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Selected aspects of testing the positioning accuracy of GNSS receivers used in sports and recreation by dynamic measurements

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Abstract

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Keywords

positioning accuracy, dynamic testing, receivers' testing, GNSS, GPS, GLONASS

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OPINION

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Authors' Contribution:
A Study Design
B Data Collection
C Statistical Analysis
D Data Interpretation
E Manuscript Preparation
F Literature Search
G Funds Collection

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abstract

Background: Satellite navigation systems have been used in professional navigation and geodesy for many years. The past decade has been a time of extending their application to devices also accessible to non-professional users. Sports and recreation is one of the major new areas in which satellite receivers are used. Since device manufacturers do not inform precisely (or at all) about the level of the positioning accuracy provided by such devices, it is necessary to propose a method of its assessment. This paper presents selected aspects of testing receivers in dynamic measurements to determine their accuracy based on international recommendations and standards applicable to validation of professional navigation GNSS devices. It also presents a number of examples of practical tests, based on many years of the authors' experience, to which comments were added.

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INTRODUCTION

Human locomotion on land, on the sea and in the air, especially long-distance travel, has always been supported by suitable devices which assisted in navigation, understood as “the process of controlling an object’s movements” [1]. The use of radio waves in positioning was a milestone in the process – first in land-based systems (Loran, Decca – the 1st half of the 20th century, Omega – the 1970s), followed by global range satellite systems (GNSS – Global Navigation Satellite Systems) as well as local range (IRNS, QZSS) and supporting systems (SBAS – Space Based Augmentation Systems) such as: EGNOS, WAAS, MSAS, SDCM, GAGAN. Two global systems: American GPS NAVSTAR and Russian GLONASS – the only two fully operational ones, have the leading position in this regard [2]. The Chinese Beidou and European Galileo will also become equally functional in the nearest future. The absence of area-related limitations and relatively high accuracy (for example, the declared horizontal error for GPS is not larger than 9 m, and the vertical error is 15 m, p = 0.95 [3]), supported by general technological progress in the late 20th and early 21st centuries resulted in a rapid increase in the popularity of GNSS receivers. Currently, they are available both as stand-alone devices, providing the user with information on the location (dedicated devices for different types of human activity and for land, water or airborne vehicles), and they are implemented in other devices (e.g. cameras, smartphones [4]). An example of differentiated applications is provided by one of the leading manufacturers of stand-alone receivers – Garmin, whose offer includes over 90 GNSS receivers used in the following areas: motor vehicles, sport and fitness, outdoor recreation, swimming vessels and aircraft (the number of portable models available at garmin.com in the 3rd quarter of 2018).

GNSS receivers are specific measurement tools because of the positioning method. Among the most popular ones (code receivers), it involves a measurement of the time it takes a signal to travel between navigation satellites and a receiver, which is used to determine the so-called “pseudo-distance” and to calculate the position (geographic longitude and latitude) on the Earth. Since the technical characteristics of the receiving system of the receiver (satellite signal tracking channels) and navigation algorithms are the principal features that determine the GNSS receiver positioning accuracy, the same model made by a manufacturer can have different locomotion values depending on the time of measurement (the geometry of the satellite constellation).

Apart from well-designed software and its functions, the average user of a sport-and-recreation GNSS receiver will find it more important to answer the question: which device will determine the kinematic quantities (velocity, distance, etc.) with the highest accuracy? Meanwhile, reviewing documentation provided by receiver manufacturers shows that the basic operational characteristics (including the positioning accuracy) are published very rarely or not at all. This gap is partly filled by studies which focus on an assessment of usability (validity and reliability) in particular disciplines or motion tests, and leaves out the technical aspects [5–13]. The device accuracy in these tests is analysed by the distances covered, maximum velocity and acceleration. However, these are derivative quantities, resulting from a change in the receiver’s position. If the position is determined with low accuracy, these quantities will also have errors. Studies aimed at assessing the receiver accuracy are very rarely undertaken and have usually concerned universal recorders [14] and smartphones – specific GNSS receivers [15–17], although various methods of accuracy assessment have been applied.

