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Original article

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ACCURACY ANALYSIS OF A WIRELESS INDOOR POSITIONING SYSTEM USING GEODETIC METHODS

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Abstract

Ubisense RTLS is one of the Indoor positioning systems using an Ultra Wide Band. AOA and TDOA methods are used as a principle of positioning. The accuracy of positioning depends primarily on the accuracy of determined angles and distance differences. The paper presents the results of accuracy research which includes a theoretical accuracy prediction and a practical test. Theoretical accuracy was calculated for two variants of system components geometry, assuming the parameters declared by the system manufacturer. Total station measurements were taken as a reference during the practical test. The results of the analysis are presented in a graphical form. A sample implementation (MagMaster) developed by Globema is presented in the final part of the paper.

Keywords: *Ubisense, indoor positioning,*

1. Introduction

Indoor positioning systems are becoming more and more popular nowadays. They allow for tracing spatial positions of humans, animals or any other objects in real-time with high accuracy. Such systems can be extremely useful in applications where information on precise location is necessary and can be used, for instance, to increase the efficiency of production processes, increase security levels in a hazardous environment or simply make life easier in smart homes or offices.

Such systems make use of several different technologies, which gives them some advantages and disadvantages in specific situations. Depending on a technology used (e.g. GPS, GSM, WLAN, RFID, UWB) precision and working range can slightly differ, which should be considered when building an application.

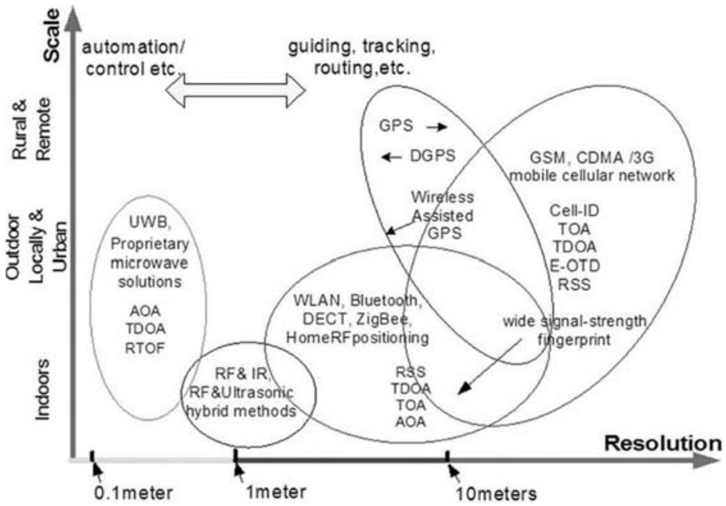


Fig. 1. Positioning systems overview (Liu et al., 2007)

As seen above (Fig. 1.) the best for indoor use are microwave solutions utilizing WLAN, RFID or UWB technologies. They give the best accuracy and their working range is sufficient for even big indoor locations (e.g. production sites or warehouses). They can also return location information quickly enough to work in real-time. To determine object positions such systems use one or a combination of the following techniques (fig.2):

- Lateration techniques:
    - Received Signal Strengths (RSS),
    - Time Of Arrival (TOA),
    - Time Difference Of Arrival (TDOA),
    - Roundtrip Time Of Flight (RTOF),
- Angulation techniques:
    - Angle Of Arrival (AOA).

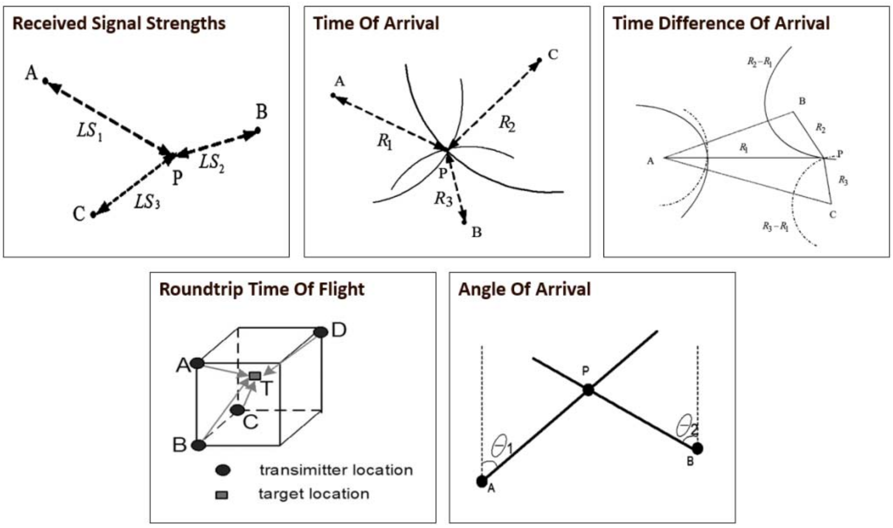


Fig. 2. 3D positioning principles (Ubisense)

Another version of RSS method is RSSI Fingerprint. It doesn't utilize pure geometrical relations, so it won't be considered.

In this article, we will look closer at the UWB real-time location system (RTLS) developed by Ubisense, which has been implemented in over a hundred applications worldwide.

The main goal of the paper is the research of accuracy which includes a theoretical accuracy prediction and a practical test. Theoretical accuracy analysis contains two variants of system components geometry. Practical test was conducted using Total station measurements as a reference.

We will also briefly describe one sample implementation – the MagMaster system developed by Globema company (co-funded by PARP under POIG 1.4).

2. Principle of operation of the Ubisense system

The Ubisense RTLS (Real Time Location System) utilizes the Ultra Wide Band (UWB) frequency range for a localization engine (EU band ranges from 6 GHz to 8,5 GHz) and an additional 2.4 GHz (ISM) radio channel for wireless communication between its components.

The UWB is a radio technology that transmits data using very narrow and low power energy pulses. It allows very high data rate communication and does not interfere with conventional radio transmission in the same frequency band. UWB solutions also allow effective elimination of noises caused by the signal multipath and give very good location determination accuracy, which is very important for precise real-time location systems because it ensures very good location determination accuracy.

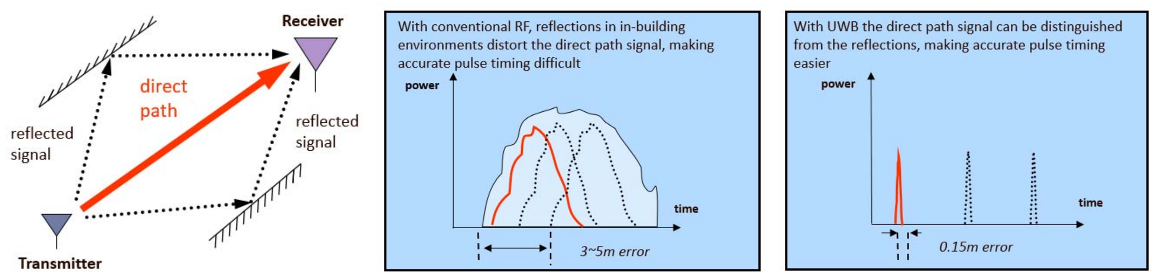


Fig. 3. Noise elimination of signal multipath

The Ubisense RTLS consists of stationary sensors (receivers - Fig. 4) which are mounted at fixed positions, small mobile tags (transmitters - Fig. 5) which are carried by monitored objects and a PC server with the Ubisense Location Engine (ULE) software package which controls sensors and calculates tag positions.

Fig. 4. Ubisense sensors (Ubisense)

Fig. 5. Ubisense tags (Ubisense)

The monitored space must be organized into a grid of sensor cells. Every sensor cell is controlled by two or more sensors (typically 4) and every part of the cell should be visible by at least two sensors. The system allows for simultaneous tracing of many tags. Tags can move between sensor cells because space is continuous and has one common coordinate system. The tag position can be determined with a frequency up to 10Hz.

