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SUM-DIFFERENCE METHOD IN MONOPULSE RADAR: A REVIEW

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Abstract

This article reviews the sum and difference methods on monopulse radar used to detect targets during the tracking process. These methods are described in detail and comprehensively regarding optimizing the size of the subarray elements, optimizing the radiation energy of tracking targets, optimizing for obtaining lower sidelobe level and optimizing computations for digital processing. Considerations of potential strategies for configuring an implementable monopulse radar are also given. This article also provides answers when faced with the challenge of building a monopulse subarray radar that meets the implementation needs of both software and hardware. The expected result of this subarray on monopulse radar is to obtain flexible and general capabilities for detection and tracking that can adapt to target and environmental conditions, including countering interference and jamming.

Keywords:
Monopulse radar; subarray radar; sum and difference

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1. Introduction

The aim of this paper is to review the methods that have been proposed to improve performance and explore the development potential of monopulse radar. In general, monopulse radar is used to detect targets using beam sum and difference. The monopulse angle estimation technique is used to determine the target location during the target tracking process [1]. By comparing different signals received by two or more antennas simultaneously, monopulse radar can obtain angular information from the target. The monopulse ratio of a detection target is determined based on the ratio of the beam sum to the difference in the target location. Ideally the characteristic curve of the monopulse ratio is linear. To calculate the monopulse ratio, the beam sum and difference must be formed simultaneously and at the same time the sidelobe level (SLL) in both beams must also be suppressed [2]-[11]. There are two monopulse radar techniques for obtaining information about the angle of the target from the reflected signal, i.e., amplitude comparison and phased-comparison. In amplitude comparison, determining the pattern sum and difference is obtained from the beam amplitudes of two or more adjacent beams, so that to estimate the target angle it is necessary to determine the sum beam, horizontal difference beam (elevation direction information), and vertical difference beam (azimuth direction information). In amplitude comparison, the two beams have the same phase [14][22].

Based on the structure of the radar antenna array, monopulse radar is divided into monopulse phased array (PA) radar [1]-[7], monopulse multiple-input multiple-output (MIMO) radar [12]-[20], and/or monopulse subarray radar [21]-[31]. PA radar is a radar whose antenna elements are arranged closely spaced where the coherent gain obtained is high so that it is appropriate for tracking radar targets. There are three types of PA radar used, namely uniform linear array (ULA) [1][3], uniform planar array [2][5][7], and non-uniform planar array [4]. Accurate target location determination is determined by monopulse estimation radar PA through monopulse slope design and calculation using the Cramér-Rao bound (CRB) method [1]. There is also a monopulse ratio calculation on the planar PA radar which is used to determine two-dimensional target locations (elevation and azimuth) and is equipped with mainlobe jamming cancellation to increase target detection accuracy [2]. A study that proposes adaptive beamforming on ULA with interference cancellation so as to increase the monopulse ratio has been proposed by [3]. Likewise, the use of a nonuniform planar array with phased comparison monopulse produces performance that is as good as a uniform planar array, which has been reported by [4]. If the size of the antenna array is very large, it is necessary to adjust the excitation elements periodically so that it is more reliable and consistent in forming the desired sidelobe pattern as reported by [5]. Apart from setting the excited elements, it is also necessary to optimize them to produce a sum beam with maximum slope in the boresight (target) direction and optimally lowering the sidelobe envelope [6]. A study by [7] has reported that for fixed planar arrays it is necessary to design a pattern of sum and difference so that the radiation performance is maximum, such as field slope, amplitude, directivity and lower sidelobe.

For MIMO radar, the diversity gain will be explored because usually the antenna elements in transmit-receive are widely separated so they will have different angle values when viewing the target, especially related to the reflection coefficient of the target. In the research presented in [12], a technique is needed that is created using a 3-dimensional distributed array antenna on a MIMO radar so that a very narrow beam is formed. Apart from that, several advantages of MIMO radar compared to PA radar are the increase in spatial degree of freedom and detection/estimation probability [13]. According to [14] that the use of multiple widely separated antennas will provide significant improvements in spatial diversity compared to PA radar. Multiple widely separated antennas can also be equipped with frequency diversity, spatial diversity, and polarization diversity so that they are able to mitigate angular glints and at the same time increase the amount of energy in the reflected signal from the detection target [15]. The use of orthogonal waveform transmission will increase angular resolution in coherent MIMO scenarios and higher detection probability in statistical MIMO scenarios [16].

