PASSIVE BISTATIC RADAR AND WAVEFORM DIVERSITY

H.D. Griffiths
Principal, Defence College of Management and Technology
Cranfield University
Defence Academy of the United Kingdom
Shrivenham, Swindon SN6 8LA, UK
Tel: +44 1793 785436; fax: +44 1793 782546; email: hgriffiths.cu@defenceacademy.mod.uk

Keywords: radar, waveform diversity, bistatic radar, passive bistatic radar

SUMMARY

This tutorial describes the basis of passive bistatic radar (PBR) systems, and in particular the nature of the waveforms of illuminators of opportunity that they exploit. It shows that there is a wide variety of such waveforms, from broadcast, communications and radionavigation transmissions, and that in general they are not optimum for radar purposes. In addition, they usually vary significantly as a function of time, with the imposed modulation. It is therefore necessary to understand the effect of the waveform on the performance of the passive bistatic radar, so as to be able to choose the most appropriate illuminator, and to use the waveform in the optimal way, and it is in this sense that PBR forms a part of the subject of waveform diversity. The tutorial presents a short summary of the properties of bistatic radar, then goes on to consider the specific case of passive bistatic radar. Next, two brief sections provide a review of the radar equation for bistatic radar and of the ambiguity function for bistatic radar, before considering the properties of a variety of different waveforms that may be used for passive bistatic radar purposes and how best to exploit them. Finally, a description is given of some practical passive bistatic radar systems and examples of results.

1. INTRODUCTION

Bistatic radar may be defined as a radar in which the transmitter and receiver are at separate locations. The very first radars were bistatic, until pulsed waveforms and T/R switches were developed. Since then interest has varied up and down, but is demonstrably now at a high level, with numerous experimental systems being built and the results reported in the literature. Rather fewer operational systems, though, have been deployed.

Some of the properties of bistatic radar, which may account for the present high degree of interest, are as follows:

(a) The receiving system is completely passive, and hence undetectable, and is immune to the effects of deliberate directional interference. Because it is passive it may also be simple and cheap.

(b) The dynamic range of signals to be handled is reduced, because of the defined minimum range.

(c) It is necessary to provide synchronisation between transmitter and receiver in respect of (i) instant of transmission of pulse, (ii) transmit antenna azimuth (in the case of a scanning transmit antenna), and (iii) transmit signal phase (if coherent processing is to be employed). This may take the form of a land-line link, although with a co-operative transmitter it is possible to realise a totally independent bistatic system by means of 'flywheel' clocks at the receiver which are resynchronised each time the transmitter beam sweeps past [47]. Additionally, a coherent reference for MTI cancellation may be obtained from close-in stable clutter echoes [20].

(d) There is a co-ordinate distortion effect [35]; targets on the transmitter-receiver baseline have zero bistatic range. Elsewhere, contours of constant bistatic range are ellipses with the transmitter and receiver sites as the two foci (Figure 1). The distortion can be corrected with a knowledge of the bistatic geometry [47].

(e) Similarly, contours of zero Doppler are the same ellipses of constant bistatic range. Contours of maximum Doppler are hyperbolae crossing the ellipses orthogonally [35]. Moving targets cannot present zero Doppler to two receiving sites simultaneously.

(f) There are several configurations of transmitters and receivers. Azimuthal discrimination (i.e. directional antennas) at both transmitter and receiver is desirable, since otherwise the system is vulnerable to responses from sidelobes. A directional receive antenna must scan at a non-uniform rate, which practically rules out mechanical scanning. The form of scanning required follows the position of the RF pulse through space, and is known as *pulse chasing*. Thus, either a small number of electronically agile beams or a static set of contiguous beams will be required. Such a receiving system is unlikely to be either simple or cheap, but because the receiver is passive it is much less vulnerable to attack.

(g) The target bistatic cross-section σ_b is not the same as the monostatic cross section, although the range of values of σ_b for a particular (non-stealthy) target will be comparable with the range of values of monostatic cross section. Thus a particular target is unlikely to present a low cross section to more than one transmitter-target-receiver geometry. Additionally, at large angles target glint is drastically reduced, eliminating this contribution to radar inaccuracies.

(h) Stealthy targets are designed to have a low monostatic cross section, partly by shaping so as to scatter energy in directions other than the monostatic direction. Hence the bistatic radar cross section of stealthy targets may be larger. This is especially true in the forward scatter geometry [58] (Figure 2).

(i) Receiving or transmitting stations can be used interferometrically to obtain high azimuthal discrimination; sources of interference can be located by triangulation, and passive detection (correlation) techniques can be employed to locate noise-like interference sources.

