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Analysis of the Possibilities of Using GNSS Satellite Systems in Determining the Geometry and Examining the Deformation of Rail Routes

M. Strach

**Department of Engineering Surveying and Civil Engineering,
AGH University of Krakow
Krakow, Poland**

Abstract

The study describes geodetic inventory measurement techniques used to study the geometry of a selected section of a railway track. Specialized trolleys equipped with various measurement sensors were used in the field tests. The research was carried out in several hardware configurations using various measurement techniques. Then, designs for adjusting the track centerline were prepared for two parallel tracks. The adjustment results were verified with the track geometry included in the longitudinal track profile. Discrepancies between the existing document and the current track geometry were revealed. A new geometry was proposed to optimize the alignment of adjacent tracks. Conclusions were drawn regarding the selection of the optimal inventory measurement technique.

Keywords: analysis of track axis geometry, trolley railway track measurement system, track realignment and rectification, GNSS Surveying, RTK-RTN surveying, railway track deformation.

1 Introduction

Maintaining existing and building new railway lines requires maintaining high functional and construction technical standards. A correctly prepared design for a new or revised track system of individual lines and junctions is also important. The construction and subsequent operation of railway lines, as well as the supervision and ensuring the safe operation of rolling stock, require the cooperation of specialists from many industries. Specialists, having appropriate knowledge, skills and competences, use modern tools in their professional practice, guaranteeing reliability and effectiveness in carrying out tasks. These are most often appropriate computer programs supporting the design, construction, analytical and maintenance work of railway lines [1, 2, 3, 4]. Equally important are measurement systems equipped with sensors for collecting data on the condition of infrastructure [5,6,7,8,9,10], the location of rolling stock [11,12], as well as information on the location and geometric relations between objects [13, 14,15]. Surveying and diagnostic teams are most often responsible for obtaining this information. Progress in the development of mechanics, electronics and computer science, as well as the increasing requirements of device users, increase the importance of computer measurement systems. The use of computers enables unattended operation of systems and automation of measurement activities.

Performing measurement tasks related to determining the geometry of a railway track requires access to specialized equipment based on, among other things, measurement trolleys. There are several leading manufacturers offering railway measurement trolleys on the market. These include companies such as Amberg, Trimble, Leica, and Topcon. Individual manufacturers offer single and double-trolley systems, which employ various measurement sensors. These can include: electronic tacheometers, GNSS receivers, laser scanners, range finders, digital cameras, inertial measurement systems (INS), odometers, sensors for measuring track gauge and rail height differences [16, 17, 18].

The selection of the appropriate measurement technique and equipment impacts the achievable accuracy in determining the coordinates of measured points. For tasks requiring millimeter-level precision in determining the track centerline coordinates, such as geodetic support for track and switch tamping, specialized solutions are employed. Track measurement for centerline realignment design and subsequent control of the tamped track is performed using measurement trolleys and precise tacheometers with servo-motors tracking a moving reflector. Single-trolley solutions are most commonly used, where the tacheometer is mounted on a tripod off the track, while the reflector is placed on the trolley. Alternatively, a two-trolley method can be employed, with one trolley equipped with a tacheometer and the other with a reflector. The operating principle of the two-trolley method is based on the long chord technique, ensuring high accuracy in determining the track centerline coordinates. The two-trolley technique is particularly recommended for geodetic support of tamping machines on high-speed lines due to its high precision in determining the track centerline position. This enables the maintenance of the required geometric parameters necessary for safe operation of high-speed trains.

For this reason, in the studies of track centerline geometry, the decision was made to employ the latest single and double-trolley systems based on tacheometric measurements. The obtained results were used to verify the possibility of applying the GNSS satellite measurement method for design and maintenance purposes, including track centerline realignment. Additionally, track centerline realignment projects were prepared for two parallel tracks located on the studied section. The realignment results were verified against the track geometry contained in the longitudinal track profile.

Discrepancies were revealed between the existing document and the actual track geometry. A new geometry was proposed to optimize the alignment of the adjacent tracks. Conclusions were drawn regarding the selection of the optimal inventory measurement technique.

2 Characteristics of the Experimental Track and Established Geodetic Control Network

The research work was carried out in Poland on the double-track, electrified mainline no. 133 Dąbrowa Górnicza Ząbkowice - Kraków Główny (section Dąbrowa Górnicza Ząbkowice - Dąbrowa Górnicza Huta Katowice) in the kilometer range 1.500 - 1.700 with an extension to the nearest traction poles. The selected section is characterized by the following features:

- It consists of 2 tracks located near the Dąbrowa Górnicza - Ząbkowice railway station.
- Track no. 1 is located on a straight line, while track no. 2 is located on a broken straight line rounded by a curve.
- Railway switches are present on each track.
- Steel pins forming part of the special railway control network were mounted on traction poles, in accordance with the Ig-6 Standard [19].
- Along the line, three points of the horizontal geodetic control network were stabilized and measured; with alternating stabilization of points on both sides of the track at distances of approximately 100 - 150 m between points. Subsequently, a GNSS satellite measurement and coordinate adjustment were performed for the stabilized points.

Before proceeding with the track centerline measurement, the coordinates of the special railway control network were determined. For this purpose, ground points numbered 133001.50, 133001.60, and 133001.76 were stabilized in the field, and then a static GNSS measurement was performed. The measurement was carried out with three GNSS receivers during a single measurement session lasting a minimum of 60 minutes. Post-processing of the GNSS vectors was performed using Leica Infinity software.

The spatial accuracy of the worst determined point in the network was 2.3 mm, while the horizontal component has an accuracy below 1 mm. A summary of the GNSS vector adjustment results is presented in Table 1.

