associated with the use of satellite navigation systems and their augmentations to solve various problems in positioning and monitoring of mobile objects. These companies basically employ foreign software built in their navigational equipment, and in some cases they utilize high hierarchy software, for example, the application used for scheduling and messaging between user terminals that have embedded satellite navigation OEM modules. Having made a comprehensive literature review, the author has not found any Kazakhstan R&D projects related with mathematical modeling and software development of augmentation satellite navigation systems. So this article discusses an initial stage of development of the similar system in Kazakhstan.

The standard accuracy of satellite navigation systems to determine coordinates of the consumer is about 10-15 meters\(^1\). But in some cases, a higher determination accuracy is required, which includes geodetic survey and mapping, civil engineering activities, precise piloting in the coastal zones, navigation in urban environment, monitoring of engineering structures and the Earth’s crust movements, etc\(^2\).
At the Institute of Space Technique and Technology, activities were conducted on development of mathematical software and hardware for user ground segment of high-precision satellite navigation system. This system makes use of GPS differential correction methods.

The method of differential correction is based on relative constancy of large part of GPS errors over time and space. The usage of GPS differential mode should meet the most demanding requirements of navigation maintenance problems for landing aircrafts, stated in ICAO (International Civil Aviation Organization) standards, navigation in the narrow waters and torrential areas, geodetic reference points, problems of geodynamics, etc.

Differential GPS requires two satellite receivers or sensors, defined as the base (BS) and mobile (MS) stations, positioned in two points relatively close to each other. The base stations usually are fixed and tied geodetically to some precise coordinate system, WGS-84 (World Geodetic System 1984) or PZ-90.02 (GLONASS reference frame). In the basic differential GPS systems, the readings obtained at base and mobile stations, including measured pseudo-ranges from “visible” satellites, are transmitted by data links in the form of differential corrections to the server where they are processed to provide corrected coordinates of the mobile station.

The accuracy of positioning after the input of corrections is influenced by the residual errors caused by variability of quasi systematic timing and ephemeris support errors of the satellite, ionosphere delays, errors of GPS selective availability, as well as errors due to noise and interference, multipath and the troposphere influence. These issues are discussed in more detail in.

Taking into account the information above, computational error of pseudo-range \( \delta D_i \) to \( i \)-th GPS satellite in differential mode can be stated as:

\[
\delta D_i = \delta D_{ie} + \delta D_{ION} - \delta D_{ABC} + \delta D_{AMC},
\]

where:

- \( \delta D_{ie} \) and \( \delta D_{ION} \) are residual errors due to the ephemeris and ionospheric errors, which are a difference between corresponding errors of base and mobile stations. That kind of errors can be totally neglected depending on the application area.
- \( \delta D_{ABC} \) and \( \delta D_{AMC} \) are noise errors of base and mobile stations, respectively, including receiver dependent errors, caused by internal and external noise, errors occurred due to multipath and interference effects.

### 2. Classification of Differential GPS Systems

Studies show that the accuracy of positioning and timing in the GPS differential mode largely depends on measurement accuracy of the base and mobile stations, the distance between BS and MS, correction age and relative positions of BS, MS and navigational satellite.

Implementation of differential mode and external integrity check is carried out through the setup of GPS differential systems (DS). Differential systems are conventionally divided into wide (WDS), regional (RDS) and local systems of differential corrections (LSDC). A local system has a maximum range of operation from the transmitter or a base station up to 50-200 km. LSDC typically includes one base station (alternatively with several base stations), equipment for quality control (including integrity control) and transmission media. Common methods of integrity control in LSDC, including support of safe landing in harsh electromagnetic environment, are described in.

The system of differential correction using code measurements is based on measurement and processing of pseudo-ranges and generally has a baseline as long as 200 km, while the positioning error is equal to fraction of a meter up to several meters. The differential navigation system employing carrier phase measurements is characterized by a high precision positioning (to some fraction of a centimeter), but the scope of its action is limited to a guaranteed range of 10-12 km in the single-frequency mode and about 100 km in the dual-frequency mode. A specific feature of differential correction based on the phase measurement is integer ambiguity of these measurements, making them difficult to use. The navigational system of differential phase measurements is also often called a relative positioning system.

