# Modeling the Localization of Hidden Radio Transmitters Using Redundant Multi-Antenna Measurements

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### Abstract

Today, the world is experiencing a sharp increase in the volume of industrial espionage. To counteract unauthorized information leakage, companies are forced to install expensive hardware of constant monitoring of the radio spectrum, which monitor radio transmitters activity in the certain area. In such hardware, the location of hidden transmitters is determined using appropriate software. Such software works well enough with the minimum required number of measurements, but in large complex buildings the minimum number of measurements may not be enough. Therefore, it is necessary to create a model for developing software to work with redundant measurements. The purpose of this study is to develop a model for determining hidden radio transmitters for a multi-position monitoring hardware taking into account information redundancy. To achieve the goal of the study, the article develops an algorithm for determining the coordinates of the transmitter by the redundant sample of distance measurements based on the Gauss-Newton method. The localization accuracy was investigated using a model based on the Least Squares Method. The main results of the study confirm the developed model effectiveness and show the dependence of localization accuracy on the number and geometry of the location of receiving antennas in the building. It was confirmed that the highest localization accuracy is achieved in the center of the tetrahedron formed by the receiving antennas. The practical value of the study is the possibility of creating automated monitoring complexes with specified localization accuracy parameters within specific building areas.

### Keywords

Modeling, localization, hidden transmitter, redundant measurements, Least Squares Method, Mean Square Error, Dilution of Precision.



## 1. Introduction

Detection and localization of hidden cameras, microphones and transmitters remains a difficult practical problem and requires the development of both hardware and software [1]. Modern hardware used to counter industrial espionage works quite well with the minimum required number of measurements from receiving antennas. However, in large buildings, when additional antennas are involved and redundant measurements are available, the continuous monitoring system requires improvement of the appropriate software. To develop such software, in this study we focus on a mathematical model and algorithm for localization of a hidden transmitter, which

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can work in conditions of redundant measurements. It is important that such an algorithm provides high speed and sufficient localization accuracy.

## 2. Problem statement

Continuous monitoring scanners used in organizations where classified information circulates consist of an antenna complex of different frequency ranges, combined with a centralized monitoring data processing processor. The receiving antennas of the complex are located in different parts of the building, which allows localizing the radio radiation of a hidden transmitter using the ranging, difference-based ranging and quasi-ranging methods [2]. The purpose of mathematical modeling of the above-mentioned hardware is to assess the impact of antenna placement, ranging measurement accuracy and signal propagation conditions on the overall localization efficiency. Such modeling should become the basis for selecting optimal system parameters and ensuring reliable detection in real conditions.

In the software complex, localization of an unknown transmitter is performed by solving a system of equations based on distance measurements to several receivers, performed simultaneously or at different times. Although three measurements are sufficient for spatial localization, it is assumed that increasing the number of antennas, depending on the building layout, will allow for increased accuracy due to mathematical redundancy [3], which highlights the need to improve the localization model under such conditions.

## 3. Related works overview

Localization based on ranging methods is widely used in navigation. GPS-based positioning systems use complex signal processing algorithms to achieve high accuracy [4].

In [5], the mathematical foundations of ranging methods are considered and factors affecting high range determination accuracy are investigated, using the example of marine radars. The authors also proposed a positioning method using several radar stations by crossing several radar range measurements.

In [6], various localization methods are considered and it is concluded that localization accuracy depends on the number of receivers. However, the authors of this study concentrate their attention only on the influence of the ionosphere on the propagation of RF signals. This makes such a mathematical basis unsuitable for the analysis of hidden transmitters in the VHF range.

In [7], cluster analysis methods (network clustering), graph theory (analytical models for constructing cluster topology), telecommunication network theory (when calculating bandwidth in radio channels), and telecommunication aerial platform positioning theory are used to solve the positioning problem. However, this publication does not investigate the impact of topology on system accuracy.

The authors of [8] study the localization problem with an unknown distribution of measurement errors. The localization problem is formulated as an optimization problem to minimize the estimation error in the worst case, showing that the objective function is non-convex. Then, the authors apply relaxation to transform it into a convex form and propose a distributed computation algorithm that converges in several iterations. The geometry of the receiving-transmitting system is also taken into account. However, the proposed approach is excessively complicated for practical application.

