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TESTING METHODOLOGY FOR GNSS RECEIVERS USED IN SPORTS AND RECREATION. OUTLINE OF ISSUES

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Introduction

Satellite navigation systems, primarily designed for military purposes, in the 90s were made available to civil users. Although for many years those were commonly used in professional navigation and land surveying, it was only in the last decade that can be observed intense extend of their use to the general public applications. One of the new, yet important areas of use of GNSS receivers is in sports and recreation.

Currently, apart from the US NAVSTAR GPS system, the only fully operational satellite navigation system is the Russian GLONASS. Simultaneously are developed Chinese Compass and the European Galileo. Since the measurement using GNSS consists in determining the distance from the receiver to the satellite, it can be done using various methods. The most popular among civilian users are code GPS receivers with an accuracy of several meters (according to GPS official document no less than 9 m horizontally and 15 m vertically, $p = 0.95$; GPS SPS PS 2008). More complex code GPS receivers are supported by geostationary systems (differential method) or dual-system code receivers – with an accuracy of less than 2.5 m horizontally. The most complex, used for professional applications, are GNSS RTK phase receivers with accuracy reaching centimeter.

Currently available for sale are hundreds of models of GPS receivers. They feature diverse operating attributes resulting essentially from their purpose, but their main measure of comparison is accuracy to determine coordinates of the user’s position. Also important are: the time of signals reacquisition in case of their loss, the ability to determine the direction of movement, and many other technical features. These result essentially from the measurement accuracy of pseudorange to the satellites, from the frequency of position determination and from the use of additional supporting sensors (accelerometers, gyroscopes, magnetic direction sensors et al.). A leading group of receivers are those designed for sport and recreation.

For the average user of the sport and recreation receiver, apart from the aspect of software, the most important thing would be answering the question: which device will accurately determine the amount of kinematics (speed, distance et al.). Meanwhile, acquainting with the contents of documentation supplied by the manufacturers of receivers leads to observation that the basic operational characteristics are published rarely or in a way that prevents comparison with other devices. Previous studies associated with the use of satellite navigation receivers in sports are focused on evaluating fitness in individual disciplines / events, skipping the technical aspects of the equipment. According to the Authors of this article, due to the nature of satellite measurement, equally important, if not more important aspect is the accuracy of the receivers, which affects collected by the researchers kinematic volumes.

Material & methods

To help users classification and adjustment to the needs defined by personal preference or the requirements of sports / competition, in this article the Authors attempt to outline testing methodology of GNSS receivers used in sport and recreation, because so far it was not raised neither by a national nor world literature. Following research questions were put: (1) what measure of accuracy of determining position will be suitable to evaluate the GNSS receivers used in sport and recreation? (2) whether and to what extent the testing methodology from other areas of science can be used to evaluate receivers in sports and recreation? (3) whether the accepted testing methodology allows evaluation of the accuracy of determining position coordinates in sports and recreational receivers?

Determination of the position

The concept and types of positions coordinate quality

The accuracy of the receiver position determination is a conformity degree of statistic (its distributions) measured (defined) position coordinates with the actual values or those that we take as actual. The measure of position determination accuracy is its error, which can be assessed in relation to any dimension: space or surface (horizontal error – 2D, vertical error – 3D).

Navigation sets out the following types of accuracy: (1) the accuracy of predicted position determination (called predictable accuracy) – accuracy expressed in geodetic coordinate system, associated with the model of the Earth (ellipsoid). It informs about the distribution of positions measured by the system relative to their actual values, set with high precision (theoretically – without errors) in the coordinate system used by the system. In case of GPS it will be WGS-84, (2) the repeatable accuracy to determine the position (called repeatable accuracy) is the accuracy with which the system allows user to return to a previously determined position in system-specific coordinates. In contrast to the predictable accuracy that relates the measurements to “the actual position coordinates,” a repeatable accuracy informs with a statistical distribution of the position relative to some arbitrarily set value. Most often as such is considered a position averaged over the measurement series, which does not necessarily correspond to the previously mentioned real (actual) coordinates, (3) the relative precision position determination (called relative accuracy) – the accuracy of determining the position in relation to another user of the same system at the same time and in the same coordinate system. Expressed error reflects the level of correlation between the errors of several receivers working simultaneously. This measure informs you what are the measurement errors of several GPS receivers at the same moment. In contrast to the relative accuracy and predicted accuracy, its verification or evaluation requires at least two receivers working by the same procedure of processing and handling signals received.