Point No.	Point Role	Y (East) [m]	X (North) [m]	Orthometric Height [m]	3D Acc. [m]	2D Acc. [m]	1D Acc. [m]
133001.50	Adjusted	6589451.193	5580601.949	294.082	0.0023	0.0007	0.0021
133001.60	Adjusted	6589438.296	5580507.707	294.578	0.0023	0.0008	0.0022
133001.76	Adjusted	6589417.362	5580341.395	295.010	0.0016	0.0009	0.0014
DABR	Fixed 3D	6589442.284	5581201.573	303.324	-	-	-
JAWORZNO	Fixed 3D	6591183.274	5569213.305	281.127	-	-	-
KATOWICE -LIGOTA	Fixed 3D	6569907.743	5565294.237	290.449	-	-	-
TRZEBINA	Fixed 3D	6604063.675	5558521.431	305.959	-	-	-

Table 1: Summary of GNSS Vector Adjustment Results.

In accordance with the guidelines contained in the Ig-6 Standard, the points measured using GNSS technology were densified with points stabilized on traction poles constituting the special railway control network. The measurement was performed using the angle-distance method, tied to 3 points of the detailed control network stabilized along the measured section. Each of the determined points of the railway control network was measured from at least two tacheometric stations. The angle-distance observations were adjusted in commercial software (GEONET) using the least squares method, adopting 3 points determined by the GNSS method as fixed reference points. As a result of the control network adjustment, the following coordinate accuracies of the special railway control network points were obtained:

- Average position error $\sigma_{p(avg)}$: 0.0011 m
- Maximum position error $\sigma_{p(max)}$: 0.0013 m

To determine the heights of the special railway control network points, a leveling measurement was performed, tied to the points determined by the GNSS method. The misclosure of the leveling loop was 1 mm. The point heights were adopted as the average of two measurements in the forward and backward directions.

3 Measurements on the Test Track Section

The field research involved the application of various measurement techniques to determine the track geometry. It was conducted on the characterized section. Both measurement cycles were performed on the same day, with approximately a 2.5-hour break between cycles. During this time, there was a change in the satellite configuration, and the research work was carried out under different measurement conditions.

The following devices and measurement systems were used in the surveying works:

- Trimble S8 electronic tacheometer (accuracy: 1" for angle measurements, ±1 mm + 1 mm/km for distance measurements to the reflector)
- Trimble DiNi digital level (height determination accuracy: 0.3 mm)
- Trimble GEDO CE 2 trolley system for track measurements, consisting of a prism trolley and a tacheometer trolley
- Two GNSS receivers (with controllers and poles) intended for RTK and RTN kinematic measurements – Leica GS18 T

The test track section was measured using several techniques. A brief description of each is provided below:

3.1 Track Measurement Using the Tacheometric Method with the GEDO Rec Single-Trolley System

In this method, the measurement of the track layout is carried out using a tacheometer set up outside the track. During the field tests, a mounting bracket for the tacheometer on the traction poles was used.

During the tests, observations were made of the reflector located on the prism trolley. As a result of the measurement, the XYZ coordinates of the rail tracks along with the track centerline were obtained, as well as the values of cant and clearance in each measured cross-section. Each station was determined from at least 3 points of the special railway control network.

3.2 Track Measurement Using the Two-Trolley Method with the GEDO Vorsys System

In this method, the measurement of the track layout is carried out by referencing a chord, determined based on points from the special railway control network. In the first phase, the tacheometer trolley is positioned on the track opposite the control network point. The tacheometer performs measurements, including determining the distance and height difference between the first chord point on the track and the control network point. Subsequently, the tacheometer trolley moves to the second point (end) of the chord (approximately 120 m) and is positioned opposite the control network point. Then, a similar measurement is performed, involving sighting the tacheometer telescope onto the control network point located perpendicular to the trolley's position. In this way, the chord is defined, with respect to which the geometry of the track centerline is determined. Finally, the tacheometer is aimed at the reflector located on the prism trolley, set up at the first chord point. This procedure defines the parameters of the chord. After the chord is established, the prism trolley moves towards the tacheometer trolley, performing measurements at specified locations. The results of the measurement are the XYZ coordinates of the rail tracks along with the track centerline, as well as the cant and clearance values for the given cross-section.

3.3 GNSS Satellite Track Measurement

Depending on the measurement method used, the location of the prism reflector and GNSS antenna varied. In the case of single-trolley GedoRec measurements, the reflector was positioned above one of the rail threads. Then, the GNSS satellite receiver antenna could be mounted on a hand-held pole near the track centerline.

For two-trolley VorSys measurements, the reflector was located above the track centerline. In this case, the GNSS satellite receiver antenna could be permanently mounted on a column above one of the rail threads.

4 Assumptions Adopted for the Analysis of the Results

For the purposes of analyses, specific rules were adopted for numbering points. Each station consists of a sequence of letters and numbers that uniquely identifies: the location, measurement method, series, track number, and station number. The numbering rules are outlined below:

Location	RTN Method	Trolley Method	Track No.	Series	Point No.
D - Dąbrowa Górnicza	T – Hand-held pole	R - GedoRec (1 trolley)	1	I	1
	W – Rigid column on trolley	V - VorSys (2 trolleys)	2	II	2

Examples:

DT1II.120 - Dąbrowa Górnicza section, GNSS RTN measurement with hand-held (leveled) pole, Track 1, Series II, Cross-section Point 120.

DV2I.40 - Dąbrowa Górnicza section, VorSys measurement (2 trolleys), Track 2, Series I, Cross-section Point 40.

For the purpose of analyzing the accuracy of measurements performed by all techniques, it was necessary to recalculate the coordinates of the geometric center of the prism reflector and the phase center of the antenna to the track centerline. Therefore, it was necessary to know the geometric relationships between the track centerline and the trolley, as well as the prism reflectors and GNSS antennas. The GedoRec measurement system software, as well as VorSys, automatically recalculates the coordinates of the geometric center of the prism reflector to the track centerline and the right and left rails. The GNSS antennas used were not an integral part of the measurement system. For this reason, the coordinates of the phase center of the antenna had to be recalculated independently.

