Scientific Journal of Riga Technical University
Telecommunications and Electronics

2010

Volume 10

GPS and IMU Complex System Experimental Research

Ansis Kluga, *Riga Technical University*, Janis Kluga, *Riga Technical University*, Elan Grab, *Riga Technical University*, Veronika Belinska, *Riga Technical University*

Abstract **– This article contains experimental results of GPS and IMU complex system research for real-time kinematics positioning. The research was made both in static and dynamic modes for a device MTi-G manufactured by Xsens Technologies. The dynamics research was made both at low (on foot) and high speed, in the last case by means of vehicle.**

The research shows the possibility to use complex GPS and IMU device for undersurface radar positioning applications. When the visibility of the satellites is limited or satellites are unavailable, the errors increase very rapidly over time.

Keywords**: Global Positioning System, Inertial Measurement Unit, real-time kinematics, the route view on the map.**

I. Introduction

RTK – or real-time kinematics – positioning has become an industry standard procedure in surveying, machine control, and other high-precision applications. RTK uses the carrier-phase and pseudorange measurements which are usually recorded at a fixed reference location with known coordinates and transmitted in real time to a user's vehicle receiver by using any kind of a radio link. The vehicle's receiver processes the double differences of observations between satellites and receiver to determine its coordinates with less than 10 cm error. It is possible only when receiver can solve the integer uncertainties in the carrier-phase measurements. These uncertainties are the bane of carrier-phase positioning. In order to convert the carrier-phase measurements into unbiased range measurements, it is necessary to solve these uncertainties [1, 2].

For the mobile objects with high dynamics (cars, airplanes, etc.) GPS with frequency-phase measurements can be replaced by pseudo-range measurements and differential correction.

In such applications, the most frequently used solution is a complex system, which consists of GPS and inertial navigation system (INS). At the present moment, there is research in many countries with purpose to realize such a complex system at a low cost. Since pseudo-range GPS receivers are cheap and wide area differential corrections are relatively inexpensive to obtain, the low cost complex systems are using Inertial Measurement Unit (IMU) instead of traditional INS.

II. GPS and IMU Complex System Precision Research

We have used the company's Xsens complex system named MTi-G for our research. This device includes 12 channel GPS receiver and the 3-axis inertial sensor (accelerometers and gyroscopes) with barometric altitude meter, as well as 3-axis magnetometers. Also, this device has onboard DSP processor for 6-dimensions Kalman filtering. In order to convert data from Xsens binary file format into NMEA-compatible format, which is suitable for data processing by GPS-oriented programs, we developed few conversion programs. Note, that the NMEA standard is much wider, while this program just partially uses the $GPGGA type message lines [7]. The following fields are filled: UTC time, latitude, longitude, height; while the rest of the fields are filled with zeroes. This is just enough for showing track of the movement on a map.

The complete complex system data was compared with its own receiver unprocessed data (without Kalman's filter). The experiments were made at the same locations where we have studied the phase measurements device. The pedestrian bridge at the railway station "Wagon Park" is the first place, where we have performed our experiment for MTi-G device both for data with complex processing and raw GPS data. We used our converting programs to get NMEA-compatible file format. Afterwards, these files were used for track visualization on the Google Map. We have used *http://www.gpsvisualizer.com* web-site for this purpose (see Fig. 1 for visualized results).

The problem is that the raw data usually has a noise. The values of dependent variables vary even though all the independent variables are constant. Therefore, the estimation of the trend is needed for the dependent variables. This process is called a regression or curve fitting. The estimated equation can satisfy the raw data, however this equation is usually not unique.

The equation or curve with a minimal deviation from all data points is desirable. This desirable the best-fitting equation can be obtained by applying least squares method - LSM [3], which uses the squared minimal sum of all deviations from a given set of data (in our case, the raw GPS data). Since the trajectory of the movement in this experiment is nearly linear (assuming we moved with constant acceleration), it can be approximated by the following linear function:

$$y_i = A + B \cdot x_i, \qquad (1)$$

where:

y_i - latitude or longitude values;

x_i - time samples, $x_i = 1, 2, ..., N$,

A and B constants are calculated by using least squares fitting method (LSF, [3]).

$$A = \frac{(\sum_{i=1}^{N} x_i^2) \cdot (\sum_{i=1}^{N} y_i) - (\sum_{i=1}^{N} x_i) \cdot (\sum_{i=1}^{N} x_i \cdot y_i)}{\Delta}, \qquad (2.1)$$

Fig. 1. Experiment on the bridge for GPS and IMU data complex processing.

