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Novel Design method for multistatic radar radiolocation system

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ABSTRACT :*This paper proposes new design method for the deployment of transceiver antennas that can be used for multistatic radar location systems in order to improve location accuracy The goal is to choose the best coordinates of the receiving and transmitting antennasin a judicious way in order to improve the precision. Architectures of the aligned and distributed (not aligned)antennas have been compared using time of arrival (TOA) and received signal strength (RSS) parameters. The method of localization used here is the multilateration and the method of design based on that is the antennas with an opening. The results show that the error in precision of the distributed antenna is almost twice lower than that of the aligned antenna when the parameter is the RSS.While using a TOA parameter, the precision is almost the samefor two architectures in the line-of-sight (LOS) situation.*

KEYWORDS:*Architecture of deployment, multilateration, multistatic radar.*

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I. INTRODUCTION

One of the most attractive characteristics in the modern wireless network systems is their localization capacity.In general, depending on the nature of the target to be determined, localization systems can be classified into activate and passive. Actually, the passive geolocalization arouses an increasing interest. This application is particularly interesting for the monitoring of critical environments such as the power stations, the tanks or any other critical infrastructure vulnerable to the attacks [1].

It is known that the multistatic radar systems and the wireless networks for the detection and the follow-up of the intruders share several common characteristics. According to the radar jargon, whenthe transmitter and the receiver of the radar share electronics and a common antenna, we speak then about monostatic radar.The bistatic radar expression is used for the radar systems which include a transmitter and a receiver separated by a distance comparable with the distance from the target [1-3]. The multistatic configuration indicates a radar system comprising several transmitters and a receiver or a transmitter and several receivers. It is, in fact, a generalization of the bistaticradar. One and the other configuration offer advantages and disadvantages. The multistatic constellations allow to increase the sensitivity of the radar, to improve classification and the recognition of the targets, and to reduce the losses of detection caused by fading and the directivity of the diffusion of the target and the tumble. In addition, the multistaticradar systemconsiders a space diversity and visualizes simultaneously various aspects of a target and a potential of information gain in comparison with the conventional systems. However, the multistatic radars are affected by critical problems of synchronization, and require that the transmitters and the receivers share information to locate and follow the target in cooperation [1, 4].

The setting of non-co-located radar transmitter(s) and receiver(s), *i.e*., the *bistatic* or *multistatic*radar configuration[4-6], dates back to the Second World War with the KleinHeidelberg radar. The non-co-located radar can either use transmitters of opportunity, e.g., FM radio, analogue TV, DVB-T, which is known as passivemultistatic radar, or use dedicated transmitters also known as activemultistatic radar. In the active setting, the transmitter(s) and receiver(s) can operate in a cooperativefashion by exchanginginformation, such as trajectory of the pulse, waveform type, frequency, etc., to increase the overall accuracy[5].

The classical problem of target localization continues to receive great attention due to its importance to a wide range of applications in wireless communication systems, sonar and radar, and surveillance and navigation systems. The most common localization techniques are developed based on time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), Doppler shift, and received signal strength (RSS) [6].The traditional design of the systems of localization per radar is generally done by deployment of the antennas with coordinates of the figure entireties.In Ref. [7, 8], for example,they use the imagery to locate through a wall.In the field of the air traffic, the system of the antenna deployment has a random and is not a planned form particularly for modern crowdsourced air traffic networks with a random andimperfect deployment geometry [7]. This type of problem can also be found in the radars' ground-based systems [5]. In these systems, the coordinates of the antennas are always given in an arbitrary way.Many research are devoted to find the techniques and algorithms allowing to detect the signal [9-11].

In this article, we propose a semi-elliptical system for the deploymentof the transmitter-receiving antennas to improve the precision of localization. Using the technique of localization, calledmultilateration, and TOAand RSS parameters,we investigate the error in precision for both aligned and not-aligned multistaticantennas. We show that the error in precision of the not-aligned antenna is approximately twice lower than that of the aligned antenna when the parameter is the RSS. While using a TOA parameter, the precision is almost the same for two radar systems in the line-of-sight (LOS) situation.The paper is organized as follows: Section II is devoted to the formulation of problem, while Section III considers a design procedure. The application of our architecture to the multistatic radar is considered in Section IV. The flow chart of the design procedure is described in Section V. Numerical results are illustrated and discussed in Section VI. Finally, conclusion is presented in Section VII.