The final coordinates of the track centerline points were loaded into specialized software supporting the design of railway tracks. One of the most popular programs for designing conventional and high-speed rail tracks was selected. The software was used to prepare a project for track centerline realignment in the horizontal plane and to determine the values of track shifts in individual cross-sections.

Having the coordinates of the track centerline from all methods and measurement series, as well as information about the geometry of both tracks, it was possible to proceed with the preparation of track centerline realignment projects. As many projects had to be prepared as there were sets of coordinates. Each track was measured using four methods, and each method was performed in two series. In total, 8 realignment projects had to be prepared for a single track. Therefore, 16 projects were prepared for the studied section, which were compared with each other.

The calculations of the geometric parameters of the track were performed by fitting the designed geometry of the centerline into the set of points measured at the cross-sections. During the fitting of the geometry, a multi-element regression analysis was applied. The following assumptions were made in the calculations:

- Maintaining the geometric parameters closest to the existing track centerline,
- The radius of the circular arc and the length of the transition curve not less than the values given in the track centerline realignment lists or on the longitudinal profile,
- Maintaining curvature continuity for individual track sections,
- Minimizing shifts of the existing track centerline,
- Maintaining the construction clearance.

The result of a correct fitting of geometric elements in the horizontal plane is a report. Its content is divided into parts characterizing individual components of the track geometry.

It was assumed that the reference method for comparing other track inventory methods would be the measurement from the VorSys two-trolley method. In this method, both a tacheometric trolley and a reflector trolley are used. The method used here is based on the long chord method, identical to the one used by high-performance track machines, such as the EM-SAT by Plasser & Theurer. Due to the high accuracy of determining the coordinates of the track centerline, this technique is particularly recommended for geodetic support of tamping machines on high-speed lines.

5 Analysis of Track Measurements on the Studied Section

Information on the geometry of sections of track No. 1 and 2, located on line 133, can be read from the longitudinal profile of line 133: Dąbrowa G. Ząbkowice - Kraków Gł. Osobowy, as well as from the handover and acceptance protocols for track centerline realignment. Both documents show that:

- Track No. 1 (from km 1+493.90 to km 1+702.72) is a straight section in the plan,
- Track No. 2 (from km 1+492.83 to km 1+702.34) in the plan consists of a straight section, a rounding curve, and a straight section.

Comparison of both documents reveals discrepancies in the data for track 2. The differences concern the geometric parameters of the circular arc in the plan (longitudinal profile: R = -3150 m; D = 40 m vs. Handover and acceptance protocol: R = -20000 m; D = 43.10 m). Additionally, discrepancies in the longitudinal profile for both tracks were observed. They concern differences in the kilometrage of the profile bends, as well as the length of the longitudinal profile sections.

5.1 Analysis for Track No. 1

The project for realignment the straight section of Track No. 1 aimed to minimize the shifts of the existing track centerline. From the report for the VorSys two-trolley method from the first measurement series - DV1I, it follows that the analyzed section of Track No. 1 is 200.008 m long. A regression line was fitted into it, assuming minimization of shifts and equal weight for each point. As a result, a fit was obtained with maximum horizontal shifts of +9 mm (points at kilometrage 1528.753 and 1698.880) and -9 mm (point at kilometrage 1608.903). A realignment project was also prepared for the second measurement series for the VorSys two-trolley method - DV1II. The report shows that the analyzed section of Track No. 1 is 200.013 m long. A regression line was fitted into it, assuming minimization of shifts and equal weight for each point. As a result, a fit was obtained with maximum horizontal shifts of +8 mm and +9 mm (points at kilometrage 1528.750 m and 1698.880 m, respectively) and -8 mm (point at kilometrage 1608.901 m).

Comparing the shifts for all points/cross-sections, it can be seen that both series, performed completely independently a few hours apart, are characterized by high accuracy and repeatability of results. The differences in shifts reach single millimeter values. However, it should be noted that any differences in coordinates in individual series and measurement methods affect the azimuth (direction) of the tangent of the analyzed section. In the case of regression lines in the DV1I and DV1II methods, the difference in tangent directions is 4cc. This means that for straight lines with a length of 200 m, the maximum distance between them can be 1.4 mm.

The results obtained from the VorSys two-trolley measurement confirm the possibility of using them as reference data for comparative analyses of other measurement methods. It was decided that the data from the DV1I method would be the reference for further analyses.

The track measurement by each of the tested methods was carried out at cross-sections marked on one of the rail threads. During the measurement, an attempt was made to stop the trolley over the vertical line indicating the track division at 5-meter intervals. It was drawn on the outer, vertical surface of the rail head. The accuracy of positioning the trolley over the measurement cross-section ranged from a few millimeters to single centimeters. Therefore, the situational coordinates X, Y from different methods and measurement series were not compared. Instead, it was decided to compare the data from the realignment projects. In the case of Track No. 1, the distances between the regression line from the DV1I method and the regression lines fitted into the individual methods and measurement series were analyzed. Table 2 summarizes the basic descriptive statistics for the calculations performed. Figure 1 provides a graphical illustration of the results.

	DV1II	DR1I	DR1II	DT1I	DT1II	DW1I	DW1II
Minimum	-0.001	-0.016	-0.004	-0.004	-0.006	-0.012	-0.011
Maximum	0.001	0.011	-0.001	-0.003	0.003	-0.004	-0.008
Median	0.000	-0.002	-0.003	-0.004	-0.002	-0.008	-0.009
Mean	0.000	-0.002	-0.003	-0.004	-0.002	-0.008	-0.009
Standard Deviation	0.000	0.008	0.001	0.000	0.003	0.002	0.001

Table 2. Basic descriptive statistics for the distances between realignment projects for Track No. 1 (results in meters).