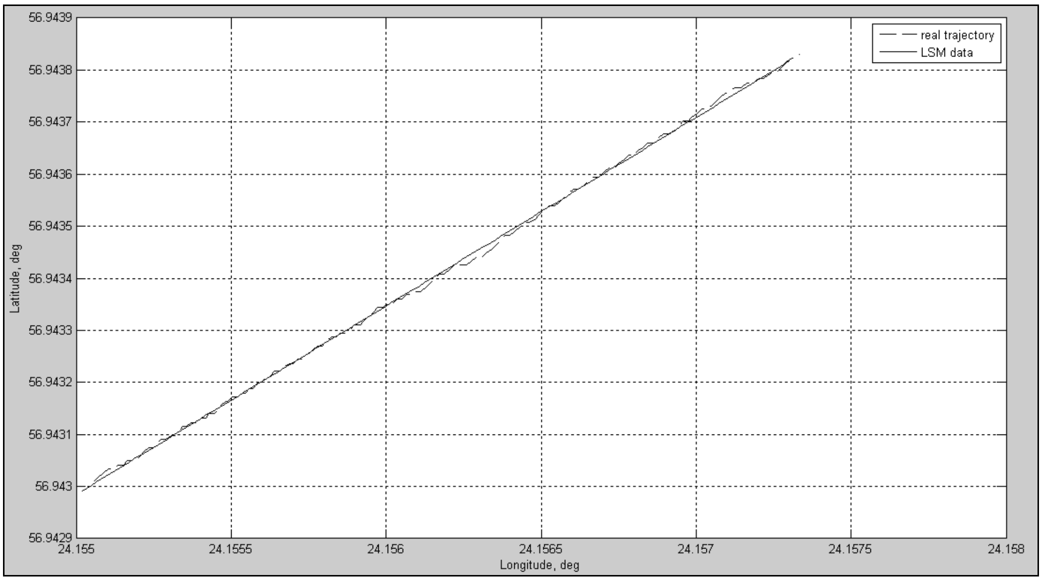


Fig. 2. Experiment on the bridge in one direction, the results after applying LSF method by using MatLab

$$B = \frac{N(\sum_{i=1}^{N} x_i \cdot y_i) - (\sum_{i=1}^{N} x_i) \cdot (\sum_{i=1}^{N} y_i)}{\Delta}, \qquad (2.2)$$

where:

$$\Delta = N(\sum_{i=1}^{N} x_i^2) - (\sum_{i=1}^{N} x_i)^2 . \qquad (2.3)$$

Expressions (2.1)-(2.3) gives the best estimates for A and B constants of the straight line (1) based on the N measured points. When, for example, we evaluate the latitude, we can write down the expression (1) in form of (3):

$$Lat_i[\text{deg}] = A_{Lat}[\text{deg}] + B_{Lat}[\frac{\text{deg}}{\text{sec}}] \cdot t_i[\text{sec}], \qquad (3)$$

Then we can interpret the B_{Lat} as latitude direction movement velocity. In case of our experiment with the MTi-G receiver (see Fig. 1):

$$B_{Lat} = 5{,}5498 \cdot 10^{-6}[\frac{\text{deg}}{\text{sec}}] \approx 0{,}6[\frac{m}{\text{sec}}] \cdot \qquad (4)$$

We are assuming that the latitude measurement value of each Lat_i is normally distributed and is centered by its true value (3) with width parameter – the error σ_{Lat}. So, the constants A_{Lat} and B_{Lat} have its errors too. The latitude direction movement velocity error is:

$$\sigma_{B_{Lat}} = 3{,}887 \cdot 10^{-19}[\frac{\text{deg}}{\text{sec}}], \qquad (5)$$

in that case, the velocity error is:

$$\sigma_B \approx 1{,}6 \cdot 10^{-11}[\frac{m}{\text{sec}}] \cdot \qquad (6)$$

After expressing both the latitude and the longitude as functions (1), we can get a line on the map, after applying NMEA-compatible file format converting programs to resulting set of data.

