Study of Accuracy and Measurement Uncertainty of Asset Localization in Logistics 4.0 Using GNSS-RTK Technologies

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Abstract. The accuracy and measurement uncertainty associated with real-time asset localization represent a fundamental role in decision-making processes in Logistics 4.0. The global uncertainty, which encompasses errors and uncertainties, determines the time required to locate an asset and the success rate of asset movement operations. This study evaluated the accuracy and measurement uncertainty of the localization of a GNSS-RTK rover and asset location in an outdoor environment under different signal reception conditions, time of day, and sky conditions. In the outdoor environment of SENAI ISI-SIM, 2D position errors and orientation errors, along with their measurement uncertainties, were determined using a GNSS-RTK rover installed on a pallet truck. GNSS-RTK technology is a highly precise positioning technique that utilizes carrier phase measurements from GNSS signals to achieve centimeter-level accuracy in real-time. The metrological reliability was based on the coordinates of a GNSS station from IBGE and the use of a total station. The measurement uncertainties were calculated using the ISO GUM method. The system also features a magnetometer to estimate the orientation of the pallet truck, this orientation is utilized in the process of coordinate transfer, taking into consideration the position of the rover's GNSS-RTK antenna and the position of the asset. As a result of this study, a position measurement uncertainty of 0.03 m was estimated, with an asset localization accuracy ranging from 0.10 m to 0.24 m, resulting in a global uncertainty of 0.27 m.

1. Introduction

Logistics systems in industries have been significantly impacted by the Industry 4.0 revolution, leading to the emergence of Logistics 4.0 [1-2]. This term, which first appeared in a 2017 article identified through a search on the ScienceDirect website [1], refers to an advanced approach to logistics management that leverages digital technologies and connectivity to optimize logistic processes [1-3]. Logistics 4.0 represents an evolution from traditional logistics, driven by digital transformation and the adoption of Industry 4.0 technologies. It encompasses key concepts such as the Internet of Things (IoT), Big Data, artificial intelligence (AI), automation, Real-Time Locating System (RTLS), and robotics. By employing these technologies, real-time collection of accurate and comprehensive data throughout the supply chain is made possible, resulting in enhanced visibility, traceability, accuracy, and control over the location of assets (products and materials) [1-4].

The accuracy of position determination, crucial for assessing the efficiency and precision of a localization system, relies on the specific type of RTLS technology employed within the IoT architecture of Logistics 4.0. RTLS is a wireless system capable of precisely locating assets within a defined space, in near real-time. The asset's position is determined through measurements of the propagation properties of electromagnetic waves, which establish the communication link between the transmitter and receiver [4-7]. In outdoor environments, a range of technologies can be utilized, such as 5G technology (the fifth generation of wireless communication systems for mobile telephony), GPS (Global Positioning System), or GNSS-RTK (Global Navigation Satellite System – Real-Time Kinematic). Among these, GPS is the most used technology for tracking and remotely managing assets in an external environment [4-7]. In this paper, GNSS-RTK is employed.

GNSS-RTK technology is a highly precise positioning technique that utilizes carrier phase measurements from GNSS signals to achieve centimeter-level accuracy in real-time [8]. By combining the data from multiple satellite constellations, such as GPS, GLONASS, Galileo, and BeiDou, along with a reference station, GNSS-RTK calculates precise geodetic coordinates by resolving the integer ambiguities [8-9]. This technique provides high precision positioning information, allowing for a wide range of applications including autonomous vehicle navigation, surveying, precision agriculture, and construction. With its ability to deliver accurate and instantaneous positioning information, GNSS-RTK technology has become a vital tool in various industries requiring reliable and precise positioning data. In this paper, the GNSS-RTK was integrated into a GNSS-RTK rover, which also contains an inertial measurement unit that consists of an accelerometer, a gyroscope, and a magnetometer.

Geodetic coordinates obtained with GNSS-RTK can be transformed into other coordinate systems. To convert them into Cartesian coordinates, the Universal Transverse Mercator (UTM) system is used. The UTM system employs 60 transverse and secant cylindrical projections with respect to the reference ellipsoid (Earth's representation). Each cylinder is responsible for representing a 6° longitudinal extent (zone) [12-13]. For instance, the city of São Leopoldo – RS is situated in the 6° zone between longitudes 48° and 54°, so the central meridian (CM) of this UTM representation cylinder is the CM 51, representing the longitude 51°. Each one of the 60 cylinders has its own reference coordinate system, with the origin at the intersection of the Equator and the CM line of each zone. The abscissas in the UTM system are referred to as east coordinates (E) or UTM(E), and the ordinates are designated as north coordinates (N) or UTM(N) [12-13].

The objective of this study was to quantify the accuracy and measurement uncertainty of a GNSS-RTK system in an outdoor environment with variable signal reception conditions, time of day, and sky visibility. This allowed determining the 2D position errors of the GNSS-RTK rover in its best usage condition, i.e., when it is precisely positioned over a reference point and leveled. Additionally, for the pallet truck, it was possible to determine the 2D position error of the installed GNSS-RTK rover (hardware on the pallet truck), the 2D position error of the asset, and the orientation error of the GNSS-RTK rover (pallet truck). In addition to position and orientation errors, the position measurement uncertainties ($U_{position}$) and orientation uncertainties ($U_{orientation}$) were also estimated, along with the global GNSS-RTK rover position uncertainty (U_{GNSS}), which is the sum of the position absolute error and $U_{position}$ [7, 10-11].