The Ubisense RTLS utilizes the Ultra Wide Band (UWB) frequency range for a localization engine (EU band ranges from 6 GHz to 8,5 GHz) and an additional 2.4 GHz (ISM) radio channel for wireless communication between its components. The UWB solution allows for effective elimination of noises caused by the signal multipath and gives very good location determination accuracy.

The tag position is determined using a combination of the two aforementioned techniques: the angular technique AOA (Angle of Arrival), which delivers direction of propagation of RF signal received by antenna array, and the pseudo-range technique TDOA (Time Difference of Arrival), which delivers information about the difference of the tag distance from particular sensors.

The RF pulse emitted by the tag is received by every sensor in its sight. The receiving sensors determine the two angular components of the tag pulse direction. In every sensor cell, exactly one sensor is called the Master. and it is the central node of the star-topology network (which can be extended by daisy-chaining). For every other sensor that received the signal, the system determines time differences of signal arrival, and as a result, the difference of the distance. Together with the angular values, the difference of the distance is used for tag positioning. The tag position is the location of a geometric intersection of appropriate positioning lines and surfaces (Fig. 6).

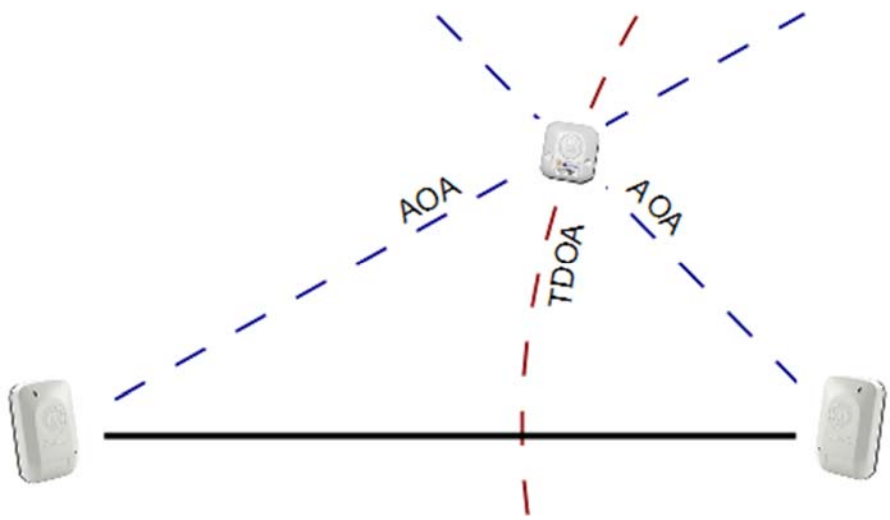


Fig. 6. The object location as an intersection of lines and surfaces

3. Theoretical accuracy of the system

The accuracy of the Ubisense RTLS system was the subject of several studies described in Coyle et al. (2007); Curran et al. (2011); Gremigni & Porcino (2006); Muthukrishnan & Hazas (2009); Stephan et al. (2009); Zhang et al. (2007) or Woźniak et al. (2013). In this paper, we intend to extend the previous analysis.

The values which are measured by sensors to determine the tag position are horizontal angles, vertical angles, and differences in distances. In order to evaluate the accuracy of tag positioning, besides the positions of the tag and the sensors, the accuracy of measured values should be known. The method of a preliminary accuracy analysis, applied by the authors, is based on mean errors. The mean error corresponds to the standard deviation value of Gauss distribution for the observation, equated with the random variable.

The documentation published by the system manufacturer doesn't contain information concerning the accuracy of operations performed by the sensor subsystems. More information may be found in accessible scientific papers. The issue of positioning accuracy was the subject of research described by K. Muthukrishnan and Mike Hazas (2009). The results obtained by them differ for various test sites. Besides, considerable diversification of accuracy between horizontal and vertical angles was suggested. However, it has not been confirmed by other works or information presented by the manufacturer. Different values were obtained by Ying Zhang, Kurt Partridge and Jim Reich (2007). They estimated the accuracy of determination of horizontal and vertical angles as 0.01 ÷ 0.03 radian.

Observations allow determining the values of spatial coordinates. We compose the matrix of an equation of observations. The elements of the matrix are a differential coefficient of observation functions in relation to the coordinates of the tag.

We have assumed that:

X_T, Y_T, Z_T – coordinates of the tag,
X_R, Y_R, Z_R – coordinates of the sensor,
D_{XY} – horizontal distance,
D_{XYZ} – slope distance,
α – horizontal angle,
β – vertical angle,
L – difference of distance,
A_1, A_2 – angles (azimuths) from receivers to the tag,

Observation functions can be described by following formulas:

- for the horizontal angle *α*

$$\alpha = arctan\frac{Y_T - Y_R}{X_T - X_R} \tag{1}$$

- for the vertical angle *β*

$$\beta = arctan\frac{Z_T - Z_R}{D_{XY}} \tag{2}$$

- for the difference of distance *L*

$$L = \sqrt{(X_T - X_{R1})^2 + (Y_T - Y_{R1})^2 + (Z_T - Z_{R1})^2} - \sqrt{(X_T - X_{R1})^2 + (Y_T - Y_{R1})^2 + (Z_T - Z_{R1})^2} \tag{3}$$

The value of a differential coefficient can be assigned from the dependence:

- for the horizontal angle *α*

$$\frac{\delta\alpha}{\delta X} = \frac{-Y_T - Y_R}{D_{XY}^2} \qquad \frac{\delta a}{\delta Y} = \frac{XY_T - X_R}{D_{XY}^2} \qquad \frac{\delta a}{\delta Z} = 0 \tag{4}$$

- for the vertical angle *β*

$$\frac{\delta\beta}{\delta X} = \frac{(X_T - X_R)\tan\beta}{D_{XY}^2} \qquad \frac{\delta\beta}{\delta Y} = \frac{(Y_T - Y_R)\tan\beta}{D_{XY}^2} \qquad \frac{\delta\beta}{\delta Z} = \frac{D_{XY}}{D_{XYZ}^2} \tag{5}$$

- for the difference of distance *L*

$$\frac{\delta L}{\delta X} = cosA_2 cos\beta_2 - cosA_1 cos\beta_1 \tag{6}$$

$$\frac{\delta L}{\delta Y} = sinA_1 sin\beta_1 - sinA_2 sin\beta_2 \tag{7}$$

$$\frac{\delta L}{\delta Z} = sin\beta_1 - sin\beta_2 \tag{8}$$

To determine the value of a differential coefficient we use a numerical differentiation method. For the function *f(x)* the value of a differential coefficient is computed according to the formula:

$$\frac{\delta f(x)}{\delta X} = \frac{f(x_2) - f(x_1)}{x_2 - x_1} \tag{9}$$

where: x_1, x_2 - the symmetrical values for differential small changes of an argument of the function.

Matrix A is normalized using mean errors of the observations. The normalization means the division of each element in a line of the matrix by the value of a mean error of this observation. The values of the errors were taken adequately: the mean error of angles ±0.02 radian and of difference distance ±0.3m. In effect, we obtained matrix A_s, and next, we determined the variance-covariance matrix *Q*.

$$Q = (A_S^T A_S)^{-1} \tag{10}$$

The value of the mean error of a coordinate of points is the square root of the value of a diagonal element of the matrix Q

$$m_x = m_0\sqrt{Q_{xx}} \qquad m_y = m_0\sqrt{Q_{yy}} \qquad m_z = m_0\sqrt{Q_{zz}} \tag{11}$$

As we don't know residuals of the model necessary do calculate m_o in equation (11) we assume m_o = 1.