The monopulse subarray structure usually uses PA radar as its constituent and is non-overlapped. The types of subarrays are linear arrays [21]-[22], [28]-[31], uniform planar arrays [23]-[25], and nonuniform arrays [26] as shown in Fig. 1. The general purpose of using subarrays in monopulse radar is to reduce hardware costs and circuit complexity, making it easier for digital processing [21]-[23], to optimize subarray excitation with various methods [24]-[26], overcome beam shape loss and suppress jamming. and interference [27][31], maximizing directivity [28], and minimizing sidelobe levels [29][30].

Based on the literature used in this paper, the monopulse subarray method is widely used in uniform array radars, both linear arrays and planar arrays. To obtain information on the angle of the detection target in the elevation and azimuth directions, a planar array is used. Monopulse with AC is more attractive and simple to implement compared to PC. However, when using subarrays in monopulse radar, you must also consider things such as subarray element size, subarray excitation, maximum directivity, lower SLL to minimize the effect of interference and jamming, simplifying the computing time of digital processing, and considering implementation costs.

2. Method

This section provides an explanation of the monopulse radar signal model, existing methods for this radar and potential strategies for implementing this radar including its challenges.

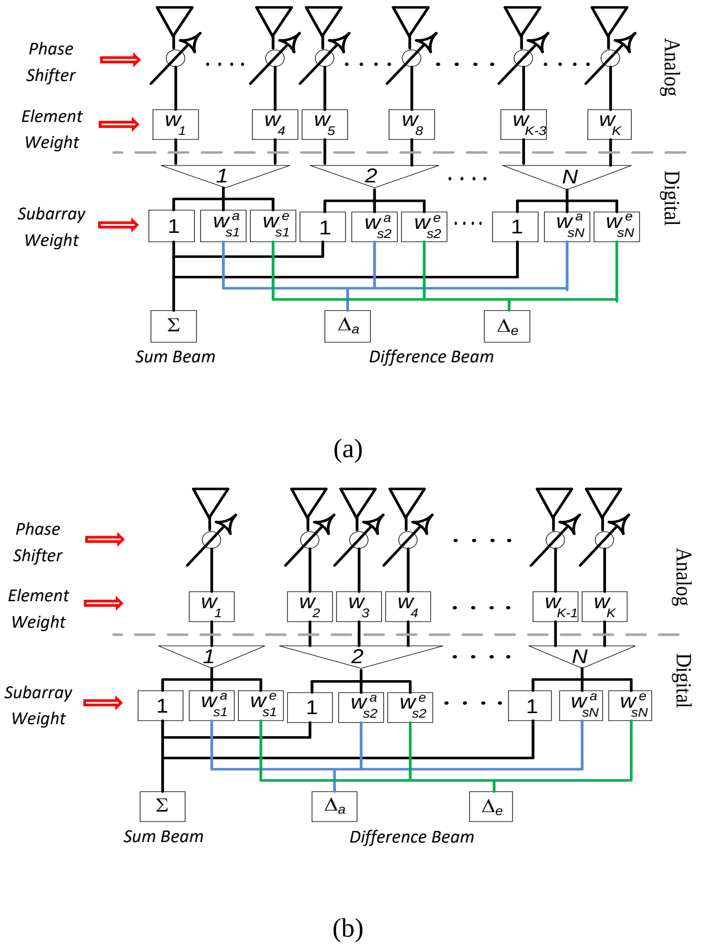
A. Monopulse Radar Signal Model

In this section, a general illustration for monopulse radar will be given so as to provide systematic thinking about things that need to be developed in monopulse radar. If it is assumed that there are K antenna elements grouped into N-subarrays as shown in Figs. 1(a)-(b) where Fig. 1(a) for uniform and uniform subarrays the number of elements per subarray and Fig. 1(b) for varying subarrays. The weighting at the analog level is called $\mathbf{w}_k$ with $k = 1, 2, ..., K$ and there are two types of weighting at the digital level, i.e., subarray weighting for beam difference azimuth and elevation respectively, i.e., $\boldsymbol{w}_{sn}^{a}$ and $\boldsymbol{w}_{sn}^{e}$ with $n = 1, 2, ..., N$. Meanwhile, the beampattern sum is Σ and the beampattern difference angles of azimuth (φ) and elevation (θ) are Δ_a and Δ_e, respectively. If it is stated that the transformation operation of elements into subarrays is non-overlapped, it is expressed by the following $K \times N$ dimensional matrix $\mathbf{T}$ [23]