As the Fig. 2 shows, applying LSF method to the raw GPS data makes the track visually smoother. We get the uniformly accelerated movement by using approximation method, although the movement wasn't ideally linear, because the human walking couldn't be regular, and therefore the acceleration isn't constant too.

III. The Analysis of Practical Applicability for GPS and Inertial System

The use of the complex system is very common in transport systems applications. We have made research to find out about the possibility of using this system for undersurface radar [4]. So far, these radar systems use simple rotating wheel and usual GPS receiver to get the reference point. Then it calculates the distances recorded, while walking the path (straight line, usually). The example of such undersurface radars is "OKO-2" [5].

In order to develop such a simple system, it's necessary to have a high-precision positioning system. When using the conventional GPS receiver, the errors can exceed 3 m, which is considered to be too high error, when searching for much smaller objects. That's why we created Xsens binary file format data conversion program to make it possible to study complex GPS and IMU system.

According to the results of our research, Fig. 3 shows the path traveled after Kalman filter processing.

It is obvious, that the use of the complex GPS and IMU system in dynamics increases the accuracy of the trajectory detection [6]. The Fig. 3 shows possibility to mark any point of the trajectory and display its coordinates. It's also possible to display trajectory (independently of the radar software) on the map, just like it was done before for the bridge experiment results.

However, when using GPS and IMU complex system, there are new problems occurring as well. Although the complex filtering algorithm can significantly reduce the errors, it's still a GPS receiver, which is the "weakest" spot [7]. When the number of available satellites is limited, which commonly happens in urban or forest environments, the accuracy of the complex system can decrease, since no precise coordinates are

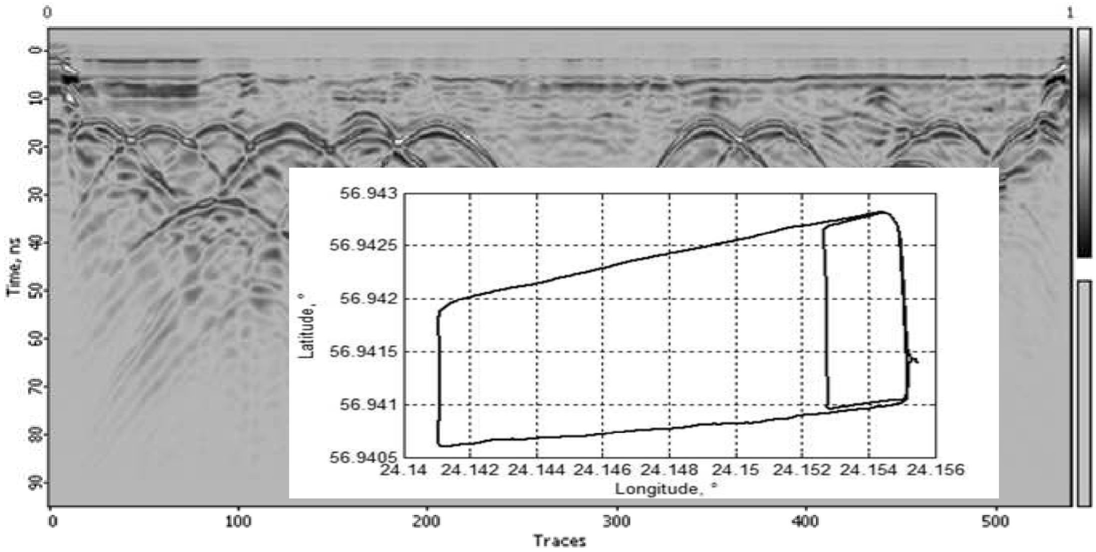


Fig. 3. The measurements of the undersurface radar and the trajectory of the movement for GPS and IMU complex system with Kalman filtering.

available from GPS, and IMU measurements have a drifting error, which constantly increases over time. That's why it is very important to determine a relative IMU measurements accuracy.

IV. The Relative IMU Precision In Room

Unlike it was in the above experiments, the general attention in this experiment was paid to the IMU accelerometers data. The special program written in MatLab integrates acceleration with a sampling period of 0.01 sec (the sampling frequency set to 100 Hz), thus calculating velocity for respective time moments. By integrating this velocity again, we obtain the length of the trajectory, or relative movement. In this experiment, the movement was present only along the X axis, as it happens most often, for example in the car or in case of undersurface radar. Therefore, the other projections are omitted.