(j) The constraints on radar waveform design can be different to those for the monostatic case. As a simple example, a higher-than-normal PRF may be used, and the range ambiguities resolved by triangulation from several receiver sites or by using staggered PRIs.

(k) The transmitter may be located remotely. An example of this is the US SANCTUARY programme [18]. This may be particularly desirable for short-range surveillance applications. In addition, multiple 'winking' transmitters may be employed, as a counter to homing missiles.

2. PASSIVE BISTATIC RADAR

Bistatic radars can operate with their own dedicated transmitters, which are specially designed for bistatic operation, or with *transmitters of opportunity*, which are designed for other purposes but found suitable for bistatic operation. When the transmitter of opportunity is from a monostatic radar the bistatic radar is often called a *hitchhiker*. When the transmitter of opportunity is from a non-radar transmission, such as broadcast, communications or radionavigation signal, the bistatic radar has been called many things including *passive radar, passive coherent location, parasitic radar* and *piggy-back radar*. Here, we use the term *passive bistatic radar* (PBR). Finally, transmitters of opportunity in military scenarios can be designated either *cooperative* or *non-cooperative*, where cooperative denotes an allied or friendly transmitter and non-cooperative denotes a hostile or neutral transmitter. Passive bistatic radar operations are more restricted when using the latter.

PBR systems have some significant attractions, in addition to those listed in Section 1. As well as being completely passive and hence potentially undetectable, they allow the use of parts of the RF spectrum (VHF and UHF) that are not usually available for radar operation, and which may offer a counterstealth advantage, since stealth treatments designed for microwave radar frequencies may be less effective at VHF and UHF. Broadcast transmissions at these frequencies can have substantial transmit powers and the transmitters are usually sited to give excellent coverage [4, 28].

Nevertheless, such waveforms are not fundamentally designed for radar operation, so their performance in radar applications will in general be sub-optimal. It is therefore necessary to understand the effect of the waveform on the performance of the passive bistatic radar, so as to be able to choose the most appropriate illuminator, and to use the waveform in the optimal way, and it is in this sense that PBR forms a part of the subject of waveform diversity. In section 5 we give a description of a variety of types of PBR waveform. First, though, we discuss the bistatic radar equation and the ambiguity function, as tools to be used in evaluating the PBR performance.

3. THE RADAR EQUATION IN BISTATIC RADAR

The radar equation for the bistatic geometry is derived in a similar way to that for a monostatic radar. In its simplest, free-space propagation form, this is:

$$P_r = \frac{P_t G_t}{4\pi r_1^2}.\sigma_b.\frac{1}{4\pi r_2^2}.\frac{G_r \lambda^2}{4\pi} \tag{1}$$

where P_r is the received signal power
P_t is the transmit power
G_t is the transmit antenna gain
r_1 is the transmitter-to-target range
σ_b is the target bistatic radar cross-section
r_2 is the target-to-receiver range
G_r is the receive antenna gain
λ is the radar wavelength

The signal-to-noise ratio is obtained by dividing (1) by the receiver noise power $P_n = kT_0BF$ (where k is Boltzmann's constant, T_0 is 290 K, B is the receiver bandwidth and F the receiver noise figure), and multiplying by the receiver processing gain, also taking into account the various losses. This allows the detection performance to be determined as a function of σ_b, r_1 and r_2. Contours of constant detection signal-to-noise ratio are loci corresponding to r_1r_2 = const., which describe *ovals of Cassini* [35].

The quantity $\dfrac{P_t G_t}{4\pi r_1^2}$ (2)

in equation (1) represents the power density (in Wm^{-2}) of the transmitter signal at the target, and is denoted by the symbol Φ. This is an important parameter in characterising the transmitter for PBR purposes; in practice it is modified by the pattern propagation factor for the transmitter-to-target path, taking into account factors such as multipath and propagation losses.

4. THE AMBIGUITY FUNCTION IN BISTATIC RADAR

Classically, the performance of a radar waveform is evaluated and presented in terms of the ambiguity function, originated in the 1950s by Woodward [59], and which expresses the point target response of the signal $u(t)$ as a function of delay τ and Doppler shift ν (or equivalently target range and velocity)

$$\left|\chi(\tau,\nu)\right|^2 = \left|\int u(x)u^*(x+\tau)\exp(j2\pi\nu x)\,dx\right|^2 \tag{3}$$

and provides an elegant way of showing the resolution, sidelobe levels, and ambiguities of a given waveform, in the form of a two-dimensional plot.