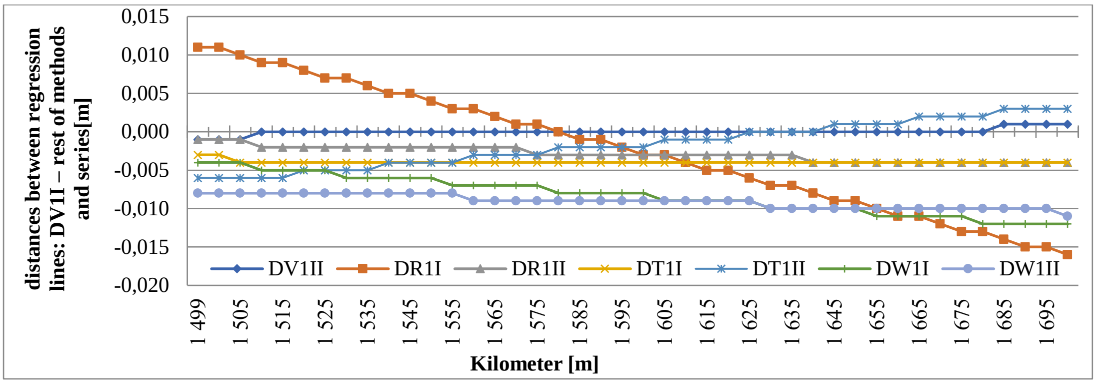

Figure 1. Distances between the regression line from the DV1I method and the regression lines fitted into the individual methods and measurement series.

The analysis of the graph and descriptive statistics allows drawing several important conclusions:

- The results for the DR1I method are outliers due to a slight change in the reference direction, hence the distance differences are in the range from -16 mm to +11 mm.
- The mean values calculated for the distances from the realignment projects for DW1I and DW1II are -8 mm and -9 mm with standard deviations of 2 mm and 1 mm, respectively; therefore, a future correction of the PC point eccentricity with respect to the rail/track centerline by 8÷9 mm will be necessary.
- In trolley measurements, the standard deviations do not exceed 1 mm (except for the DR1I method).
- The standard deviations for satellite methods do not exceed 3 mm (handheld pole) and 2 mm and 1 mm (pole on a column).
- Excluding the DR1I method, it can be observed that in all trolley methods and series, the distance spread does not exceed 3 mm, while for satellite methods it is 9 mm (handheld pole) and 8 mm (pole on a column).

5.2 Analysis for Track No. 2

The longitudinal profile of Line 133: Dąbrowa G. Ząbkowice - Kraków Gł. Osobowy and the handover and acceptance protocols for track centerline realignment indicated that Track No. 2 in the plan consists of a straight section, a rounding curve, and a straight section. However, the information contained in the longitudinal profile and the handover and acceptance protocols differed, so a verification of the geometry was necessary.

First, a curvature graph was generated for the analyzed section using the coordinates from the Vorsys two-trolley measurement series DV2II. Unfortunately, the shape of the curvature graph did not allow for the identification and selection of sections with curved sections. Therefore, the distance (track spacing) between the DV1I and DV2I measurements was calculated.

The results of the distance (track spacing) between the DV1I and DV2I measurements showed that the geometry of the measured track did not match the data from the handover and acceptance protocols and the longitudinal profile. Despite the discrepancies in the data, it was decided to attempt to prepare a realignment project using the parameters specified in the documentation. In all cases where a single circular arc with different radii was assumed, the software reported a lack of a solution and the inability to maintain continuity of curvature between the individual sections of the route.

It was decided to look for another solution that would better correspond to the geometry of the measured section, while taking into account the turnouts installed in the track. In the project based on the data from the DV2I measurement method, the maximum displacements were within the range of -7 mm to +5 mm. Importantly, the first and last cross-sections of the section fit into the existing track, as the displacements at these points are zero. Ultimately, the best fit of the geometry was adopted for further analysis.

Analogous to the calculations performed for Track No. 1, it was decided to compare the data from the realignment projects. For Track No. 2, the distances between the realignment project for the track centerline measured by the DV2I method and the realignment projects implemented for the other measurement methods and series were analyzed. Table 3 summarizes the basic descriptive statistics for the calculations performed. Figure 2 provides a graphical illustration of the results.

	DV2II	DR2I	DR2II	DT2I	DT2II	DW2I	DW2II
Minimum	-0.001	-0.016	-0.004	-0.008	-0.008	-0.009	-0.011
Maximum	0.000	0.010	0.005	0.008	-0.005	0.006	0.003
Median	-0.001	0.004	0.002	0.004	-0.006	0.002	-0.002
Mean	-0.001	0.000	0.001	0.002	-0.006	0.000	-0.003
Standard Deviation	0.000	0.008	0.003	0.005	0.001	0.005	0.004

Table 3. Basic descriptive statistics for the distances between realignment projects for Track No. 2 (results in meters).

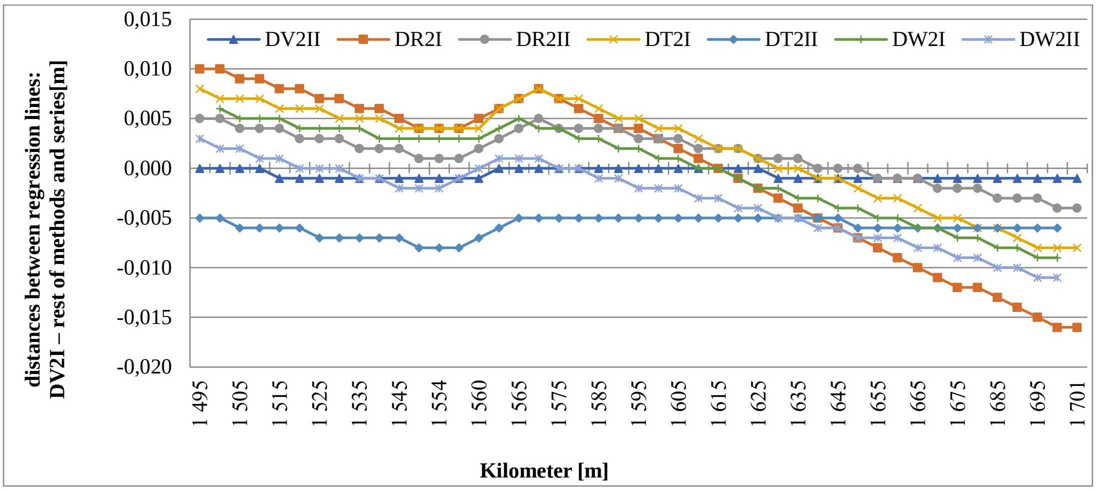

Figure 2. Distances between the regression line from the DV2I method and the regression lines fitted into the individual methods and measurement series.