Analysis of accuracy, feasible with two sensors (basis), was made in two variants. The positions of sensors are marked as A and B. The origin of the coordinate system is station A (X=0, Y=0). The position of station B is different in a particular variant.

Due to limitations in the extension of angles registered by the sensors, it is not possible to determine the tag position in an arbitrary point of the analysed area. In the real case, the area possible for determination will become a common part of appropriate sectors which correspond to each sensor. The analysis of the area defined in this way results from the fact that, depending on the orientation of the sensors, the common area may be an arbitrary part of the analysed area.

The first analysis was made for the case of two sensors turned in the same direction. In practice, such a case can be realized as a movable system mounted on a fire engine and intended for keeping track of people in a dangerous area. Research of application UWB positioning technology in a hazardous area was described in Xin L. et al. (2014).

The positions of sensors are shown in Fig. 7. The distance between sensors was assumed as 20m.

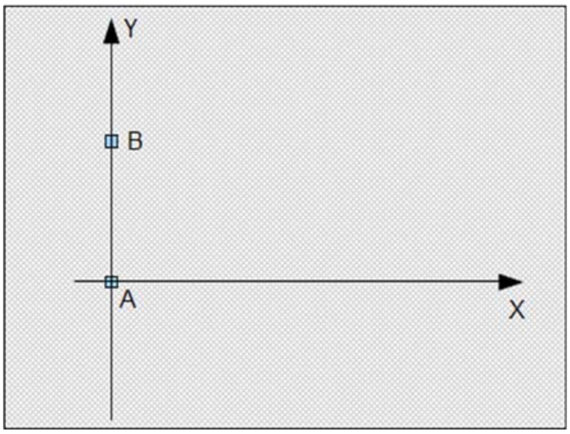


Fig. 7. Test field for analysis 1

Graphical illustrations of the results were presented in Fig. 8 a, b and c. As it can be seen in Figures 8, individual coordinates are determined with different accuracy. The accuracy of coordinate X does not exceed 0.5m in the area of analysis. The main factor determining the X accuracy is the distance from the midpoint of the base (a pair of sensors). As far as the Y coordinate is concerned, the situation is more complex. The area of best accuracy is determined by the symmetry axis of the base. The accuracy of Y decreases rapidly by increasing the distance from the axis. It exceeds 2m at the edges of the analysed area. It does not look well, but when of used to locate people in a dangerous area, such accuracy can be satisfactory. The best-determined coordinate is the height (Z). Its distribution is similar to coordinate X. The main factor of the error value can be described as the distance from the closer sensor.

As the common area of the optimal accuracy for every coordinate is located around the centre of basis line, sensors should be located at the opposite edges of the area of interest and mutually oriented face to face.

Such a case was the subject of the second analysis (Fig. 9).The coordinates of sensor B were assumed as X=30, Y=30. The analyzed area was extended by 10 m in every direction, making a 50x50m square.

Graphical illustrations of the analysis results were presented in Fig. 10 a, b and c. As it was in the previous analysis the unit is 1m for coordinates and 1 cm for accuracies.

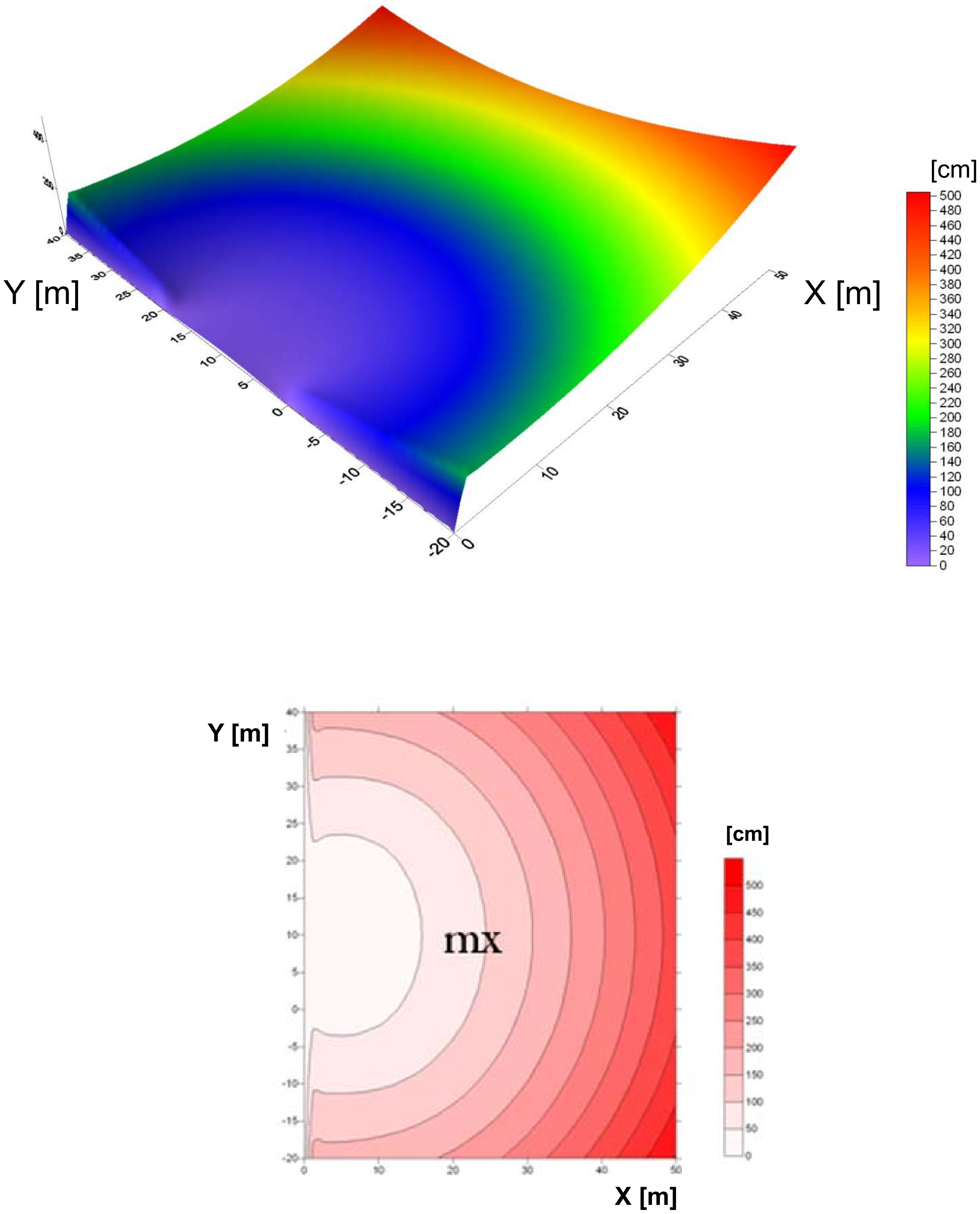


Fig. 8a. Distribution of predicted accuracy of the X coordinate
(2 sensor stations turned in the same direction)