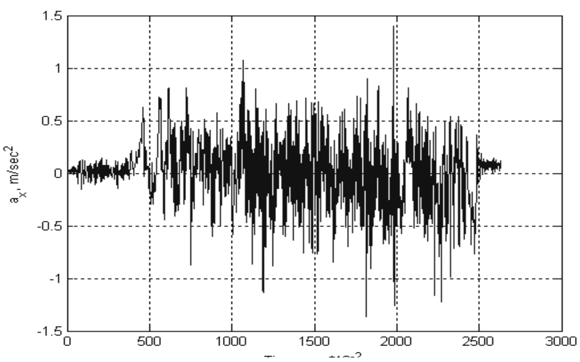
Since MTi-G device requires GPS satellites signals to operate, we used our Re-reference system in this experiment. The MTi-G device was fixed to the cart, both the device itself and its GPS receiver's antenna, therefore these two components don't move relatively each to other. The cart with MTI-G equipment was adjusted so that the accelerometers for X and Y axis were horizontal (roll and pitch angles do not exceed 0.5° – 1°). When the preparations part was completed, we measured X axis acceleration in static conditions over 5 minutes to estimate the noise (bias) mean value, which is necessary for the further calibration of X axis accelerometer (by subtracting this mean value from measured values). The statistical characteristics of the bias for X axis are shown in Table I.

TABLE I
THE STATISTICAL CHARACTERISTICS OF THE X AXIS BIAS

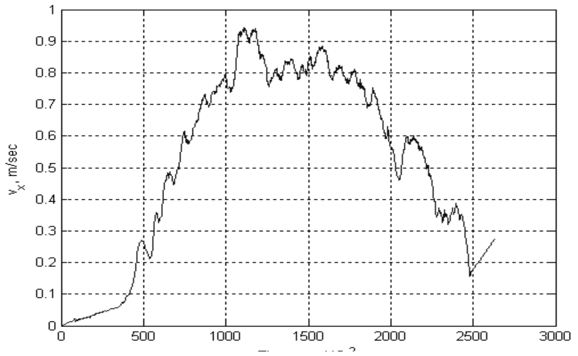
Mean value, $E[a_x]$	0.0902 m/s^2
Variance, $D[a_x]$	$6.91{\cdot}10\text{-}5$ m^2/s^4
Standard deviation, σ_x	0.0083 m/s^2

After estimating bias for X axis, there is experiment part. The cart was pushed across the room, and accelerometer's data was logged to file. Afterwards, by processing the binary file

a)



b)



c)

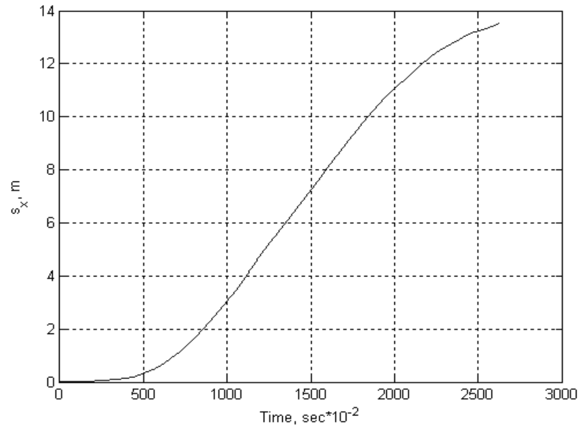


Fig. 4. MatLab plots for the IMU experiment: a) acceleration data, b) velocity data, c) distance data.

with conversion program, we receive array of the X axis accelerations values. By loading this array in MatLab program and running it, we get three plots: the acceleration plot, the velocity plot and the distance plot, shown in Fig. 4 a), b) and c) respectively.

As it can be seen from Fig. 4, even though the cart is "jumping" all the way, thus the acceleration is changing all the time, these "jumps" get compensated a lot at the velocity plot already. The changes of the velocity are obviously caused by the nature of human walking; it's possible to see each step on the velocity plot. After the second integration cycle, these jumps disappear completely and there is uniformly accelerated motion in plot, except the beginning of the motion and its end, where the speed changes gradually.

V. Conclusions

This article shows the possibility to use complex GPS and IMU device for the mobile objects with high dynamics (cars, airplanes, etc.) place determination. We use this system for undersurface radar place indication. It helps to save the trajectory of the movement even when the GPS satellites' signals are weak or unavailable. The results of coordinate detection with IMU show, that when GPS satellites are not visible relative movement parameters can be determinate.