The analysis of the graph and descriptive statistics allows for the following conclusions:

- The results for the DR2I method are outliers due to a slight change in the reference direction; as a result, the distance differences are in the range of -16 mm to +10 mm.
- In the bogie-based measurements, the standard deviations do not exceed 3 mm (except for the DR2I method).
- The average values calculated for the distances from the realignment projects for the satellite measurement methods do not exceed -6 mm (hand-held pole) and -3 mm (pole on a rigid column).
- The standard deviations for the differences for both satellite measurement methods do not exceed 5 mm and 1 mm (hand-held pole) and 5 mm and 4 mm (pole on a column).
- Excluding the DR1I method, it can be observed that in all bogie-based methods and series, the scatter of distances does not exceed 9 mm, while for the satellite methods it is 16 mm (hand-held pole) and 15 mm (pole on a column).

6 Analysis of the Surveyed Track Height

The calculations of the height and the analyses of the accuracy of their determination were performed similarly to the analyses of the positional measurements. The data sets were separated into the two tracks. Comparisons were made between the series for the same measurement techniques, but also between the individual inventory measurement techniques.

In the single-trolley GedoRec measurements, it was possible to set up the GNSS antenna on a pole held and leveled by hand. In the case of the two-trolley VorSys measurements, the GNSS antenna was mounted rigidly on a column. Thanks to the measurement methods used, natural pairs for comparisons emerged: GedoRec - pole held by hand and VorSys - pole on a column.

Since the observations in two independent methods were recorded simultaneously at a single trolley stop in a given cross-section, there was no need to prepare realignment projects for the leveling. It was sufficient to compare the heights directly. Of course, to make this possible, geometric reductions had to be introduced, taking into account the position of the GNSS antenna phase center and the geometric center of the prism reflector.

6.1 Analyses for Track No. 1

First, analyses were performed for the single-trolley set (GedoRec). Table 4 below lists the basic descriptive statistics for the height differences between the two series of the same measurements, as well as the height differences obtained from independent measurement methods: the GedoRec single-trolley set and the GNSS measurement with the antenna mounted on a pole held by hand. Figure 3 contains a graphical illustration of the results.

	Height differences between series and measurement methods [m]			
	DR1I - DR1II	DT1I - DT1II	DR1I - DT1I	DR1II - DT1II
Minimum	-0.004	-0.035	-0.006	-0.016
Maximum	0.004	0.006	0.016	0.009
Median	-0.001	-0.006	0.004	-0.001
Mean	-0.001	-0.006	0.004	-0.002
Standard Deviation	0.002	0.008	0.005	0.006

Table 4. Basic descriptive statistics for height differences between two series of the same measurements, as well as height differences obtained from independent measurement methods: the single-trolley GedoRec set and the GNSS measurement with the antenna mounted on a pole held by hand (results in meters).

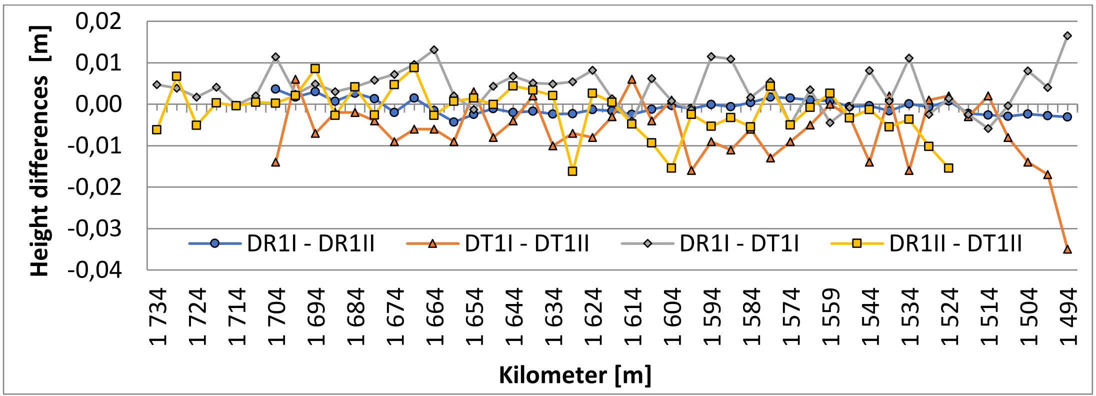

Figure 3. Line graphs for height differences between two series of the same measurements, as well as height differences obtained from independent measurement methods: the single-trolley GedoRec set and the GNSS measurement with the antenna mounted on a pole held by hand.

The analysis of the graph and descriptive statistics allows us to draw several important conclusions:

- the results for the height differences obtained from the comparison of the series for the trolley method DR1I and DR1II are fully satisfactory. The mean is -1 mm, and the standard deviation is 2 mm,
- the results for the height differences obtained from the comparison of the series for the GNSS satellite method: DT1I and DT1II are not satisfactory; the mean is -6 mm, and the standard deviation is 8 mm; the minimum value for one of the points is as much as -35 mm; and it is this single value that has a key impact on the results; in other cases, the differences do not exceed 16-17 mm,
- the results of statistical analyses for the differences between the individual methods (trolley and pole-mounted antenna) reach values of -2 mm and +4 mm for the means and 5 mm and 6 mm for the standard deviations,
- disregarding one outlier value for the satellite measurement method, it can be stated that the comparison of height differences between the two independent measurement techniques does not exceed the range from -16 mm to +9 mm.

