10.53477/2668-2028-21-12

PASSIVE RADIOLOCATION. DISTANCE ESTIMATION METHODS

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Abstract: *The timely discovery of existing threats in the airspace is a permanent concern of the relevant military powers of this century and sensor networks have been developed in this regard, arranged over very large geographical areas in order to achieve a permanent and continuous surveillance of the areas of interest. Research conducted by the scientific community has demonstrated the potential of bistatic (passive) radar as a means of surveillance, the efforts focusing on improving receiver parameters and signal processing algorithms. An important role in these scientific approaches is played by the geodetic distance estimation methods, as well as by the diversification of technical solutions that provide the necessary support for their application and the establishment of algorithms for refining the data provided.*

Keywords: *aerial surveillance; passive radar; trilateration; triangulation; aerial threat.*

On October 5, 1914, near the city of Reims, the first air battle in history took place in which a German plane was shot down by a French plane. This confrontation was the beginning of air combat between the air forces of the states involved in the war, triggering a continuous process of improvement and transformation of the airplane into an effective means of combat, capable of performing a diverse range of combat missions. The increased destructive potential of an aircraft had the effect of perceiving it as a real threat to the combat forces, requiring the identification of solutions to ensure defense against it. Its ability to penetrate and attack targets deep inside the opponent's territory without being detected has created panic among the population and the authorities of the states involved in the conflict. The need to neutralize this threat was the catalyst for sustained conceptual and practical efforts with the purpose to achieve an air surveillance system capable of detecting and identifying the flight means of the opponent and of ensuring timely information to the structures specialized in fighting them. Thus, in 1915, the first elements of ambush and aerial surveillance have been established for this purpose and integrated in the aircraft defense system, in a unitary, flexible design, that allowed the adaptation of the aerial surveillance system to the realities of the battlefield. In essence, the aerial surveillance systems organized by Germany, France, the United Kingdom and Italy were conceptually similar, given their focus of efforts on the operations' area, while in the territory, the focus was on discovery, pursuit and identification of the air enemy following the probable directions of attack. The impact of the establishment of the air surveillance system by the above-mentioned states was immediate, this being proven by the large number of aircrafts that were shot down in comparison to the period prior to its establishment.

From the point of view of the endowment with combat equipment, the aerial surveillance system of the four states included passive means of visual and auditory detection, made up of optical devices and listening funnels, which were the only means capable of detecting the opponent's aircrafts throughout the war. Even if in 1904 the German Federal Bureau of Inventions and Innovations has granted to engineer Christian Hülsmeyer the Patent no. 165546/1904 for distant detection of metallic objects by means of electromagnetic waves, the existing technological level at the time did not allow the respective patent to be exploited and the potential of active detection of air means with the help of electromagnetic waves could not be used for aerial surveillance systems. The scientific and technological progress registered by the relevant powers of the interwar period has allowed for the construction of transmitters and receivers with superior technical parameters, with the possibility of detecting aircrafts by means of electromagnetic waves, over long distances, thus leading to the emergence of a new aerial surveillance equipment – the radar.[1] World War II has confirmed the radar apparatus as the main element of the air surveillance system, ensuring detection of the opponent's air attack means and providing the necessary data for air defense against them. The emergence of this active means of detection had the effect of reducing the importance and, finally, of eliminating the passive detection systems used for air space surveillance during the First World War. However, the replacement by the radar of these passive detection systems in the air surveillance system of the states involved in the war did not mean the disappearance of the passive method of air means detection. The technological level existing in the interwar period and the effort made by the belligerent states to identify new theoretical solutions have contributed to the design and development of air detection systems, including passive detection systems, used as information sources, complementary to the radar system. And here we can use as an example the surveillance system composed of passive radars developed by Germany during World War II, known as *Klein Heidelberg*[2]. This subsystem of the aerial surveillance system consisted of six stations acting as passive receivers (located at Oostvoorne, Ostend, Boulogne, Vaudricourt, Cap d'Antifer and Cherbourg) and ensuring the reception of electromagnetic emissions from British radars, which acted as electromagnetic illuminators. Passive radars built by the Germans were detecting air attack means based on the electromagnetic emissions from British radars, without being detected or disturbed by the Allies, and their existence was discovered only after the landing in Normandy.