II. PROBLEM FORMULATION

Let us consider a deployment architecture of the radiolocation system made up of four receivers $R_N(N = 1, 2, 3, 4)$and of a transmitter, which has a shape of the rectangular waveguide and forms an ellipse of virtual center Oas shown in Figure1.The study presented here considersonly the fundamental mode of transverse electricpropagationTE_{10}because it allows a uniform distribution of the field at the opening of the waveguide. Then, the problem consists of solving the following parametric equation:

$$\begin{cases} x = x_0 + a \sin t \\ y = y_0 + b \sin t \end{cases}, \tag{1}$$

where x_0 and $y_0$are the coordinates of the center of the ellipse O,$a = \frac{A}{2}$ and $b = a_H$.It is necessary to determine the values of a and b in order to trace the ellipse which will be used as a waveguide. Here, it is important to note that a must be larger than $b$to prevent that the transmitter$T$is far away from the receivers,R_1andR_N.

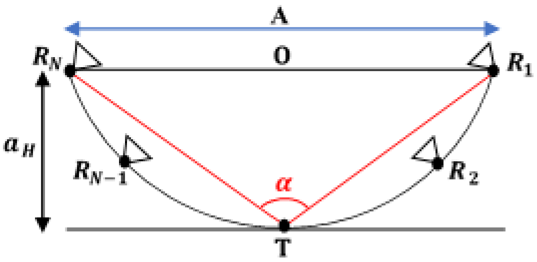

Figure 1. Architecture of deployment

III. DESIGN PROCEDURE

In this section, we present the various stages of new architecture designof deployment.

III.1 Determination of the dimensions for deployment

The design of the antennas with an opening must include all necessary dimensions so that the conditions of propagation should be observed. As a starting point, we take the geometry of Figure 2 in the electric field plane E and magnetic field plane H,and use the same calculations shown in Ref. [12].

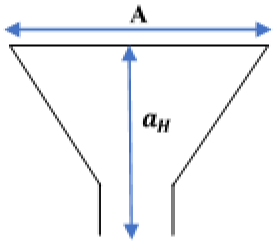

Figure 2. Geometry of dimension

Now, a_H can be obtained as follows: $a_H = \frac{A^2}{16\lambda t_e} - \frac{\lambda t_e}{2}$ with $t_e = \left(\frac{A}{\lambda}\right)^2 \frac{1}{8t}\left\{\left[1 + \left(\frac{\lambda}{A}\right)^2 16t^2 - 1\right]^{1/2} - 1\right\}$, where $t$is the error of phase measured on the magnetic field plane.

It is known that the gain of the antennas $(G)$with an opening depends on the surface of the opening, the effectiveness of the opening, and the wavelength:

$$G = \frac{4\pi}{\lambda^2} \varepsilon_{ap}\, AB \qquad (2)$$

where AB is the surface area of the waveguide, ε_{ap} is the effectiveness of the opening, and λ is the wavelength.Thus, we obtain:

$$A = \sqrt{\frac{\lambda^2}{4\pi\varepsilon_{ap}} G}\,, \qquad (3)$$

with $A = B$.Now, since we know $A$and a_H, we can trace the ellipse of the antennaas shown in Figure 1.