Therefore, due to the uniqueness of this measurement device, it is worth taking up the issue of testing satellite navigation receivers used in sport and recreation based on standards and methods of testing used in professional navigation, obviously taking into account the capabilities and limitations of currently available sport-and-recreation receivers. Considering the wide range of this issue, the aim of this paper is to present selected key aspects of testing receivers based on practical examples from the authors' own studies.

METHODS OF TESTING GNSS RECEIVERS

One of the first documents which determined the methods of testing GNSS receivers and which remains the comprehensive compendium in this regard is the standard published by the Institute of Navigation of the USA [18] entitled "Recommended test procedures for GPS receivers". It provides definitions followed by the basic groups of tests usable in marine, land and portable receivers. This document shows that tests of static and dynamic accuracy are the two main methods of receiver accuracy assessment. They determine the accuracy with which a receiver can determine its position: in a static test (in a stationary manner, relative to a known position) and in a dynamic test (in motion, relative to a reference trajectory, determined with the highest possible accuracy). The document also points out that since GPS errors are random by nature, it is in the tester's interest to determine the vehicle trajectory (dynamic accuracy) and the antenna (static accuracy) with the greatest possible accuracy to be able to know the performance of the receiver under assessment. The Standard proposes that during dynamic accuracy testing three data collection periods should be conducted, each lasting at least one hour, with at least 1,000 properly calculated position points (the three periods should be more or less evenly distributed over a 24-hour day).

Another group of tests presented in the ION Standard are those describing the functional parameters of receivers: INIT TTFF (Initialized Time to First Fix), WARM TTFF (Warm Start Time To First Fix) and REAQ (REAcQuisition time). The first test determines the length of time which is necessary for a stationary receiver to determine the current position (2D or 3D) from the moment of switching on after a several-hour break. The second one determines the time needed for a stationary receiver to determine the current position from the moment of switching on after a short break, and the third one (the reacquisition time) represents the length of time necessary for a stationary receiver to determine the current position after the temporary blocking of signals from all GPS satellites.

The general comments in the Standard include: the need for ensuring an undisturbed field of observation of all satellites over 10 degrees above the horizon, ensuring the absence of signal interference and protecting against unwanted movement (in both types of tests).

Considering the specificity of the sports and recreation area, it seems that the test of dynamic accuracy best characterises GNSS receivers. This is because it recreates the basic locomotion movements, such as how a human-athlete moves, independently or using machines and devices at various speeds. The difficulty one faces in the dynamic accuracy test is to create a reference trajectory to which a receiver will be compared, especially taking into account the volume of data collection suggested in the ION Standard (the length of time of data collection periods or the number of correctly calculated position points).

Choosing the right positioning reference system is a very important problem which has to be solved in dynamic measurements to guarantee the required positioning accuracy for reference receivers. Their readings should form the basis for determination of a GNSS receiver position in motion. It is a general principle of choosing the reference system that its positioning accuracy should be one order higher (par. 6.3 and 7.3 [18]). For example, if eLoran with the accuracy of 10 m ($p = 0.95$) is the tested system [19] then, for example, the GPS system should not be the reference system. For a multi-system sports and recreation receiver, whose typical accuracy is 3–5 m, the reference system should have a positioning accuracy of 30–50 cm. It would be the optimum solution to use a multisystem GNSS geodetic network with an accuracy of 2–3 cm [20].

POSITIONING ACCURACY AND ITS MEASURES

The positioning accuracy, which can be defined as the degree of closeness between the estimated or measured position of a GNSS receiver and its actual position, is the main assessment criterion of GNSS satellite receivers. The positioning accuracy can be determined with various statistics – calculated for real coordinates (if any) or, if the position is not known - for the averaged position. All coordinates must be based on the same reference frame (WGS-84). Three types of accuracy are identified [21]: (a) predicted accuracy – accuracy of position determination by the system relative to the actual values, (b) repeatable accuracy – the level of accuracy which allows the user to return to the coordinates determined earlier by the same system, and (c) relative accuracy – which describes the ability to measure (determine) the coordinates relative to a different user within the same system at the same time.

The literature on navigation and geodesy mentions a number of measures which can be used to describe the positioning accuracy. The most frequently used measures are presented in Table 1 [22–24].