$$\mathbf{T} = diag(\boldsymbol{\psi} \circ \mathbf{w}_k)\mathbf{T}_o \tag{1}$$

where $\circ$ is the Hadamard product, $diag(\cdot)$ is the diagonal matrix, $\boldsymbol{\psi}$ is the analog phase shifting vector, $\mathbf{w}_k$ is the amplitude tapering on the k-th antenna element, and $\mathbf{T}_o$ is the transformation subarray matrix which is given a value, i.e.,

$$[\mathbf{T}_o]_{kn} = \begin{cases} 1 & k\text{th element} \in n\text{th subarray} \\ 0 & k\text{th element} \notin n\text{th subarray} \end{cases} \tag{2}$$



(a)

(b)

Figure 1. Illustration of subarray configuration on K-elements into N-unit non-overlapping subarrays with: (a) uniform subarrays and (b) non-uniform subarrays.

The sum pattern is optimized with fixed excitation at the element level so that $\mathbf{w}_k = \mathbf{w}_{os} = \mathbf{a}_{os}$ where $\mathbf{w}_{os}$ is the element weighting through optimization synthesis, $\mathbf{a}_{os}$ is the optimization sum vector of array factors, $u = \sin(\theta)\cos(\varphi)$, and $v = \sin(\theta)\sin(\varphi)$ [23], while the difference pattern is synthesized at the subarray level whose value is the same as the reference weight. The following are the equations for beampattern sum (Σ), beampattern difference azimuth (Δ_a), and elevation beampattern (Δ_e), respectively, i.e.,

$$\Sigma(u,v) = \mathbf{w}_k^H \mathbf{a}(u,v) \tag{3}$$

$$\Delta_a(u,v) = \mathbf{w}_{sn}^{aH} \mathbf{T}^H \mathbf{a}(u,v) \tag{4}$$

$$\Delta_e(u,v) = \mathbf{w}_{sn}^{eH} \mathbf{T}^H \mathbf{a}(u,v) \tag{5}$$

where $\mathbf{a}(u,v)$ is the steering vector in the planar array.

