Fundamental Performance Limitations of Radar Networks

I Papoutsis, C J Baker, H D Griffiths
University College London
Department of Electrical and Electronic Engineering
Torrington Place, London, WC1E 7JE

Abstract

Most current radar systems are monostatic i.e. the transmitter and receiver are co-located. The performance of these forms of radar has been greatly enhanced by the advent of high resolution, imaging, low side lobe antennas and, high speed digital signal processing and other technology improvements. However, it is well known that when a target is illuminated by Electro-Magnetic radiation scattering occurs in all directions. Hence a single receiver can only intercept a very small portion of this energy and much of the signal and its information is lost. Netted (or multi static) topologies overcome this limitation and offer the potential to extend the capabilities and performance of current radar systems. In this paper, an introduction to the concept of netted radars is provided and the various advantages and technical challenges are presented. An initial classification and categorization of the types of possible radar network is introduced. Additionally the ambiguity function is described for both monostatic and bistatic geometries and is used as the basis for developing a description of the key performance parameters in a radar network. The paper concludes with a description of future research activities aimed at evaluating the fundamental performance limitations of radar networks.

Keywords: Netted radars, Bistatic, Multistatic, Ambiguity function, Matched filter

Introduction

It is well known that when a target is illuminated by Electro-Magnetic radiation scattering occurs in all directions. Hence the single receiver of a monostatic radar system can only intercept a very small portion of this energy and much of the signal and its information is lost. Netted topologies overcome this limitation by using a number of transmitters and receivers and hence offer the potential to extend the capabilities and performance of current radar systems. In the most general case of a netted system, multiple transmitters and receivers are used and the echoes from the target in different directions are collected. In essence, with multiple transmitters and receivers one can have many perspectives of the same target and can exploit, in an optimum way, the scattered electromagnetic energy.

One of the inherent properties of netted radars is the increase in the number of degrees of freedom [1] for system design. This is, of course, due to the spatial diversity resulting from distribution of the elements (transmitters and receivers) that comprise the total sensing system. It is this feature that leads to the potentially superior performance of this class of radar system.

There are a number of advantages that this provides. For example spatial distribution of the nodes of the radar network enables the area to be surveyed and to be tailored according to the specific application. Additionally, it is possible to increase sensitivity, as more of the scattered energy (in the different directions) can be collected and hence detection performance can be improved. Target classification and recognition can also be enhanced. This is because the target is observed from different perspectives. Increased survivability and reliability is also achieved because of the 'silent' or passive operation of the receivers. These receivers can improve the location accuracy of possible jammers by fusing the information from the network nodes. Often monostatic radar systems do not have line of sight to a target and hence cannot provide detections. The likelihood of obtaining a line of sight is greatly improved in a network. Finally, if a single node is lost in the network it can still provide a level of (reduced) performance and the network is said to exhibit graceful degradation.

The technical challenges of a radar network are numerous because of the increased complexity of the system. The most important is probably time and frequency synchronization for coherent operation. Work presented at [2] for multistatic radars has proven that by using the Global Positioning System (GPS) as a reference timing signal, the network can be made coherent. Another important parameter is location optimization, which is of primary interest [3] for detection and tracking of targets. Finally, netted radar data fusion is also much more complex and the distributed nature of the system requires a distributed approach to most effectively combining the various data streams. This also, of course, implies the need for reliable, effective and high capacity communication links in the network [4].

There are many possible applications of multistatic radars, both in the military and civilian domains. For defence purposes, multisite radars can be used to form a specially designed surveillance area and hence more efficiently detect targets based upon known patterns of military behaviour. In addition, systems sensitivity can be improved and enable the detection of stealthy targets. Current stealth aircraft are generally designed to be stealthy to monostatic radars. This means that energy is scattered at other angles and can thus be collected within a netted topology [5]. Finally, a network, is capable of generating multi-perspective SAR or ISAR imagery that can be used for military ground surveillance and targeting [6]. This can also be used as an input to a tomographic reconstruction of a targets three-dimensional reflectivity function.