In [9], the authors propose a scalable dynamic estimator for obtaining the relative bearing of static landmarks in the local coordinate system of a moving object in real time. The convergence of the proposed bearing estimator for different ranges is analyzed and the upper and lower bounds for the gain of the estimator are presented. However, this approach is poorly adapted for the ranging method of determining the coordinates of hidden transmitters.

In [10], the authors consider the localization of the signal source from measurements based on the difference in range, taking into account the measurement noise and sensor positioning, in order to guarantee asymptotic identification of the model using the Maximum Likelihood method. The problem is solved by performing local iterations based on the Gauss-Newton algorithm. In this case, the main attention is focused on obtaining a preliminary consistent estimate with the subsequent solution of the linear problem by the Least Squares Method. This approach is the most appropriate in terms of computational complexity and localization accuracy. At the same time, the authors do not specify how the method will work in the case of information redundancy.

In [11], the authors investigate two methods of measuring the distance between the transmitter and the receiver using UWB technology. The method of calculating the position is presented together with a method of predicting errors based on the geometry of the room. The authors focus on UWB technologies and discuss Bluetooth technology, which is used to connect the monitoring system to the environment.

The issues of measurement errors and device calibration are studied in [12], where the authors investigate the influence of calibration modules in a real-time three-dimensional localization system during the calibration of the anchor position. This study demonstrates that the positional error can be successfully reduced by using calibration modules. However, this approach cannot completely solve the localization accuracy problem and requires further research.

In [13], various indoor localization systems are considered and a comparison is made between these systems in terms of accuracy, cost, advantages and disadvantages. Also, the article investigates various detection methods and compares them in terms of accuracy and complexity. Such a study can be considered as a summary of the localization of objects indoors, at the same time, in a direct formulation, the considered methods cannot be used for the localization of hidden transmitters.

Thus, the analysis shows that the problem of determining the optimal configuration of direction finding systems and creating effective algorithms for localizing hidden transmitters remains insufficiently studied, with existing research focusing mainly on remote measurement methods, positioning technologies, or GPS-based tools. Methods for localizing hidden transmitters in large buildings are particularly underdeveloped.

**The purpose of this study** is to develop a mathematical model for detecting hidden radio transmitters in a multi-position system, which can serve as the basis for creating specialized software that accounts for measurement redundancy. To achieve this goal, the following tasks must be performed:

- To consider the general theoretical foundations of multi-position localization.
- To develop an algorithm for determining the transmitter coordinates using a redundant sample of distance measurements.
- To investigate the issue of localization accuracy.
- To model various configurations of the radio monitoring system and evaluate their effectiveness.

## 4. Theoretical foundations of localization

To determine the spatial coordinates of the transmitter by the ranging method, it is sufficient to obtain measurements from three receivers. In this case, in the *XYZ* coordinate system, the location of the unknown emitter can be found by solving the system of equations [14]:

$$r_i = \sqrt{\left(x_{c_i} - x\right)^2 + \left(y_{c_i} - y\right)^2 + \left(z_{c_i} - z\right)^2}, i = 1,2,3. \quad (1)$$

where $x_{c_i}, y_{c_i}, z_{c_i}$ are known coordinates of receivers; $x, y, z$ – unknown coordinates of transmitter.

Iterative methods for solving the system of equations (1) differ in the amount of calculations and the speed of convergence of the iteration process. Among such methods, the most common is

Newton's method, as the simplest and fastest [15]. Solving the system (1) by Newton's method is a process of multiple processing of the results of distance measurements according to the formula

$$q_k = q_{k-1} + C_{k-1}^{-1} R_{k-1}, \tag{2}$$

where $R_{k-1} = R_v - R_{0(k-1)}$ is vector of residuals between measured $R_v$ and calculated $R_{0(k-1)}$ values; $C_{k-1}$ is a matrix of partial derivatives of measured distance functions by coordinates, which has the form

$$C_{k-1} = \begin{bmatrix} C_{1(k-1)} \\ \vdots \\ C_{m(k-1)} \end{bmatrix} = \begin{bmatrix} \frac{\partial R_1}{\partial q_1} & \cdots & \frac{\partial R_1}{\partial q_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial R_m}{\partial q_1} & \cdots & \frac{\partial R_m}{\partial q_m} \end{bmatrix}_{q=q_{0(k-1)}}, \tag{3}$$

where $k = 1,2,\ldots$ – iteration cycle number.