The metrological reliability of this study was based on using a GPS station from IBGE, the RSSL Station - UNISINOS [14], nearby SENAI ISI-SIM in São Leopoldo/RS - Brazil. The GPS station's geodetic coordinates (UNISINOS) were used to determine the geodetic coordinates of two reference markers located in the external yard of SENAI ISI-SIM. In addition, a total station and additional accessories were also used to transfer these UTM coordinates of the reference markers to three reference points. Having that, the UTM coordinates obtained from these reference points were then used to calculate the accuracy of the asset's location (GNSS-RTK rover position). The GNSS-RTK rover position errors were calculated as the difference between the north and east coordinates, UTM(E) and UTM(N), indicated by the GNSS-RTK system (IHM), and the UTM coordinates of these reference points [6-7]. Measurement uncertainties were calculated following the ISO GUM (Guide to the Expression of Uncertainty in Measurement) method [7, 10-11].

2. Materials and Methods

The accuracy and measurement uncertainty study of the GNSS-RTK technology was conducted in the outdoor environment of SENAI ISI-SIM (São Leopoldo, RS, Brazil). To accomplish this, a GNSS-RTK base antenna was installed on the rooftop of the institute to maximize sky visibility. Having that, a GNSS-RTK rover was used in two different scenarios - first, mounted on a mini tripod, and later, mounted on a pallet truck. Furthermore, two topographic reference markers and three reference points were established for this study (figure 1).

The GNSS antenna was responsible for transferring the geodetic coordinates from a nearby GPS station to the ISI-SIM location. In this study, the GPS station [14] used as the reference for the GNSS-RTK base antenna has the identification number 94128), belonging to the Brazilian Network of Continuous Monitoring of GNSS Systems (RBMC), and is located at Avenida Unisinos, 950 (São Leopoldo, RS, Brasil), approximately 1,342 m away from reference marker M1. These findings help define the coverage region of GNSS-RTK. Additional information is described in table 1. According to Feng and Wang [15], the performance of the GNSS-RTK system is primarily influenced by two factors: the distance between the base station and the rover, known as the baseline, and the latency of correction packets. The study also presents relationships between different baseline distances and positioning accuracy. For instance, considering a baseline of 2,500 m, a horizontal position standard deviation of approximately 0.009 m was observed. With a baseline of 31,000 m, the horizontal accuracy reached around 0.13 m. These data help define the coverage region of GNSS-RTK [15].

To determine the coordinates of the reference points, the two reference markers were established. Using GNSS technology with RTK capability, geodetic coordinates in terms of longitude (Long.) and latitude (Lat.) and were measured five times at each reference marker, following the SIRGAS2000 standard. The positioning process involved aligning the GNSS-RTK rover with mini tripod over the central point of each marker and ensuring accurate leveling using a digital protractor (figure 2).

Figure 1. Spatial perspective of GNSS-RTK study configuration at SENAI ISI-SIM.

Table 1. Characteristics of the Reference GPS Station (UNISINOS)

Longitude	Latitude	UTM(E)	UTM(N)	CM
51° 09’ 08.71973” W	29° 47’ 34.78135” S	485,268.813 m	6,704,142.402 m	51
Sigma = 0.001 m	Sigma = 0.001 m	DATUM SIRGAS2000		

Figure 2. Transfer of coordinates from the GPS station to the reference markers.

The geodetic coordinates obtained from the reference markers were transformed into Cartesian coordinates using the Universal Transverse Mercator (UTM) system and transferred to three reference points using a total station, tripod, and mini prism (figure 3). The total station used in the study has metrological traceability, supported by certificate RBC No. 01032/22, which is based on standards that are traceable to the Brazilian Calibration Network (RBC). The total station has a maximum angular error limit of 20" and a maximum linear error limit of ±[4 mm + 6 ppm x D] (mm), where D is the distance measured in millimeters and ppm is the part per million. In addition to the total station, a digital protractor (as shown in figure 2), with certificate RBC No. 01049/22, was also employed during the tests. The conversion of geodetic coordinates to UTM coordinates was achieved using a set of mathematical formulas known as Cartographic Projections. The equations responsible for the conversion between LLH (latitude, longitude, height) and UTM were derived from Krüger's work [12]. For the experiment, a Python library called pyproj [16], specifically designed for cartographic projections, was utilized.

Three reference points (P7, P8, and P9) were then installed, and their positions were measured to obtain the reference values of E_{ref} and N_{ref}. Firstly, P7 was installed in an unobstructed line of sight to the satellite. In addition, P8 was positioned near buildings and bushes, resulting in a partially obstructed line of sight. Finally, point P9 was situated under trees and close to buildings, leading to a fully obstructed line of sight.