Table 1. Selected measures of positioning accuracy

Accuracy measure	Dimension	Probability	Definition
RMS	1D	68%	The root mean squared error calculated for φ, λ or h.
DRMS	2D, 3D	63-68%	The distance root mean squared error calculated for φ, λ, h.
2DRMS	2D, 3D	95-98%	Twice the DRMS.
CEP	2D	50%	The radius of circle centred at the true position, containing the position estimate with probability of 50%.
SEP	3D	50%	The radius of sphere centred at the true position, containing the position estimate with probability of 50%.
R68	2D, 3D	68%	The radius of circle (sphere) centred at the true position, containing the position estimate with probability of 68%.
R95	2D, 3D	95%	The radius of circle (sphere) centred at the true position, containing the position estimate with probability of 95%.

where: φ –geodetic (geographic) latitude; λ –geodetic (geographic) longitude; h – ellipsoidal height.

The first three (RMS, DRMS, 2DRMS) are determined relative to normal distribution, and the others (CEP, SEP, R68, R95) are determined from a sample.

According to the authors of this paper, the assessment of satellite navigation receivers used for sports and recreation in dynamic testing is best done with the basic measure used in navigation, i.e. 2DRMS or, alternatively, R95. They can be determined for both a 2-dimensional (2D) plane and 3-dimensional (3D) space.

LIMITATIONS IN TESTING CURRENT SPORTS AND RECREATION GNSS RECEIVERS

The NMEA-0183 (National Maritime Electronic Association) protocol is the common, global standard of data exchange in maritime and land navigation. It defines a number of messages, including a GGA message, which carries e.g. information on the time, position and parameters of signal reception. However, most sports and recreation devices cannot record information in this form. Exceptions include universal recorders (now used increasingly rarely) and smartphones, in which the format of coordinate recording depends on the software used. Autonomous receivers for runners, cyclists, tourists (e.g. Garmin, Suunto, etc.), the most popular among non-professional users, usually enable recording only in one form – a universal GPX format of data exchange between satellite navigation devices and applications used for the purpose. It is a standardised XML format, which – between markers – contains information specified by the manufacturer, such as the time, position coordinates, altitude above sea level, distance covered and others, depending on the additional sensors used. The frequency of position recording is (1Hz, 5Hz, 10 Hz; [25]) or it has the form of so-called Smart Recording (Garmin receivers), in which the device itself selects the points of recording, depending on the complexity of the route and velocity. The .GPX format can be regarded as carrying enough information for static and dynamic testing.

The geographic position coordinates (latitude and longitude) presented in the angular (curvilinear) measure prevent error determination for individual measurements in meters; therefore, it is justified to transform them additionally. To this end, geographic (angular) coordinates are projected from the surface of a WGS-84 ellipsoid onto the flat plane with Gauss-Krüger transformation, commonly used in geodesy [26]. Calculations yield coordinates (x, y), where x denotes distance (in metres) of a point from the equator, calculated along the arch of the meridian (on the ellipsoid of revolution WGS-84), and y is the distance (in metres) from an arbitrarily established central meridian. After the flat coordinates are calculated, selected measures of positioning accuracy can be calculated.

METHODS OF DYNAMIC TESTING OF SPORTS AND RECREATION GNSS RECEIVERS

The following question should be answered before testing the positioning accuracy of sports receivers: is the aim of the study to compare the positioning accuracy of several sports receivers or do we expect the test results to provide us with information on the actual measures of the receiver accuracy (e.g. a technical specification in the receiver operation manual), which is much more complex than just a choice of a receiver which is more accurate in terms of the positioning error? Therefore, the positioning accuracy of GNSS sports receivers in dynamic measurements can be tested in two ways by means of:

- accuracy assessment based on a known trajectory – when the receiver being tested moves along a route whose coordinates were previously determined. The perpendicular distance between the tested receiver coordinates and the reference route – Cross Track Error – XTE – is taken as the momentary positioning error. It is a relatively simple method; however, its defect is that it does not take into account the actual coordinates of the receiver being tested (Fig. 1),
- accuracy assessment relative to a reference system – when the coordinates of the receiver being tested are compared to its actual (error-free) coordinates, which are determined on the basis of the reference system.