The matrix $C_{k-1}$ and the vector of residuals $R_{k-1}$ are calculated on the basis of a priori data in the first iteration, and on the following iterations – on the basis of data obtained in the previous iterations. The iterative cycles are repeated until the difference between the next refined values of the coordinates that are determined, compared to the previous ones, is less than the specified error, which has the content of the residual error.

The sequence of iterative calculation of the *x*, *y*, *z* coordinates of the transmitter using the minimum amount of simultaneous measurements is reduced to the following sequence of steps.

1. Input of initial data. The initial data are:

prior values of rectangular coordinates of the transmitter;

coordinates of receivers $x_{c_i}$, $y_{c_i}$, $z_{c_i}$, $(i = 1,2,3)$;

values of measured distances $r_i$.

2. Calculation of measurement errors. Distance errors are calculated by subtracting the calculated value $R_{0(k-1)}$ from the measurement $R_{v_i}$. That is,

$$\delta r_{i(k-1)} = r_i - r_{0i(k-1)}, \tag{4}$$

where $r_{0i(k-1)} = \sqrt{\left(x_{c_i} - x_{k-1}\right)^2 + \left(y_{c_i} - y_{k-1}\right)^2 + \left(z_{c_i} - z_{k-1}\right)^2}$.

3. Calculation of the observation matrix $C_{k-1}$.

$$C_{i(k-1)} = [\cos\alpha_i \quad \cos\beta_i \quad \cos\gamma_i]_{q=q_{k-1}}, \tag{5}$$

where $\cos\alpha_i = \frac{x_{c_i} - x_{k-1}}{x_{0_i(k-1)}}$, $\cos\beta_i = \frac{y_{c_i} - y_{k-1}}{y_{0_i(k-1)}}$, $\cos\gamma_i = \frac{z_{c_i} - z_{k-1}}{z_{0_i(k-1)}}$.

4. Estimation of the rectangular coordinates of the transmitter. The rectangular coordinates of the transmitter are determined by formula (2) after performing the required number of iterations. The inversion of the matrix $C_{k-1}$ provided for in (2) can be performed, for example, by the Gauss method [16].

The given method is suitable for processing the minimum necessary number of measurements. To determine three coordinates, it is enough to measure the distances from the transmitter to three receivers. In the case of a larger number of measurements, the system of equations becomes incompatible and therefore, the Least Squares Method is used to solve the localization problem [17]. With an appropriate choice of the weight matrix, the results obtained by this method coincide with the results obtained by the Maximum Likelihood Method or Bayesian methods.

## 5. A model for determining transmitter coordinates by redundant distance measurements

The solution of the vector equation (2) by the Least Squares Method can be given in the form

$$q = q_0 + \left(C^{\mathrm{T}}PC\right)^{-1}C^{\mathrm{T}}PR, \tag{6}$$

where $P$ is a symmetric non-negatively defined matrix of weight coefficients; $q_0$ is a priori estimate of the vector $q$.

Due to the linearization of the initial equations (1), the estimation by formula (6) does not yet give the best result. To eliminate the influence of the linearization error on the localization accuracy, it is necessary to organize an iterative process, usually according to the Newton scheme.

If the measurement errors are distributed according to the multidimensional Gaussian law with the second-order moment matrix $W$, then the vector of estimation parameters is random, distributed according to the multidimensional Gaussian law with the correlation matrix

$$K_q = \left(C^{\mathrm{T}}PC\right)^{-1}C^{\mathrm{T}}PWPC\left(C^{\mathrm{T}}PC\right)^{-1}. \tag{7}$$

If we assume $P = W^{-1}$, then the vector of estimation parameters has the smallest variance and coincides with the estimate by the maximum likelihood criterion.

$$q_k = q_{k-1} + \left(C_{k-1}^{\mathrm{T}}W^{-1}C_{k-1}\right)^{-1}C_{k-1}^{\mathrm{T}}W^{-1}R_{k-1}, \tag{8}$$

and also

$$K_q = \left(C^{\mathrm{T}}W^{-1}C\right)^{-1}. \tag{9}$$

If, when processing the measurement results, the errors of the a priori estimate of the transmitter state vector are taken into account and these errors are not correlated with the measurement noise, then equations (6) and (7) can be given in the form

$$q_k = q_{k-1} + \left(C_{k-1}^{\mathrm{T}}PC_{k-1} + K_{q0}^{-1}\right)^{-1}C_{k-1}^{\mathrm{T}}PR_{k-1}, \tag{10}$$