After materializing these three points and obtaining their UTM coordinates with Datum SIRGAS2000, these points were utilized to determine the 2D position errors of the GNSS-RTK rover. The GNSS-RTK rover was positioned on the points using a mini tripod and ensuring accurate leveling with the help of a digital protractor. Measurements of the GNSS-RTK rover positions on the three reference points (P7, P8, and P9) were carried out under two different "Time of Day" conditions (day and night) combined with two "Sky" conditions (clear and cloudy). The position data (E_{meas} and N_{meas}) of the GNSS-RTK rover was collected in the software with five measurements (IHM of rover) at each of the three reference points. The 2D position error of the GNSS-RTK rover (E) was calculated using the two-dimensional Euclidean distance [6-7], which is the difference between the coordinates of the tag position (E_{meas} and N_{meas}) and the reference point coordinates (E_{ref} and N_{ref}) using equation (1). The 2D position errors of the GNSS-RTK rover provided the best accuracy as they were determined under ideal positioning and leveling conditions.

$$E = \sqrt{\left(E_{meas} - E_{ref}\right)^2 + \left(N_{meas} - N_{ref}\right)^2} \quad (1)$$

In this study, the main objective was to assess the accuracy and measurement uncertainty of the asset's location. To achieve this, a GNSS-RTK rover was affixed onto a pallet truck. The asset's position was marked on the fork of the pallet truck, 0.916 m away from the GNSS-RTK rover (figure 4). To collect data from the GNSS-RTK rover's hardware, a MQTT (Message Queuing Telemetry Transport) protocol was utilized to transmit the information to a computer. The data was then displayed on an Integrated Human Machine Interface (IHM), providing access to the hardware's position in UTM coordinates, its orientation, and the asset's projected position. This projection was made possible by combining the hardware's position with magnetometer readings.

The 2D position errors of the hardware and the asset were calculated using equation (1). The pallet truck's orientation error (hardware and asset) is determined by comparing the orientation value displayed by the software (IHM) with the calculated azimuth of the alignment between the hardware and asset positions. The azimuth of this alignment is calculated based on the UTM coordinates obtained from measurements of the hardware and asset positions using the total station. Five orientation measurements were performed at angles of 10.5°, 47.0°, 108.8°, 180.3°, and 274.8°, in a space with an unobstructed view of the sky and no nearby trees or buildings. All measurement uncertainty calculations were carried out according to the ISO GUM method (Guide to the Expression of Uncertainty in Measurement) [10-11] and following the methodology described in the article of Krummenauer et al. [7], which applies the ISO GUM calculation method to 2D coordinate measurements in indoor environments using Ultra-Wideband (UWB). These methodologies are similar to those developed in this study, as some uncertainty sources are comparable.

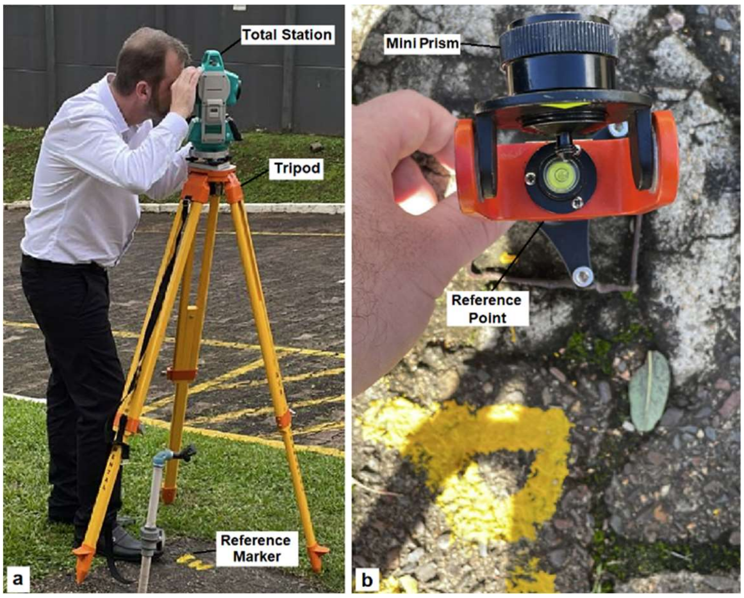

Figure 3. Transfer of coordinates from the reference markers to the reference points using the total station (a) and a mini prism (b).

Figure 4. Installation of the GNSS-RTK rover on the pallet truck.

3. Results and discussion

Any accuracy and measurement uncertainty study is based on metrological traceability. In this study, metrological traceability is established using the coordinates from a GPS station and measurements taken with a total station calibrated by the ISI-SIM RBC laboratory (Accreditation CAL 0013). The coordinates of GPS station (UNISINOS), as listed in table 1, were transferred to two reference markers, M1 and M4, which were materialized with open-sky visibility in the ISI-SIM courtyard, as shown in table 2, where longitudes are marked as west (W) and latitudes as south (S). These geodetic coordinates were converted to east (E_{ref}) and north (N_{ref}) UTM coordinates and are referred to the central meridian (CM) 51.

Table 2. Measured coordinates at the reference markers in SENAI ISI-SIM.