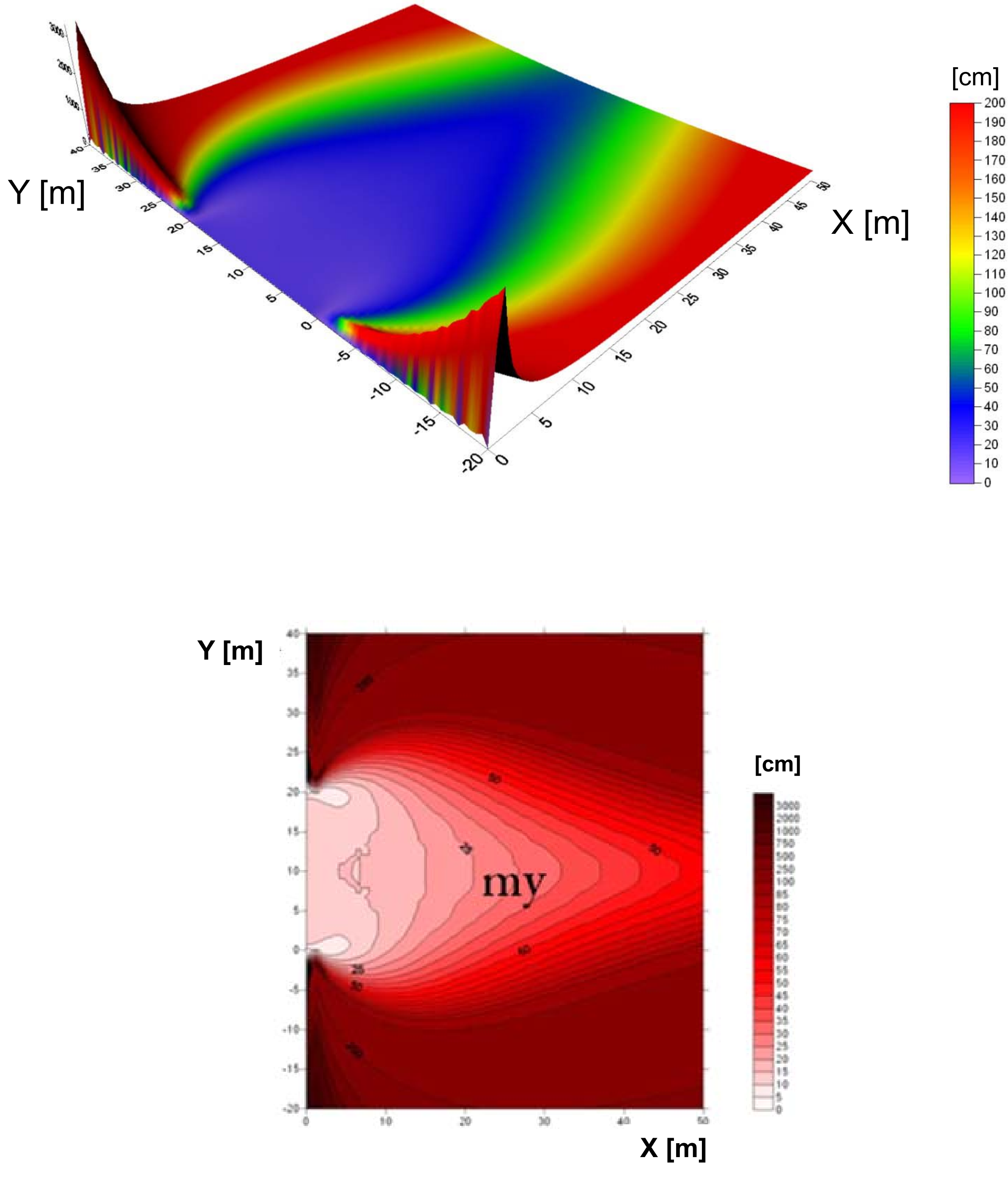


Fig. 8b. Distribution of predicted accuracy of the Y coordinate
(2 sensor stations turned in the same direction)

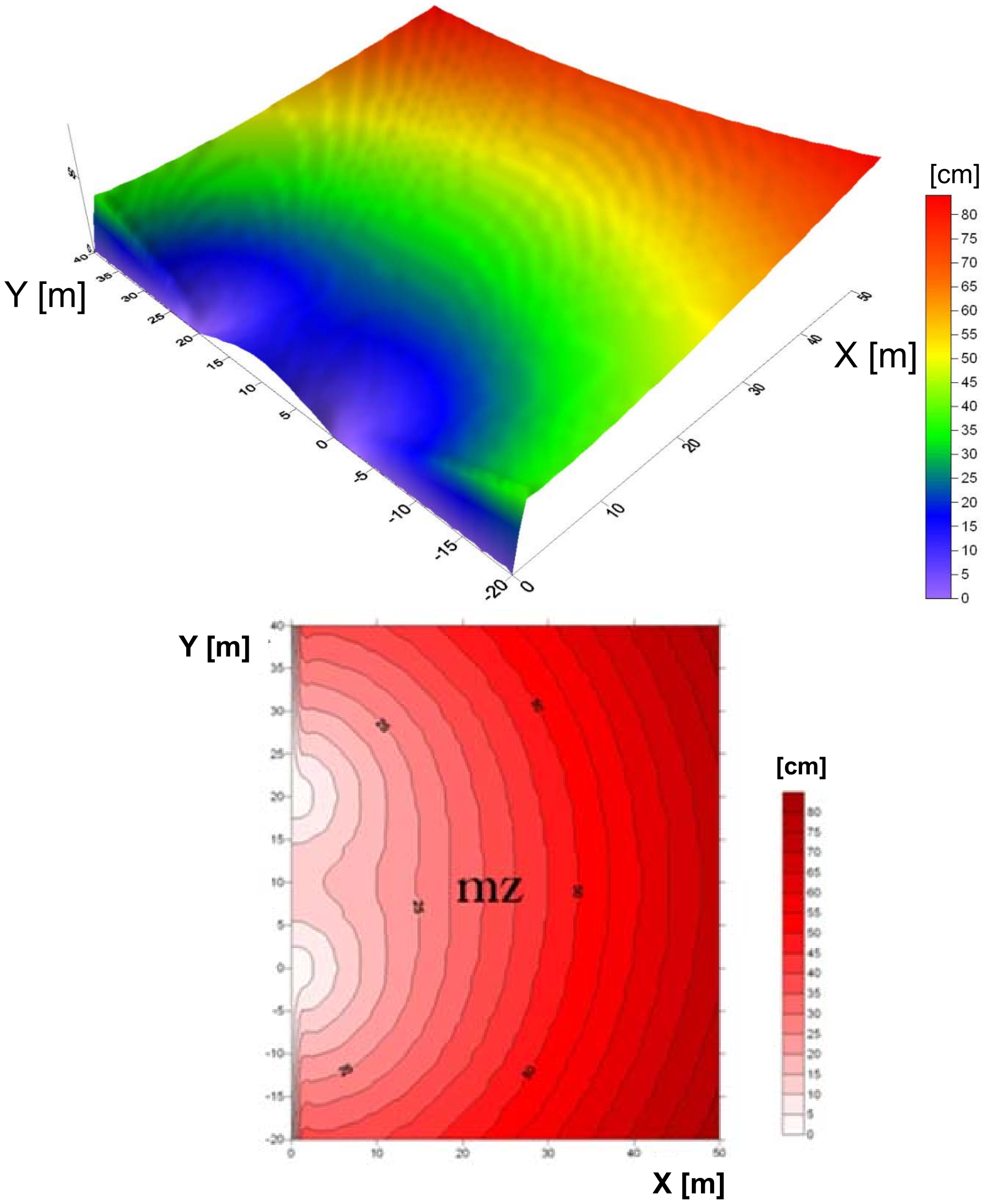


Fig. 8c. Distribution of predicted accuracy of the Z coordinate (2 sensor stations turned in the same direction