$$K_q = \left(C^{\mathrm{T}}PC + K_{q0}^{-1}\right)^{-1}\left(C^{\mathrm{T}}PWPC + K_{q0}^{-1}\right)\left(C^{\mathrm{T}}PC + K_{q0}^{-1}\right)^{-1}, \tag{11}$$

where $K_{q0}$ is the correlation matrix of errors of the a priori estimate of the transmitter state vector $q$. If $P = W^{-1}$, then the vector $q$ estimated by formula (10) coincides by the criterion of the maximum of the posterior probability density and

$$K_q = \left(C^{\mathrm{T}}W^{-1}C + K_{q0}^{-1}\right)^{-1}. \tag{12}$$

Thus, the algorithm for searching for the consumer's coordinates in the case of redundant measurements will have the form:

1. $x_{c_i}, y_{c_i}, z_{c_i}, i = 1, \ldots, n \leftarrow$ coordinates of receivers.
2. $\delta \leftarrow$ condition for stopping iterations.
3. $\delta_{max} = +\infty$ – initial approximation value.
4. $x_0, y_0, z_0 \leftarrow$ coordinates of the starting point of iterations.
5. Calculation of distances to the point $x_0, y_0, z_0$:

$$r_{0i} = \sqrt{\left(x_{c_i} - x_0\right)^2 + \left(y_{c_i} - y_0\right)^2 + \left(z_{c_i} - z_0\right)^2}, i = 1, .., n.$$

6. Calculation of the direction cosines matrix: $C=\begin{bmatrix} -\frac{x_{c_1}-x_0}{r_{01}} & -\frac{y_{c_1}-y_0}{r_{01}} & -\frac{z_{c_1}-z_0}{r_{01}} \\ \vdots & \vdots & \vdots \\ -\frac{x_{c_n}-x_0}{r_{0n}} & -\frac{y_{c_n}-x_0}{r_{0n}} & -\frac{z_{c_n}-z_0}{r_{0n}} \end{bmatrix}$.

7. Forming an array of results: $points = \{(x_0, y_0, z_0)^{\mathrm{T}}\}$.

8. $While[\delta < \delta_{max},$ – iteration cycle.

9. $r_i = \sqrt{\left(x_{c_i} - x_t\right)^2 + \left(y_{c_i} - y_t\right)^2 + \left(z_{c_i} - z_t\right)^2}, i = 1,..,n$ – measuring distances to transmitters.

10. $\delta r_i = r_i - r_{0_i}, i = 1, \ldots, n$ – calculation of residuals.

11. $(x, y, z)^{\mathrm{T}} = (x_0, y_0, z_0)^{\mathrm{T}} + \left(C^{\mathrm{T}} C\right)^{-1} C^{\mathrm{T}} (\delta r_1, \ldots, \delta r_n)^{\mathrm{T}}$ – determination of new coordinates of the approach point.

12. $\delta_{max} = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$ – recalculation of the approach distance.

13. $x_0 = x; y_0 = y; z_0 = z$ – redefinition of the initial coordinates of the approach point.

14. $r_{0i} = \sqrt{\left(x_{c_i} - x_0\right)^2 + \left(y_{c_i} - y_0\right)^2 + \left(z_{c_i} - z_0\right)^2}, i = 1,..,n$ – redefinition of distances to the transmitter.

15. $C=\begin{bmatrix} -\frac{x_{c_1}-x_0}{r_{01}} & -\frac{y_{c_1}-y_0}{r_{01}} & -\frac{z_{c_1}-z_0}{r_{01}} \\ \vdots & \vdots & \vdots \\ -\frac{x_{c_n}-x_0}{r_{0n}} & -\frac{y_{c_n}-x_0}{r_{0n}} & -\frac{z_{c_n}-z_0}{r_{0n}} \end{bmatrix}$ – redefinition of the matrix of direction cosines.

16. $points = Append[points, (x, y, z)^{\mathrm{T}}]$ – adding new coordinates to the results array.

17. $Return]$ – end of cycle.

18. $points \rightarrow$ output of results.

Fig. 1 shows an example of the localization model with redundant information. There are 4 receivers in the building that search for a hidden transmitter. The configuration of the receivers forms a regular tetrahedron, which makes it possible to avoid the singularity of the matrix $C$ during calculations and to provide the most favorable geometry of the receiving system.