Marker	Coordinate	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Mean	Standard Deviation
M1	Long. (°)	51.16361550	51.16361550	51.16361550	51.16361567	51.16361567	51.16361557	9.31E-08
	Lat. (°)	29.78583100	29.78583083	29.78583100	29.78583100	29.78583100	29.78583097	7.60E-08
	E (m)	484185.879	484185.879	484185.879	484185.862	484185.862	484185.872	0.009
	N (m)	6704934.705	6704934.724	6704934.705	6704934.705	6704934.705	6704934.709	0.008
M4	Long. (°)	51.16349450	51.16349433	51.16349433	51.16349450	51.16349450	51.16349443	9.31E-08
	Lat. (°)	29.78584100	29.78584100	29.78584067	29.78584083	29.78584083	29.78584087	1.39E-07
	E (m)	484197.575	484197.592	484197.592	484197.575	484197.575	484197.582	0.009
	N (m)	6704933.614	6704933.614	6704933.650	6704933.633	6704933.633	6704933.629	0.015

The procedure of transferring coordinates from the GPS station to the reference markers (M1 and M4) established a measurement uncertainty for determining the UTM coordinates of these markers (U_{marker}). The largest uncertainty was calculated using the highest standard deviation of the UTM coordinates in table 2, which is 0.015 m (shaded cell in table 2). The uncertainty calculation followed the ISO GUM method [7-9] and is summarized in table 3, resulting in U_{marker} equal to 0.020 m, with a coverage factor (k) of 2.87 and effective degrees of freedom (ν_{eff}) equal to 4. The main source of uncertainty considered for U_{marker} was the highest repeatability among the measurements of the reference marker coordinates (shaded cell in table 2). The second source of uncertainty arises from the sigma value of 0.001 m for the coordinates of the reference GPS station (UNISINOS) in table 1, thus determining the standard uncertainty of 0.001 m originated from this reference standard. The third source of uncertainty pertains to the variation in the positioning of the GNSS-RTK rover on the reference marker (figure 2), with an estimated maximum variation of 0.002 m and a triangular probability distribution, considering that the central positioning is more likely. The last considered source of uncertainty relates to the resolution of measurements obtained with the GNSS-RTK rover.

Table 3. Measurement uncertainty spreadsheet for E_{ref} and N_{ref} coordinates of reference markers (U_{marker}).

Input quantity	Estimate (m)	Probability distribution	Divider	Standard uncertainty (m)	Sensitivity coefficient	Contribution to standard uncertainty	Degrees of freedom
Repeatability	0.015	t-Student	$\sqrt{5}$	0.006708	1	0.006708 m	4
Uncertainty of GPS station coordinates	0.002	normal	2	0.001000	1	0.001000 m	∞
Uncertainty of rover positioning	0.002	triangular	$\sqrt{6}$	0.000816	1	0.000816 m	∞
Resolution of GNSS-RTK rover	0.001	rectangular	$\sqrt{12}$	0.000289	1	0.000289 m	∞
	$U_{marker} = 0.020$ m			$k = 2.87$	$u_c(y) =$ 0.0068 m		$\nu_{eff} = 4$

Using the UTM coordinates of the two reference markers listed in table 2 and a total station with its accessories, it was possible to determine the UTM coordinates of three reference points (P07, P08, and P09). These points serve as the reference coordinates for calculating the 2D position errors of the GNSS-

RTK rover under three line-of-sight conditions: Unobstructed, Partially Obstructed, and Fully Obstructed, respectively. The measured coordinates of these points are presented in table 4, and the spreadsheet containing the measurement uncertainty calculations for the reference points (U_{point}) is provided in table 5. Additionally, these markers M1 and M4 served as the basis for metrological traceability to determine the orientation errors of the GNSS-RTK rover installed on a pallet truck and the 2D position errors of the asset transported by the pallet truck.

The main source of uncertainty considered for U_{point} was the highest repeatability among the measurements of the reference point coordinates in table 4, which is 0.0015 m (shaded cell in table 4). The second source of uncertainty is associated with the reference markers and was calculated in table 3 as U_{marker} equal to 0.020 m (shaded cell in table 3). The third source of uncertainty pertains to the linear measurement uncertainty of the total station, as reported in ISI-SIM calibration certificate Nº. 01032/22. It was calculated as the sum of the linear uncertainty of 0.001 m and the maximum error of 0.002 m, resulting in 0.003 m with a confidence level of k = 2. The fourth source of uncertainty relates to the variation in the positioning of the total station's optical plummet over the reference marker (Figure 3a), with a maximum estimated variation of 0.002 m and a triangular probability distribution, considering that central positioning is more likely. The fifth source of uncertainty is associated with the variation in the positioning of the mini prism over the reference point (Figure 3b), and its estimation is similar to that of the total station positioning. The last considered source of uncertainty concerns the resolution of measurements obtained with the total station.

Table 4. Measured coordinates of the reference points in SENAI ISI-SIM.

Point	Coordinate	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Mean	Standard Deviation
P7	E (m)	484200.872	484200.873	484200.872	484200.871	484200.872	484200.872	0.0007
	N (m)	6704937.498	6704937.497	6704937.497	6704937.499	6704937.498	6704937.498	0.0008
P8	E (m)	484177.206	484177.207	484177.206	484177.207	484177.208	484177.207	0.0008
	N (m)	6704826.674	6704826.674	6704826.674	6704826.673	6704826.674	6704826.674	0.0004
P9	E (m)	484186.374	484186.377	484186.377	484186.376	484186.378	484186.376	0.0015
	N (m)	6704840.131	6704840.130	6704840.129	6704840.128	6704840.131	6704840.130	0.0013

Table 5. Measurement uncertainty spreadsheet for coordinates of reference points (U_{point}).