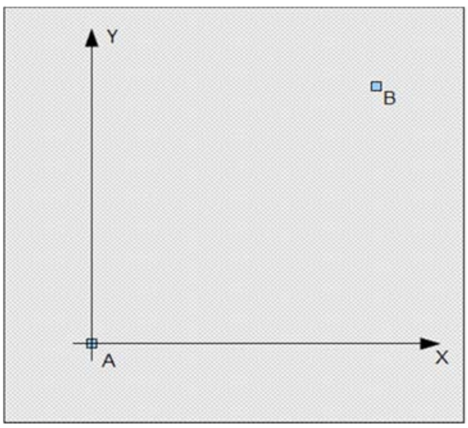


Fig. 9. Test field for analysis 2

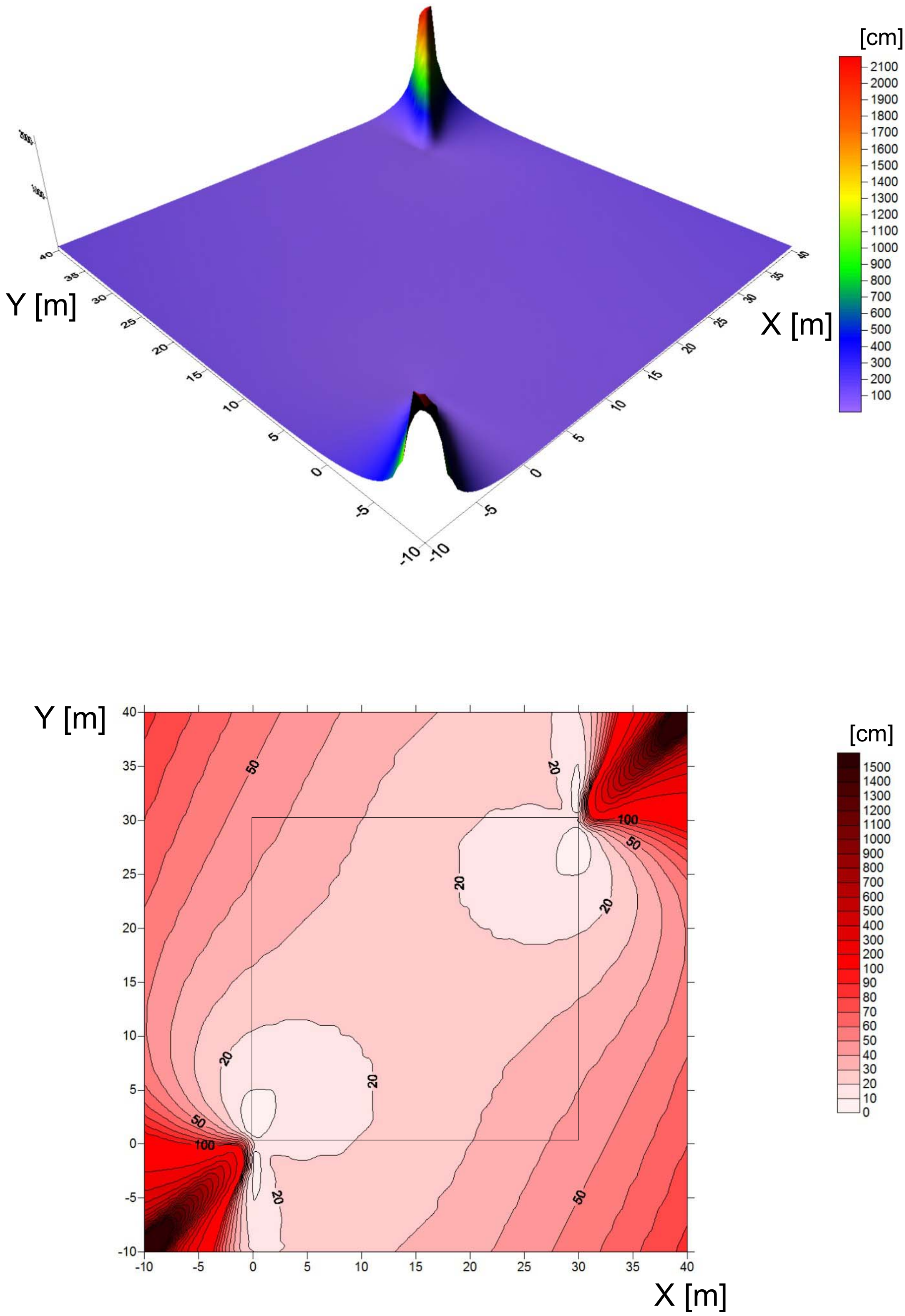
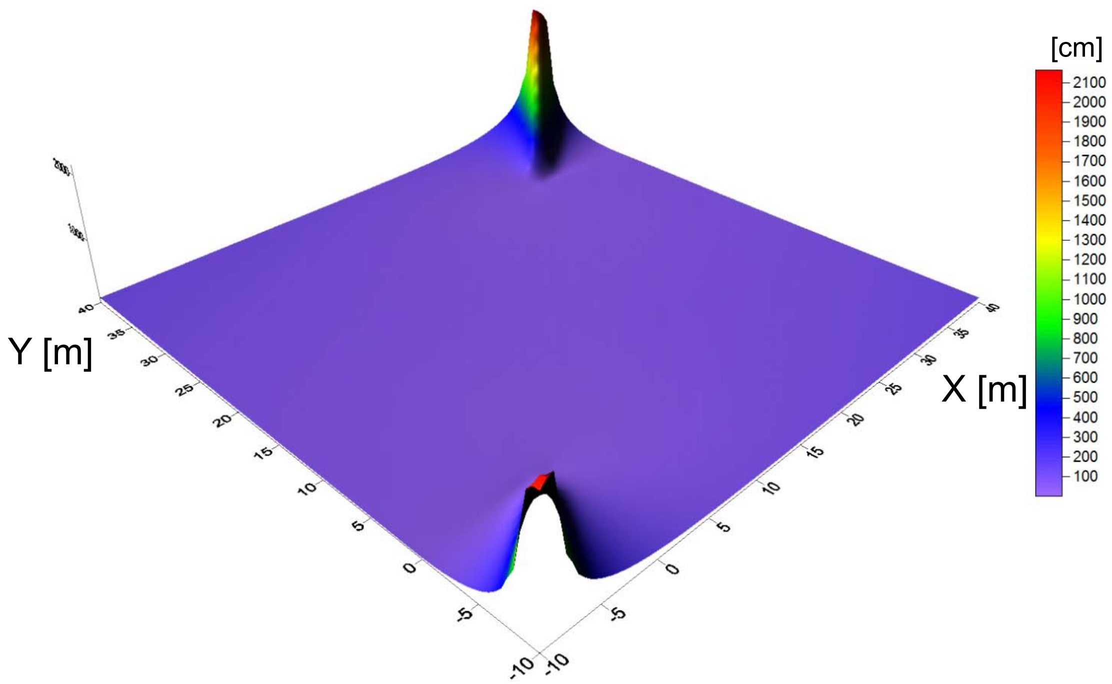


Fig. 10a. Distribution of predicted accuracy of the X coordinate
(2 sensor stations mutually turned to each other)