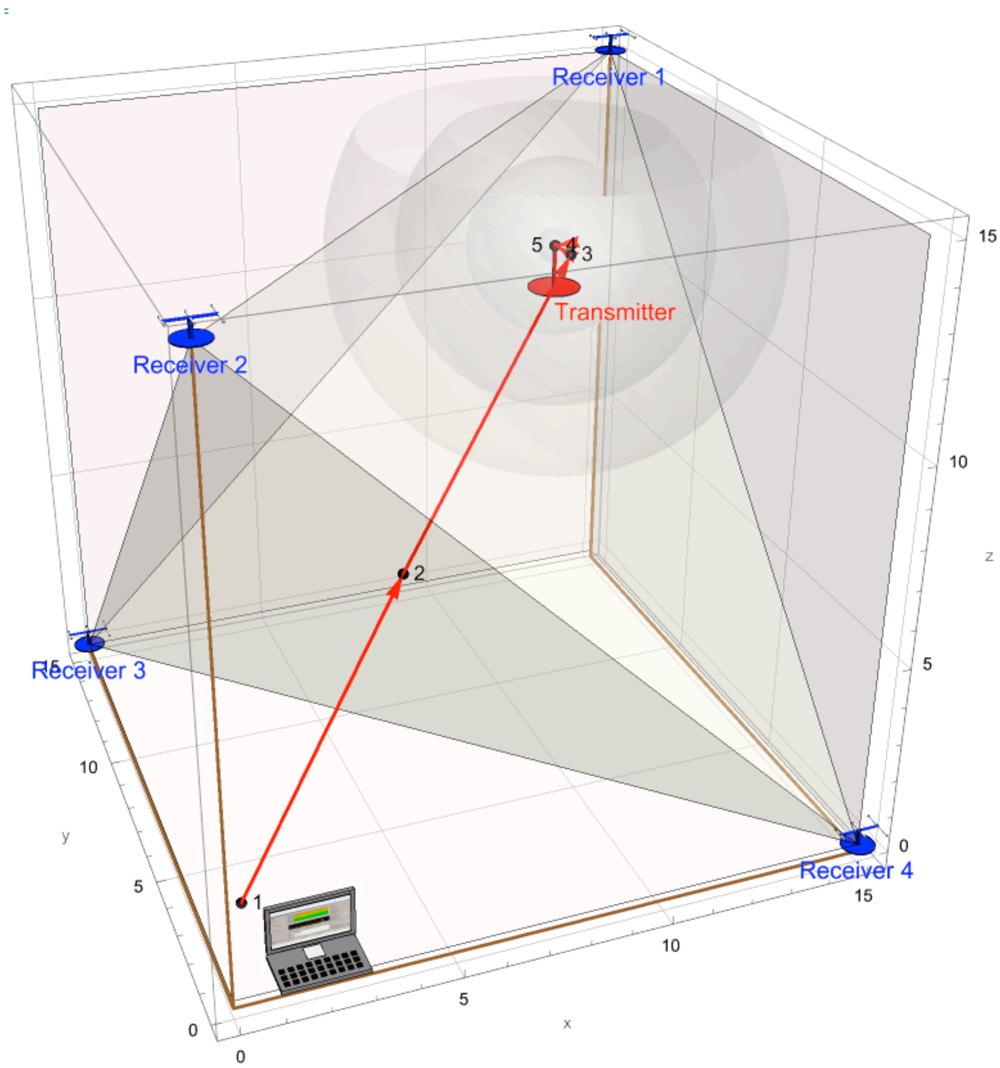


**Figure 1:** Illustration of how the localization model works.

The operation of the model is highly dependent on the state of the matrix $C$, since with poor conditioning of this matrix, numerous errors in the calculation of coordinates arise and acceptable localization accuracy is not guaranteed. In practice, cases of poor conditioning of the matrix $C$ are associated with the location of the receivers and transmitter in the same plane and when the inversion of the matrix $(C^{\mathrm{T}}C)^{-1}$ becomes impossible.

As already noted, any point in space can be taken as the starting point $x_0, y_0, z_0$ for approximation calculations. In the simplest case, this can be the origin of coordinates $x_0 = 0, y_0 = 0, z_0 = 0$. In any case, the algorithm based on Newton's scheme provides fast convergence to the specified accuracy.