Input quantity	Estimate (m)	Probability distribution	Divider	Standard uncertainty (m)	Sensitivity coefficient	Contribution to standard uncertainty	Degrees of freedom
Repeatability	0.0015	t-Student	$\sqrt{5}$	0.000671	1	0.000671 m	4
Uncertainty of markers	0.020	t-Student	2.87	0.006969	1	0.006969 m	4
Uncertainty of total station (linear)	0.003	normal	2	0.001500	1	0.001500 m	∞
Uncertainty of total station positioning	0.002	triangular	$\sqrt{6}$	0.000816	1	0.000816 m	∞
Uncertainty of mini prism positioning	0.002	triangular	$\sqrt{6}$	0.000816	1	0.000816 m	∞
Resolution of total station	0.001	rectangular	$\sqrt{12}$	0.000289	1	0.000289 m	∞
	U_{point} = 0.021 m			k = 2.87		$u_c(y)$ = 0.0073 m	ν_{eff} = 4

By comparing the results of U_{marker}, which is equal to 0.020 m (table 3), and U_{point}, which is equal to 0.021 m (table 5), we notice that the difference in uncertainty values is minimal (0.001 m). Therefore, they are values of the same order of magnitude. This indicates that there was no significant increase in uncertainty during the procedure of transferring coordinates between the reference markers and points. Furthermore, these values respect the recommendations of the publication "Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques" [18]. According to this publication, the accuracy standard for 3D surveys using space system techniques should fall between 0.01 and 0.05 m for the National Geodetic Reference System in terrestrial-based measurements (Table 1 of the document).

3.1. Determination of 2D Position Errors of the GNSS-RTK rover

A metrological study was conducted to determine the 2D position error of the GNSS-RTK rover considering three input variables: line of sight, time of day, and sky conditions. This 2D position error was calculated by taking the difference between the readings displayed on the Human-Machine Interface (HMI) when the rover was precisely positioned and leveled directly over the reference point (figure 2), and the known coordinates of the reference points, as expressed in equation (1). Three reference points, namely P7, P8, and P9 (figure 1), were used to calculate the positioning error, with fifteen measurements performed at each reference point. The values of the average position errors ($\bar{E}$), standard deviation of position errors (s), the measurement uncertainty of the average position errors ($U_{position}$), and the global uncertainty of the GNSS-RTK rover (U_{GNSS}) are depicted graphically in figure 5 and summarized in table 6. The calculation of the global uncertainty U_{GNSS} is expressed in equation (2), and the spreadsheet containing the uncertainty calculations for $U_{position}$ is presented in table 7.

$$U_{GNSS} = |\bar{E}| + U_{position} \tag{2}$$

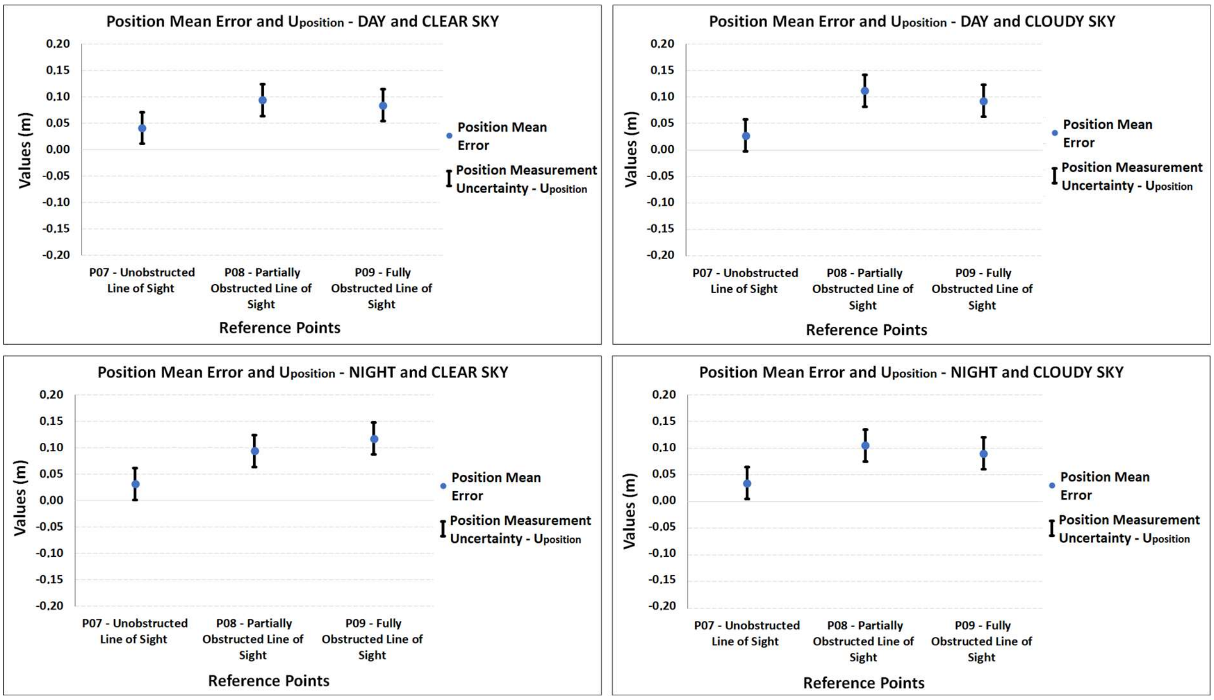

Figure 5. Position mean error and uncertainty of GNSS-RTK rover.