III.2 Determination of the positions of the receivers and the transmitter

For positioning the receivers and the transmitter, we use the following assumptions. The Cartesian coordinator of transmitter,T, in Figure 3 is taken as the origin. For the receivers, we trace a half-ellipse from a virtual center O. We choose an angle $\varphi$from a virtual center O to the clockwise and defined as

$$\varphi = \frac{\pi}{N-1}\,, \qquad (4)$$

where $N$is the number of the receivers.From a practical point of view, R_1 and $R_N$are located at $\varphi = 0$ and $\varphi = \pi$, respectively. The position of the second receiver on the basis of the first receiver, $\varphi = 0$, is shifted by an angle$\varphi = \frac{\pi}{N-1}$. We perform the same process until it reaches an angle $\varphi = \pi$ as shown in Figure 3.It is worth to note that for the better precision of location,N must be even to maintain a symmetry between the receivers. Thus, the coordinates of each receiver are given by $(\cos\varphi, \sin\varphi)$multiplied by$a$ and b, respectively. Hence, the coordinates of receivers$R_1$and$R_N$are (a, b) and $(-a, b)$,respectively.In Figure 4, the system of deployment forthe radiolocation is presented.

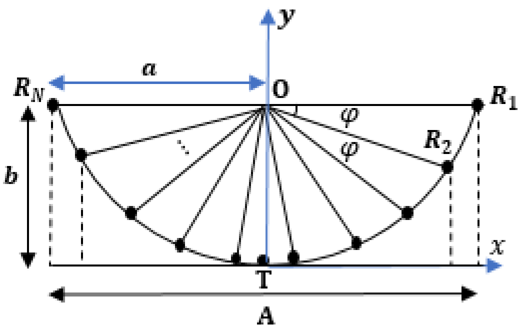

Figure 3. Arrangement of the transmitter-receiverantenna

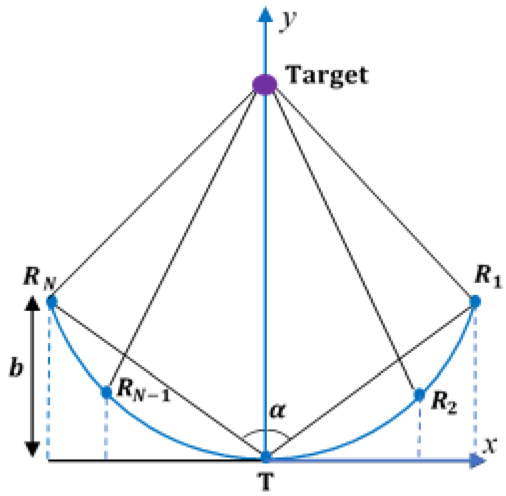

Figure 4. Geometry of deployment for the localization

IV. APPLICATION OF ARCHITECTURE TO THE MULTISTATIC RADAR

The localization of multistatic radar in term of a deployment uses a technique of trilateration, *i.e.*, a transmitter and three receivers, which gives good results.However, when we consider an architecture of the aligned or shifted antennawith more than three receivers, we should employ the multilateration method which gives several zones where the target could be located. The architecture that we propose here comes to bring a response to this concern.

The two-dimensional problems of the localization using a distributed multistatic radarare represented in Figure 5. Here, we consider the architecture made up of a transmitter and four receivers. For each receiver, the target-receiver distance $l_i$is expressed by the equation:

$$l_i = \sqrt{(x - x_i)^2 + (y + y_i)^2}, \qquad (4)$$

where x and y represent the coordinates of the target, x_i and y_i ($i = 1 \dots 4$) are the coordinates of the receivers.The aim is to determine the position of the target $P(x, y)$by knowing the position of the transmitting antenna $T(x_0, y_0)$,positions of the reception antennas $R_i(x_i, y_i)$,and the distances l_i between the target and receiving antennas.