The array $points$ is filled using the $Append[*]$ operation, which involves concatenating vectors. In this case, the next coordinate vector $(x, y, z)^{\mathrm{T}}$ is added to the existing points list $\{(x_0, y_0, z_0)^{\mathrm{T}}\}$, where the starting point $x_0, y_0, z_0$ was selected as the first value.
Redundant information increases the size of the matrix $C$ and the vector $R$, but as a result of matrix operations, the final vector has dimension 3, which corresponds to three localization coordinates.

When the algorithm works, any random point in space can be chosen as the starting point $x_0, y_0, z_0$ for calculations. In our case, this is a point with coordinates $x_0 = 1, y_0 = 3, z_0 = 1$. The stopping condition of the algorithm: $\delta = 0.1$. As already noted at the beginning and as the practice of application shows, Newton's method ensures fast convergence with sufficient accuracy. For this example, the algorithm used 5 iterations to localize the hidden transmitter with a given accuracy.

## 6. Localization accuracy

When solving the problem of localization of a hidden transmitter, an important issue is the localization accuracy [18]. Based on the matrix (9) and provided that $P = W^{-1}$, the matrix $P$ is defined as a matrix of weight coefficients that have the meaning of the accuracy of distance measurement. The matrix $P$ itself can be given as a product

$$P = P_0^{\mathrm{T}} P_0. \tag{13}$$

The matrix $P_0$ in (13) is a diagonal matrix $P_0 = \begin{bmatrix} p_{0_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & p_{0_n} \end{bmatrix}$, where $p_{0_i} = \frac{h_i}{\sigma_{r_i}}, i = 1, \dots, n$ ($\sigma_{r_i}$ is the Root Mean Square Error of distance measurement, $h_i$ is some scaling factor). For further consideration, we will assume $h_i = 1$.

Taking into account the substitutions made from equation (9), we obtain the matrix

$$K_q = \left(C^{\mathrm{T}} P_0^{\mathrm{T}} P_0 C\right)^{-1} = \left(C^{\mathrm{T}} P C\right)^{-1}. \tag{14}$$

The matrix $K_q$ in (14) is the correlation matrix of transmitter localization errors [19], on the main diagonal of which are the dispersions of the localization coordinates

$$K_q = \begin{bmatrix} \sigma_x^2 & K_{xy} & K_{xz} \\ K_{yx} & \sigma_y^2 & K_{yz} \\ K_{zx} & K_{zy} & \sigma_z^2 \end{bmatrix}. \tag{15}$$

In this case, the resulting localization error can be defined as the sum of the diagonal elements of the matrix $K_q$, i.e., through the trace of the matrix (15) in the form $\sigma_q = \sqrt{Trace[K_q]}$. In this case, the ratio $G_{dop} = \frac{\sigma_q}{\sigma_r}$, where $\sigma_q$ is the localization error of the transmitter, and $\sigma_r$ is the distance measurement error. This ratio determines the Dilution of Precision caused by the geometry of the mutual arrangement of the transmitter and receivers [21].

For the previously considered example of a building, shown in Fig. 1, let us examine the localization accuracy parameters. Fig. 2 shows the localization accuracy fields under the initial conditions: $\sigma_{r_i} = 0.1$ m; the scanning height is 3, 6, 9, 12 m, which approximately corresponds to individual floors of the building. Fig. 3 shows the same situation, but the surrounding space around the building is subject to investigation. Situations where it is necessary to monitor not only the premises, but also the surrounding space around the building may arise with more complex building structures, the presence of a cluster of buildings in a limited area, or when it is necessary to counteract more sophisticated means of remote information extraction, such as laser microphones or drone-based reconnaissance systems.