The next analysis covered the measurements with the two-trplley set (VorSys). The analysis of the descriptive statistics allows us to draw several important conclusions:

- the results for the height differences obtained from the comparison of the series for the trolley method DV1I and DV1II are fully satisfactory. The mean is 0 mm, and the standard deviation is 1 mm,
- the results for the height differences obtained from the comparison of the series for the GNSS satellite method: DW1I and DW1II are satisfactory. The mean is -3 mm, and the standard deviation is 3 mm. The minimum value for one of the points is -16 mm, and for the next one -13 mm. The remaining values do not exceed +/-9 mm,
- the results of statistical analyses for the differences between the individual methods (trolley and column-mounted antenna) reach values of 6 mm and 3 mm for the means and 4 mm for the standard deviations,
- comparing the height differences between the two independent measurement techniques, it can be stated that the scatter is within the range from -5 mm to +15 mm.

6.2 Analyses for Track No. 1

First, analyses were performed for the single-trolley set (GedoRec). The height differences were calculated between the two series of the same measurements, as well as the height differences obtained from independent measurement methods: the single-trolley GedoRec set and the GNSS measurement with the antenna mounted on a pole held by hand. The analysis of the descriptive statistics allows us to draw the following conclusions:

- the results for the height differences obtained from the comparison of the series for the trolley method DR2I and DR2II are fully satisfactory. The mean is 1 mm, and the standard deviation is 1 mm,
- the results for the height differences obtained from the comparison of the series for the GNSS satellite method: DT2I and DT2II are also satisfactory; the mean is 2 mm, and the standard deviation is 5 mm; the minimum value is -10 mm, and the maximum is 14 mm,
- the results of statistical analyses for the differences between the individual methods (trolley and pole-mounted antenna) reach values of -1 mm and 0 mm for the means and 4 mm and 6 mm for the standard deviations,
- comparing the height differences between the two independent measurement techniques, it can be stated that the scatter does not exceed the range from -13 mm to +12 mm.

The next analysis covered the measurements with the two-trolley set (VorSys). The analysis of the descriptive statistics allows us to draw several important conclusions:
- the results for the height differences obtained from the comparison of the series for the trolley method DV2I and DV2II are fully satisfactory. The mean is 0 mm, and the standard deviation is 1 mm,
- the results for the height differences obtained from the comparison of the series for the GNSS satellite method: DW2I and DW2II are not satisfactory. The mean is 3 mm, and the standard deviation is 7 mm. The minimum value is -19 mm, and the maximum is 19 mm,
- the results of statistical analyses for the differences between the individual methods (trolley and column-mounted antenna) reach values of 2 mm and 4 mm for the means and 5 mm and 7 mm for the standard deviations,
- comparing the height differences between the two independent measurement techniques, it can be stated that the scatter is within the range from -11 mm to +21 mm.

7 Conclusions

The results obtained on the experimental track section allow us to draw several conclusions, which are presented in relation to the individual measurement methods.

Two-trolley set (VorSys) measurements, which use a reflector trolley and a trolley equipped with a precise electronic tacheometer, guarantee the highest accuracy in determining spatial coordinates. Analysis of the planar rectangular coordinates X, Y indicates that the comparison of the track alignment designs for both DV1I and DV1II series, performed independently a few hours apart, is characterized by high accuracy and repeatability of results. The differences in displacements do not exceed ±1 mm. Similar conclusions can be drawn from analyzing the height measurements using the two-trolley VorSys method. In each case, the results for height differences obtained by comparing the trolley method series DV1I and DV1II are fully satisfactory. The mean is 0 mm, and the standard deviation is 1 mm. Simultaneously, this method is the most accurate among all those analyzed. The results obtained from the two-trolley

VorSys measurement confirm their applicability as reference data for comparative analyses of other measurement methods.

Single-trolley GedoRec measurements, which use a reflector trolley while the precise electronic tacheometer is set up on a tripod, guarantee high accuracy in determining spatial coordinates. In analyzing the accuracy of planimetric measurements, single-trolley measurements were compared with two-trolley measurements. The analysis examined the differences in distances between the track alignment design for the DV1I method and the coordinates originating from single-trolley measurements. The greatest variation in the observed values of the variable concerns the single-trolley GedoRec measurement of both tracks in Series I. This is evidenced by the large values of the standard deviation, minimum, and maximum. The specific distribution of differences shows the beginning of the section with maximum negative differences, transitioning to zero values in the middle of the section, and reaching maximum positive values at the end of the section. The probable cause of this result was measurement problems under difficult atmospheric and operational conditions on the track. Wind gusts from trains combined with falling snow and freezing rain slightly changed the direction of the measurement setup, resulting in a skew of the fitted regression line. In the second series of measurements using this method, the descriptive statistics give satisfactory results. Similar conclusions can be drawn from analyzing the height measurements using the single-trolley GedoRec method. In each case, the results for height differences obtained by comparing the trolley method series DR1I and DR1II are fully satisfactory. The obtained results indicate the full suitability of the method for measuring track heights for the purpose of track alignment. The obtained results demonstrate the usefulness of the single-trolley GedoRec method for measuring track geometry for the purpose of track alignment. The basic statistics calculated for the planimetric measurement results show that the maximum and minimum values do not exceed -6 mm and 8 mm, respectively. However, it is necessary to frequently check the measurement setup. A decrease in measurement accuracy may be related to the close proximity of the tacheometer to the track, as passing trains and unfavorable atmospheric conditions can affect the change in the measurement setup and the leveling of the device.