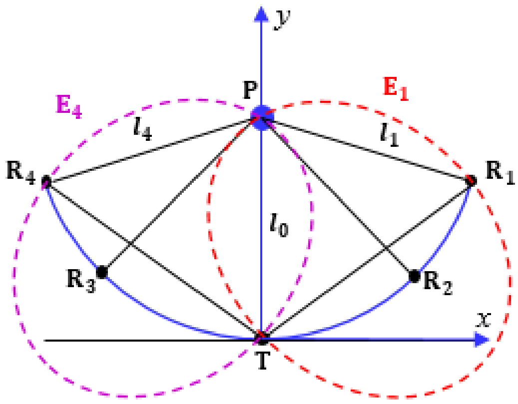

Figure 5. Multilateration using the distributed multistatic radar

IV.1 Estimation of the position using the TOA

The distanceTR_1 between the transmitter $T$and the receiver R_1through the point Pin Fig. 5is expressed by the relation$l_0 + l_1$, where $l_0$is the distance between the transmitter and the target.This distance is twice larger than the principal semi-major axis $a_1$of the ellipseE_1, where both the transmitter $T$and the receiver R_1 points are on the ellipseE_1.In general, the distance TR_i between the transmitter $T$and the receiver R_i through the point Pcan be expressed in terms of the semi-major axis a_i of the ellipsesE_i,where T andR_i lies on the ellipsesE_i,

$$a_i = \frac{l_0 + l_i}{2}. \qquad (5)$$

Here, $l_0 + l_i = c \cdot TOA$,where c is the propagation velocity in the vacuum. We note that$b_i$is the semi-minor axis of the ellipse E_i and $2e_i$is the distance between the transmitting antenna T and the receiving antennas R_i. We can thus write b_i in the form:

$$b_i = \sqrt{a_i^2 - e_i^2}. \qquad (6)$$

Assuming the coordinate of the transmitting antenna $T$is at the origin, the centers of the ellipses $C_i$arewritten as $C_i = (e_i, 0)$ or $C_i = (-e_i, 0)$ depending upon whether the reception antenna is located on the positive or negative axis. Then, the equation of the ellipses $E_i$is expressed by:

$$\frac{(x+e_i)^2}{a_i^2} + \frac{y^2}{b_i^2} = 1, \qquad (7)$$

where x and $y$are the coordinates of the target$P$. The intersection of two ellipses provides two possible solution points. However, we assume that the target is obligatorily located in the$y > 0$space in order to simplify the calculation of the target localization.

IV.2 Estimation of the position using the RSS

Another significant parameter of a radar is its range which can be calculated by the equation of the radar.This equation can take various forms according to the type of the radar.Let us assume that the target is characterized by a radar cross section (RSC)σ [2]. The RSC is a specific physical parameter to each target and is determined by the form of the object, its nature, its constitutive materials as well as wavelength, and angles of incidence and reflection of radiation.The effective opening of the reception antenna$A_R$is related to the antenna gain $G_r$at the receiver as

$$A_R = \frac{\lambda^2 G_r}{4\pi}. \qquad (8)$$

Neglecting the atmospheric attenuations, the power of the signal P_r received by the reception of the radaris then given by [2]

$$P_{r_i} = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 l_0^2 l_i^2}, \qquad (9)$$

where P_t is the transmitted power and$G_t$is the antenna gain at the transmitter.Thus, the distance $l_i$between the target and each receiveris expressed by

$$l_i = \sqrt{\frac{P_t G_t G_r \lambda^2 \sigma}{P_{r_i} (4\pi)^3 l_0^2}}. \qquad (10)$$

V. FLOW CHART OF THE DESIGN PROCEDURE

The first stage of thedesign procedure consists of fixing the ideas on the system, which is conceived with knowing the size and the type of antenna to be used, the type of radar (impulse or sweeping), and the band-width of work, etc. The second stage is to define the frequency band in which worksfor the radar.The third phase is a test to carry out the calculations by adjusting the best parametersof the antenna (gain of the antenna or the opening surface of the antenna). Knowing one of these parameters, we determine the parameters A and B, and calculatethe error of phases(s_e and t_e)measured on the plane E and H, respectively and the parameter (a_H). Having obtained all dimensions, we calculate the angle φwhich separates the various receivers,and find the positions of the various receivers on the reference mark. Lastly, we choose the localization techniques (trilateration, triangulation, etc.)and the parameter of localization (AOA, TOA, TDOA, RSS, etc.).