The development of radars has continued after the end of World War II aiming to obtain technical parameters to detect the new threats posed by ballistic and cruise missiles. The radars used in the aerial surveillance systems presented several construction options and mainly monostatic detection systems were achieved with better and better performances. Bistatic and multistatic radars have not received the attention of the scientific community, being used sporadically and for short periods of time only, acting as complementary means of detection designed to supplement data for the areas not monitored by the monostatic radars. Interest in bistatic and multistatic radars has increased in the ninth decade of the last century, when the first passive detection system has been developed using the signal generated by television transmitters to locate and track air means.

The beginning of the 21st century sees a quantitative increase in the scientific work dedicated to the bistatic (passive) radar, highlighting the importance given by the scientific community to bistatic radar as a passive system for detecting bodies.

In this approach we will present the theoretical aspects addressed by the scientific community in these papers, seeking to highlight the differences between the bistatic and the monostatic radar. In this regard, I will show in detail the main mathematical methods specific to the passive radar used to determine targets location, as well as the impact that these methods have on the development of passive systems and the architecture of aerial surveillance systems. A first step in this direction is the presentation of physical phenomena that are the scientific basis for the bistatic radar construction. Target detection by the bistatic radar is based on theoretical principles and physical laws similar to those used for the monostatic radar, the difference between the two detection systems being given by the manner in which the target's position is determined.

The bistatic radar is "*a radar that uses antennas positioned in different locations for transmission and reception*"[3]. From this definition we can deduce that the distance between the location of the transmitter antenna and the location of the receiver antenna must be large enough to

[1] Eugen Teodorescu, Visarion Neagoe, Ioan Munteanu, *Supravegherea aeriană – de la mitolocație la radiolocație*, Editura Sylvi, Bucharest, 2001, pp. 24-28.
[2] Nicholas Willis, Hugh Griffiths, Klein Heidelberg, *A WW2 bistatic radar system that was decades ahead of its time*, Technical report, p.17, available at http://www.cdvandt.org/index.htm, seen at 20:00 on 28.12.2019.
[3] Nicholas J. Willis, *Bistatic Radar*, Editura SciTech Publishing Inc., Raleigh, North Carolina, 2005, p. 2.

differentiate the characteristics of the bistatic radar from those of the monostatic radar. The value of this interval is established differently, the existing opinions among the specialists stating that it should be comparable, as magnitude, with the distance estimated for the discovery of the target[4]. The estimation of the distance to the target, compared to the monostatic radar, is based on a complicated geometry consisting of a triangle determined by the position of the transmitter antenna, the position of the receiver antenna and the position in space of the detected target, called the bistatic triangle. The bistatic triangle is presented in Figure 1.

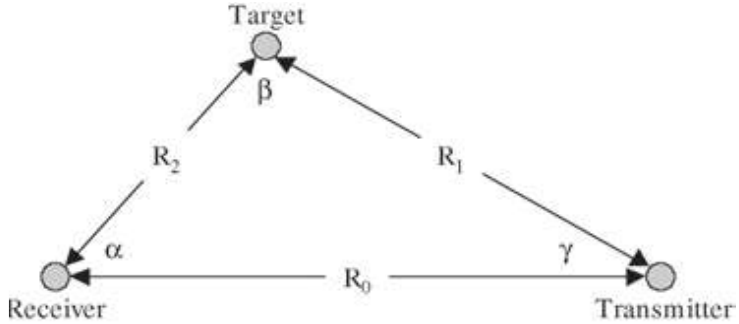

Figure 1. Bistatic radar arrangement scheme [5]

where,

R_2 – distance from the receiver to the target;

R_1 – distance from the transmitter to the target;

R_0 –distance between the transmitter and the receiver;

β – the angle formed by the target-transmitter direction and the receiver-target direction, called bistatic angle or scattering angle.