Measurement using a GNSS antenna and receiver mounted on a pole held by hand is the least comfortable and least accurate method. After positioning the trolley on the measured cross-section, the tip of the pole is each time applied to a strictly defined element of the trolley. In the described tests, it was a hole in the head of a hex bolt. Preparing the GNSS setup for measurement required setting the pole vertically. The setup should be held motionless during measurement. In the field tests, ten one-second measurement epochs were recorded. To increase measurement precision, the person operating the GNSS setup leaned the vertically positioned pole with the controller against themselves. The multi-hour measurement of the track section and the required stillness during observation recording constituted a significant physical strain on the person performing the measurements. Analyses of displacements (distances) between the track alignment design for Track 1 for the DV1I method and the coordinates originating from GNSS measurements using an antenna mounted on a hand-held pole are not fully satisfactory. In the DT1I measurement, the following descriptive statistics were obtained: minimum value of -12 mm, maximum of 11 mm, mean of -5 mm, and standard deviation of 6 mm. In the DT1II measurement, the minimum value was -17 mm, the maximum was 12 mm, the mean was -1 mm, and the standard deviation was 6 mm. Slightly better results of descriptive statistics are noted for the differences in distances between the analyzed methods. In the DT1I measurement, the minimum value was -8 mm, the maximum was 11 mm, the mean was 5 mm, and the standard deviation was 5 mm. In the DT1II measurement, the minimum value was -4 mm, the maximum was 12 mm, the mean was 2 mm, and the standard deviation was 5 mm. The results for Track 2 for the DV2I method and the coordinates originating from GNSS measurements using an antenna mounted on a hand-held pole are also not fully satisfactory. In the DT2I measurement, the minimum value was -16 mm, the maximum was 14 mm, the mean was 2 mm, and the standard deviation was 7 mm. In the DT2II measurement, the minimum value was -18 mm, the maximum was 1 mm, the mean was -6 mm, and the standard deviation was 5 mm. Slightly better results of descriptive statistics are noted for the differences in distances between the analyzed methods. In the DT2I measurement, the minimum value was -13 mm, the maximum was 12 mm, the mean was -3 mm, and the standard deviation was 7 mm. In the DT2II measurement, the minimum value was -5 mm, the maximum was 14 mm, the mean was 5 mm, and the standard deviation was 5 mm. The results for height differences obtained by comparing the series for the GNSS satellite method DT1I and DT1II are also not satisfactory. The mean is -6 mm, and the standard deviation is 8 mm. The minimum value for one of the points is as high as -35 mm. And it is this single value that has a crucial impact on the results. In other cases, the differences do not exceed 16-17 mm. The results of statistical analyses for the differences between the individual methods (trolley and antenna on a pole) reach values of -2 mm and +4 mm for the means, and 5 mm and 6 mm for the standard deviations. Omitting one outlier value for the satellite measurement method, it can be stated that the comparison of height differences between the two independent measurement techniques does not exceed the range from -16 mm to +9 mm.

Measurement using a GNSS antenna and receiver mounted on a rigid column placed on a trolley is very convenient. The constant and rigid construction means that the person performing the measurement only needs to focus on operating the GNSS receiver controller. In the field tests, ten one-second measurement epochs were recorded. To determine the coordinates of the GNSS antenna phase center, geometric reductions had to be applied to calculate the coordinates of the track centerline or one of the rails. The data for the reductions were the constant geometric parameters related to the trolley construction, but also the measured values of track superelevation and gauge. The aforementioned rigidity of the measurement construction ensured that the fieldwork was not only convenient but also guaranteed the maintenance of proper measurement geometry. The measurements were repeatable and not affected by errors of the person performing the measurements. In each case, the satellite measurements were less accurate than the trolley measurements. Comparing the satellite measurements RTN (hand-held pole and pole on a column), the measurements with the antenna rigidly mounted on the column are significantly more accurate. For the purposes of many accuracy analyses, track alignment designs were created. The data in the analyses were sets of track centerline coordinates obtained from the individual measurement methods and series. One of the analyses was a comparison of the differences in displacements between the reference method DV1I and all other methods and measurement series. In measurements with the pole on the column, the standard deviations for the mentioned differences were 4 mm and 3 mm, depending on the series. In the case of Track 1 measurement, the spread was 14 mm and 16 mm. A comparative analysis of the alignment designs was also performed. The distances between the regression line from the reference method DV1I and the remaining regression lines fitted to the individual methods and measurement series were calculated. The mean values calculated for the distances originating from the alignment designs for DW1I and DW1II were -8 mm and -9 mm with standard deviations of 2 mm and 1 mm, respectively. An analysis of the height measurement results was also conducted. The results for height differences obtained by comparing the series for the GNSS satellite method DW1I and DW1II are satisfactory. The mean is -3 mm, and the standard deviation is 3 mm. The minimum value for one of the points is -16 mm, and for another, it is -13 mm. The remaining values do not exceed +/-9 mm. The results of statistical analyses for the differences between the individual methods (trolley and antenna on a column) reach values of 6 mm and 3 mm for the means, and 4 mm for the standard deviations. Unfortunately, worse results were obtained for Track 2. The results for height differences obtained by comparing the series for the GNSS satellite method DW2I and DW2II are not satisfactory. The mean is 3 mm, and the standard deviation is 7 mm. The minimum value is -19 mm, and the maximum is 19 mm.

The conclusions formulated regarding GNSS satellite measurements and the obtained accuracies in determining the spatial coordinates of the track centerline refer to receivers from a specific manufacturer and a specific model. To extend these conclusions to other GNSS receivers, tests verifying the accuracy of those receivers would need to be conducted.

