Multistatic, MIMO and Networked Radar: the Future of Radar Sensors?

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***Abstract*— A review is presented of work on multistatic, MIMO and networked radar, explaining the current high degree of interest in these subjects. The enhancement of target signatures in the forward scatter geometry is explained, and some of the principles of Passive Bistatic Radar. The challenge here is to identify applications which offer a clear advantage over conventional radar approaches. Finally, some newer, longer term ideas on networked radar as an intelligent, adaptive distributed sensor system are presented and discussed.**

***Keywords*—Bistatic radar, multistatic radar, MIMO radar, Passive Bistatic Radar**

I. INTRODUCTION

Bistatic, multistatic and MIMO radars are presently the subject of a great deal of interest and work. The subject actually has a long history, and numerous experimental systems have been built and evaluated, though there have been rather few operational systems. One of the first bistatic systems was the German WW2 *Klein Heidelberg* which 'hitchhiked' off the British Chain Home radars [1]. This achieved remarkable results, but was too late to have any significant effect on the outcome of WW2. Since then, interest has varied cyclically, with a period of about 15 years. We are presently in the 'third resurgence' and there are now good reasons to believe that the interest will continue and grow [2], [3].

Some of the reasons for the present interest are:

- bistatic radar has potential advantages in detection of targets which are shaped to scatter energy in directions away from the monostatic;
- the receiver is covert and therefore safer in many situations;
- countermeasures are difficult to deploy against bistatic radar;
- increasing use of systems based on unmanned air vehicles (UAVs) makes bistatic systems attractive;
- many of the synchronisation and geolocation problems that were previously very difficult are now readily soluble using GPS, and
- the extra degrees of freedom may make it easier to extract information from bistatic clutter for remote sensing applications.

Fig. 1 shows an attempt to classify bistatic and multistatic radar systems according to their properties. Bistatic radars may be defined as those in which the transmitter and receiver are at separate locations, sufficiently separated that the properties are significantly different to those of a monostatic radar. Radars which use separate but co-sited transmit and receive antennas (*quasi-bistatic* radars) are classified with monostatic radars. Bistatic and multistatic radars are classified into those which use cooperative transmitters under control of the user, and those which use non-cooperative transmitters. These are further divided into those for which the transmitter is a radar, in which case the system may be known as a *hitchhiker*, and those for which the transmitter is a broadcast, communications or radionavigation signal, in which case the system is called a Passive Bistatic Radar (PBR).

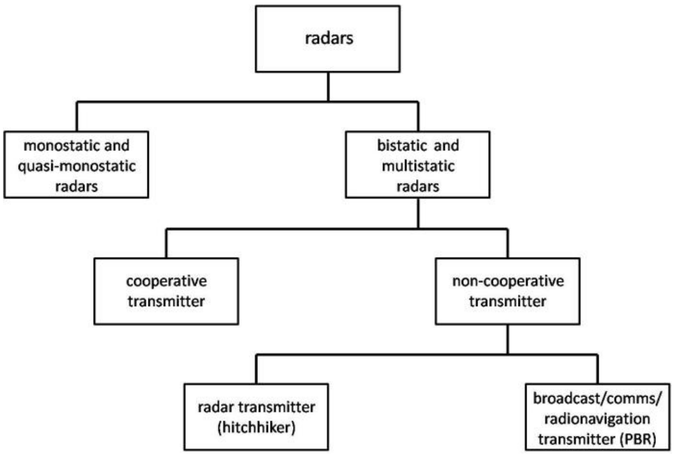


Fig. 1 Taxonomy of bistatic and multistatic radars.

MIMO is a relatively new, fast-changing, and perhaps even controversial subject (as may be seen by the titles of some of the publications on the subject [4]–[6]), and whose origins lie in the communications domain. In the radar domain MIMO should not be regarded as a separate subject, but rather as part of a continuum of different types of multistatic, networked sensing. Almost all work to date has been theoretical or based on simulations. This is perhaps similar to the evolution of work on STAP, in which it was only after several years of theoretical and simulation work that algorithms were evaluated in real environments with real data [7], [8].

II. FORWARD SCATTER

One of the mechanisms by which target bistatic signature may be enhanced is forward scatter, when the target lies on or close to the bistatic baseline between the transmitter and receiver. It was first identified by Siegel *et al*. in 1955 [9], subsequently reported by Siegel in 1958 [10], and then expanded upon in numerous papers and books.

This may be understood with reference to Babinet's Principle. Essentially, provided the wavelength λ is small compared to the target dimensions, the forward-scattered signal diffracted past a target of silhouette cross-section A must be equal and opposite to that diffracted through an equivalent target-shaped hole in an infinite screen. The forward scatter RCS is given by:

$$\sigma_B = \frac{4\pi A^2}{\lambda^2} \tag{1}$$

with an angular width of λ/d (in radians) where d is the linear dimension of the target in the appropriate plane. Fig. 2 plots these, as a function of frequency, for a typical small aircraft target (A = 10 m^2, d = 10 m).