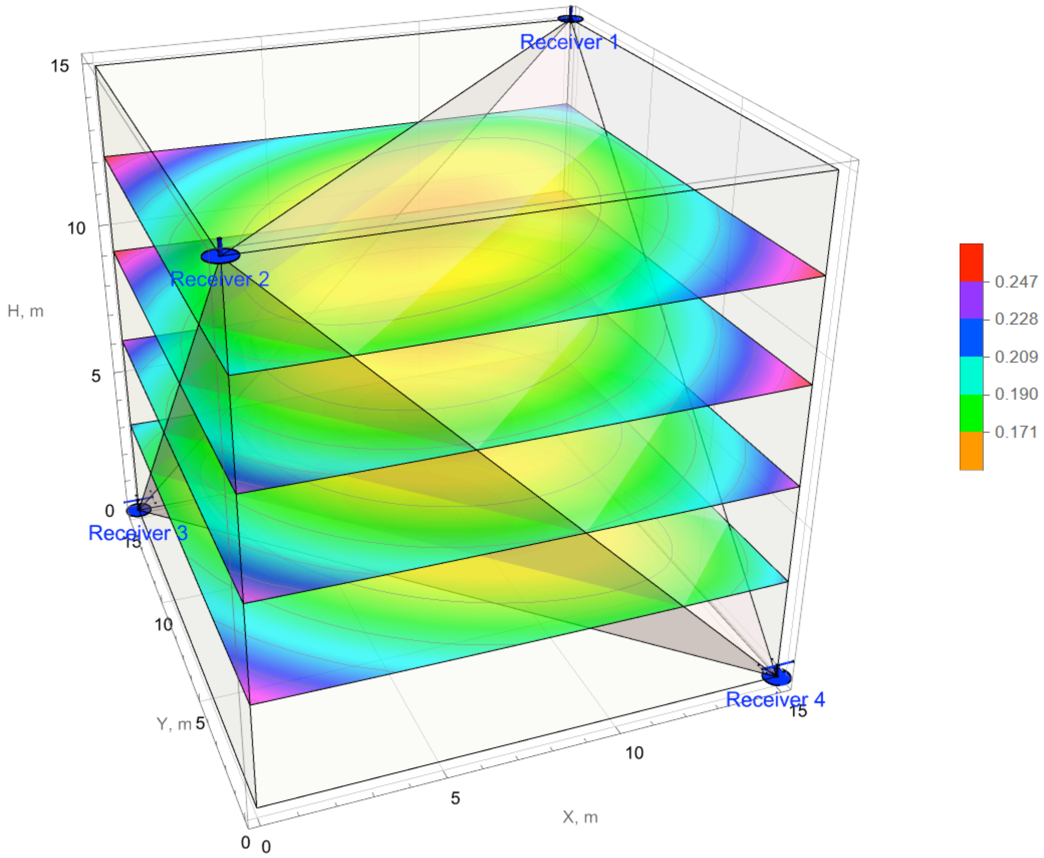


**Figure 2:** Modeling of localization accuracy inside a building.

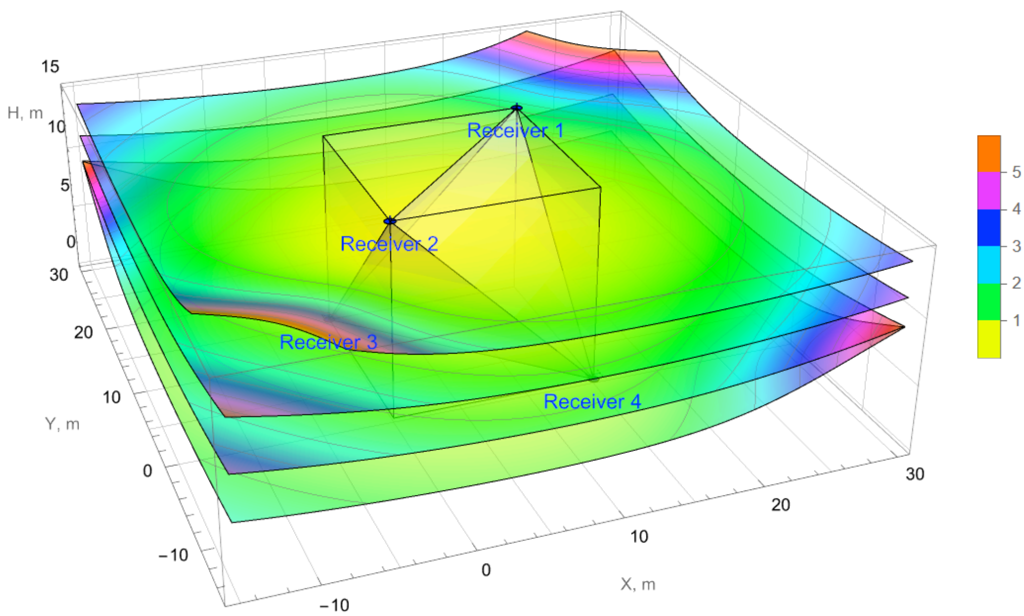


**Figure 3:** Modeling of localization accuracy around the building.

## 7. Results and discussion

As can be seen from Fig. 2, the best accuracy is provided in the central part of the regular tetrahedron formed by the receivers of the scanning system: $\sigma_{q_{min}} = 0.151$ m. The worst accuracy indicators ($\sigma_{q_{max}} = 0.268$ m) are observed at the edges of the zone. However, it should be noted that the difference between $\sigma_{q_{max}}$ and $\sigma_{q_{min}}$ is insignificant, and the overall result can be considered quite acceptable.