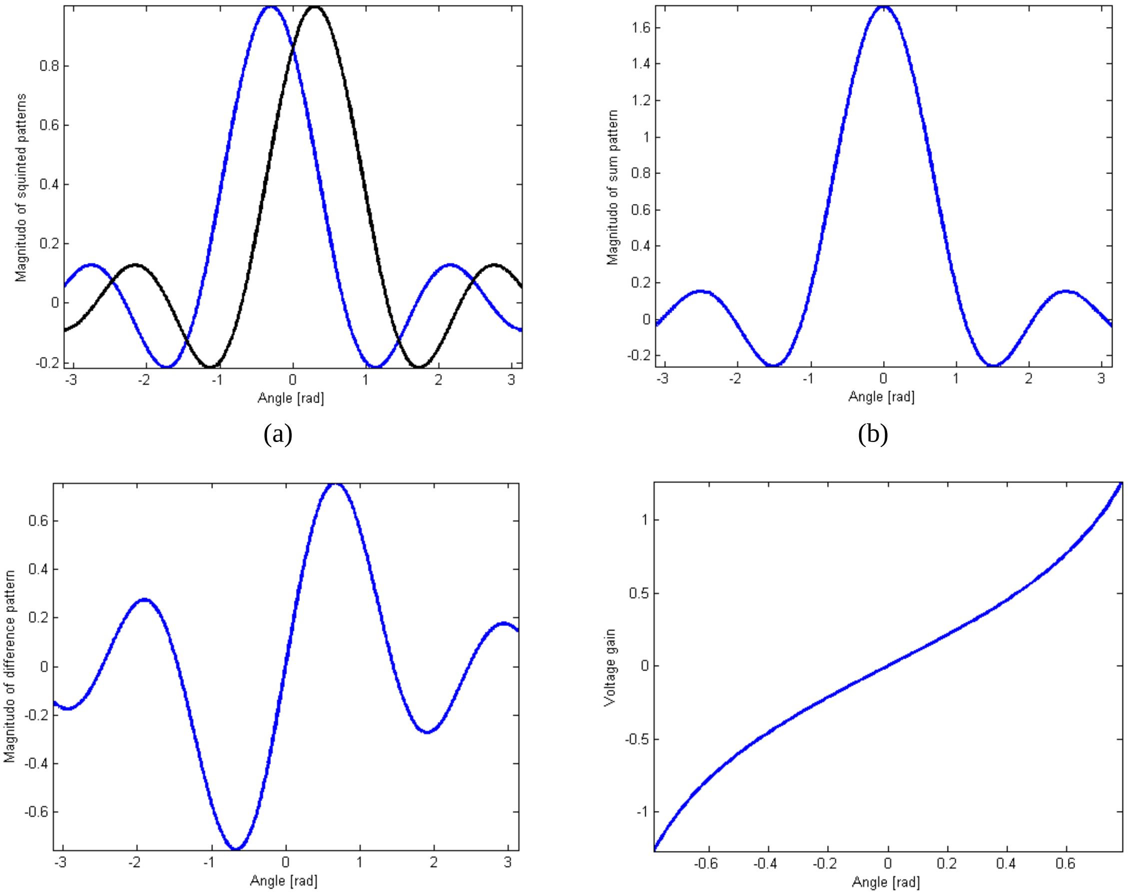
To synthesize a monopulse radar signal model, a detailed description is in the literature [21], [22], [27], [29] for the uniform subarray method and in the literature [23]-[26], [28] for the non- uniform subarray. Meanwhile, to clarify the beampattern on monopulse radar, it is presented in Fig. 2. Figures 2(a)-(d) show the antenna patterns of two monopulse beams where Fig. 2(a) shows two types of beams from a monopulse radar, Fig. 2(b) shows the beampattern sum results, Fig. 2(c) shows the beampattern difference, and Fig. 2(d) shows the ratio between beampattern difference to beampattern sum.

B. Existing Methods for Monopulse Radar

In this section, we discuss the methods proposed by researchers regarding monopulse subarray radar to improve radar performance, especially target tracking and monopulse ratio calculations. These methods relate to optimizing the size of subarray elements, optimizing excitation matching in subarrays, increasing maximum directivity, optimizing to obtain lower SLL to minimize the effects of interference and jamming, and computing optimization of digital processing.

1. Optimize the size of subarray elements

Several methods have been introduced in the literature to determine the size of subarrays in monopulse radar. The size of the subarray, which is actually a phased array, really determines the coherent gain on the mainlobe, SLL, and the directivity of the beam pattern, all of which determine the success of the target tracking process on the radar. There are uniform and nonuniform subarray sizes. Unlike uniform subarrays [21][22][27][29], in nonuniform subarrays each subarray in monopulse radar has an unequal number of antenna elements which generally aims to obtain a beampattern sum and difference with lower SLL and minimal excitation matching error. Various methods to obtain the optimum size for each non-uniform subarray so that the excitation matching error is minimal include: K-means clustering [23], excitation matching [24][25][28], and convex programming [26]. Still related to optimization methods, the differential evolution method is applied by [30] to regulate the size of subarrays with contiguous elements to reduce the influence of crosspoints. In digital processing which prioritizes fast and robust computing output, the steady state condition is desired as quickly as possible, so determining the size of the subarray must also take this into account.



(a) (b)

(c) (d)

Figure 2. Beampattern on monopulse radar for: (a) two beampatterns with an angular difference of 0.3 radians, (b) beampattern from sum, (c) beampattern from difference, and (d) ratio beampattern from difference to sum.

2. Optimization of target tracking energy radiation

In monopulse radars used for target tracking, transmission power consumption must be considered. The excitation matching optimization technique is related to the energy consumption of the transmission transmitter to the target so it is necessary to consider factors such as low SLL, low component complexity, high directivity, and low cost. In optimization techniques, the size of the subarray also influences the determination of these factors, but this technique prioritizes power consumption in its computational programming capabilities. Research on the use of the excitation matching technique is by compromising between the difference pattern and the optimum sum mode obtained by a two-stage excitation matching procedure [28]. The use of subarrays with contiguous elements reported by [30] can reduce crosspoint effects on nonuniform subarrays thereby providing efficient and practical radar performance bandwidth. Meanwhile, in a study by [39] using an ultra-wideband (UWB) monopulse radar equipped with a linear frequency modulation signal, high detection and tracking resolution was obtained.