However a bistatic radar ambiguity function also depends on the bistatic geometry. This dependence can be understood and visualized by considering a moving target crossing the transmit-receive baseline: range information becomes indeterminate and the Doppler shift becomes zero. Hence the function 'blows up' on the baseline, giving neither range nor Doppler resolution.

If the ambiguity function is evaluated for target locations elsewhere on the bistatic plane, the peak of the ambiguity function in both range and Doppler broadens with respect to the monostatic peak, and is equal to the monostatic peak only when the target lies on the extended baseline where the bistatic angle is zero. The effect was investigated by Tsao et al. [51], who noted the nonlinear relationships between target velocity and Doppler shift, and between target range and delay, and hence proposed that the ambiguity function for a bistatic radar should be written as:

$$\begin{aligned}&\left|\chi\left(R_{R_H},R_{R_a},V_H,V_a,\theta_R,L\right)\right|^2\\ &=\left|\begin{aligned}&\int_{-\infty}^{\infty}\tilde{f}\left(t-\tau_a\left(R_{R_a},\theta_R,L\right)\right)\tilde{f}^*\left(t-\tau_H\left(R_{R_H},\theta_R,L\right)\right)\\ &\exp\left[-j\left(\omega_{D_H}\left(R_{R_H},V_H,\theta_R,L\right)-\omega_{D_a}\left(R_{R_a},V_a,\theta_R,L\right)\right)t\right]dt\end{aligned}\right|^2\end{aligned} \tag{4}$$

in which R_R and R_T are the ranges of the target from the transmitter and receiver, V is the target radial velocity, θ_R is the angle of the target measured from the receiver, L is the bistatic baseline, τ is the transmitter-target-receiver delay time, and the subscripts H and a denote hypothesized and actual values respectively.

Evidently this depends on rather more than two variables, so it is not straightforward to plot and display it in a simple manner, as is readily done for the monostatic ambiguity function. They show further, by means of a simulation that a signal whose monostatic ambiguity function has a simple Gaussian shape has a bistatic ambiguity function whose shape depends significantly on the bistatic geometry, and degrades badly when the target is close to the bistatic baseline.

To illustrate this effect, Figure 3 shows the ambiguity function for four different target locations and directions of motion. The waveform in each case consists of a short sequence of three rectangular pulses.

In Figure 3(a) the target is on the baseline approaching the receiver and the ambiguity function is essentially the same as for the monostatic configuration. In Figure 3(b) the target approaches the baseline obliquely, but the ambiguity function is little altered. In Figure 3(c) the target approaches the baseline from a perpendicular direction, which broadens the main peak and alters the position of the sidelobes in the ambiguity function. Finally in Figure 3(d) the target crosses the baseline, giving effectively no resolution in either range or Doppler.

5. PASSIVE BISTATIC RADAR WAVEFORMS

5.1 FM Radio

FM radio transmissions lie in the 88–108 MHz VHF band in most countries. The modulation is broadband FM, with a channel bandwidth B of typically 50 kHz (corresponding to a monostatic range resolution $c/2B$ = 3000 m). The transmitters are usually sited on tall towers or masts in high locations. The radiation patterns are usually omnidirectional in azimuth, although the elevation-plane patterns are usually shaped to avoid wasting power above the horizontal. In the UK [61] and US the highest power transmitters are 250 kW EIRP, which from (2) yields a power density (under the assumption of free-space propagation) of $\Phi = -57$ dBW/m^2 at a target range of 100 km.

This value is a substantial power density, and may be explained by the fact that broadcast receivers often have poor noise figures and inefficient antennas, and may be sited in poor locations, so many tens of decibels of link margin need to be built into the link budget to assure full coverage. This factor works in favour of the passive radar designer, of course. Since most FM radio transmitters are located near urban and suburban areas, PBR receivers operating in these areas will be within range of at least four or five transmitters at substantial power density, which in turn provides reasonable coverage of aircraft targets, in both bistatic and multistatic modes of operation.

Evaluation of the coverage of FM radio stations, both in Europe and in the USA, show that existing commercial FM transmitters provide low-to-medium altitude coverage, from at least one transmitter, for virtually all areas of interest.

It is also useful to consider the coverage in littoral regions. Broadcast transmitters will in general be sited inland to maximize their coverage of land. If the coastal region is mountainous there may be blockage so that extended coverage out to sea is not achieved. In such cases topographic maps can be used to evaluate the available coverage.