Measures of accuracy of position determination in 2D and 3D

The basic and most commonly used in world literature measures of accuracy of position coordinates determination are:

- DRMS (Distance Root Mean Square) is an average error of position determination. It is a root of second degree calculated from the sum of the squares of the standard deviations of position coordinates set relative to the latitude and longitude (geodesic) – in the 2D space, or relative to latitude, longitude and altitude – in 3D. This corresponds to a probability of 68%. It is represented by a form of mathematical relationship:

$$\mathrm{DRMS(2D)} = \sqrt{(\sigma_x)^2 + (\sigma_y)^2} \quad \text{or} \quad \mathrm{DRMS(3D)} = \sqrt{(\sigma_x)^2 + (\sigma_y)^2 + (\sigma_h)^2}$$

where:

σ_x – the standard deviation of determinations of longitude (geodesic),
σ_y – the standard deviation of determinations of latitude (geodesic),
σ_h – the standard deviation of determinations of altitude.

- 2DRMS, the double average error of position determination. This corresponds to a probability of 95%.
- CEP (Circular Error Probability), a circular error. A 2D measure. Specifies the radius of the circle (centered at the actual position of the receiver antenna or approximated by the average values), in which there are 50% of position determinations.

- SEP (Spherical Error Probable), a spherical error. A 3D measure. Specifies the radius of the sphere in which there are 50% of position determinations.

In the process of testing GPS receivers, both in static and kinematic research, which takes place on a 2D plane, should be used the basic measures of assessing the accuracy of the position, they are DRMS (2D), 2DRMS (2D) and CEP, and for the application in sports and recreation, which are implemented in a 3D space – respectively DRMS (3D), 2DRMS (3D) and SEP.

Study of data acquired from the receivers

Acquiring data on the position coordinates of receivers is an initial stage of implementation of research or testing. The vast majority of GPS receivers manufactured today allows you to store data in an automatic way. Manufacturers use two basic strategies of data recording. The first one allows you to do it in a proprietary standard of the producer, which in further proceedings allows you to convert data using dedicated software. The second group are widely available receivers with the ability to automatically save measurement data in the form of text files with defined data formats. The most commonly used among them and the most comprehensively engaging recording positions is the NMEA (National Maritime Electronic Association), which uses dedicated to recording the coordinates GGA message (Fig. 1). Red color marks data significant for analysis of position determination accuracy.

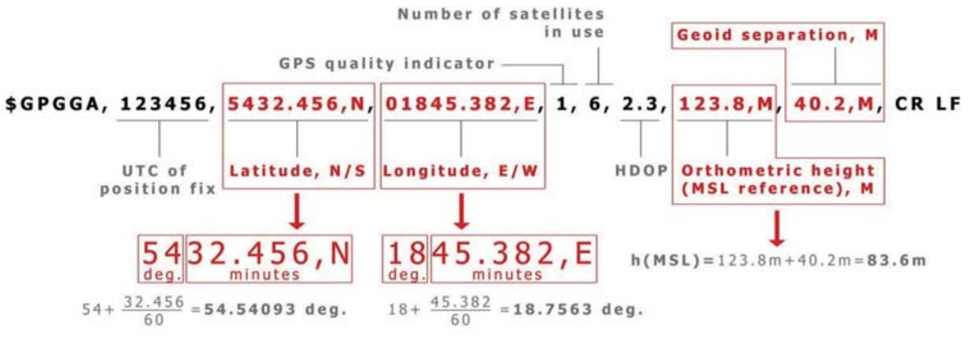


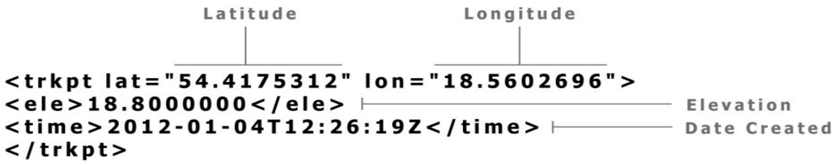
Fig. 1. Description of the GGA message in NMEA standard. Example for the calculation of latitude and height relative to the MSL (Mean Sea Level).