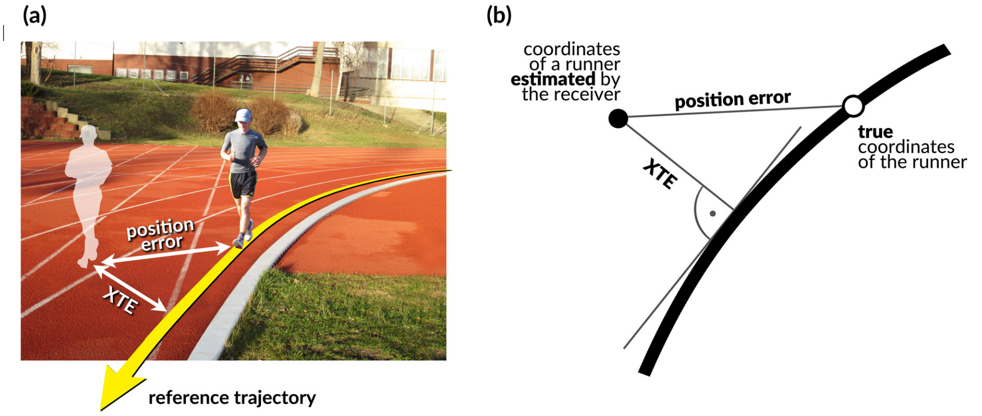

Fig. 1. The 3D spatial projection (a) and 2D projection from above (b) showing the positioning error relative to the reference trajectory

In a theoretical sense, the positioning error vector is the main difference between the two methods; it will be analysed statistically. In the first case (XTE), it is a (perpendicular) projection of a position onto an outlined trajectory – the oval of a stadium; in the second case, it corresponds to the actual value of the position error. There is no doubt that the first of the methods requires only the point coordinates of the trajectory along which the receiver being tested will be moving.

This method was used in a study [27] which tested receivers at a sports stadium. As a starting point, precision geodetic measurements were conducted at the athletics stadium of the University of Physical Education and Sport (Gdańsk, Poland). The position of two reference tracks was determined with a measurement kit consisting of a geodetic receiver GNSS Leica VIVA GS-15 with a CS-15 controller, with a positioning accuracy of 2–3 cm (p = 0.95), and the measurements were verified by the conventional geodetic tachymetric method. The principle was adopted that point positions would be determined every 10 metres on a straight line and on curves – every 1 m. The first track was determined at a distance of 30 cm from the running track edge, according to guidelines [28], and the second was determined based on the course of the line separating the first and second track (Fig. 2). The measurements yielded coordinates of 259 points for each of the two ovals:

- the reference (inner) 400 m trajectory of the stadium, which can be used when receivers are tested by runners (e.g. by mounting a receiver on a runner's arm);
- the trajectory of a line between the first and the second track in the stadium – which makes it possible to test receivers by using a vehicle with a larger number of receivers mounted on it; such a vehicle would follow along the line.

Using the track-separating line, tests were performed for receivers used by runners, cyclists, tourists and universal recorders, which were deployed one after another on a trolley specially prepared for the purpose (Fig. 3). The trolley was led at a constant speed of 5.5–6 km/h for two laps (800 m), obtaining approx. 600 positioning points in this manner for each of the receivers.

In another method for performing a dynamic test on a specific (measured) trajectory, the authors used a railway track (Fig. 4) on sections: Osowa-Somonino, approx. 26 km long, on which tests of a universal 1 Hz recorder were performed and over 5 thousand position points were gathered ([29], test 2B) and Koszalin-Manowo (12 km), where 5 Hz sport receivers were tested, each of which recorded approx. 35 thousand points. In both cases, the reference trajectory was established with an accuracy of 2–3 cm (p = 0.95) with geodetic GNSS Leica Viva GS-15 receivers (the line stock taking process was described in [30] and [31]).