Over the ocean, atmospheric and precipitation losses can usually be ignored at VHF and UHF frequencies, but interference between the direct path signal and the reflected signal from the sea surface (multipath or the ‘Lloyd’s mirror’ effect) can cause deep nulls in the receiver’s antenna pattern. For both of these reasons, coverage in the littoral region against low-altitude targets may not be complete.

The ambiguity performance of FM transmissions will depend on the instantaneous modulation, which will depend on the program content – in other words, the spectral content of the modulation and how it varies with time. It is found, not surprisingly, that music with high spectral content, such as rock music, gives the narrowest ambiguity function peak and hence best range resolution. With speech, the width of the peak of the ambiguity function, and hence the range resolution, becomes very poor during pauses between words [4, 24, 44]. Of course, the majority of FM radio channels – even music channels – will broadcast speech, in the form of news bulletins, on the hour, or speech from the program-host or an advertisement will interrupt the music every few minutes.

These points are illustrated in Figures 4 and 5. Figure 4(a) shows the ambiguity function of a station with speech modulation (BBC Radio 4). The peak and the sidelobe structure are well-defined, though the peak is relatively broad, as a consequence of the low spectral content of the modulation. Figure 4(b) shows the equivalent result for a station with fast-tempo jazz music modulation (Jazz FM). The peak and the sidelobe structure are correspondingly sharper due to the broader spectral content of the modulation. In both cases the floor of the ambiguity function is down by a factor of $(B\tau)^{1/2}$, rather than $(B\tau)$ which would be expected for coherent waveforms.

Figure 5 compares the range resolution against time (sample) for a number of differing transmission types, over a time interval of approximately two seconds. The two news channels (BBC Radio 3 and Radio 4) show a high degree of temporal variability in range resolution compared to the music channels, since for speech the range resolution will be poor during pauses between words. Overall the range resolution varies approximately between 1.5 km and 16.5 km. The pop and dance music channels exhibit the least variation, rock and jazz music have slightly poorer performance and classical music is degraded a little further, reflecting the spectral content of these different types of music.

5.2 Analogue Television

The majority of analogue television transmissions lie in the UHF band around 500-600 MHz. Some countries also use VHF bands for television; in the US the band allocations are 54-88, 174-216 and 470-806 MHz. In the UK the PAL (Phase Alternating Line) modulation format is used, in which the video information is coded as two interlaced scans of a total of 625 lines at a frame rate of 50 Hz. The start of each line is marked with a sync pulse, and the total duration of each line is 64 μs. The video information is modulated onto a carrier as vestigial-sideband AM, coded as *luminance* (Red + Green + Blue) and two *chrominance* signals (Green – Blue) and (Red – Blue). The two chrominance sub carriers are in phase quadrature, so that they can be separately recovered. The sound information (including stereo information) is frequency-modulated onto a second carrier. Variants of this basic scheme are used in different countries; in the USA the NTSC (National Television System Committee) format is used; in France and in Eastern Europe the SECAM (*Sequentiel Couleurs avec Memoire*) format.

Figure 6 shows the measured spectrum of an analogue TV signal (PAL modulation format) with the various components of the spectrum identified. For comparison, on the left-hand side of the spectrum is the corresponding digital TV signal, which has a flat spectrum with a bandwidth of 7 MHz.

The bandwidth of the analogue video modulation is typically 5.5 MHz (corresponding to a monostatic range resolution $c/2B$ = 30 m). As with FM transmissions, the radiation patterns are usually omni-directional in azimuth, although the elevation-plane patterns are usually shaped to avoid wasting power above the horizontal. In the UK, and in most other countries, the highest power transmitters are 1 MW EIRP, which corresponds to a power density $\Phi = -51$ dBW/m^2 at a target range of 100 km, under the assumption of line-of-sight propagation.

It can be appreciated that there will be pronounced range ambiguities associated with the analogue line and frame scan rates. In particular, since in general one line of a TV picture will be very similar to the previous one, there will be strong range ambiguities corresponding to the line scan period of 64 μs, equating to a bistatic range of 9.6 km. Figure 7(a) shows the measured ambiguity function corresponding to the chrominance sub-carrier of an analogue TV signal. The ambiguities associated with the frame scan rate are easily visible, appearing as rapid modulation on the basic peak of the ambiguity function. Figure 7(b) shows the measured ambiguity function for the FM sound carrier and its modulation, which is similar in most respects to that of Figure 4(a).