Table 6. Summary of 2D position errors and global uncertainties of the GNSS-RTK rover.

Point	Line of sight	Time of day	Sky	$\bar{E}$ (m)	s (m)	$U_{position}$ (m)	U_{GNSS} (m)
P7	Unobstructed	Day	Clear	0.04	0.018	0.03	0.07
			Cloudy	0.03	0.013		0.06
		Night	Clear	0.03	0.010		0.06
			Cloudy	0.03	0.026		0.06
P8	Partially Obstructed	Day	Clear	0.09	0.013	0.03	0.12
			Cloudy	0.11	0.040		0.14
		Night	Clear	0.09	0.013		0.12
			Cloudy	0.11	0.015		0.14
P9	Fully Obstructed	Day	Clear	0.08	0.015	0.03	0.11
			Cloudy	0.09	0.007		0.12
		Night	Clear	0.12	0.036		0.15
			Cloudy	0.09	0.009		0.12

In table 7, it can be observed that the primary source of uncertainty considered for $U_{position}$ was the highest repeatability among the 2D position error measurements in table 6, which is 0.040 m (shaded cell in table 6). The second source of uncertainty is associated with the reference points and was calculated in table 5 as U_{point} equal to 0.021 m (shaded cell in table 5). The third source of uncertainty relates to the variation in the positioning of the GNSS-RTK rover over the reference point, with a maximum estimated variation of 0.002 m and a triangular probability distribution, considering that centralization of positioning is more likely. The last source of uncertainty considered pertains to the resolution of measurements obtained with the GNSS-RTK rover.

Table 7. GNSS-RTK Rover position mean error uncertainty spreadsheet ($U_{position}$).

Input quantity	Estimate (m)	Probability distribution	Divider	Standard uncertainty (m)	Sensitivity coefficient	Contribution to standard uncertainty	Degrees of freedom
Repeatability	0.040	t-Student	$\sqrt{15}$	0.010422	1	0.010422	14
Uncertainty of reference point	0.021	t-Student	2.87	0.007317	1	0.007317	4
Uncertainty of rover positioning	0.002	triangular	$\sqrt{6}$	0.000816	1	0.000816	∞
Resolution of GNSS-RTK rover	0.001	rectangular	$\sqrt{12}$	0.000289	1	0.000289	∞
	$U_{position}$ = 0.03 m			k = 2.16	$u_c(y)$ = 0.0128		ν_{eff} = 17

In order to investigate whether there were significant differences among the means of the results concerning the input variables, a three-factor analysis of variance (ANOVA) was conducted using Minitab 21 software. The results of this ANOVA test are presented in table 8. In the ANOVA analysis, a factor is considered significant if the p-value is less than 0.05 (α = 5 %), indicating a 95 % confidence level [17]. Upon reviewing table 8, it becomes evident that only the "line of sight" factor is significant with a 95 % confidence level. On the other hand, the "time of day" and "sky" factors were not significant in this study, as their p-values are greater than 0.05. From table 6, it can be observed that the 2D position errors for the point with an unobstructed line of sight (P07) are four times smaller than the errors for points with some form of line of sight obstruction. The maximum 2D position error for point P-07 (unobstructed line of sight) was 0.04 m. This 2D position error is consistent with the study conducted by Specht et al. [19], which determined 2D errors ranging from 0.054 to 0.017 m in non-built-up areas using GNSS-RTK. Specht et al. [19] also established that the 2D position errors in areas with numerous terrain obstacles, such as multi-storey buildings or tall trees, ranged from 0.961 m to 0.246 m. Hence, our measured 2D errors between 0.08 and 0.12 m are smaller than those reported in Specht et al.'s study. Garrido et al. [8] presented the horizontal accuracy of a GNSS-RTK positioning system in the range of 0.005 to 0.047 m. Thus, the values obtained in our study fall within the same order of magnitude and are consistent with Garrido et al.'s findings.

Table 8. Three-factor ANOVA study of position errors of the GNSS-RTK rover.

Factor	Degrees of freedom	Sum of squares	Mean square	p-value
Line of sight	2	0.170450	0.085225	0.000
Time of day	1	0.000617	0.000617	0.263
Sky	1	0.000000	0.000000	0.985
Error	175	0.085525	0.000489	
Total	179	0.256591		

In this study, it was determined that the global uncertainty of the GNSS-RTK rover ranged between 0.06 and 0.15 m, even considering points with obstructed line of sight. Comparing this global uncertainty of the GNSS-RTK rover with the global uncertainty of the UWB system with unobstructed line of sight, which ranged between 0.21 and 0.35 m in an indoor environment, according to the study by Krummenauer et al. [7], it can be established that the GNSS-RTK uncertainty is of the same order of magnitude or approximately two times smaller. Therefore, depending on the measurement conditions, especially the distance between the GNSS-RTK antenna and the GNSS-RTK rover, GNSS-RTK technology used in outdoor environments may have better accuracy than UWB technology used in indoor environments.