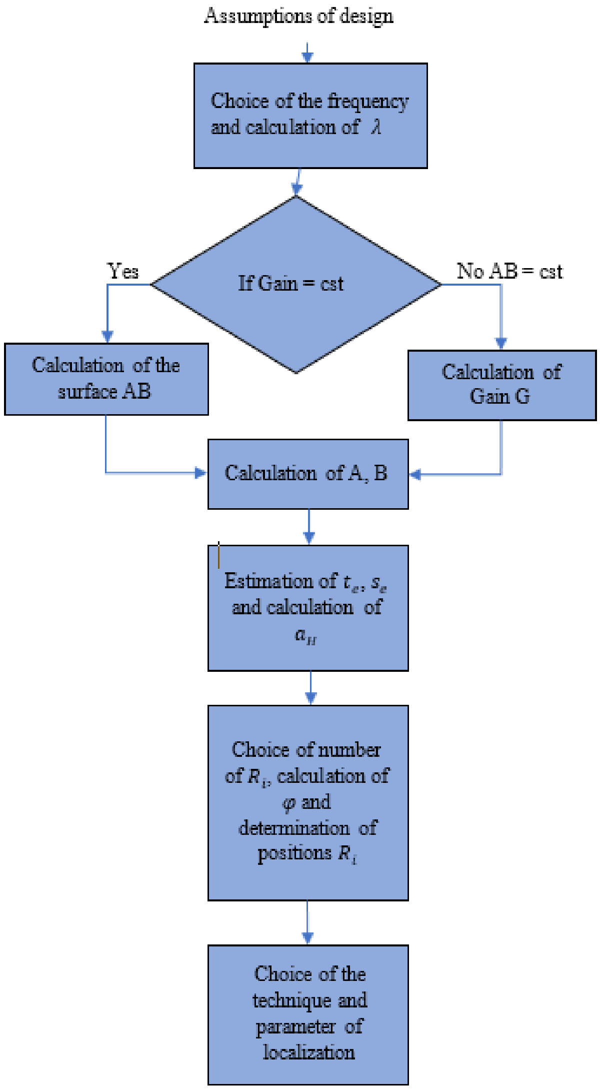

Figure 6. Flow chart of the design procedure

VI. NUMERICAL RESULTS

The characteristics of the antennas and target in this study are as follows: The power of emission is $80\ Watt$, the frequency is $2\ GHz$, the range in line-of-sight (LOS) situation is $50\ m$, a radar cross sectionσ is$1m^2$, the gain of the emitting antennais$60\ dB$, the gain of the receiving antenna is $3\ dB$, the angular opening is 60^0, the number of receivers N is 4, and the coordinates of the target is $(0, 300\ cm)$. For the deployment dimensions of the multistatic system, we use the data obtained from Ref. [13]. These parameters of the deployment are $A = 119.68\ cm$ and $R_p = a_H = 83.23\ cm$. The coordinates of the receivers and their received powers for $\varphi = \frac{\pi}{3}$are presented in Table 1. We also calculate the parameters of the ellipse and the coordinates of the ellipse centers using the method shown in Ref. [14], and present the result in Table 2.

Table 1. Coordinates of the receivers and their received powers

Coordinates of the receivers (x, y)		**Receiverspowers**
R_1(cm)	(59.84, 83.23)	-26.4499 dB
R_2(cm)	(29.92, 72.03)	-27.6412 dB
R_3(cm)	(-29.92, 72.07)	-27.6412 dB
R_4(cm)	(-59.84, 83.29)	-26.4499 dB

Table 2. Parametersand coordinates of the centers of the ellipse

Centers of e ellipse	Coordinates (x_i, y_i)	Parameters of the ellipse (a_i, b_i)
C_1(cm)	(29.92, 41.64)	(262.4100, 260.6987)
C_2 (cm)	(14.96, 36.07)	(264.9129, 264.4902)
C_3(cm)	(-14.96, 36.07)	(264.9129, 264.4902)
C_4(cm)	(-29.92, 41.64)	(262.4100, 260.6987)