5.3 Digital Radio and TV

Many countries are now introducing digital radio and television. These transmissions use coded orthogonal frequency division multiplex (CODFM) modulation, in which all transmitters for a given station use the same frequency (so-called ‘single-frequency networks’). Details of this modulation format may be found in [1], but an essential feature is that the information is transmitted in synchronized frames.

Each frame contains a large number of orthogonally-coded sub-carriers, which carry the modulation information. The receiver samples each frame only after a guard interval delay, whose duration is greater than the maximum delay of the propagation path. This means that any multipath or signal from another co-channel transmitter will be stationary.

According to Poullin [43], typical parameters of a DAB modulation scheme are:

- symbols of 1 ms useful duration with a guard interval of 0.246 ms,
- 1536 sub-carriers transmitted simultaneously per symbol,
- quadrature phase shift keying (QPSK) modulation for each sub-carrier,
- symbols are organised into frames of 77 symbols,
- the first symbol is null (with no-frequency transmitted or only the centre frequency),
- the second symbol is a reference, where all the sub-carriers are transmitted with reference code elements. This symbol is used for the propagation channel estimation, and hence equalization.

Since this type of modulation is more noise-like and does not show the same dependence on program content or variability with time as FM radio, it has potentially favourable PBR properties. Offsetting this advantage is the lower radiated power for DAB transmitters, which at about 1 kW is significantly less than the equivalent VHF FM transmissions.

5.4 Cell Phone Networks

Cell phone networks are now ubiquitous in most countries [49]. The GSM system uses bands centred on 900 MHz and 1.8 GHz, and 1.9 GHz in the USA [15]. The uplink and downlink bands are each of 25 MHz bandwidth, split into 125 FDMA (Frequency Division Multiple Access) carriers spaced by 200 kHz. A given base-station will only use a small number of these channels. Each of these carriers is divided into 8 TDMA (Time Division Multiple Access) time slots, with each time slot of duration 577 µs. Each carrier is modulated with using GMSK (Gaussian Minimum-Shift Keying) modulation. A single bit corresponds to 3.692 µs, giving a modulation rate of 270.833 kbits/s. Figure 8(a) and (b) show time-domain and frequency-domain representations of these signals.

The third generation (3G) system uses a band in the region of 2 GHz. The UMTS (Universal Mobile Telecommunication System) is the main implementation of 3G, with the following characteristics [52, 53]:

- There are two forms, Frequency Division Duplex (FDD) and Time Division Duplex (TDD). FDD requires two frequency bands (for the up-link and one for the down link); TDD requires a single band. A given band (or pair of bands) is allocated to a particular operator.

- FDD and TDD bands are of 5 MHz nominal width/channel spacing. The width can be reduced (in 200 kHz steps) to 4.4 MHz if operators wish.

- The transmission is Wideband CDMA (WCDMA) using Walsh-Hadamard coding. The transmission rate is always 3.84 Mchips/s. The data rate may be varied, which means that the selected spreading code length is dependent on the data rate. The codes used are referred to as Orthogonal Variable Spreading Factor Codes (OSVF). Code length may vary from 4 (giving data rate of 960 kbit/s) up to 512 (giving data rate of 7.5 kbit/s). Data is also scrambled, but this does not affect the rate.

- The modulation used is QPSK. The null-to-null bandwidth is effectively 3.84 MHz, hence the 4.4 MHz minimum channel spacing. The signals are shaped with a 0.2 Root Raised Cosine Filter.

The choice of frequency band for UMTS in Europe and Asia is consistent, but in the USA these bands were not available. At the World Radio Conference (WRC-2000) in Istanbul, Turkey in May 2000, three bands were suggested for the implementation of UMTS in the USA: 806-890 MHz (used for cellular and other mobile services, 1710-1885 MHz (used by the US Department of Defense), and 2500-2960 MHz (used commercially for instructional TV and wireless data providers). However, the fact that these bands are already used for other purposes led to further consultation, with the result that 45 MHz of bandwidth in the 1710-1755 MHz band, and 45 MHz of bandwidth in the 2110-2170 MHz, are to be made available for 3G services.

The radiation patterns of cell phone base-station antennas are typically arranged in 120˚ sectors, with the vertical-plane radiation pattern shaped to avoid wasting power above the horizontal. Typical base-station separations are of the order of 10 km, with transmit powers of the order of 100 W, though with closer spacing and lower powers in cities. Future trends will be to more base-stations, with lower transmit powers and the use of ‘smart antennas’.