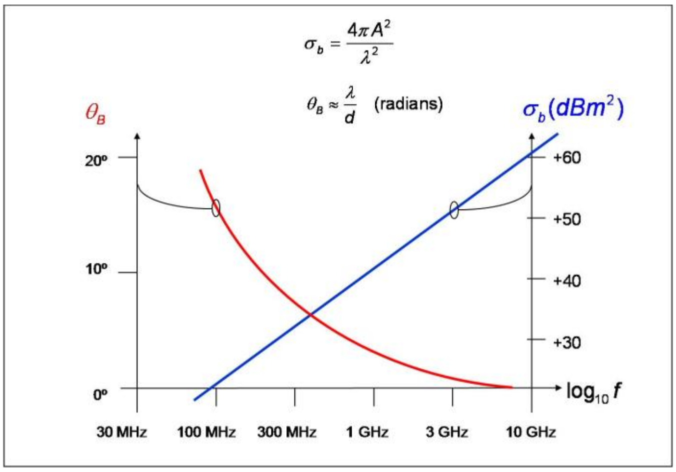


Fig. 2 Forward scatter RCS (σ_B) and angular width of scatter for a typical small aircraft target (A = 10 m^2, d = 10m), as a function of frequency.

It can be seen that this RCS can be substantially higher than the conventional monostatic RCS (which might be of the order of 10 – 100 m^2, and rather less for a stealthy target). However, this advantage comes at a price, since the forward scatter geometry gives very poor range and Doppler resolution. This can be appreciated more formally by evaluating the ambiguity function of the radar waveform as a function of the bistatic geometry, when the width of the peak of the ambiguity function 'blows up' for targets on or close to the bistatic baseline [11].

III. PASSIVE BISTATIC RADAR

Passive Bistatic Radar (PBR) is the name given to a type of bistatic radar in which the illuminating source is a broadcast, communications or radionavigation signal. PBR has a number of obvious attractions, in addition to those identified in Section A. PBR systems will often use VHF or UHF frequencies which are not normally available for radar use, and where RCS reduction techniques may be less effective than at microwave frequencies, since target dimensions will often be of the same order as the radar wavelength. Also, the ever-greater congestion of the electromagnetic spectrum represents a problem for almost all radar applications, but for PBR is actually an advantage. Finally, the receiver systems can often be rather simple and low cost, and there is no need for any licence for the transmitter.

These factors, and particularly the latter two, have meant that PBR has been an ideal subject for research by university labs, and many such systems have been built and demonstrated. Despite this, there have been rather few examples where PBR systems have been able to offer a clear advantage over conventional radar approaches.

Notable exceptions to this include low-cost scientific measurements of the ionosphere [12], planets [13], wind [14], [15] or thunderstorms [16]. PBR has also been proposed as a 'gap filler' where coverage of conventional air surveillance radars is compromised, for example by wind farms. Two examples of commercially-available PBR systems are Lockheed Martin's *Silent Sentry* [17] and THALES's *Homeland Alerter*. Nevertheless, the challenge to bistatic /multistatic systems in general and PBR systems in particular remains to identify and exploit applications where there is a clear advantage – in terms of performance and/or cost.

A. PBR Signals and Waveforms

There is a wide variety of sources that may be exploited for PBR (radio and television broadcast, cellphone basestations, WiFi and WiMAX, satellite communications, broadcast and radionavigation, ...). They can be characterised in terms firstly of their power density at the target:

$$\Phi = \frac{P_T G_T F_T^2}{4\pi R_T^2} \tag{2}$$

where P_T is the transmit power, G_T the transmit antenna gain, F_T the voltage pattern propagation factor for the transmitter-to-target path and R_T the transmitter-to-target range. Secondly their coverage (spatial and temporal). And thirdly, their waveform properties (range and Doppler resolution, range and Doppler ambiguities and sidelobe levels), expressed in terms of the ambiguity function.

It is found that in general such waveforms are not ideal for radar purposes. In particular, analogue broadcast modulation formats depend on the programme material (i.e. speech or music) and may be strongly time-varying. On the other hand, digital modulation formats, which are now being introduced in many countries for radio and television broadcasting, are much more suitable, since their signals are more noise-like, more constant with time, and therefore their ambiguity functions closer to the ideal.