REFERENCES

[1] M. Ge, G. Gendt, M. Rothacher, C. Shi, and J. Liu. Resolution of GPS Carrier-Phase Ambiguities in Precise Point Positioning (PPP) with Daily Observations // Journal of Geodesy. - Vol. 82, No. 7 (2008, July), P. 389–399.

[2] Bisnath S, Gao Y. Precise Point Positioning a Powerful Technique with a Promising Future // GPS World - 2009 (April), P.43-50.

[3] Taylor, John. An Introduction to Error Analysis, 2nd.ed. – Sausalito: CA, University Science Books, 1997. – P. 181-200.

[4] James D. Taylor. Ultra-Wideband Radar Technology. - New Work, Boca Raton: CRC Press, 2000. - P.18.

[5] GEOTECH Homepage , "OKO-2 GPR with Control Unit", *GEOTECH company*, 2010. [Online]. Available: http://www.geotech.ru/en/market/geophysical_equipment/ground_penetrating_radar_gpr/oko-2_gpr_with_control_unit/ [Accessed: Dec. 16, 2010].

[6] Bistrovs V., Kluga A. Combined Information Processing from GPS and IMU using Kalman Filtering Algorithm // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 5(93). – P. 15–20.

[7] Belinska V., Boicov V., Kluga A. Data processing methods for GPS user devices control system // Scientific proceeding of RTU. - Riga 2008, section "Telecommunications and Electronics" – Series 7, vol. 8. – P. 48 – 51.

[8] Accuracy Estimation of GPS Receiver Parameters with Simulator in Dynamic Mode /A. Kluga, A.Zelenkov, E.Grab, V.Belinska. // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 6(94). – P. 9–14.

Ansis Kluga, Dr.sc.ing., professor, head of Transport Electronics and Telematics department of Riga Technical university.

The work experience: 1980-1999- Riga Aviation university, Associate Professor of Computer Technics, Pilotage and Navigation Department; 1999 dean of Radioelectronics and Computer Systems Department**.** One of the previous publication: GPS user devices parameter control methods / **Kluga A.,** Kulikovs M., Semjonova V., Zelenkovs A. // Scientific proceeding of RTU. – Riga 2007, section "Telecommunications and Electronics" - Series 7. - P. 45 – 48. Field of research is radio electronics, avionics, radio systems. Email: ansis.kluga@rtu.lv.

Janis Kluga, B. sc.ing., assistant lecture of department Transport Electronics and Telematics of Riga Technical university from 2005. Bachelor's degree in computer science earned during 2002 - 2004. Now is last year student of master program "Transport computer management, information and electronic systems" in Riga Technical university.

One of the publication: Application of Least Square Method with Variable Parameters for GPS Accuracy Improvement**.**/ Kluga A., **Kluga J**., Beļinska V. // „Electronics and Electrical Engineering"- Kaunas: Telecommunications Engineering , 2010, No.8 (104), pp.109-112 Field of research is information and computer science. Email: janis.kluga@rtu.lv.

Elan Grab, Education place - Riga Technical University, Faculty of Electornics and Telecomunications, Transport Electronics and Telematics Department. Bachelor's degree in transport electronics and telematics earned during 2004 - 2007. Professional master's degree in transport electronics and telematics earned during 2007 - 2010. Currently undertaking doctoral studies at the same place and program.

Formerly worked at Hansa Electronics factory as a manufacturing process operator in 2006 – 2007. Currently working at the university simultaneously with studies at the same place since 2007. Current assignments – science assistant, participating in department's research projects, and lector – reading following courses: "Transmission of Information and Transport Digital Communication Systems" and "Principles of Communication Systems" to undergraduate students. Current work place: Lomonosova 1, V-315 cabinet, Riga, Latvia. Author has been awarded the following rewards:

1. The 2-nd level Samsung Electronics Annual Grant for good results in studies.
2. Diploma of the 49-th RTU Student Conference of Science and Technics

Author's e-mail address: konnektor@gmail.com

Veronika Belinska, M.sc.ing., Bachelor degree of Engineering Science in Electrical Engineering (year 2003 - 2006), Master degree of Engineering Science in Transport Telematics (year 2006 - 2008). Field of study is electrical engineering and transport telematics.