The bistatic radar geometry understanding is based on the operating principle of the bistatic radar. The operating principle presented schematically in the triangle consists of receiving a reference signal from an opportunity illuminator and an echo signal from the same opportunity illuminator, reflected in this case by the target. The processing of the reference signal and of the echo signal will contribute to the determination of the detected target coordinates by the bistatic radar. [6]

The bistatic radar is manufactured in two variants: with a dedicated transmitter and, in this case, the radar system has its own transmission system arranged in a different location from that of the receiver, and without a dedicated transmitter and, in this case, it uses the existing radar or non-radar transmitters as opportunity illuminators. In both construction variants, the reception system has two receivers, one for receiving the reference signal directly from the transmitter and the second for receiving the echo signal from the target. According to Figure 1, the determination of the target coordinates by the bistatic radar is a much more complicated process, in which the total signal propagation time, the location of the opportunity illuminator and the bistatic angle β formed at the target surface between the incident wave and the reflected wave are taken into consideration. The methods used to determine the target coordinates are varied, their qualitative and quantitative evolution being dependent on the technological level of the bistatic radar, both in terms of target detection potential and of the equipment ability to process data and use increasingly complex mathematical algorithms. In this paper I will detail the mathematical methods underlying the estimation of target coordinates by the bistatic radar, both for the dedicated transmitter version where the position is known and for the version without a dedicated transmitter where there is a possibility that its location is not known exactly.

[4] Nicholas J. Willis, *op.cit.*, p. 3.

[5] John C. Toomay, Paul J. Hannen, *Radar Principles for the Non-specialist*, Third Edition, Scitech Publishing. Inc., Raleigh, North Carolina, 2004, p. 203.

[6] Mateusz Malanowski, *Signal Processing for Passive Bistatic Radar*, Artech House Publishing, Boston, 2019, p. 9.

The mathematical methods used to determine the targets coordinates by the bistatic radar are:

- The trilateration method;
- The triangulation method.[7]

Trilateration, as a mathematical method to estimate distances, is a method used by radionavigation systems and is a „*geodetic method based on measuring the sides of network triangles*". The trilateral method involves arranging the detection sensors so that the surveillance area can be decomposed into triangles at the vertices of which the passive radar receivers used to determine the target coordinates can be found.

Triangulation is a method for determining the position of a target by measuring the angles between the nodal points of the network and the point where the target is located. Triangulation is defined as a „*set of geodetic operations aiming at a very precise measurement of the coordinates of a number of points in the field, by means of triangles whose vertices are these points*."[8] In order to simplify the calculations related to this method, a disposition of the network nodal points is followed so as to obtain equilateral triangles.

The difference between trilateration and triangulation is that trilateration determines the position of a target by measuring the distances between the target and the receiver, and by triangulation the position of the target is estimated measuring the angles between the target and the bistatic radar reception system.

Trilateration, as a mathematical method, is achieved by:

- time difference of arrival estimation;
- target time of flight measurement;
- time of arrival measurement;
- measurement of the receiver signal value.[9]

The TDOA[10] method consists in determining the time difference between the moment of receiving the signal reflected by the target and the moment of receiving the reference signal, the value expressing the distance from the target to the receiver. The TDOA method involves a pair of target detection systems with a known location for which the time difference of arrival is transformed into a distance the value of which represents an infinity of positions in space, graphically represented in the form of a hyperbola. In order to locate the target, it is necessary to set up another pair of target detection systems with a known location, sharing a common detection station with the first pair, and the distance obtained is represented by a new hyperbola which intersects with the first hyperbola thus generating an area where the target is located. To increase the accuracy of the target position estimation, it is necessary to set up a third pair of target detection stations, sharing a common single detection station with the other pairs, which will generate a third hyperbola corresponding to the distance determined by measuring the time difference of arrival. The intersection of the third hyperbola with the other two hyperbolas will generate a limited number of target positions, thus contributing to increasing the accuracy of target location estimation.[11]

From the analysis of the TDOA method we can tell that this method does not imply the existence of a time synchronization between the opportunity illuminator and the receivers and

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[7] Cristopher Langlois, Saideep Tiku, Sudeep Pasricha, *Indoor Localization with Smartphones: Harnessing the Sensor Suite in Your Pocket*, IEEE Consumer Electronics Magazine, vol.6, issue 4, October 2014, pp. 70-80, available onlinr at https://ieeexplore.ieee.org/document/8048717, seen at 20:00 on 15.02.2021.

[8] *** *Dicționarul explicativ al limbii române*, Editura Univers Enciclopedic, ediţia a II-a, Bucharest, 1998, p. 1111.

[9] Cristopher Langlois, Saideep Tiku, Sudeep Pasricha, *op. cit.*, pp. 70-80.