The recording format of latitude and longitude stored in the form of full degrees and minutes within one (unseparated record) requires additional explanation. It should be converted to full degrees according to the example below in the figure (for the coordinates of latitude). Generally recommended is to prepare data in a format of full degrees, because in the course of further calculations it will be converted to coordinates in meters. Another important element is to calculate the orthometric height (relative to the mean sea level). Because the GPS system determines the height relative to reference ellipsoid, which is WGS-84, that does not coincide with the mean sea level, there should be added to this value the difference between an ellipsoid and geoid given in the message (according to the example of Fig. 1). Details on this value are stored in the receiver's memory for the area of the globe and are presented within the GGA message.

Some of the receivers dedicated for sport and recreation carry out themselves the conversion of coordinates into full degrees and represent height relative to mean sea level, recording the the data in a CSV file (Fig. 2, for example the universal GPS recorders – dataloggers) or in a universal format GPX / xml (Fig. 3, for example most receivers for sports and recreation and smartphones). Those do not require to perform calculations presented in Fig. 1, however, contain less data than the NMEA format.

```
18,54.2876815,19.0878959,4.00,07/15/2010 09:25:20 AM,0.005,0.000,194.04
```

Fig. 2. Description of a typical a message used by the universal dataloggers



```
<trkpt lat="54.4175312" lon="18.5602696">
<ele>18.8000000</ele>
<time>2012-01-04T12:26:19Z</time>
</trkpt>
```

Fig. 3. Description of a typical GPX / xml file – the most popular format for positioning data exchange.

The type of GPX files often contain additional information, depending on sensors in the device and the preset options.

Latitude and longitude coordinates presented in angular measure (curvilinear) prevent the determination of the individual measurements errors. To do this, make the projection from surface of the ellipsoid of revolution (WGS-84) on a flat surface using the Gauss-Kruger transformation commonly applied in land surveying. The calculations result in coordinates (x, y), where the value of x denotes the distance (in meters) of the point from the equator, measured along the arc of the meridian (on the ellipsoid rotational WGS-84), and the variable y is the distance (in meters) from arbitrarily set middle meridian. Detailed calculation algorithm was presented in an earlier paper.

Methodology of testing using ION STD 101 standard

Providing civil users with the GPS system and related increase in the number of recipients entailed the need to set standards for testing the receivers. The most important document issued in the last two decades remains the standard published by the Satellite Department of the Institute of Navigation in USA (ION STD 101, 1997) titled "Recommended Test Procedures for GPS Receivers." It presents definitions and the basic groups of tests useful in marine, land and handheld receivers (Table 1).

Table 1. Overview of tests in the ION STD 101 standard

No.	Test type	General description of the test
1	INIT TTFF – Initialized Time to First Fix	Specifies the time that it takes motionless receiver to determine the current position since the first activation [turning on] after a few hours interruption [break].
2	WARM TTFF – Warm Start Time to First Fix	Specifies the time that it takes motionless receiver to determine the current position since the first activation [turning on] after a short break.
3	REAQ – Reacquisition Time	Specifies the time that it takes motionless receiver to determine the current position after a temporary interruption in tracking signals from GPS satellites.
4	Static navigation accuracy	Specifies the precision with which the receiver can determine its position in relation to a known position (predictable accuracy) on the surface of the Earth or not far from it.
5	Dynamic navigation accuracy	Specifies how accurately the receiver can determine its position during movement. The source of reference in this test is data of reference trajectory, determined as accurately as possible.
6	Radio frequency interference	Test determines the ability of a receiver to operate while receiving interference radio signals through the antenna.

Among the general comments regarding the testing standard attention is paid to: ensure no obstacles to track signals from satellites (more than 10 degrees above the horizon), ensure the absence of signal interference (in all tests in Tab. 1), no motion or movement (in the static tests, Tab. 1 pos. 1-4). In case of static and dynamic accuracy authors of the standard note that in general terms engineering practice dictates that measured accuracy of the actual position (antenna) should be 10 times greater than the accuracy of the receiver, which is subjected to tests. Since the GPS errors are inherently random, in the interest of the tester is to determine as accurately as possible the trajectory of the vehicle so that one can get to know the performance of the receiver (Dynamic accuracy, Tab. 1, pos. 5) and to determine as precisely as possible the position of the antenna (Static accuracy, Tab. 1, pos. 4). Specific recommendations for each of the tests are quite sophisticated, hence was omitted in this article.