3. Optimization obtains lower SLL

There are several methods for reducing SLL in several literatures. Digital weighting in the form of Taylor for the beam sum and Bayliss taper for the difference beam is carried out at the subarray level so that the mainlobe of both beams increases [21]. In the study reported by [22] that to reduce the SLL, subarray weight selection was used using the Wiener-Hopf method, i.e., by determining the minimum square error rule on the monopulse signal output and the desired signal. Apart from getting the optimum size of each subarray so that the excitation matching error is minimal, K-means clustering also reduces SLL [23]. The K-means clustering method is a development of the excitation matching method by [24], [25], and [28] to obtain the optimum weighting and size of monopulse subarrays as well as subarray weighting with convex programming by [26]. Still related to optimization methods, the differential evolution method is applied by [30] to arrange subarrays with contiguous elements to reduce the influence of crosspoints. Apart from this, the optimization method is interesting for further research but is relatively difficult to implement. A simple method to minimize SLL while overcoming the effects of interference and jamming is adaptive beamforming in the form of moving variance distortionless response (MVDR) by [27] with a similar working principle to the study by [22]. Also, no less important was the development by [29], i.e., forming an ultra-SLL with a phase shifter control type time modulated array antenna.

Of the methods that have been developed to obtain lower SLL, they can be classified into two types, namely programming optimization methods and adaptive filtering methods. For implementation considerations, it seems that the adaptive filtering method is more relevant than the programming optimization method. The development of digital processors with high computing capabilities supports the application of this subarray optimization method.

4. Computational optimization for digital processing

Determining the subarray size clearly requires high and fast computational optimization. The consideration is to obtain a beam sum and difference in monopulse radar that has low SLL, low component complexity, high directivity, and low cost. The optimization methods developed in [23]-[26] and [28] attempt to answer these challenges, but have not yet attempted to consider transmit energy consumption and its implementation. In the study reported by [31], the implementation of FPGA with adaptive subarray or random subarray has overcome high computing requirements and resource availability.

C. Potential Strategies and Challenges in Monopulse Radar

After getting an overview of several methods used in existing monopulse radars, a scenario or strategy will be created to form a reliable subarray monopulse radar in accordance with implementation considerations. These considerations are based on various factors, i.e.: (a). simplicity of design in terms of digital processing software and hardware, (b). monopulse subarray radar design with adaptive beamforming using programming optimization, and (c). using overlapped subarrays with either equal or unequal number of elements to overcome resource limitations and involve high computing in digital processing.

Research on antennas for monopulse radar applications has been widely investigated as well as transmit/receive (T/R) modules, thus supporting the implementation of point (a). For example, in the study presented by [32], the design of a monopulse microstrip antenna array with a single layer, a working frequency of 13.85–15.1 GHz, and cheaply can provide two-dimensional target tracking performance and also supports subarray operations. Antenna design for K-band single layer with substrate integrated waveguide (SIW) for a planar array type monopulse tracking system has been reported by [33]. Another planar array antenna design with a slotted waveguide working in the Ka-band has been discussed by [34]. Meanwhile, an example of a T/R module design for monopulse radar is a study by [35] regarding a T/R module and microstrip antenna for millimeter-wave applications.

Points (b) and (c) can be a challenge and have the potential to become the latest research on monopulse radar. Point (b) has been supported by research [23]-[26], [28], and [31] how the monopulse subarray radar has subarrays that are ununiform, non-overlapped but perform satisfactorily, namely high diversity, lower SLL, and adaptive beamforming. The potential that occurs is a hybrid method of existing optimization methods or their development and the next challenge is its practical implementation. Meanwhile, point (c), which is related to monopulse overlapped subarray radar, has not yet been investigated in detail, especially with regard to the beam sum and difference calculation methods up to the monopulse ratio.