Most modern systems of differential navigation are local. They use only measurements from one base station to generate differential corrections. The base station is usually located in the center of the local area, being up to 200 km in diameter. In the center of the area maximal positioning accuracy is provided. On the periphery, the precision deteriorates and gradually approaches the accuracy of single point positioning.

Local systems of GPS are divided into the following classes:

- naval LSDC for navigation in straits, narrows, the waters of ports and harbors in accordance with
the requirements of IMO (International Maritime Organization);
- aviation LSDC for assistance in aircraft landing in accordance with ICAO standards;
- LSDC for geodetic, surveying and other applications.\(^1\)

Corrected information of naval LSDC is transmitted in accordance with generally accepted standard RTCM SC-104, originally designed for GPS by the Special Committee 104, Radio Technical Commission for Maritime Services and supported by IALA (International Association of Lighthouse Authorities).

RTCM SC-104 format suggests usage of 30-bit words, the content of which is made by 24 information bits and 6 control bits. Each message has a header of two words, and the following words of transmitted data are specific for each type of message.

Corrections and non-immediate supplementary information are transmitted as a continuous stream of messages consisting of individual data frames. One frame is composed of \(N + 2\) words.

Nowadays several types of aviation LSDC are developed. These systems are characterized by several advantages. Relatively mediocre equipment can reduce the costs of enhanced operations in harsh weather conditions; it allows meeting the first and potentially more complex ICAO standards to support landing activities in the area within a radius of 55 km, which makes the system more cost-effective than other technological options designated for one aircraft runway. This enables to equip local airlines with aviation LSDC that is quite flexible and allows implementing the technique with a variable geometry, minimizing the flight time and providing anti-interference. Modern design principles are used to ensure control over operation states and accelerate system repairs.

One example of the aviation LSDC is a system D920/ D930 of DASA (Germany) company operating on the GPS base. D920 equipment is certified in accordance with a special ICAO category I, while D930 system is able to meet requirements of the ICAO I and II category. The active baseline range of these systems reaches 37 km.

D920 includes a base station with ability to monitor GNSS, VHF and other data links (standard RTCA / DO-217), as well as common display for management and control.

The system has a fault tolerance design and is certified to endeavor in critical situations through the appropriate standards. Its software is certified according to the RTCA / DO-178B requirements.

In order to meet strict requirements of aircraft landing, LSDC incorporates ability to monitor integrity with the following features:

- Detection and elimination of abnormal signals and errors affecting the measurement channels;
- Certification of computed differential pseudo-range by comparing the uncorrelated readings on receivers;
- Detection and elimination of phase jumps (cycle slips) when tracking carrier phase;
- Control of transmitted messages before and after aerial transmission.

LSDC geodetic support system with a range of 50-200 km and decimeter or centimeter accuracy level is one of the most important and promising classes. As a rule, their use allows for a comprehensive measurement processing, after the measurement is taken. Moreover, they are almost required to implement phase tracking algorithms of the carrier frequency signal. At the same time the requirement of continuity, integrity and availability for these systems may be significantly weakened.

Technology of differential correction gives opportunity for consumers to improve effective performance of their activities. For example, satellite navigation technology complements traditional geodetic technologies and increases their efficiency. The main disadvantages of traditional technologies are high labor intensity and high cost of field activities. On average, the cost and time-consuming field work comprises at least 60% of the total work. Traditional geodetic technology, especially in the field work, cannot be automated. Satellite navigation technology is free from the majority of these drawbacks. High degree of automation of satellite technologies is based on the use of electronic and computer equipment. Positioning by means of satellite geodetic technologies superseded traditional labor-intensive technologies of Kazakhstan – triangulation and traverse measurements that require carrying out construction of high exterior signs and cutting glades which may cause ecological issues.

### 3. UML Modeling of LSDC

Analysis and synthesis of functional features of differential correction systems for different applications integrate them into a set of functional requirements for the local system of differential correction, which is a list of functional
requirements for LSDC. The list of these functional requirements includes: M – Mandatory requirements, which are fundamental to the system (Must have); S – Important requirements, which may be omitted (Should Have); C – truly optional requirement (implemented if there is time) (Could have); W – requirements that can wait until the next version of the system (Want to have).

Generalization of functional requirements will allow combining them into groups of requirements and present a model of using local differential correction in the form of case diagrams, shown in Figure 1.