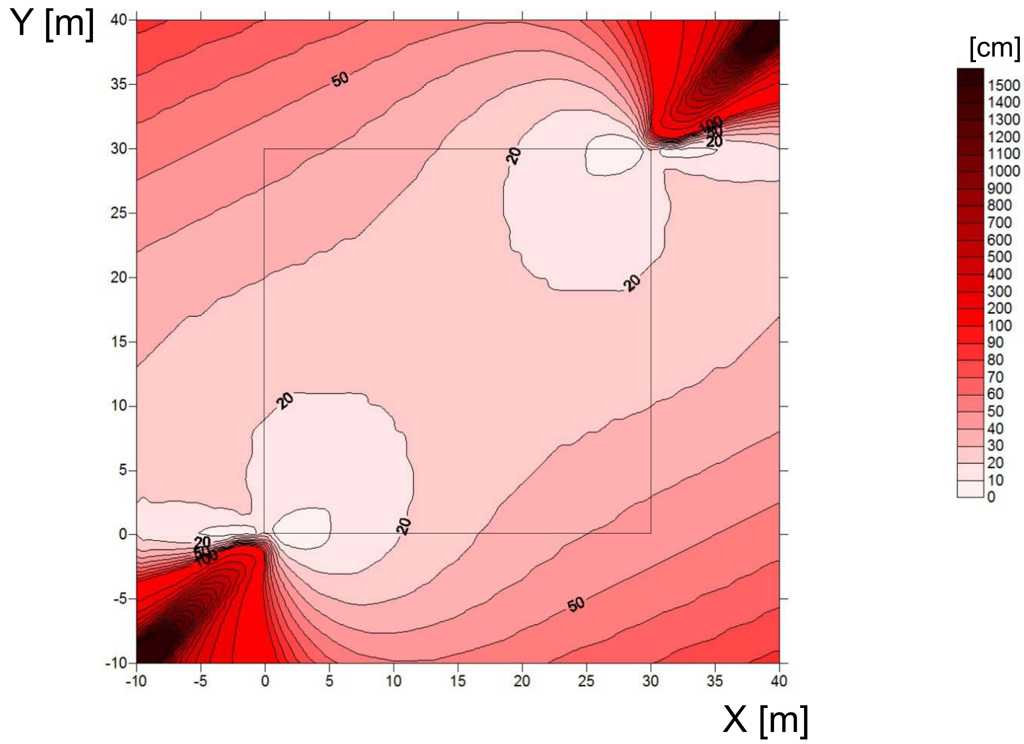
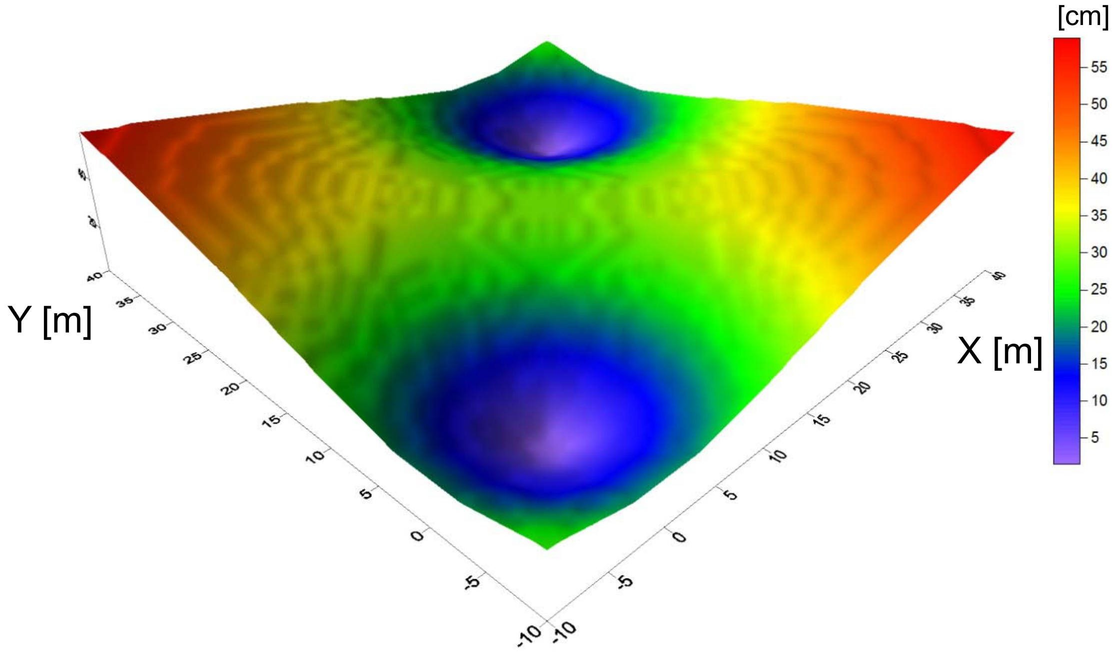


Fig. 10b. Distribution of predicted accuracy of the Y coordinate (2 sensor stations mutually turned to each other)



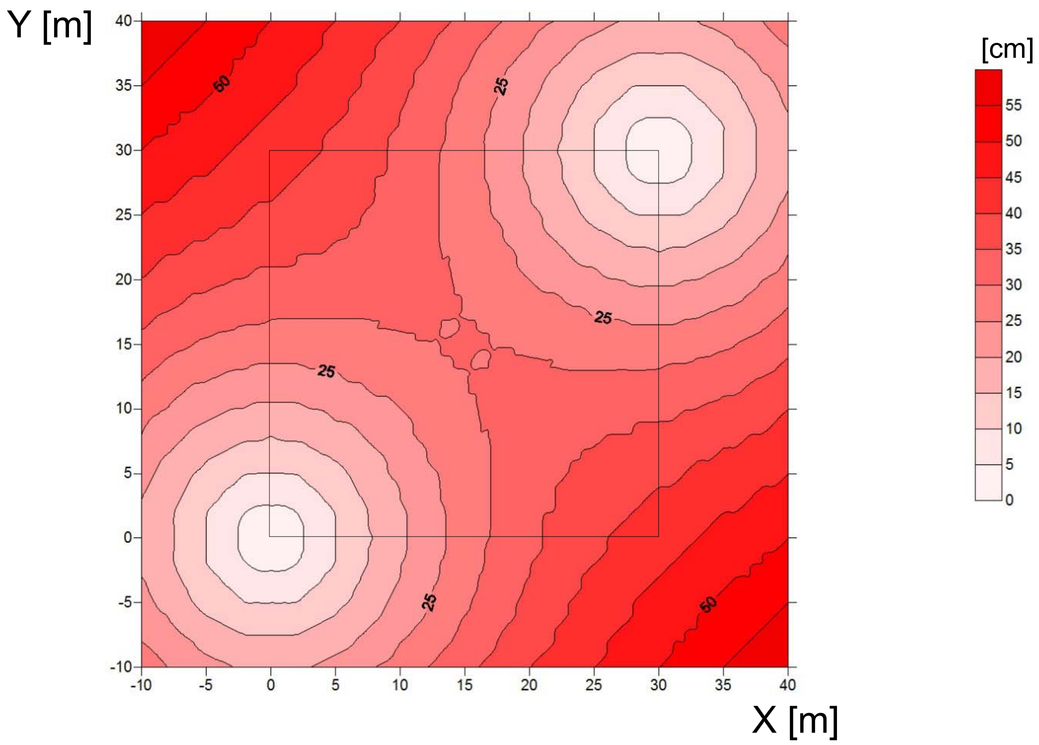


Fig. 10c. Distribution of predicted accuracy of the Z coordinate
(2 sensor stations mutually turned to each other)

The results are shown in Fig. 10 correspond to the results obtained in the previous analysis. The differences come from the fact that the base is turned by 45º in relation to the coordinate axis. The accuracy distribution of coordinates X and Y (Fig. 10 a, b) is very similar (axially symmetrical) which was anticipated considering the fact that each axis intersects the base at an angle of 45º.

Another conclusion concerns the level of accuracy. From Fig. 10a and b we can read that the worst coordinate accuracy does not exceed 0.9m in the corners of the analysed area. Taking into consideration that the area limited to the rectangle formed by sensors positions this value falls to 0.45m. Two regions in the corners of the analysed area located behind the sensors have no practical meaning due to the orientation of sensors.