An illustration of the overlapped subarray configuration is presented in Fig. 3. However, research on radar overlapped subarrays has started with the number of elements per subarray being equal by [36] and the number of elements per subarray being unequal by [37] and [38]. In the study by [36] proposed a Phased-MIMO (PMIMO) radar approach, which is a compromise of the main advantages of PA radar, namely coherent gain, and the main advantages of MIMO radar, which produces radar performance for transmit-receive gain that outperforms two other types of radar, namely PA and MIMO. and robust against interference. Other advantages of PMIMO are increasing angular resolution, high number of detection targets, increasing identification parameters, expanding the array aperture, increasing degrees of freedom, forming virtual arrays, and robustness against beam-shape loss [36]-[38]. Thus, the challenge is to derive a signal model for the overlapped subarray and then analyze and synthesize it as done by [23]. It is possible to find a general approach or generalization of existing monopulse subarray radars.

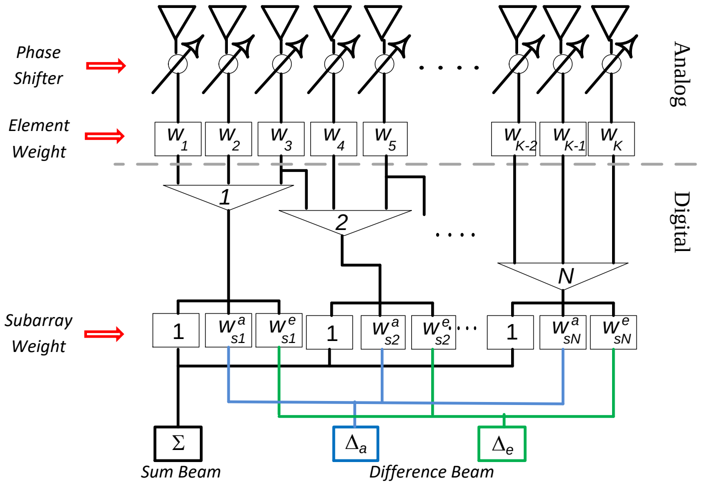


Figure 3. Illustration of the configuration of a *K*-element subarray into *N*-unit overlapped subarrays with uniform subarrays.

Table 1. Summary of Key Parameters for Monopulse Radar

Ref. No.	**Types and Conditions of Arrays**	**Number of Targets**	**Key Findings**
[1], [32], [39]	PA-ULA Rx	Single	Decreased monopulse angle accuracy with the CRB method, use of the DBF difference subarray, and microstrip antenna array
[2], [5], [22], [29]	PA-Planar array	Single	There are two beams, namely sum beam, difference/delta beam azimuth and delta elevation and sidelobe control is carried out on the sum beam with Taylor weighting and the delta beam with Bayliss weighting
[3], [9]	ULA	Single	Taylor and Bayliss weighting to reduce sidelobes and observe the effect of interference and jamming on the monopulse ratio and using a Doppler filter
[4]	Nonuniform planar array	Single	Overcoming grating lobe

[6], [7]	Planar array	Single	Synthesis of optimal excitation from sum and difference patterns using convex (quadratic) programming procedure to solve computational problems on large planar arrays
[8], [10]-[20]	MIMO	Multiple	Using the adaptive monopulse estimation method in mainlobe jamming and phase comparison beamforming
[21], [24], [27]	PA-subarray	Multiple	Using full digital weighting
[23], [25]-[26], [28]	Planar-subarray	Multiple	Optimization using the K-Means clustering method
[30], [31]	PA-subarray	Multiple	Optimization with DE algorithm
[33]-[35]	PA	Single	SIW method with slot antenna
[36]-[38]	PMIMO-uniform subarray	Multiple	Application of subarrays in ULA antennas

3. Conclusion

In this article we review sum-difference methods in monopulse radar. Several methods to improve the performance of monopulse radar such as subarray element size optimization, target tracking energy radiation optimization, optimization of obtaining lower SLL, and computational optimization for digital processing have been presented comprehensively. Considerations for potentially implementable monopulse radar configuration strategies are also presented. Finally, this paper aims to answer the challenge of creating a monopulse subarray radar that meets implementation requirements both in software and hardware. In the future, the author would like to investigate the implementation and explore the possibility of combining all methods from monopulse radar into a prototype form and tested for detection and tracking of single or multiple targets which also takes into account the presence or absence of noise, interference and jamming.

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