Figure 9 shows typical ambiguity functions for digital transmissions (DAB, DBV-TV and GSM, respectively). These functions are more favourable for passive bistatic radar purposes than signals with analogue modulation (Figures 4 and 7), since the peak of the ambiguity function is narrower and the sidelobes are lower. In addition they do not depend on the programme content and are much more constant with time.

5.5 Other Transmissions

Other transmitters have been considered as illuminators for passive bistatic radars, principally satellite-borne transmitters. They include broadcast TV (DBS, Echo Star, …), communications (INMARSAT, IRIDIUM, …) and navigation (GPS, GLONASS, GALILEO, …). Satellites in geostationary orbit give continuous coverage, but the power density at the Earth’s surface is very low: many tens of dB below that of terrestrial emitters. In some cases, for example DBS, the antenna footprint is arranged to give coverage only over land. Satellites in Low Earth Orbit (LEO) give somewhat higher power density, but only illuminate a given target scene for a very brief period. Exploiting any of these low EIRP satellite transmissions is constrained to either very short range operation or forward scatter fences, neither particularly suited for air surveillance. One potential, short-range application is coupling the more powerful geostationary DBS transmitters with a bistatic synthetic aperture radar (SAR) receiver carried by a unmanned air vehicle (UAV) flying at low altitudes. Here, the short range and long integration times might provide some useful ground target surveillance capability.

Another class of transmission that has occasionally been considered for PBR illumination is HF (Short Wave) broadcast signals, including the new, very powerful Digital Radio Mondiale (DRM) format. In DRM the digitised audio stream is source coded using a combination of Advanced Audio Coding (AAC) and Spectral Band Replication (SBR) to reduce the data rate before time division multiplexing with two data streams (which are required for decoding at the receiver). A Coded Orthogonal Frequency Division Multiplexing (COFDM) channel coding scheme is then applied, nominally with 200 sub-carriers and a Quadrature Amplitude Modulation (QAM) mapping of these sub-carriers is used to transmit the encoded data [50]. The effective bandwidth is 10 kHz. This scheme is designed to combat channel fading, multipath and Doppler spread, enabling reception of data in the most demanding of propagation environments.

Figure 10 shows the unweighted ambiguity function of a typical DRM signal after 80 ms of integration time [50]. There are no ambiguities in either domain within practical ranges and Doppler shifts. The DRM signal does in fact exhibit range ambiguities at multiples of 60,000 km, a result of the 400 ms frame synchronisation of the signal transmission, but these are significantly beyond the detection ranges of interest. The sidelobe structure of the ambiguity function is flat, as would be expected for a noise-like signal, and the sidelobe level, which is proportional to the bandwidth and the integration time, is approximately 25 dB below the peak. In this example the range resolution of the signal is 16 km and the Doppler resolution is 3.4 Hz (equivalent to a velocity resolution of 39.2 m/s). Analysis was performed on a variety of speech and music signals. The resulting ambiguity functions had very similar properties, indicating that the radar ambiguity functions are virtually independent of the broadcast content and are essentially a function of the modulation format.

The range resolution of DRM signals (and indeed of all HF signals) is poor compared with higher-frequency radars, but for PBR purposes Doppler resolution is equally important as an input to localisation and tracking algorithms. In HF radar it is common to have integration times of many tens of seconds for air and surface targets, thus in an HF passive radar application, similar integration times are likely to be used. Evaluating the Doppler resolution for a more practical integration time of 5 s gives a value of 0.2 Hz (inversely proportional to the integration time) and a decrease in interference floor level to approximately –40 dB. This corresponds to a radial velocity resolution of 2.3 m/s, sufficient for many radar applications. Experimental results have shown that for 30 s integration times (appropriate for sea surface target detection) the interference floor approaches –50 dB and the Doppler resolution has improved still further.

5.6 Summary of Transmitters

Table 1 summarises properties of transmitters that have been considered for passive bistatic radar operation. Figure 11 arranges some of them in a ‘league table’ in order of power density at representative target ranges. Satellite transmitters have been added for comparison.

Transmission	Frequency	Modulation, bandwidth	P_tG_t (typical)
HF broadcast	10 – 30 MHz[1]	DSB AM, 9 kHz DRM, 10 kHz	50 MW
VHF FM (analogue)	~ 100 MHz	FM, 50 kHz	250 kW
UHF TV (analogue)	~ 550 MHz	vestigial-sideband AM (vision); FM (sound), 5.5 MHz	1 MW
Digital Audio Broadcast	~ 220 MHz	digital, COFDM 220 kHz	10 kW
Digital TV	~750 MHz	digital, 6 MHz	8 kW
Cell-phone Networks (GSM)	900 MHz, 1.8 GHz	GMSK, FDM/TDMA/FDD 200 kHz	100 W [2]
Cell-phone Networks(3G)	~2 GHz	CDMA 3.84 MHz	100 W

Table 1: Signal parameters for a range of passive radar illumination sources.