A number of civilian applications are also worth mentioning. As in the military field, the surveillance capabilities in an airport can be enhanced. Air Traffic Control benefits by reducing the degrading multipath phenomena and exploiting spatial diversity [7]. Other applications involve sensor networks for next generation vehicular management [8,9], weather radar, investigation of flow phenomena such as wind vector measurements [10] and medical imaging.

Related work

Netted radar is a concept that has been considered previously and there has even been a special issue on bistatic/multistatic radars [23]. However, only combining data at the output of individual monostatic radar systems was considered so these may be thought of as non-coherent networks. Many of these ideas are now embodied in the concepts underpinning the 'Network Enable Capability' (NEC). Advances in digital signal processing technology have enabled the inherent increase in complexity of these systems, especially in terms of achieving coherency, to now become realistically feasible.

The obvious benefits offered by netted radar systems has led to continuous research on this field albeit, until recently, at a relatively low level. In [12], defence scenarios using multiple radar sensors were investigated, focusing on detection and classification of targets. Here, radars are positioned on 100 foot towers with the objective of detecting human motion in a 20Km by 20Km area. Aspects such as finding an appropriate common coordinate system were addressed.

Another alternative but complementary approach is that proposed in [13] where the system includes a number of transmitters (television signals) and a single receiver. This is multistatic synthetic aperture imaging where each bistatic measurement represents a sample of the Fourier transform of the reflectivity function of the target.

A number of issues which affect the performance of netted radars have been studied. It should be noted that these are often studied for a particular and very specific application. These studies have examined aspects of the data fusion layer [14], clutter rejection techniques [15], classification of targets [16] and target location and tracking [17].

Lastly, we note a project initiated by the US Air Force Research Laboratory known as TechSat 21. Its purpose is to perform various missions, such as RF imaging, moving target indication, geolocation, anti-jamming and terrain elevation measurement [11]. TechSat 21 is a speceborne satellite radar network, employing a cluster of satellites in a single orbital plane. Each satellite transmits its own orthogonal signal at X-band and is receiving all reflected signals. The coherent network is acting as a large interferometer. The main problems identified were the difficulty to establish coherency, the ability to achieve distributed processing in an optimum way, grating lobes appearing due to the sparsely filled arrays and the cost [11].

Categorisation of radar networks

Before proceeding to analyze the fundamental technical characteristics of netted radars, it is appropriate to categorise the various types of radar network in terms of their physical properties and potential applications.

The first aspect in this categorization is the transmitting and receiving options of the nodes in the network. There are three main categories: monostatic, bistatic and a combination of the two. In the multiple monostatic case, each radar system is transmitting a specific signal and receiving only the echo originating from its own station. An example of the multiple bistatic case is a network comprising one common emitter and N spatially separated receivers. Each transmitter-receiver pair is a bistatic radar. Lastly, a combination of these is possible, where in the most general case each node in the network has a transmitter and a receiver. Each receiver can accept echoes reflected for any transmission.

Another feature of multisite radars is topology. This concerns the location of the radar nodes comprising the overall system [18]. The radar network can be a ground based multisite radar system with fixed baselines. This does not imply that the system components cannot be relocated. It does however, make the point that a fixed configuration is important in that the relative positions of the nodes need to be known to a high degree of accuracy. If the ground nodes can move, the baselines change. This mobility introduces more degrees of freedom but also increases complexity (i.e. we still need to know where the nodes are and at what time). Another approach is to locate only the transmitters on an air or space platform and the receivers on the ground. This can be taken further with both the transmitting and the receiving stations located on a platform that is entirely airborne or spaceborne [11].

Finally, shipborne multisite radar is possible where the radar nodes are on more than one ship. An example of this is shown in [19], where a bistatic sonar system is implemented, with one ship operating in a passive listening mode and another ship carries the active sonar.

The last example implies a further degree of categorization: i.e. active and passive modes of operation. The active mode is used to locate non-cooperative targets. It's also possible to have many spatially separated receivers collecting radiation emitted from other sources. This system is therefore operating in a passive mode. It should be noted that this type of operation is useful for locating jamming sources. Also, a combination of these two modes can also be employed. Indeed the distinction between radar and ESM systems becomes very blurred.