Research on receivers using the selected tests

Selection of tests and of testing methodology

Civilian GPS receivers, especially in sports and versatile use, since the publication of the ION STD 101 until now undergone significant changes. They do not allow to perform such specialized tasks, described detailed recommendations for testing, such as: erasing the ephemeris data, entering the current UTC time to determine the actual, approximate position of the antenna, checking the age of supported almanac (information on all the satellites in the constellation) and the like. They are compact devices with integrated power and antenna, therefore applying [?] for example the radio interference test is just not possible (Tab. 1, pos. 6), as well as carrying out a suggested full time (24 h) static test of position determination (Tab. 1, pos. 4). Tests INIT TTFF and the WARM TTFF (Tab. 1, pos. 1-2) are published by some manufacturers in specifications, although there is used a different nomenclature. Popularized have been terms: a hot start (the unit "remembers" your last calculated position, satellites, almanac and the UTC time, then tries to establish a new position using this data), a warm start (the unit "remembers" the last calculated position, the almanac and the UTC time, but "does not know" which satellites have been used for this), a cold start (the device does not have any information). It is similar in the case of determining the accuracy for positioning – there are various measures used. The information from the manufacturers manuals are given in Table 2, pos. 3-6.

Given the above factors it was decided to perform the pilot test of two types of tests:

Test 1. Test of the static position determination (Static navigation accuracy)

It was conducted at the geodetic point POLREF 5501 in Rybina with coordinates (B = 54° 17' 15.68430" N, L = 19° 05' 16.38710" E, h= 30.266 m) (Photo 1). This point is part of the Polish Reference Frame – basic geodetic control network in Poland, and its location is known with an accuracy of <1 cm. In connection with the pilot nature of the test and the fact that one of the devices would not be able to operate for recommended by ION STD period of time, it was decided to shorten the test to approx. 2.5 h. Time of day was chosen due to the minimum values of geometric DOP coefficients, for which Trimble Planning software was used (Specht and Szot 2012a).

Test 2. Test of the dynamic position determination (Dynamic navigation accuracy):

Test 2A. The reference trajectory set at a fixed object

The reference trajectory were lines of track of the Athletics Stadium at the University of Physical Education and Sport in Gdańsk (Photo 2). Determined position of the two lines using an electronic total station Leica TPS 1103 (accuracy +/- 2mm), as well as (for comparative purposes) using a GNSS phase receiver Leica VIVA GS-15 with CS-15 controller (accuracy +/- 10 mm horizontally). Then along the trace of the line was conducted measurement trolley (speed of approx. 1.5 m / s), which provided the test receivers (Specht et al. 2013). Due to the pilot character instead of the specified in the test ION STD three rounds of at least 60 minutes each, the test was limited to perform the two laps of the stadium (Specht and Szot 2012b).

Test 2B. The reference trajectory determined dynamically

Inventory measurement was made on the section of the railway connecting the stations Somonino and Gdańsk Osowa with a length of about 26 km. The platform, being towed by a motor trolley WM15A, was installed with the receiver Leica VIVA and 2 [two] GPS sports receivers (Photo 3). Geodetic receiver used the service NAWGEO of active geodetic network ASG-EUPOS, providing phase GNSS solution with accuracies of 2-3 cm (p = 0.95). Measurements were carried out in real time with a frequency of 2 Hz (Leica). The solution of position was obtained using a Virtual Reference Station, enabling to obtain the highest accuracy of determinations without the influence of the distance between the reference station and the mobile receiver. First measuring session was carried out in the hours of 10:26-12:22, while the second – in the hours: 12:31-14:12. For the purposes of this article we selected one of the sessions. Travel speed was approx. 4.6 m/s. We analyzed 5074 measurements.

Photo 1. Test of the static position determination (Test 1) – receivers at the point POLREF.

Photo 2. Test of dynamic position determination (Test 2A) – measurement trolley run on the line that separates the tracks of the Athletics Stadium.

Photo 3. Test of the dynamic position determination (Test 2B) – a rail platform with the receivers.

Receivers

The individual tests were performed in different years, so only some of the models of receivers reappeared. Altogether were tested: Test 1 – 8 models (3 sport, 3 universal recorders, 2 mobile phones with built-in GPS), Test 2A – 13 models (8 sport, 3 universal recorders, 2 tourist), Test 2B – 2 models (universal recorders).