To construct the architecture of the local system of differential correction object-oriented analysis was performed, where the resource base has essentially become the entire list of references.

As a result of modeling, we designed a diagram for simulation of the local system of differential correction, shown in Figure 2. This diagram shows that main part of the planned system in terms of types of provision consists of:

1) mathematical software (MSW):
   a) MSW of code differential correction;
   b) MSW of phase differential correction;
   c) MSW of code-phase differential correction;
2) informational provision:
   a) raw data of the navigational receiver;
   b) SP3-files;
3) technical provision:
   a) microprocessor;

Figure 1. Use case diagram of the LSDC operating in post-processing mode.

b) GPS-processor;

c) enclosure, external storage device, power supply, etc.

Standard Product 3 (SP3) format is used to assess satellite ephemeris accuracy. It is an international standard governing the format of the satellite data, for example, precise orbital data and satellite clock data. Time system of SP3 is a 60-digit ASCII file divided into two sections: the header and the data. The header contains information about monitoring session, such as an epoch and number of satellites. The data are organized by epochs. Each epoch contains ephemeris and clock corrections for each satellite (GPS or GLONASS). Each line of the ASCII data file corresponds to its own satellite.

Research done through the object-oriented modeling let us define the main functional and nonfunctional requirements for LSDC and present them in the form of use case diagrams, shown in Figure 1.

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2) informational provision:
   a) raw data of the navigational receiver;
   b) SP3-files;
3) technical provision:
   a) microprocessor;

Figure 2. Object diagram of the local system of differential correction in post processing mode.

4. Computational Methods of Differential GPS

The methods of differential correction are aimed to determine coordinates of the rover employing a navigation system, consisting of two GPS receivers (base and mobile stations). The base station is fixed, and its coordinates are assumed to be given with great precision. Therefore, determination of the mobile station coordinates
implies computation of the baseline vector between these stations.

The problem of differential correction is reduced to the solution of over determined system of linear equations in the form:

\[ AX = B \] (2)

The system (2) determined above is solved by least squares method (search for \( X \) that gives a minimal value of \( ||AX - B|| \)) by reducing a matrix to upper triangular form by Householder method which is based on orthogonal transformation.\(^7\) Then (2) takes the following form:

\[
\begin{bmatrix}
R & W \\
0 & S
\end{bmatrix}
\begin{bmatrix}
X \\
V
\end{bmatrix} =
\begin{bmatrix}
Q \\
V
\end{bmatrix}
\] (3)

where \( R \) and \( S \) – upper triangular matrices, and \( R \) has dimension of 3х3. In practical implementation the upper triangular form is calculated recursively, as data appear at successive epochs. The outcome of the problem solution will be the baseline vector \( X \).

Differential correction on code measurements in post processing or real time modes may provide accuracy not greater than 1 meter. The main part of error in this method is related with the fact that the second orthogonal code difference cannot compensate for troposphere errors as well as errors due to reflections. Only usage of phase measurements to solve the navigation problem improves accuracy up to several centimeters in the post-processing mode.

Phase differential correction differs from code correction in that the matrices in the equation (2) take other values, which are:

\[
A_i = [P \cdot E_i, F] \quad (i \text{ within } [1,m]);
\]

\[
B_i = P \cdot y_{qi} \quad (i \text{ within } [1,m]);
\]

In the formulas given above:

\[
y_{qi} \quad \text{-- first carrier phase differences;}
\]

\[(x, y, z) \quad \text{-- coordinates of the baseline vector, linking base and mobile receivers;}
\]

The solution of \( X \), found by least squares method, contains real valued ambiguities \( (N_2, ..., N_n) \):

\( n \) – number of GPS satellites visible to both stations;

\( m \) – number of epochs or synchronized GPS measurements.

Real valued mixed solution is derived from the formula:

\[
(x, y, z)^T = R^{-1}(Q - W \cdot (N_2, ..., N_n)),
\]

where \( (N_2, ..., N_n) \) – vector of real values (real valued ambiguities) obtained by solving the system of equations:

\[
S \cdot (N_2, ..., N_n)^T = V.
\]

Full use of integer nature of ambiguities requires resolution of the integer ambiguities. It uses a modified version of the well-known method called LAMBDA in the theory of information. The method input is fed by real-valued ambiguities (as the initial value), the covariance matrix of uncertainties \( (S^T S)^{-1} \) and some required number of candidate vectors, which usually equals to 2.