References

[1] S. Cellmer, J. Rapiński, M. Skala, K. Palikowska, “New approach to arc fitting for railway track realignment”, Journal of Surveying Engineering, 2016, 142.2: 06015005. doi:.(ASCE)SU.1943-5428.0000163

[2] R. S. Rampriya, R. Suganya, “RSNet: Rail semantic segmentation network for extracting aerial railroad images”, Journal of Intelligent & Fuzzy Systems, 2021, 41.2: 4051-4068. doi: 10.3233/JIFS-210349

[3] G. Lenda, M. Strach, “Determining the geometry of rail routes using the approximating spline functions”, PAK (12), 2012, 1082-1086.

[4] Y. Zheng, P. Cross, “Integrated GNSS with different accuracy of track database for safety-critical railway control systems”, GPS solutions, 2012, 16: 169-179. doi: 10.1007/s10291-011-0216-x

[5] J. Sadeghi, M. M. Najar, J. A. Zakeri, C. Kuttelwascher, “Development of railway ballast geometry index using automated measurement system”, Measurement, 2019, 138: 132-142. doi: 10.1016/j.measurement.2019.01.092

[6] G. Lenda, A. Uznański, M. Strach, P. Lewińska, "Laser scanning in engineering surveying: methods of measurement and modeling of structures", Reports on Geodesy and Geoinformatics. ISSN 2391-8152. 2016 vol. 100 iss. 1, s. 109-130. 2016. doi: 10.1515/rgg-2016-0010

[7] S. Sushant, S. Anand, T. James, V. Aravind, G. Narayanan, "Localization of an unmanned aerial vehicle for crack detection in railway tracks", In2017 International Conference on Advances in Computing, Communications and Informatics (ICACCI), pp. 1360-1365. IEEE. 2017 Sep 13. doi: 10.1109/ICACCI.2017.8126030

[8] P. Dronszczyk, M. Strach, "Zastosowanie technologii skaningu laserowego i termowizji do inwentaryzacji tunelu i znajdujących się w nim urządzeń przeciwpożarowych / The use of laser scanning technology and infrared thermography to survey a tunnel and its fire protection devices", Bezpieczeństwo i Technika Pożarnicza / Safety & Fire Technique; ISSN 1895-8443. BiTP. 2016 vol. 43 iss. 3, s. 199-214. 2016.

[9] Y. Geng, F. Pan, L. Jia, Z. Wang, Y. Qin, L. Tong, S. Li, "UAV-LiDAR-based measuring framework for height and stagger of high-speed railway contact wire", IEEE Transactions on Intelligent Transportation Systems. 2021 May 24. doi: 10.1109/TITS.2021.3071445

[10] F. Flammini, C. Pragliola, G. Smarra, "Railway infrastructure monitoring by drones", In2016 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), pp. 1-6. IEEE. 2016 Nov 2. doi: 10.1109/ESARS-ITEC.2016.7841398

[11] C. Ulianov, P. Hyde, R. Shaltout, "Railway applications for monitoring and tracking systems", In: Sustainable Rail Transport: Proceedings of RailNewcastle Talks 2016. Springer International Publishing, 2018. p. 77-91. doi: 10.1007/978-3-319-58643-4_6

[12] J. Fikejz, A. Kavička, "RegioRail - GNSS Train-Positioning System for Automatic Indications of Crisis Traffic Situations on Regional Rail Lines", Applied Sciences, 2022, 12.12: 5797. doi: 10.3390/app12125797

[13] M. Strach, P. Dronszczyk, "Comprehensive 3D measurements of tram tracks in the tunnel using the combination of laser scanning technology and traditional TPS/GPS surveying", Transportation Research Procedia. ISSN 2352-1465. 2016 vol. 14, s. 1940-1949. 6th Transport Research Arena TRA, April 18-21 2016. doi: 10.1016/j.trpro.2016.05.161

[14] J. Szmagliński, A. Wilk, W. Koc, K. Karwowski, P. Chrostowski, J. Skibicki, ..., T. Widerski, "Verification of Satellite Railway Track Position Measurements Making Use of Standard Coordinate Determination Techniques", Remote Sensing, 2022, 14.8: 1855. doi: 10.3390/rs14081855

[15] M. Specht, C. Specht, P. Dąbrowski, K. Czaplewski, L. Smolarek, O. Lewicka, "Road tests of the positioning accuracy of INS/GNSS systems based on MEMS technology for navigating railway vehicles", Energies, 2020, 13.17: 4463. doi: 10.3390/en13174463

[16] Y. Zhou, Q. Chen, X. Niu, "Kinematic measurement of the railway track centerline position by GNSS/INS/odometer integration", IEEE Access, 2019, 7: 157241-157253. doi: 10.1109/ACCESS.2019.2946981
[17] Z. Gao, M. Ge, Y. Li, W. Shen, H. Zhang, H. Schuh, "Railway irregularity measuring using Rauch–Tung–Striebel smoothed multi-sensors fusion system: Quad-GNSS PPP, IMU, odometer, and track gauge", GPS Solutions, 2018, 22: 1-14. doi: 10.1007/s10291-018-0702-5
[18] Q. Chen, X. Niu, L. Zuo, T. Zhang, F. Xiao, Y. Liu, J. Liu, "A railway track geometry measuring trolley system based on aided INS", Sensors, 2018, 18.2: 538. doi: 10.3390/s18020538
[19] Standard dla kolejowej osnowy geodezyjnej, znaków regulacji osi torów, wykonywania pomiarów geodezyjnych oraz opracowań map na zlecenie PKP Polskie Linie Kolejowe S.A. Ig-6. PKP Polskie Linie Kolejowe S.A. Centrala, Biuro Terenów Kolejowych i Ochrony Środowiska. Warszawa, 2023 r. (Standard for the Railway Geodetic Control Network, Track Centerline Realignment, Geodetic Measurements, and Map Compilations Commissioned by PKP Polish Railway Lines S.A. Ig-6. PKP Polish Railway Lines S.A. Headquarters, Department of Railway Lands and Environmental Protection. Warsaw, 2023)