[10] Time Difference of Arrival.

[11] Kamiar Radnosrati, Carsten Fritsche, Gustaf Hendeby, Fredrik Gunnarsson and Fredrik Gustafsson, Fusion of TOF and TDOA for 3GPP Positioning, Fusion 2016, 19th International Conference on Information Fusion: Proceedings, Institute of Electrical and Electronics Engineers (IEEE), 2016, p. 1454-1460, available online at http://liu.diva-portal.org/smash/record.jsf?pid=diva2%3A949059&dswid=3382; seen at 22:00 on 16.02.2021.

that the time synchronization is necessary only between the receivers since the target location is the product of the intersection of hyperbolas generated by the time difference between the reflected and reference signal measured at the receivers. The accuracy, in this case, is influenced by the synchronization of the receivers, by the geometry of the network constituted by the pairs of receivers, by the existing obstacles in the area of the network layout and by the characteristics of the signal generated by the opportunity illuminators.

Another method used for locating targets is TOA[12]. To determine the distance at which the target is located, TOA uses the absolute value of the reflected signal arrival time at a base station, without the need to measure the time difference of arrival. TOA is a much simpler method for determining the position of an object, with applicability in various fields such as navigation, GPS[13], mobile phone networks, etc. The method has a limitation given by the accuracy with which the reception time of the radio signal by the base station is determined. Increasing the accuracy of the target position estimation using the TOA method involves measuring the absolute arrival time of the reflected signal in at least three receiver stations.

In practice, errors occur in accurately determining the position of the object due to errors in measuring the arrival time but also due to the interference phenomenon in the propagation environment of the signal reflected by the target. These errors can be eliminated by applying advanced data processing techniques but also by using high sensitivity receivers that can ensure a quality reception of the echo signal, thus facilitating an efficient use of specific processing algorithms.[14]

TOF[15] is another method used in passive radiolocation to determine the distance and consists in measuring the time required for the radio signal to travel the distance from the sensor to the target, and after it is reflected, from the target to the sensor. The value obtained is used to determine the distance as a function of the propagation speed of the probe signal through the existing environment between the sensor and the target.

RSSI[16] is another method of determining the position of a target and is based on a model of spatial distribution of the signal strength according to which, under the same propagation conditions and for the same signal parameters, there are points in space located at equal distances from the transmission source for which equal values of the received signal strength are obtained. Based on this model, the distance between an object and the receiver can be determined by establishing the correspondences between the value of the received signal strength and its corresponding distance.[17]

The strength of the received signal is expressed by the following relation:

$$RSSI=P_t - P_L(d)$$ [18]

where,

P_t – is the signal transmission strength;

$P_L(d)$ – is the signal strength that is lost from distance d to the receiver.

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[12] Time of Arrival.

[13] Global Positioning System.

[14] Xinrong Li, Kaveh Pahlavan, Jacques Beneat, *Performance of TOA Estimation Techniques In Indoor Multipath Channels,* The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, vol. 2, Lisboa, Portugal, 2002, pp. 911-915 available online at https://ieeexplore. ieee.org/xpl/tocresult.jsp?isnumber=22451, seen at 21:00 on 08.09.2020.

[15] Time of Flight.

[16] Received Signal Strength Indicator.

[17] Jungang Zheng, Chengdong Wu, Hao Chu, Yang Xu, *An Improved RSSI Measurement In Wireless Sensor Networks,* Procedia Engineering, vol.15, 2011, p. 877, available online at https://www.sciencedirect.com/ science/ article/pii/S1877705811016638, seen at 19:00 on 17.02.2021.

[18] Jungang Zheng, Chengdong Wu, Hao Chu, Yang Xu, *An Improved RSSI Measurement In Wireless Sensor Networks,* Procedia Engineering, vol. 15, 2011, p. 877, available online at https://www.sciencedirect.com/ science/article/ pii/S1877705811016638, seen at 19:00 on 17.02.2021.