3.2. Determination of Pallet Truck Orientation Errors and 2D Position Errors of the Hardware and Asset

In this study, the pallet truck's orientation error (hardware and asset) is determined by calculating the difference between the orientation value presented by the software and the calculated azimuth of the alignment between the hardware and the asset's position. The azimuth of this alignment is calculated from the UTM coordinates obtained through measurements of the hardware and the asset's position using a total station. Five orientation measurements were taken at the following angles: 10.5°, 47.0°, 108.8°, 180.3°, and 274.8°.

The distance between the hardware installed on the pallet truck and the transported asset is approximately 0.916 m, and the pallet truck's positioning was conducted with an unobstructed line of sight. To calculate the 2D position error of the hardware, equation (1) was used having E_{meas} and N_{meas} coordinates as the hardware's position, as indicated on the GNSS-RTK rover's HMI, and the reference coordinates measured with the total station (E_{ref} and N_{ref}). Similarly, the 2D position error of the asset was also calculated using equation (1) by having the asset's position as E_{meas} and N_{meas}, indicated on the GNSS-RTK rover's HMI, and the reference coordinates measured with the total station (E_{ref} and N_{ref}).

Table 9 presents a summary of the average values obtained from the measurements of the hardware's position, the asset's position, and the pallet truck's orientation. Table 10 displays the mean errors of the measurements of the hardware and asset positions taken with the total station, along with the calculated orientations (azimuths). Additionally, table 11 presents the calculations of the mean errors for the hardware and asset positions, as well as the pallet truck's orientations. These mean errors for the hardware and asset positions, along with their uncertainties, are graphically represented in figure 6.

The calculations of the measurement uncertainty for the 2D position errors of the hardware and the asset are the same as presented in table 7 for $U_{position}$, in which presents a final value of 0.03 m (shaded cell in table 7).

Table 9. Indications of hardware positions, asset positions, and orientations displayed by the pallet truck's HMI.

Hardware position - IHM		Asset position - IHM		Orientation - IHM
E_{meas} (m)	N_{meas} (m)	E_{meas} (m)	N_{meas} (m)	(°)
484204.554	6704941.513	484204.775	6704942.401	14.0
484201.821	6704941.650	484202.461	6704942.307	44.2
484197.802	6704939.295	484198.645	6704938.937	113.0
484196.660	6704936.384	484196.619	6704935.469	182.6
484187.391	6704935.427	484186.475	6704935.434	270.5

Table 10. Measurements of hardware and asset positions and calculations of orientations (azimuths).

Hardware position – Total station		Asset position – Total station		Orientation – Total station	
E_{ref} (m)	N_{ref} (m)	E_{ref} (m)	N_{ref} (m)	Mean (°)	Standard Deviation (°)
484204.566	6704941.616	484204.733	6704942.516	10.5	0.04
484201.894	6704941.727	484202.563	6704942.352	47.0	0.01
484197.897	6704939.305	484198.762	6704939.010	108.8	0.01
484196.791	6704936.207	484196.786	6704935.291	180.3	0.13
484187.282	6704935.361	484186.370	6704935.438	274.8	0.07

Table 11. Hardware position errors, asset position errors, and orientation errors.

Orientation	Hardware position error (m)		Asset position error (m)		Orientation error (°)	
(°)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
10.5	0.10	0.014	0.12	0.009	3.5	0.76
47.0	0.11	0.004	0.11	0.006	-2.8	0.57
108.8	0.10	0.005	0.14	0.005	4.2	0.75
180.3	0.22	0.004	0.24	0.002	2.3	0.37
274.8	0.13	0.004	0.10	0.005	-4.3	0.55

Figure 7 illustrates the mean orientation errors of the pallet truck along with the uncertainty in measuring these orientation errors. The spreadsheet containing the calculations of the measurement uncertainty for the orientation ($U_{orientation}$) is provided in table 12, yielding a final value of 1.0° (shaded cell in table 12), with a coverage factor (k) of 2.87 and effective degrees of freedom (v_{eff}) equal to 4.

The main source of uncertainty observed in table 12 is the highest repeatability among the orientation error measurements calculated for the hardware, which is 0.76° (shaded cell in table 11). The second source of uncertainty is the highest repeatability value among the orientation measurements calculated using the coordinates obtained from the total station, which is 0.13° (shaded cell in table 10). The third source of uncertainty is related to the maximum angular error limit of 20" for the total station, which is equivalent to 0.006°, having it converted to degrees. The last considered source of uncertainty pertains to the angular measurement resolution of 0.01° obtained with the GNSS-RTK rover.