An important aspect in netted radars is coherency. Information extraction in coherent networks is enhanced significantly when compared to non-coherent systems. Temporal coherence, which may be achieved with GPS time transfer or via an atomic clock will be examined in a later paper.

A final discrimination of netted radar systems is in terms of the distributed aspects of radar signal processing characteristics. The main categories are centralized and decentralized (distributed) processing for netted systems. As presented in [20], there are several parameters to be taken into account when examining the distribution characteristics: the sensitivity and the robustness of the network and the grouping of the measurements from each radar system. Sensitivity of the system is related to the communication capacity capabilities of the network. The more data (i.e. energy) that can be sent, the better the overall sensitivity and the more centralized the system. This though, requires wideband transmission which may be prohibitively expensive. Alternatively each radar can perform some preprocessing of the data before transmitting to the central station. These results are sent to the central station for fusion, where the final processing and decision making is carried out. This is decentralized processing. Alternatively, all radar measurements can be sent to the central station for direct detection and tracking.

Ambiguity function

The ambiguity function has been widely recognized as a very important tool for radar signal design and for quantitatively assessing the performance of a system in terms of range and Doppler ambiguities and range and Doppler resolution. It is formed from the output of a matched filter in the receiver. The input signal is a copy of the transmitted one but shifted in the frequency domain due to the Doppler Effect. Thus the output is:

$$X(\tau,\nu)=\int_{-\infty}^{\infty}u(t)u^{*}(t-\tau)e^{j2\pi\nu t}dt$$

where $u(t)$ is the complex envelope of the transmitted signal, τ is the expected delay of the original signal and ν is its Doppler shift. The ambiguity function is defined as $\left|X(\tau,\nu)\right|^{2}$.

The original formulation of the ambiguity function was by Woodward [21]. It must be stressed that this was only to describe simple monostatic radar. The netted case is considerably more complicated. Here we introduce the ambiguity function for monostatic radar to indicate the features that must be preserved in a netted formulation. Figures 1-3 illustrate typical properties of a monostatic ambiguity function.

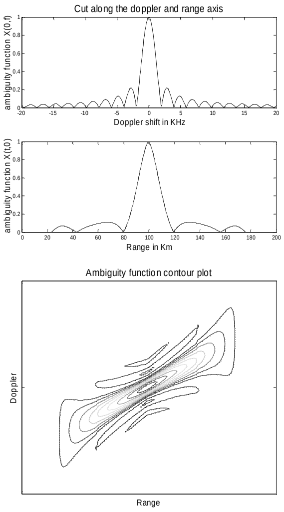

Figure 1: FM pulse (500µs period). Cut along the Doppler and Range axis and contour plot. Stationary target at 100km.

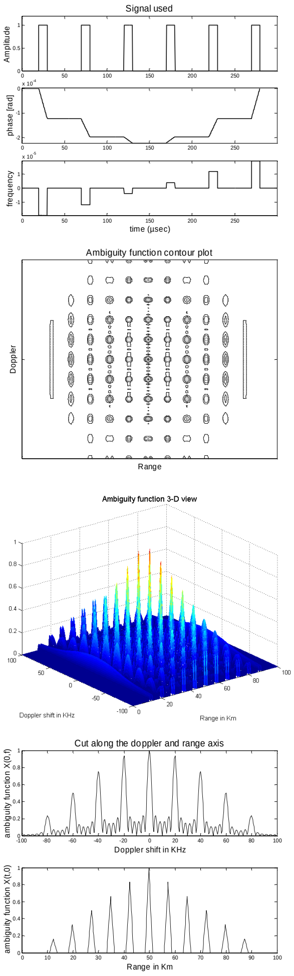

Figure 2: Stepped frequency pulse train (10µs pulse duration). Signal representation, contour plot, 3-D plot and cut along the Doppler and Range axis. Stationary target at 50km.