Table 2 presents the characteristics of several receivers, which appeared in at least two tests (Test 1, Test 2A, Test 2B). These are the three universal GPS recorders (Pentagram P3106, Qstarz BT-Q1000, Wintec WBT-100), and a device dedicated for sports and recreation (Garmin Edge 205).

Table 2. Selected characteristics of the tested receivers

No.	Model	Garmin Edge 205	Pentagram P3106	Qstarz BT-Q1000	Wintec WBT-100
1	Operating time	12 hrs	25 hrs	32 hrs	16 hrs
2	Frequency of position saving	1/s or Auto **	1/s and less	1/s and less	1/s and less
3	Acquisition time				
	hot start	<1 s	1 s	1 s	8 s
	warm start	<38 s	33 s	33 s	38 s
	cold start	<45 s	36 s	36 s	40 s
4	2D position error	<10m (p=0.5)	<3m ***	< 3m CEP (p=0.5)	<6m (p=0.95)
5	3D position error				<3m (p=0.95)
6	Reacquisition	Unknown [N.A.]	<1 s	Unknown [N.A.]	Unknown [N.A.]

Source: manufacturers instructions manuals, *) for recording of 1 point every 4 s, **) Garmin automatic mode – Smart Recording, ***) not specified whether the error relates to 2D or 3D.

As can be noticed in the pos. 4 and 5 of Table 2 there are no uniform standards by which producers inform the user about the characteristics of receivers (CEP measure, 2DRMS). This also applies to distinguishing the type of error (2D/3D).

Results

Table 3. Selected results of the static position determination test (T1)

	Receiver	DRMS	2DRMS
1	Garmin Edge 205	2.011	4.022
2	Garmin Forerunner 305	3.531	7.062
3	Pentagram P3106	1.418	2.836
4	Qstarz BT-Q1000	1.091	2.182
5	Wintec WBT-100	1.484	2.967

Table 4. Selected results of the dynamic position determination test (T2A)

	Receiver	CEP	DRMS	2DRMS
1	Garmin Edge 205	1.123	1.776	3.552
2	Garmin Edge 800	1.720	2.367	4.734
3	Garmin Forerunner 310	2.567	3.955	7.910
4	Garmin Forerunner 405	1.600	1.963	3.926
5	Pentagram P3106	0.924	1.323	2.646
6	Qstarz BT 1000	1.267	1.684	3.368

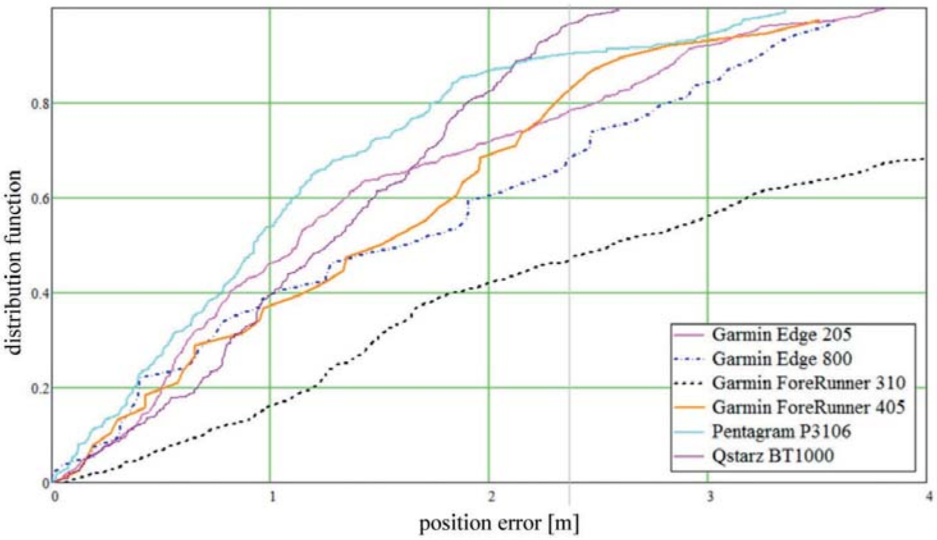


Fig. 4. The value of the cumulative distribution function of receivers position error in the test T2A

Table 5. The results of the dynamic position determination test (T2B)

	Type	CEP	DRMS	2DRMS
1	Pentagram P3106	2.082	2.316	4.632
2	Wintec WBT-100	1.169	1.603	3.206