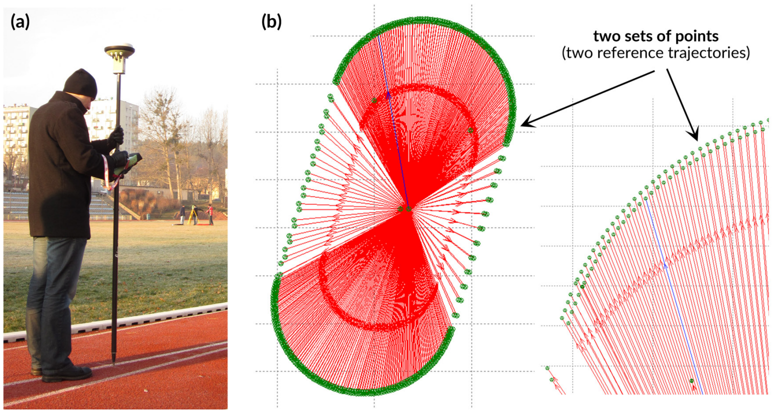

Fig. 2. Stock taking measurements of two tracks on a stadium using a GNSS receiver (a) and the two sets of reference points obtained (b)

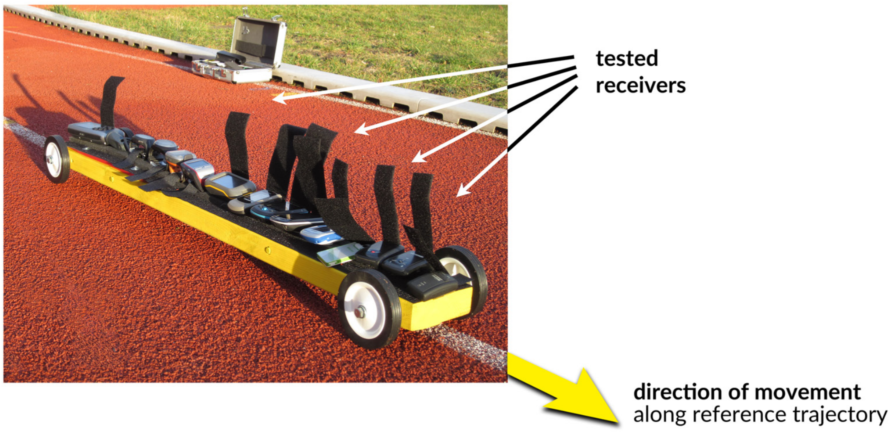

Fig. 3. Deployment of receivers on the measurement trolley during a dynamic test at a stadium

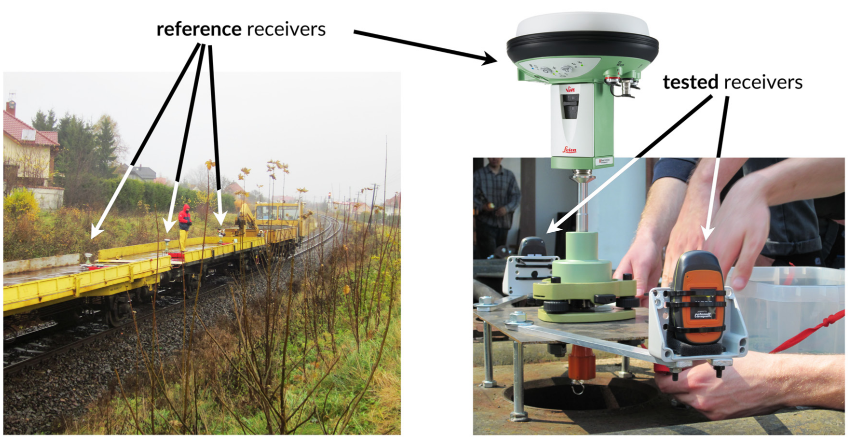

Fig. 4. Deployment of reference receivers and those tested in railway tests

Accuracy assessment relative to the reference system is more complex than the method based on a known trajectory. It requires using geodetic GNSS receivers with both high positioning accuracy (8–10 mm) and high measurement frequency – 20 Hz [30]. Using GNSS geodetic networks [32] and minimising the geometric factor DOP have a crucial effect in this regard.