Figures 7 and 8 represent the multistatic localization by radar with estimated parameters of the position in the TOA and the RSS, respectively. The obtained results here show that the new approach of choosing the coordinates of the receivers or of laying them out allows to locate a target whatever the situation is. In other word, we do not need to define a zone as a preliminary to deploy a multistatic localization per radarin this system.We also note that the precision is different according to the parameter of localization in this new method.The coordinate of the target position, which is the center of the zone in the intersection of four ellipses, is (0, 300 cm).In Figure 7 and 8,the estimated coordinates of the target position in the LOS situation are (0, 300.05 cm) and (0, 303 cm) for TOA and RSS, respectively. By comparing the difference between these two target positions, we obtain a precision error of 0 cm on the x-axis and 0.05 cm on the y-axis for the TOA case and 0 cm on the x-axis and 3 cm on the y-axis for the RSS case. Hence, the actual distance between these two target positionsis 0.05 cm and 3 cm for TOA and RSS, respectively.

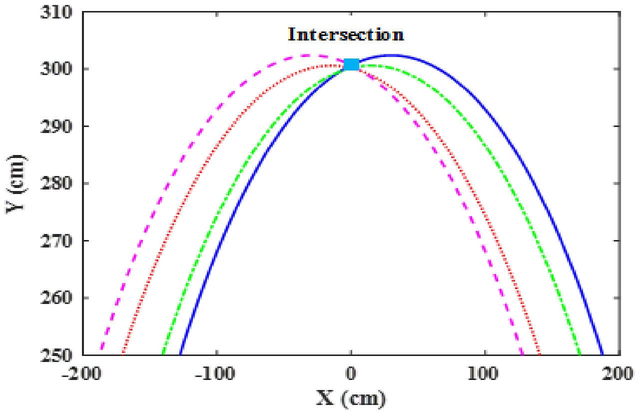

Figure 7. Localization by multilateration using the TOA. The solid blue line corresponds to the receiver R_1, dash-dotted green line toR_2,dotted red line toR_3, and dashed purple line to R_4.

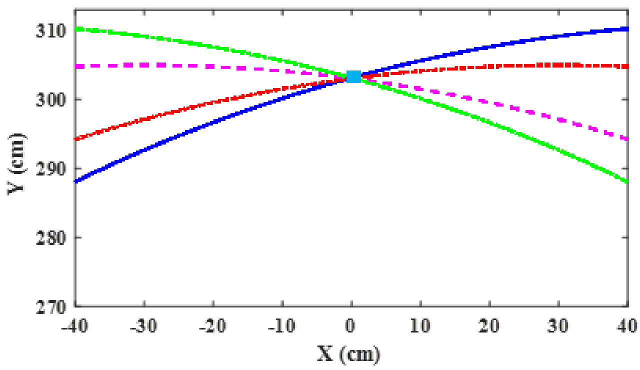

Figure 8. Localization by multilateration using the RSS.

Next, we consider amultistatic localization by radar when the antennas are aligned. The coordinates of the receivers and their received powers for an aligned antenna systemare presented in Table 3. In addition, the parameters of the ellipse and the coordinates of the ellipse centers for the aligned antenna systemare presented in Table 4.

Table 3. Coordinates of the receivers and the received powers for the aligned antenna

Coordinates of the receivers (x, y)		Received powers
R_1 (cm)	(59.84, 0)	-28.1251 dB
R_2 (cm)	(29.92, 0)	-27.9987 dB
R_3 (cm)	(-29.92, 0)	-27.9987 dB
R_4 (cm)	(-59.84, 0)	-28.1251 dB

Table 4. Parametersand coordinates of the centers of the ellipse for the aligned antenna

Centers of e ellipse	Coordinates (x_i, y_i)	Parameters of the ellipse (a_i, b_i)
C_1(cm)	(29.92, 0)	(302.9539, 301.4738)
C_2 (cm)	(14.96, 0)	(300.7442, 300.3818)
C_3(cm)	(-14.96, 0)	(300.7442, 300.3818)
C_4(cm)	(-29.92, 0)	(302.9539, 301.4738)