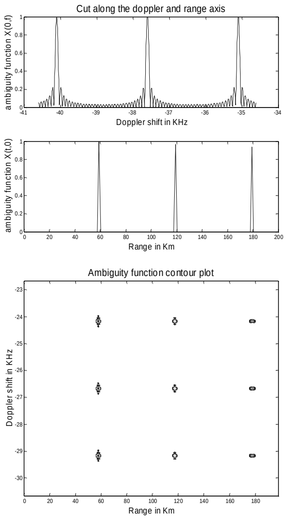

Figure 3: Coherent pulse train (2.5 KHz PRF). Doppler and Range cuts and contour plot. Moving target at 60km

The next step is to examine the bistatic configuration. This analysis is based on [22] and stresses the importance of target location in determining the shape of the bistatic ambiguity function. Figure 4 illustrates a typical bistatic geometry.

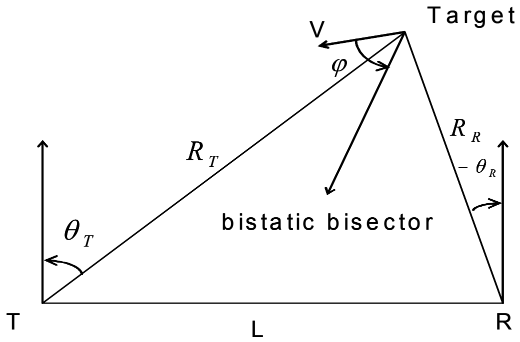

Figure 4: Bistatic topology

And the general bistatic ambiguity function is:

$$X(T,\omega_D)=\int_{-\infty}^{\infty}u(t)u^*\left(T\left(R,\theta_R,L\right)-t\right)e^{j\omega_D\left(R,\theta_R,L,V,\varphi\right)t}\,dt$$

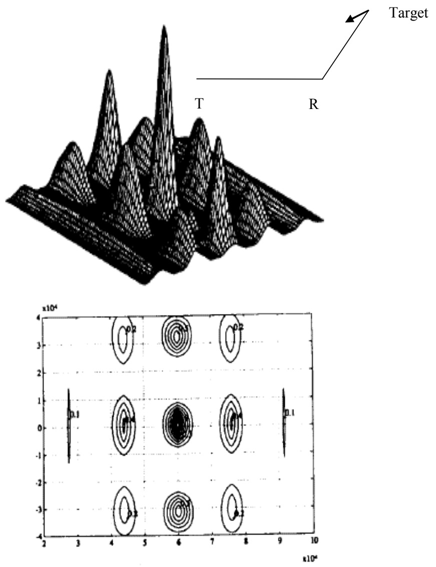

Figure 5: Coherent pulse train.3-D view and contour plot for the geometry shown [22].

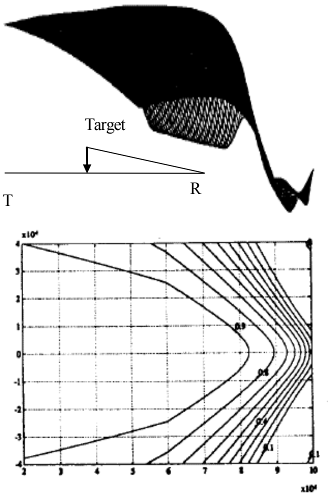

Figure 6: Coherent pulse train.3-D view and contour plot for the geometry shown [22].

It is evident that target's location is crucial for determining the output of the matched filter. In the second case, where the target is close to the baseline, the ambiguity function shows that information extraction with this topology is near impossible. This will also be a characteristic of netted radar systems and must be catered for in any mathematical formulation and in the design of real systems.

Conclusions and further work

In this paper we have reviewed netted radar outlining the performance advantages and technology challenges. The different types of possible network have been identified and a set of categorisations developed. In particular we have identified the need to quantify detection performance. We have also highlighted the utility of the ambiguity function as a tool for determining ambiguity and resolution properties in range and Doppler. This is greatly complicated in the case of netted radar with target position influencing the ambiguity behaviour.

Further work will evaluate netted radar advantages in terms of target detection performance using a method for extracting the parameters normally deduced from the ambiguity function and will thus enable the fundamental performance limitations of netted radar to be interrogated.

Acknowledgments

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