After integer ambiguity resolution, the solution takes form of the following equation:

\[
(x, y, z)^T = R^{-1}(Q - W \cdot (K_2, ..., K_n)),
\]

which has accuracy of about 1-2 cm, where vector \( (K_2, ..., K_n) \) denotes an integer vector obtained at the output of LAMBDA.

During the integer ambiguity determination procedure, it is possible to experience cycle slips of carrier phases of some satellites that lead to instant changes of double phase differences of the satellites by an integer or a half-integer number of cycles. In the post-processing static mode of positioning, one can apply algorithms of detection and repair of cycle slips by accumulating triple phase differences and rounding them to the nearest half-integer
number. Taking into account reliable resolution of integer ambiguities and insignificant influence of multiple carrier reflections, the author leaves without estimating only one type of errors which is caused by electromagnetic noise in the receiver channels.

The most widely adopted differential satellite navigation system is based on code-phase corrections, which at the same time takes into account pseudo-range values measured by carrier phase and code. The main difference of code-phase correction from phase differential correction is found in matrices of the linear equations $A_i$ and $B_i$:

$$A_i = \begin{bmatrix} P \cdot E_i & 0 \\ 0_{n \times 1} & 0 \end{bmatrix}, \quad B_i = \begin{bmatrix} P \cdot y_{i,j} \\ 0 \end{bmatrix}$$

The mathematical solution of the navigation problem using the code-phase correction method is similar in the rest of the part to the way of problem solving by means of phase differential correction.

In practice, it is possible that accuracy of the phase differential correction algorithm will be higher than accuracy in solving the problem by code-phase correction method. The matter is that the accuracy of initial measurement of pseudo-range by means of code and carrier phase may vary depending on the manufacturer of GPS receivers utilized. For example, some receivers generate code measurement errors which are so high that we are left with only option of applying phase differential corrections.

5. Experimental Verification of Accuracy

Two stages of experiments were conducted to verify the accuracy of the developed system of differential correction in the post-processing mode. U-blox LEA-4T single frequency GPS receivers were used as base and mobile stations in these experiments. The base station was placed on the roof of the building, while the mobile station was taken to some open field in the countryside. The slant range between the base and the open field stations was approximately 19.5 km, and height difference was about 200 m.

At the first stage, the developed software computed a baseline vector of the motionless mobile station based on GPS readings obtained within 20 minutes with a period of 1 s. The results of data processing by code differential and
code-phase differential modes are shown in Figure 3 and Figure 4. X, Y, and Z in the graphs represent local ENU (east-north-up) coordinates of the calibrated baseline vector.

At the second stage of experiments, three points A, B, and C were chosen at a distance of 13.241, 12.536, and 9.140 meters from each other, respectively. The distances AB, BC, and CA were measured by making use of a laser rangefinder that has a stated accuracy of 1 mm. Then the mobile station was installed consequently in points A, B and C for the duration of four minutes in each position. All measurements of the mobile station were stored in U-blox GPS files and transferred to the server of the base station to calculate corrected coordinates and distances between the fixed points. The implemented software gave the following results: the distance between points A and B is 13.437 m, which differs from the measured value by 4 mm; the distance between points B and C is 12.545 m, which differs from the measured value by 9 mm; and the distance between points A and C is 9.145 m, which differs from the measured value by 5 mm.

6. Conclusions

The article presents the results of research and development of the local system of GPS differential correction. The composition, structure and model are examined using of LSDC in the post-processing mode. The publication reveals a set of states and events fundamental for the LSDC information model development in the post-processing mode. Functional specifications and complex diagrams using Unified Modeling Language (UML) were developed for the system as a whole and for each type of provision that consists of mathematical, software and firmware layers. As a result of this research, a systematic project of the GPS LSDC was developed.

Furthermore, computational methods of differential correction that employ measurements from single-frequency GPS receivers were introduced in this article. Estimation accuracy of the methods was also verified in post-processing mode by experimental results which proved that the developed differential GPS system demonstrated appropriate performance when compared with the existing analogous systems in the world. The system should be developed further to be able to cover other modes of operation.

7. Acknowledgements

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8. References