Analyzing the results presented in table 11 and figure 6, it is evident that the values of the 2D position errors of the hardware increased and ranged between 0.10 and 0.22 m (unobstructed line of sight), compared to the results of the 2D position errors of the GNSS-RTK rover (table 6), which ranged between 0.03 and 0.04 m with unobstructed line of sight. This difference is attributed to several factors, including the placement of the rover on the top of the pallet truck (figure 4), mechanical tolerances, and the lack of vehicle leveling control. In contrast, the GNSS-RTK rover's measurement system was directly positioned and leveled over the reference points, similar to its positioning over the survey mark in figure 2. Consequently, the smaller errors observed in the study of the GNSS-RTK rover's 2D position errors can be attributed to these controlled positioning conditions. Concerning the 2D position errors of the asset, it is also evident that they are similar to the 2D position errors of the hardware (figure 6). Another observation pertains to the orientation errors being limited to ± 6° (figure 7). By improvements in calibration procedures, the orientation error could be even reduced to 3° accuracy in the azimuth estimates without GPS aiding [20].

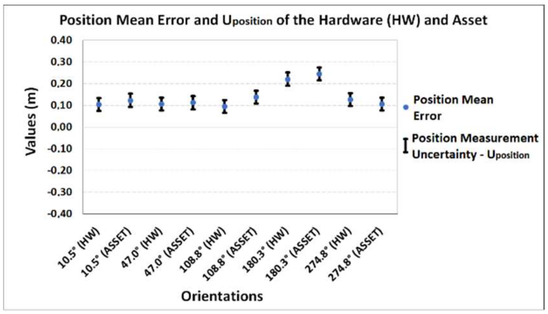

Figure 6. Position mean error and position uncertainty of the hardware and asset in five orientations.

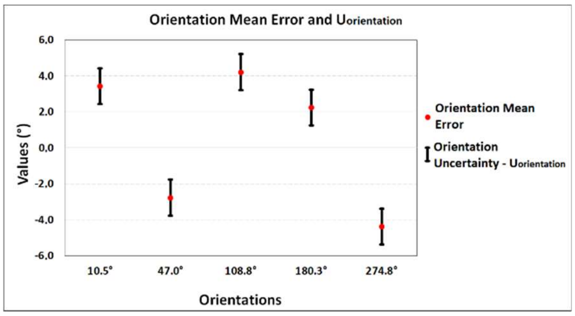

Figure 7. Orientation mean error and orientation uncertainty.

Table 12. Orientation mean error uncertainty spreadsheet ($U_{orientation}$).

Input quantity	Estimate (°)	Probability distribution	Divider	Standard uncertainty (°)	Sensitivity coefficient	Contribution to standard uncertainty	Degrees of freedom
Repeatability of rover	0.76	t-Student	$\sqrt{5}$	0.338678	1	0.338678°	4
Repeatability of total station	0.13	t-Student	$\sqrt{5}$	0.056461	1	0.056461°	4
Angular uncertainty of the total station	0.006	normal	2	0.003000	1	0.003000°	∞
Resolution of GNSS-RTK rover	0.01	rectangular	$\sqrt{12}$	0.002887	1	0.002887°	∞
	$U_{orientation}$ = 1.0°			k = 2.87	$u_c(y)$ = 0.3434°		ν_{eff} = 4

4. Conclusion

This case study demonstrated the method applied to determine the 2D position errors of the GNSS-RTK rover under its optimal usage condition, specifically when it is precisely positioned over a reference point and leveled. Consequently, the smallest measurement errors were determined, ranging between 0.03 and 0.04 m when the rover is situated in an area free from buildings or nearby trees. However, in the presence of constructions or trees nearby, the errors increase to a range of 0.08 to 0.12 m, approximately four times larger. The measurement uncertainty of the 2D position error ($U_{position}$) was estimated to be 0.03 m, resulting in a maximum global uncertainty (U_{GNSS}) of the GNSS-RTK rover under these conditions of 0.15 m. Nevertheless, the installation of the GNSS-RTK rover on a pallet truck amplifies the position errors, which fall in the range of 0.10 to 0.22 m, and the U_{GNSS} in this case reaches 0.25 m. As the primary objective of the pallet truck is to position or move assets in an outdoor environment, the 2D position error of the asset was calculated, yielding values between 0.10 and 0.24 m. Consequently, the U_{GNSS} for the asset resulted in 0.27 m. The lack of a significant increase in the 2D position error of the asset was attributed to the orientation errors being less than ± 6°, a consequence of using the magnetometer to determine this orientation. If a system without a magnetometer were considered, the 2D position error solely due to the distance between the rover (hardware) and asset in this study would be up to 0.916 m, which is the linear distance between them on this pallet truck. Therefore, in cases where it is not possible to install the GNSS-RTK rover exactly at the point where an asset is located, the installation of an orientation system capable of determining the projection of the measured coordinates from the position sensor becomes necessary. It is noteworthy that the obtained values of the 2D position errors and the measurement uncertainties of the GNSS-RTK rover are comparable to other studies and/or documents referenced in this article. Ultimately, it can be concluded that the 2D position errors of the GNSS-RTK system are of the same order of magnitude or approximately two times smaller than the 2D position errors of the UWB system, provided that the baseline is less than 2,500 m. Consequently, it is concluded that GNSS-RTK technology is suitable for asset location control in outdoor environments and for decision-making processes in Logistics 4.0.

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