The work experience: The Secretariat of the Special Assignments Minister for Electronic Government Affairs, Project leader assistant (year 2006); Riga Technical university, Scientific assistant of department Transport Electronics and Telematics (year 2008 - 2010). One of the previous publication: GPS user devices parameter control methods / Kluga A., Kulikovs M., **Semjonova V**., Zelenkovs A. // Scientific proceeding of RTU. – Riga 2007, section "Telecommunications and Electronics" - Series 7. - P. 45 – 48. Field of research is information and navigation systems.
Email: veronika_belinska@inbox.lv

Ansis Klūga, Janis Klūga, Elan Grabs, Veronika Beļinska. GPS un IMU Kompleksās Sistēmas Eksperimentālie Pētījumi

Šajā rakstā ir izklāstīti GPS un IMU kompleksās sistēmas eksperimentālo rezultātu pētījumi reāllaika kinemātikas pozicionēšanā. Pētījumi tika veikti firmas Xsens Technologies ierīcei MTi-G – gan statiskajā, gan dinamiskajā režīmā. Dinamikas pētījumi tika veikti gan pie maza ātruma (kājām), gan pie augstā, pēdējā gadījumā tika izmantots automobilis.

Šīs raksts apraksta arī minimālo kvadrātu metodes pielietojumu lineārās vienmērīgas kustības trajektorijas aprakstīšanai. Kaut arī pētījumu rezultāti norāda, ka šo metodi var pielietot tikai šīs trajektorijas formas novērtēšanai, izmantojot GPS uztvērēja datus, var eksistēt cits paņēmiens (vai vairāki), kas dotu iespēju novērtēt patiesas koordinātes katrai nolasei tās attiecīgajā laika momentā. Viens no tādiem risinājumiem ir realizēt Kalmana filtrāciju, uz ko arī tiks vērsti nākošie pētījumi.

MTi-G kompleksās apstrādes sistēma izmanto gan GPS signālus, gan IMU datus, kas tiek pastāvīgi mērīti ar akselerometru palīdzību. Viens no šajā rakstā aprakstītajiem eksperimentiem ir „tīro" IMU datu izmantošana trajektorijas garuma aprēķinam. Lai to panāktu, nepieciešams pastāvīgi mērīt paātrinājumu kustības ass virzienā un, pielietojot, divkāršu integrēšanu, novērtēt koordinātu izmaiņas.

Šie pētījumi parāda, kā pastāv iespējas izmantot GPS un IMU komplekso ierīci zemvirsmas radiolokācijas atrašanas vietas noteikšanas uzdevumos. Gadījumā, kad satelītu redzamība ir ierobežota, vai arī satelīti nav pieejami, noteikšanas kļūdas ievērojami pieaug laikā.

Ансис Клуга, Янис Клуга, Элан Граб, Вероника Белинская. Экспериментальные Исследования Комплексной Системы IMU и GPS

В данной статье приведены результаты экспериментальных исследований комплексной системы IMU и GPS при определении местонахождения для кинематики в реальном времени. Исследования проводились как в статическом, так и в динамическом режиме для устройства MTi-G, производимого компанией Xsens Technologies. Исследования динамики проводились как на низкой скорости (пешком), так и при высокой – в последнем случае использовался автомобиль.

Помимо этого, в данной статье также рассматривается применение метода наименьших квадратов для оценки траектории прямолинейного равномерного движения. Хотя исследования показывают, что данный метод применим лишь для оценивания формы этой траектории, могут существовать и другие методы, позволяющие оценивать истинные координаты каждого отсчета в их соответствующие моменты времени. Одно из решений – реализовать фильтрацию Калмана, и дальнейшие исследования будут проводиться именно в этой области.

Комплексная система MTi-G полагается как на сигналы GPS, так и на данные IMU, постоянно измеряемые акселерометрами. Один из экспериментов в данной статье описывает использование только «сырых» данных IMU для расчета длины траектории. Для достижения этой цели необходимо осуществить серию измерений ускорения по оси направления движения и выполнить двойное интегрирование для оценки изменения координат.

Проведенные исследования указывают на возможность применения комплексной системы IMU и GPS для определения местонахождения в приложениях подповерхностной радиолокации. В случаях, когда видимость спутников ограничена, или же спутники недоступны, погрешность определения местонахождения быстро растет во времени.