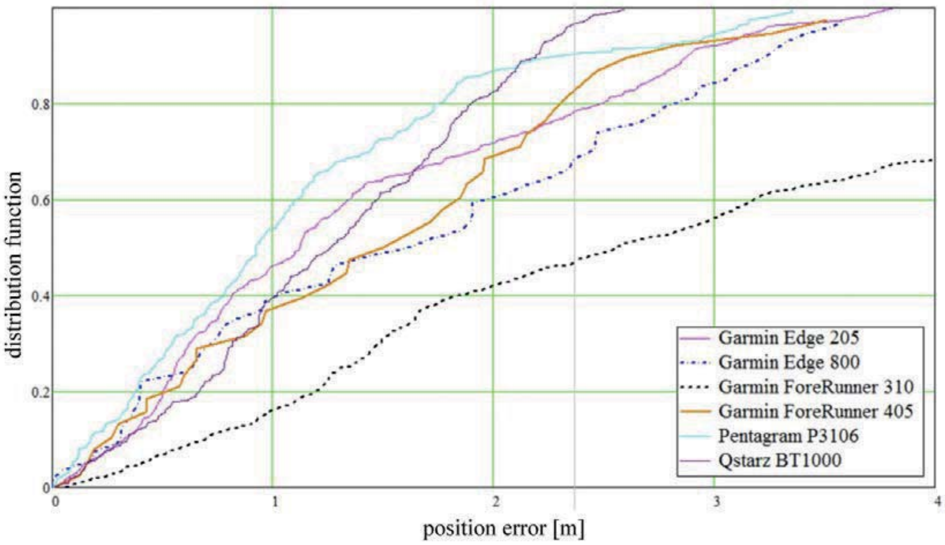


Fig. 5. The value of the cumulative distribution function of receivers position error in the test T2B

Discussion

Making in this article an attempt to determine the testing methodology of GNSS receivers the Authors focused on two tests described in the document ION STD 101: static and dynamic determination of position, adopting for evaluation the CEP, DRMS and 2DRMS measures.

The first test (Test 1) – Static navigation accuracy – was carried out at the geodetic point of very accurately known position. In accordance with the recommendations of the ION standard it should last 24 hours. The Authors due to the pilot nature of the test decided to shorten it to 2.5 hrs, therefore bearing in mind this modification – selected the time of measurement with very low coefficients of DOP (favorable constellation of satellites). The results presented in Table 3 allow to observe that the receivers by Pentagram, Qstarz, Wintec (universal recorders) determined its positions significantly better than the others. The most accurate was the Qstarz BT-Q1000 receiver, in which 95% of position responses did not exceed a distance of 2,182 meters.

The second test (Test 2) – Dynamic navigation accuracy – was carried out in two different ways. Because the ION standard does not specify how should the reference trajectory be determined, this was done using both a stationary object – the Athletics Stadium, where previously was set the reference trajectory (Test 2A), as well as in motion – a railway truck – where the reference receiver defining the trajectory moved simultaneously with the tested receivers(Test 2B). Both approaches allowed the evaluation of the accuracy (Tab. 4 and 5) and in addition included graphs (Figs. 4 and 5) showing the erros distribution of the tested receivers. In Test 2A lowest values were reached by the receiver Pentagram P3106 (CEP 0.924 m, DRMS 1,323 m, 2DRMS 2.646 m) and in Test 2B – Wintec WBT-100 (respectively 1.169, 1.603 and 3.206 m).

Based on the knowledge gained during the course of the above tests the Authors draw the following conclusions:

- the testing methodology presented in the ION STD standard can be successfully used for assessing indications accuracy of receivers in sports and recreation,
- in the test of the static position determination, for some receivers it will be problematic to carry out the full length test, due to the built-in battery and the inability to supply external power,
- in the dynamic position determination test appointment of reference trajectory as shown in Test 2B (railway line, reference and tested receivers placed on the

running platform) is definitely more cost-intensive than in Test 2A (athletics stadium reference trajectory measured once),

- when conducting both static and dynamic tests, one should pay attention to capacity of internal memory of tested receivers. If it is a non-removable memory one should use external memory media or connect directly to the computer.

Undoubtedly, the issue of testing methodology of GNSS receivers used in sports and leisure, which has been outlined in this article, requires further attention.

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