B. Direct Signal Suppression

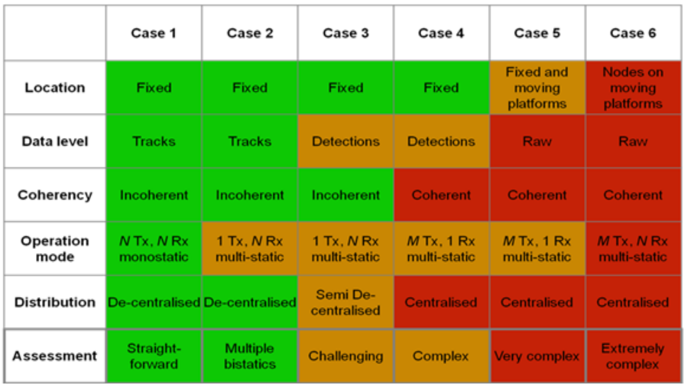
A second issue concerns the suppression of the direct signal at the receivers [18]. Because most PBR signals are continuous and high-power it is necessary to suppress them at the receiver in order to have an adequately-low noise level against which to detect the target echoes. Some simple calculation show that the level of direct signals, multipath and other co-channel signals may be 90 dB or more above thermal noise.

It is necessary to use a combination of techniques, including appropriate siting and physical shielding of the receive antenna, and adaptive filtering. The use of an array antenna and the associated processing adds significantly to the complexity of the receive system. Even then, it is most unlikely that the noise level can be suppressed right down to thermal noise, so a value of receiver Noise Figure of the order of 25 dB should be used in performance calculations to ensure realistic predictions.

IV. NETWORKED RADAR

The use of multiple multistatic radar transmitters and receivers has some obvious attractions – at the simplest level because it will provide additional information to detect and track targets [19]. Whilst a single geometry may suffer from obscuration or fading, it is highly unlikely that this will be the case with multiple, different transmitter-target-receiver paths. This is essentially the philosophy behind MIMO radar, and the subject is currently a very fertile one for research and for publication.

These concepts are facilitated by the huge increases in processing power and in communications, so that it is now possible to contemplate systems which were formerly impractical.



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Location	Fixed	Fixed	Fixed	Fixed	Fixed and moving platforms	Nodes on moving platforms
Data level	Tracks	Tracks	Detections	Detections	Raw	Raw
Coherency	Incoherent	Incoherent	Incoherent	Coherent	Coherent	Coherent
Operation mode	*N* Tx, *N* Rx monostatic	1 Tx, *N* Rx multi-static	1 Tx, *N* Rx multi-static	*M* Tx, 1 Rx multi-static	*M* Tx, 1 Rx multi-static	*M* Tx, *N* Rx multi-static
Distribution	De-centralised	De-centralised	Semi De-centralised	Centralised	Centralised	Centralised
Assessment	Straight-forward	Multiple bistatics	Challenging	Complex	Very complex	Extremely complex

Fig. 2 Increasing levels of sophistication of networked radar (after Baker).

Baker has shown how various stages of sophistication may be contemplated (Fig.3). In Case 1 the tracks from a number of conventional, fixed monostatic radars are fused. In principle this is straightforward. Case 2 is similar, but with a single transmitter and a number of multistatic receivers. In Case 3 the fusion is performed at the detection level, rather than tracks. The level of complexity (and feasibility with present capabilities) increases at each stage, till Case 6 has M transmitter and N receiver nodes on moving platforms, processing the echoes coherently, and hence giving a high-resolution imaging capability.

This leads to the concept of an intelligent multistatic radar network using electronically-steered transmit and receive beams at each node. Targets may be detected and tracked by scheduling appropriate instantaneous transmit and receive beam directions and transmitted waveforms, exploiting forward scatter where appropriate (recognising that this will give high detection sensitivity but poor range and Doppler information.

The control of the network and the tracking of targets has strong similarities to the resource management, scheduling and tracking of a monostatic MultiFunction Radar (MFR). Thus if a target appears to be moving on a constant track and does not represent a threat, it only needs occasional track updates to be scheduled. On the other hand, if a target is unknown or hostile, and is manoeuvring unpredictably, more frequent track updates need to be scheduled [20], [21].

In this sense the radar network may be considered as a type of MFR, but one where the array elements are distributed in space, and the targets actually exist *within* the phased array. Also, in the same way that an active phased array has the benefit of *graceful degradation*, so that failure of a single module has only a small effect on the performance of the overall system, a networked radar will have a similar advantage in respect of nodes which fail, or which need to stay silent.

Furthermore, the wide bandwidths conventionally required for high resolution imaging may be traded for high angular sampling with low-bandwidth waveforms, leading to the concept of ‘ultra narrow band’ (UNB) operation.

Finally, the concepts can readily be extended to networks of dissimilar sensors, exploiting the particular advantages of each sensor type.

V. CONCLUSIONS

Multistatic and MIMO radar have applications as diverse as air defence, maritime surveillance and indoor surveillance. These can take advantage of the huge improvements in processing power, and in communications and geolocation (GPS) technology. However, the challenge to bistatic/multistatic systems in general and PBR systems in particular remains to identify and exploit applications where there is a clear advantage – in terms of performance and/or cost. There is also a pressing need to improve our understanding of bistatic target and clutter signatures.

The concept of an intelligent, adaptive radar network using electronically-steered transmit and receive beams at each node has obvious attractions. There are big challenges to understand and optimise the control of such a network, and these may take advantage of the ideas of knowledge-based signal processing [22] and cognitive radar [23].

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