A different picture is observed in Fig. 3. As we can see, the accuracy field outside the tetrahedron formed by the receiving antennas is heterogeneous and depends on the mutual location of the transmitter and receivers. The minimum value of the MSE, as in the previous case, is $\sigma_{q_{min}} = 0.151$ m, while the maximum value $\sigma_{q_{max}} = 6.3$ m, which is unacceptable. This is especially important to consider when constructing a scanning system in large buildings with complex architecture.

Thus, the conducted study confirms the possibility of localization of hidden transmitters by redundant observations. In this case, the algorithm usually requires 4-7 steps before stopping, when the coordinates obtained at subsequent steps change insignificantly relative to the previous ones. This indicates the rapid convergence of the algorithm and its efficiency.

Further research shows that localization accuracy depends on both distance measurement precision and the spatial arrangement of the transmitter and receivers. With 4 antennas, minimum MSE is achieved at $\sigma_q = 1.44\sigma_{r_i}$ in the center of a regular tetrahedron, while accuracy deteriorates at the edges and is worst outside the building. Increasing the number of receivers improves accuracy due to redundant data, but requires an antenna layout that maximizes the volume of the geometric figure formed by their positions.

The proposed model offers several significant advantages for software developers.

First, it demonstrates high adaptability to various antenna configurations, which allows them to be effectively deployed both in open areas and in limited, architecturally complex indoor environments. Such versatility reduces the volume of software and the time for its development, since similar software can be used for different organizations without being tied to its specific structure and building layout.

Second, the use of redundant measurements not only increases the localization accuracy, but also increases fault tolerance, ensuring stable operation even in the event of failure of individual receivers or interference. In this case, the developer will not have to solve the problem of how and what to replace individual measurements that can be distorted by various interferences. Also, the localization algorithm will be more resistant to various measurement errors, since with significant errors, individual measurements can simply be ignored.

Thirdly, the fast convergence of the algorithm significantly reduces the computational cost, which makes it suitable for real-time applications. In many cases, this requirement can be key, because modern covert transmitters can use different transmission modes: for example, pulsed. When the accumulated information is not released gradually, but in one packet over a short period of time. In this case, the problem of direction finding such a signal can become key and therefore fast localization will make it possible to effectively counteract information leakage.

Finally, the scalability of the approach allows it to be used both for full coverage of the building and for targeted localization in certain rooms, which makes the model universal for various security and monitoring tasks. In real conditions, not the entire area of the building may be equally suitable for installing covert transmitters. There are places where their presence is more likely than others. Therefore, by configuring the position of the receiving antennas, you can achieve the best sensitivity and localization accuracy in specific places, while ignoring other spaces. This can be very convenient in the practical activities of security services, when the system configuration can be changed covertly without the need for installation work.

## 8. Conclusions

The development of special software for applied problems requires the search for appropriate models and preliminary modeling of the problem. For the considered problem of localization of hidden transmitters in conditions of redundant measurements, such software should take into account some features of practical solution of the problem.

In particular, when creating a model, it is important to ensure fast convergence of the algorithm and sufficient accuracy of localization of the hidden transmitter. This is extremely necessary for monitoring systems operating in real time. As has been shown, the localization accuracy depends on both the accuracy of distance measurements and the geometry of the receiver placement, and can vary significantly. At the same time, redundant measurements can significantly improve the accuracy. Under these conditions, the Newton method is the most suitable, offering fast convergence and reliable results. The assessment of the model accuracy using the Mean Square Error proves the adequacy of the developed model taking into account the geometry and accuracy parameters of the measurements.

The software developed based on the proposed model allows you to predict the performance of the monitoring system, optimize the placement of receivers in the building, and minimize system costs. Such modeling also allows you to choose the most effective algorithm under various architectural and structural constraints of the building. It also allows for remote configuration changes without additional installation work.

Further research on modeling the localization of hidden transmitters could focus on studying the energy parameters of signal propagation, the influence of structural elements of buildings on the accuracy of distance measurement and the influence of interference on signals, including radio electronic jamming.

## Declaration on Generative AI

The authors have not employed any Generative AI tools.

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