Triangulation is achieved through the AOA[19] method and consists in measuring the angle between the arrival direction of the signal reflected by the target and the signal source, using for this purpose AOA measuring equipment and techniques. The measurement technique consists in determining the receiving direction of the signal reflected by the target object through the receivers existing in the area intended for surveillance. If the number of receiver points where the signal reflected by the target object is high (the measurement can be performed with at least two), then it is possible to accurately determine the position of the target object. The data obtained from these receiver points are transmitted to an AOA measuring station that has the possibility to estimate the three-dimensional position of the target object, by calculating the angle between the measuring station and the receivers transmitting data on the target direction and thus, by processing the obtained data, determining the AOA between the station and the target object. The presented algorithm ensures a high precision position estimation of an object and it can also be used to determine existing signal sources in the supervised area.[20]

The data provided by the existing receivers, most often constituted in complex sensor networks in which they are the nodes of the network, refer to the received signal strength or to the angles formed between the nodes that detect the signal from the target. Precise location of the target involves using data concerning the distance and direction from where the signal is received, then opting - depending on the processing algorithm, for the trilateration method - if processing distance data or for the triangulation method – if processing data about the receivers' direction or about the angles between the network receivers that receive the signal reflected by the target object.

Trilateration as a mathematical method for locating targets is used much more often compared to the triangulation method due to the high accuracy in obtaining data as well as the much lower production costs of object detection and location systems. As disadvantages in the use of the trilateration method we can mention the geometric restrictions generated by the landscape or other existing elements in the field that constitute an impediment to achieving a uniform trilateration network. Removing these shortcomings involves applying – depending on the complexity of the network and the dynamic characteristics of the monitored environment – solutions to increase redundancy, including: estimation of the angular values between network nodes, independent measurement of distance through the triangulation method, etc.

Comparing the two methods, trilateration and triangulation, we have identified limitations specific to each method that involve taking measures to remove them. Even if trilateration has the disadvantages mentioned in the above, we cannot assume that triangulation offers more precise location solutions compared to trilateration. On the contrary, if networks are properly configured, trilateration ensures accurate location at minimal costs. Triangulation is in turn dependent on angle measurement errors and the factors that can produce measurement errors are difficult to manage in small spaces, which are in a permanent dynamic. In conclusion, triangulation is preferable in open spaces, outside localities, while trilateration provides precise object location in narrow spaces, inside localities.

To this purpose, in order to reduce the impact of the limitations specific to each method and to increase the accuracy of target location, a combination of the geodetic methods of trilateration and triangulation is necessary. Triangulation and trilateration can be a redundant source to one another, contributing to the precise determination of objects within the same area of interest. The combined use of these methods will help obtain and maintain control on the situation of targets or objects in very large areas, both in airspace and on land or sea.

In the case of the passive radar, natural or artificial obstacles existing in the field limit the possibilities of detecting targets, by creating shading areas that will influence the monitoring

[19] Angle of Arrival.

[20] Davide Dardari, Emanuela Falletti, Marco Luise, *Satellite and Terrestrial Radio Positioning Techniques. A Signal Processing Perspective*, First Edition, Editura Academic Press, Oxford, United Kingdom of Great Britain, 2012, p. 4.

possibilities for the area of interest. In order to reduce the impact of these obstacles on the possibilities to accurately estimate the distance, it is necessary to identify solutions to ensure the optimization of the network made of radio receivers and opportunity illuminators existing in the field. One of the considered solutions involves locating the receivers on dominant elevations in the field, ensuring the reduction of shading areas created by the field obstacles, and the disposition in the form of a network will help increase the accuracy of target location.[21]

Given the above, we can conclude that a network of sensors must take into account the following aspects:

- existence of opportunity illuminators in the area of interest that can be exploited within the network in order to detect and locate targets;
- achievement of an optimal density in the network nodes, represented by opportunity illuminators and radio receivers, so as to ensure continuous surveillance of the area of interest;
- disposition of radio receivers on dominant land.

Regardless of the scientific apparatus used in the elaboration of algorithms and the geodetic methods used to determine the distance, passive detection systems will be the necessary means for monitoring very large areas of interest at much lower costs compared to the monostatic radar.

In conclusion, we can say that passive radiolocation through bistatic radars with or without a dedicated transmitter will play an important part in obtaining the real image of our area of interest. The inclusion of this category of radars in the aerial surveillance system and their disposition in the form of a network will ensure the improvement of detection possibilities and of the target location accuracy, providing higher quality information that will help increase the efficiency of air forces decision-making processes and their adaptation to the requirements of the battlefield.

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