5.7 Discussion

The preceding sections have shown that there are a great variety of signals that can be used for PBR purposes, and that their performance in PBR systems will vary significantly, depending on a variety of factors. In simple terms the performance can be assessed in terms of (i) power density at target (according to equation (2); (ii) coverage (both spatial and temporal), and (iii) ambiguity function (recognising that this depends both on the waveform and on the transmitter-target-receiver geometry).

[1] Appropriate frequency will depend on time of day.
[2] http://www.sitefinder.radio.gov.uk

We can note the following conclusions and comments:

For analogue modulation formats, the ambiguity performance depends strongly on instantaneous modulation. Periodic modulation features, such as the sync parts of the waveform in analogue television waveforms, result in ambiguities. For VHF FM radio the ambiguity performance varies significantly, and some types of music; those with high spectral content) are better than others. On the other hand, with speech, the ambiguity performance is poor during pauses between words.

For digital modulation formats, the ambiguity performance is much more constant with time, and does not depend on the programme content, since signals are more noise-like. Digital transmissions are therefore to be preferred, even though they tend to be of lower power than their analogue counterparts.

A practical PBR system will in general have several signals available, of various types and in various locations. The ambiguity performance depends strongly both on geometry and (for analogue modulation formats at least) on instantaneous modulation. Both these dependencies are deterministic. This suggests that the way in which the information from each signal is combined should be varied dynamically, either by selecting at a given instant only those signals for which the ambiguity performance is favourable, or by weighting that from signals with better ambiguity functions more strongly;

It may also be attractive to investigate the feasibility of spectral interpolation [10] to realise high range resolution from multiple channels from a single transmitter.

Also, in predicting the detection performance of a PBR system, it must be appreciated that the ambient noise level, particularly in the VHF and UHF bands, and particularly in urban environments, due to the direct signal, co-channel signals, spectral ‘slop’, multipath, and noise from (for example) computers and imperfectly-suppressed vehicle ignition [29]. This means that the dynamic range of a PBR receiver will need to be substantial to cope with the wide range of signal levels (typically > 90 dB). Thus significant adaptive processing, both in the angular (antenna) domain and in the spectral domain, is necessary to suppress these noise sources, and even then an effective noise figure of the order of 25 dB should realistically be used.

6. EXAMPLES OF PRACTICAL SYSTEMS

Among the first published accounts of passive bistatic radar is the 1960 *IRE* paper by Rittenbach and Fishbein: ‘Semiactive correlation radar employing satellite-borne illumination’ [45] An annotated summary is reproduced as follows:

> ‘This paper describes a semi-active radar system [the U.S. Army’s preferred nomenclature, although the term ‘bistatic’ had been coined by Seigel and Machol in 1952] in which the transmitter is carried in a [geosynchronous] satellite. The satellite transmits a randomly modulated signal [proposed at 100 W-CW, illuminating a ground area of 7,000 miles in diameter]. On the ground the radar has two antennas and receivers. One antenna points at the satellite, the other at the target [a ground vehicle]. The signal from the satellite-oriented receiver is delayed and [time-] correlated with the satellite signal reflected from the target. The delay corresponding to the peak of the correlation function is used to determine range [1,000 yds for a 1 m^2 target, 10,000 yds for 100 m^2]. It is planned to test this system with various communications satellites [once they are orbited].’

Also of interest, both historically and technically, is a 1966 publication [48], describing some elegant experiments by a radio amateur, detecting aircraft targets using a VHF television transmission from north-eastern France.

Early work on passive bistatic radar at University College London (UCL) was published in the mid-1980s [21]. This made use of UHF analogue television transmissions to detect and track aircraft flying into and out of London's Heathrow airport, with a receiver located in central London, and measuring the bistatic range by comparing the propagation delay of the echo with that of the direct signal. The results were for the most part negative, but the paper emphasised the effect on performance of the PBR waveform and that broadcast waveforms are in general not optimum for radar purposes.

A different approach was taken in the 1990s by another UK group, using the vision carrier component of a UHF television signal, and measuring angle of arrival and Doppler shift, and using these parameters as inputs to an extended Kalman filter (EKF) algorithm. Successful tracking of aircraft at ranges well in excess of 100 km was demonstrated, though not in real time [31].