The second measurement method is also much more difficult to carry out because of the testing the positioning accuracy relative to the actual coordinates of the receiver being tested. Based on previous experience gained from dynamic receiver tests on land, the authors proposed that two reference receivers should be used in such tests, with tested receivers situated between them [33]. Reference and tested receivers (Samsung Galaxy smartphones) were fixed on the upper deck of the Tucana ship (Fig. 5). The planned and completed measurement route was about 10 km long, and it was planned at the sea port and at its roadstead (Gdynia Port, Poland). Geodetic GNSS receivers (two Trimble R10, Trimble GA530 and Simrad MXB5), receiving RTN corrections from an active geodetic network, ensuring the positioning accuracy of 2–3 cm (p = 0.95) [34] were used to determine the reference quantities. The tested smartphones recorded from 3.4 thousand to nearly 11 thousand position points.

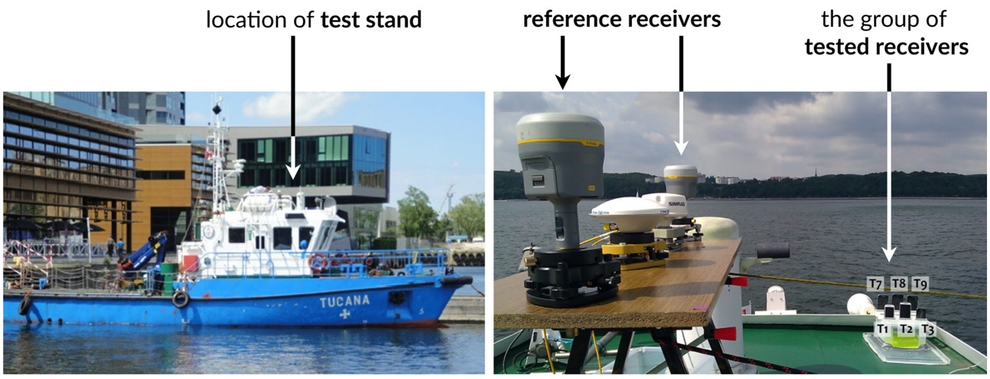

Fig. 5. Deployment of reference and tested GNSS receivers on a vessel

CONCLUSION

This paper presents selected aspects of testing the positioning accuracy of satellite navigation receivers used in sports and recreation, based on the authors' many years of experience in the area.

Obviously (as the authors note), the greatest difficulty lies in identifying the reference system. Measures of accuracy used in professional navigation and geodesy can be applied only if a real point is determined for each point recorded by the tested receiver at the same time. The high complexity of this solution prevents its widespread application (a comprehensive description of satellite methods which enable achieving high positioning accuracy is provided in [35]). It is considerably easier to refer the coordinates of the tested receiver to a reference trajectory, which can be determined with receivers more accurate by an order of magnitude than the tested ones, or (as a last resort) the trajectory can be read out from Google Maps. This approach does not enable calculating such measures used in navigation and geodesy as RMS, DRMS, 2DRMS, but it allows for comparing receivers and determining which of them determines its position better (more accurately). In such cases, XTE should be used as a random variable whose statistics allow for comparing the receivers with each other in terms of the positioning accuracy.

Another important aspect is the need to perform a measurement of a proper duration, i.e. to gather a sufficiently large number of tested receivers positioning points, which affects the quality of the calculated statistics (e.g. measures). The ION Standard guidelines for the maritime and railway tests described above were met in this regard, whereas the tests at the stadium should be regarded as too short. In such a case, the receiver (especially single-system ones) quality assessment can be affected by the right satellite constellation, described with DOP (Dilution of Precision) coefficients.

The last issue which the authors regard as rather important in the testing aspect (it is also mentioned in the ION Standard) is the need to provide receivers with access to direct signals from navigation satellites of GNSS systems. As regards the tests using the railway lines, the authors point out that with such long test sections, it was impossible to avoid fragments of the route where signals reaching the receivers were reflected (e.g. fragments of the route in the forest), which caused disruptions (considerable deterioration of accuracy) of positioning. Therefore, it seems that tests conducted at places with no obstacles, such as at sea or in open places (an athletics stadium) are an appropriate method for dynamic testing.

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