We note from Tables 3 and 4 that all four receives are on the x-axis because y-axis coordinates of all receivers are zero. Figures 9 and 10 represent the multistatic localization by radar with an aligned antenna system using the TOA and the RSS, respectively. The estimated coordinates of the target position in the LOS situation are (0, 300.08 cm) and (0, 305.3 cm) for TOA and RSS, respectively. By comparing the difference between the estimated and real target positions, we obtaina precision error of 0 cm on the x-axis and 0.08 cm on the y-axis for the TOA case and 0 cm on x-axis and 5.3 cm on the y-axis for the RSS case. Thus, the actual distance between these two target positions is 0.08 cm and 5.3 cm for TOA and RSS, respectively.

Therefore, the precision of the distributed multistaticantennais better than that of the aligned antenna when the parameter of localization is the RSS. However, the precision remains almost the same when the parameter of localizationis the TOA. Our proposed architecture could be used for the design of the localization through the walls in the radar devices. It is worthwhile to stress that when the radar is rotary, which would be of capital importance for the monitoring in urban environment,the improvement of the precision is possible.

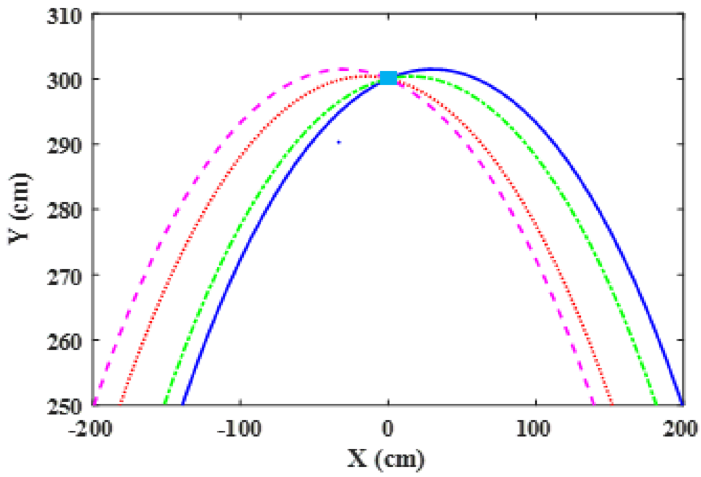

Figure 9. Localization by multilateration with the aligned antennas using the TOA.

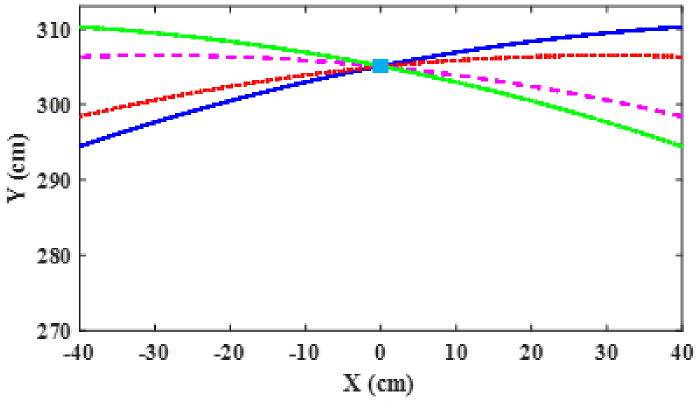

Figure 10. Localization by multilateration with the aligned antennas using the RSS.

VII. CONCLUSION

In conclusion, we proposed new method of design and deployment of the antennas in a multistatic radar system based on the wavelength and the gain of the transmitting antenna.We have shown that the surface of the rectangular waveguide makes a clear improvement of the localization precision. Moreover, the proposed choice of the coordinates for the receiving and transmitting antennashas indicated that we are not obliged to delimit the required zone of the target. In other words, it is more than enough that the target is in the zone of the radar detection.Finally, the analysis of the numerical results has shown that the precision of localization is better by using the parameter TOAthan by using parameter RSS. The error in precision of the distributed multistaticantenna is approximately twice lower than that of the aligned antenna.

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