Coordinate Z (height) is the most stably determined one. In the worst place (corner of the area) we can determine Z with an accuracy under 0.6m. In the small corner made by sensors, the accuracy is 0.43m.

4. Practical accuracy of positioning the tags

To determine the real accuracy of the Ubisense RTLS system, a measuring test was performed, covering the entire area of its operations. The test was based on a comparison of tag coordinates, read out from the RTLS system and coordinates measured using a precise total station Leica TCRP 1201+. A similar test was performed by De Angelis et al, (2012) or Perrat et al. (2015).

The accuracy of the TCRP 1201+ allowed for consideration of differences between coordinates obtained from the total station and the Ubisense system in static mode and as true errors. Several tests were performed for various configurations of the sensors. The results from one of the tests are presented in Fig. 11 a, b and c. Measured points were arranged in regular, rectangular network of 2x2m nodes.

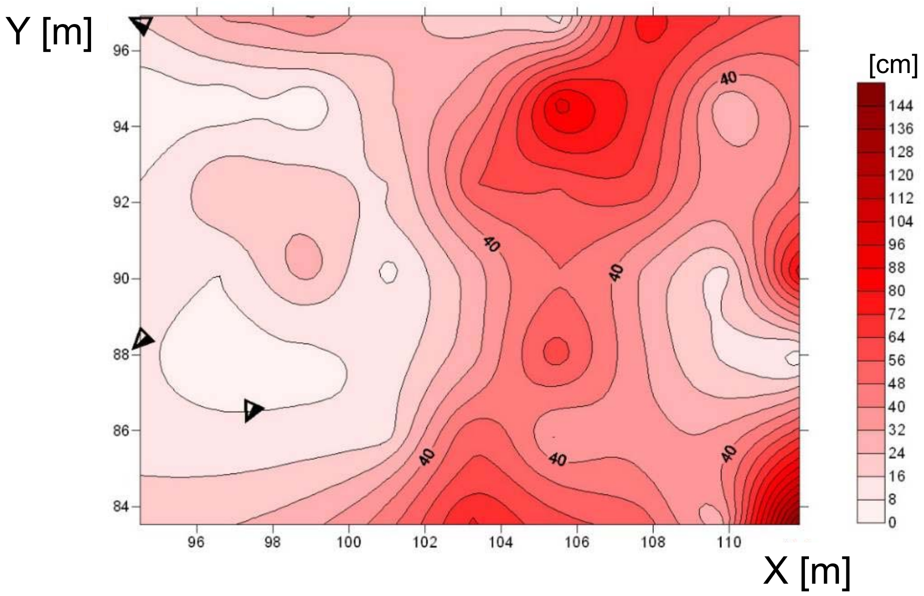


Fig. 11a. Graphical presentation of differences dx between the coordinates obtained from the Ubisense system and the TCRP 1201+ for a configuration of 3 sensor stations

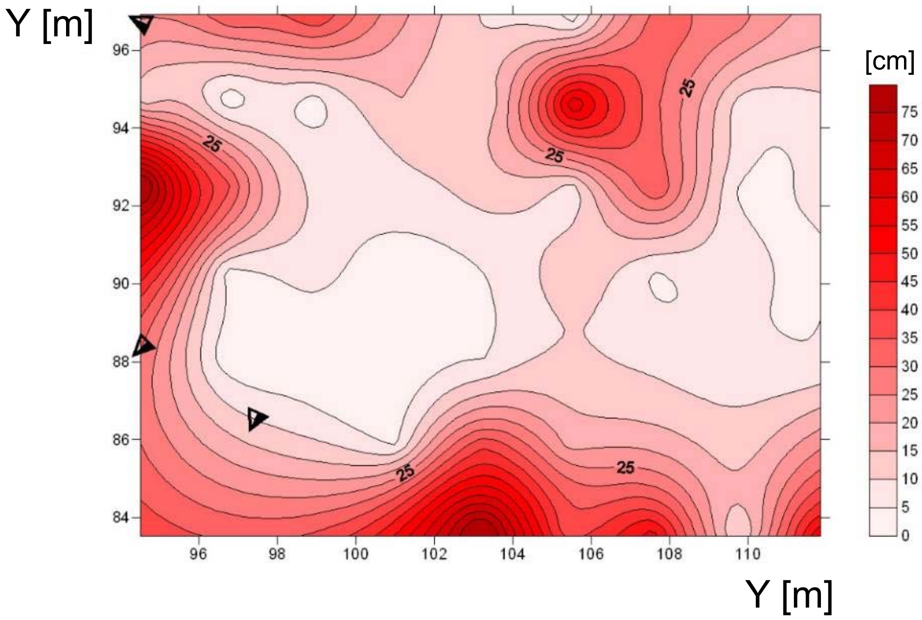


Fig. 11b. Graphical presentation of differences dy between the coordinates obtained from the Ubisense system and the TCRP 1201+ for a configuration of 3 sensor stations

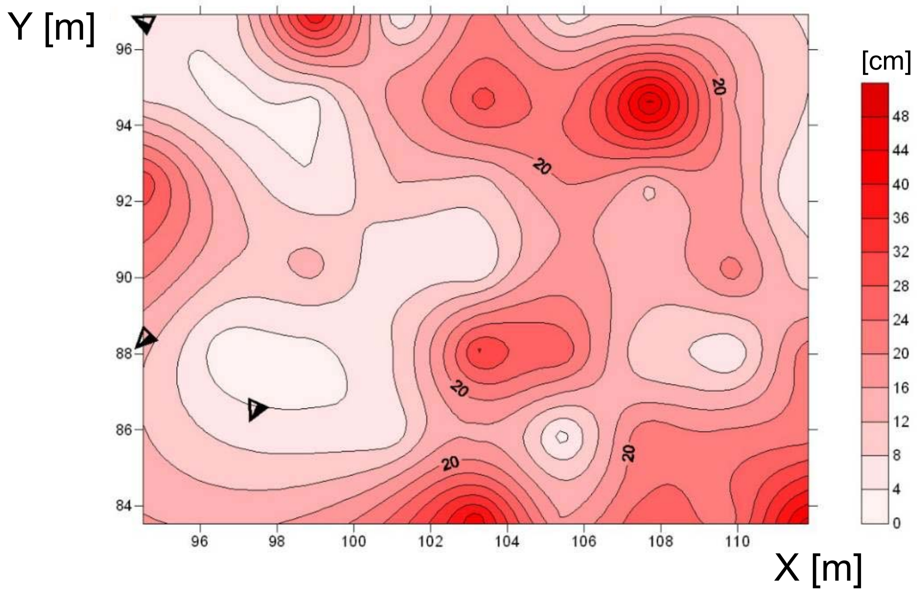


Fig. 11c. Graphical presentation of differences dz between the coordinates obtained from the Ubisense system and the TCRP 1201+ for a configuration of 3 sensor stations

As it can be seen in the pictures above (Fig. 11), the test results confirm the accuracy of positioning declared by Ubisense. The worst accuracy was obtained for coordinate X (perpendicular to the basis). The deviations are about twice bigger than in the case of Y and Z and reach 1.4m. The distribution of differences for X suggests that it is related to the distance from the receivers. As the configuration of the sensor during the measuring test was different than in the theoretical analysis, another analysis was conducted for the configuration of sensors corresponding to a practical test.

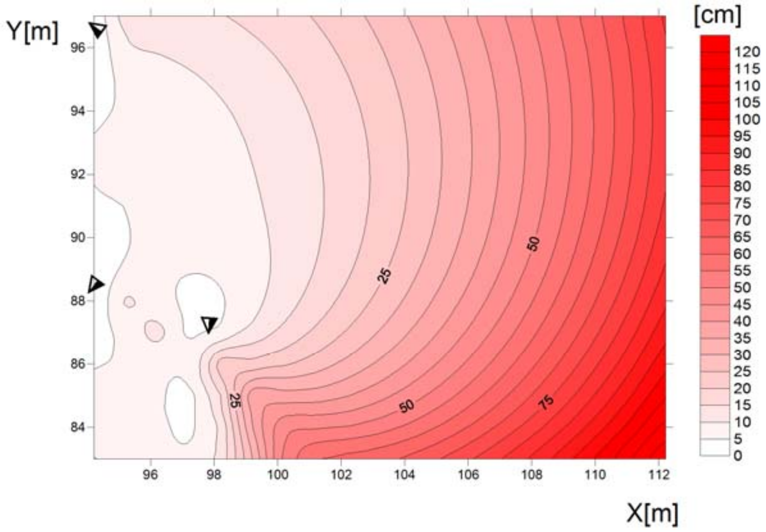


Fig. 12a. Distribution of predicted accuracy of the X coordinate (3 sensor – configuration of the practical test)

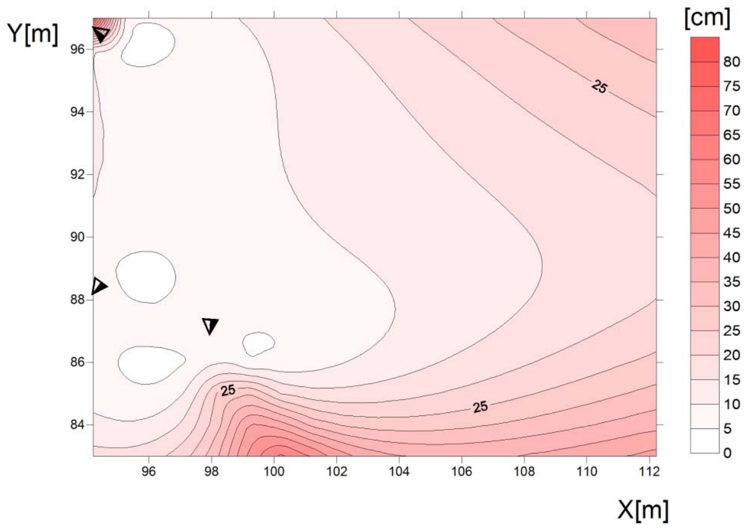


Fig. 12b. Distribution of predicted accuracy of the Y coordinate (3 sensor – configuration of the practical test)

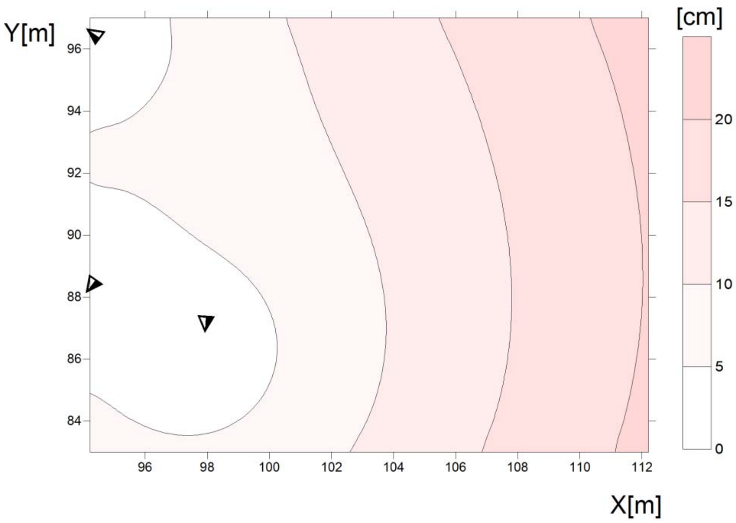


Fig. 12c. Distribution of predicted accuracy of the Z coordinate (3 sensor – configuration of the practical test)

Due to a limited number of measured points and deviations of RTLS measurement, we can't expect exact congruence of the pictures 11 and 12. Nevertheless, we can say that practical test confirmed theoretical analysis. It is apparent in the case of each coordinate. Values of true errors shown in pictures 11 are similar to theoretical accuracies shown in pictures 12 and distribution of errors visibly correspond to the distribution of accuracies. Another theoretical analysis for the case of 3 sensors was made in Woźniak et al., (2013).

5. Sample implementation utilizing theoretical and practical analysis

All results of theoretical and practical analysis shown in the previous section were utilized in analysis and design phase of the MagMaster system developed by Globema company (co-funded by PARP under POIG 1.4), which aim is to optimize objects' movement in warehouse spaces. Analysis results were mainly used to optimize sensor positions to ensure the best possible accuracy using the minimal possible sensor count which helped in keeping the hardware cost at the acceptable level.

Thanks to utilized localization and visualization technologies the system can precisely determine pallets positions, calculate optimal transport routes for forklifts and record in the database real forklifts and person movements for further analysis and process optimization. During the MagMaster project, Globema performed a deep analysis (5 months) of the FMCG logistics market based on the data provided by potential customers and their experience. The result of the analysis was potential benefits estimation (savings compared to current operating costs) of the MagMaster system implementation, which was calculated as 24-26% cost savings per year. This result clearly shows that the use of precise location technologies can greatly improve the efficiency of companies, which economically justifies their usage.

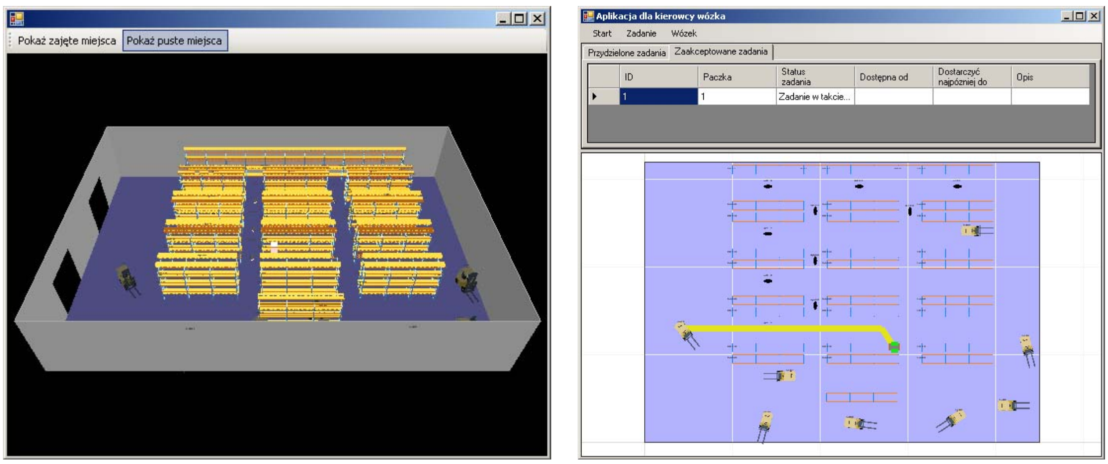


Fig. 12. Sample warehouse space and route visualization - MagMaster application

6. Conclusions

The performed theoretical and practical analysis confirmed the accuracy declared by the system manufacturer - Ubisense. It can be noticed that the area of the highest localization accuracy is placed between the sensors, in particular when the sensors are mutually turned to each other. To obtain the optimum accuracy within the entire analysed area, the sensors should be evenly distributed on the area borders, assuming that the increased number of sensors considerably increases the accuracy and reliability of the localization results. The localization precision and working range of Ubisense UWB system is sufficient for indoor industrial spaces (e.g. warehouses or production sites). This technology was used in many systems worldwide (e.g. MagMaster) and these systems have a great positive impact on business efficiency and operation costs.

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