Developments of both of these approaches are now used: triangulation with multiple transmitters and/or receivers, or using measurements of delay, Doppler and/or angle of arrival from several transmitters as inputs to a tracking process [31, 32].

Since these early experiments, a significant number of experimental systems have been conceived and demonstrated, and most radar conferences nowadays include examples of PBR work. Notable among these is the Manastash Ridge Radar (MRR), developed by Sahr and co-workers at the University of Washington, in Seattle [46]. The purpose of this system is to study turbulence in the ionosphere, specifically auroral E-region irregularities, using range, Doppler and direction-of-arrival measurements. Results are made available on a continuous and near-real-time basis on their website. The receiver hardware is notably low-cost, using simple antennas, a standard PC digitiser card and off-the-shelf GPS hardware for synchronisation (Figure 12).

Also of great relevance and interest is Lockheed Martin's *Silent Sentry* [3], which is arguably the nearest thing to a practical, operational PBR system. This uses analogue FM radio transmissions, and has demonstrated real-time tracking of multiple aircraft targets over a wide area, and also real-time tracking of Space Shuttle launches. In each case use is made of transmissions from a number (typically 5 or 6, but in any case > 3) of stations.

Another example of a low-cost PBR system [34] is due to Howland and co-workers at the NATO C3 Agency at The Hague in the Netherlands (Figure 13). This uses a single FM broadcast transmission, and demonstrates detection and tracking of aircraft targets over the North Sea at ranges well in excess of 100 km (Figure 14).

More recently, systems have been developed which exploit digital transmissions, such as digital radio and television [2, 43, 49]. These confirm the improved performance over analogue transmissions predicted by the discussions in section 5 above, and point the way for future PBR systems, as such digital broadcast systems are being introduced in many countries worldwide.

7. CONCLUSIONS

This tutorial has attempted to describe the basis of passive bistatic radar systems, and in particular the nature of the waveforms of illuminators of opportunity that they exploit. It has been shown that there is a wide variety of such waveforms, from broadcast, communications and radionavigation transmissions, and that in general they are not optimum for radar purposes. In addition, they usually vary significantly as a function of time. It is therefore necessary to understand the effect of the waveform on the performance of the passive bistatic radar, so as to be able to choose the most appropriate illuminator, and to use the waveform in the optimal way, and it is in this sense that PBR forms a part of the subject of waveform diversity.

Two particular ideas [27] that emerge are (i) the dynamic selection of illumination sources, based on the instantaneous modulation and on the bistatic geometry (for a given target), and (ii) the use of spectral interpolation to realise high range resolution from multiple channels from a single transmitter. Both of these remain to be explored.

8. ACKNOWLEDGEMENTS

I gratefully acknowledge invaluable discussions with many people from whom I have learned much about radar and signal processing in general, and bistatic radar in particular, over the years. I would particularly like to mention Chris Baker, Mike Cherniakov, Izzat Darwazeh, DEN Davies, John Forrest, Paul Howland, Darek Maksimiuk, Daniel O'Hagan, Chris Pell, Jim Schoenenberger, Marc Thomas, Aric Whitewood, Nick Willis and Gill Yates. I also acknowledge with thanks the various funding agencies who have supported our work.

9. REFERENCES

Useful publications, not all referred to in the text:

1. Alard, M., Halbert, R. and Lassalle, R., 'Principles of modulation and channel coding for digital broadcasting for mobile receivers', *EBU Rev. Tech.*, 224, pp3–25, 1987.
2. Andrews, A., 'HDTV-based passive radar', AOC 4th Multinational PCR Conference, Syracuse, New York, 5–7 October 2005.
3. Baniak, J., Baker, G., Cunningham A.M. and Martin, L., 'Silent Sentry passive surveillance', *Aviation Week and Space Technology*, 7 June 1999.
4. Baker, C.J., Griffiths, H.D. and Papoutsis, I., 'Passive Coherent Radar systems - part II: waveform properties', Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, pp160–168, June 2005.
5. Brown, L.C., *Technical and Military Imperatives: A Radar History of World War II*, Taylor & Francis, 1999.
6. Cherniakov, M., Nezlin, D. and Kubik, K., 'Air target detection via bistatic radar based on LEOS communication signals', *IEE Proc. Radar Sonar and Navigation*, Vol. 149, No. 1, pp33-38, February 2002.
7. Cherniakov, M., Saini, R., Zuo, R. and Antoniou, M., 'Space-surface bistatic synthetic aperture radar with global navigation satellite system transmitter of opportunity – experimental results', Special Issue of *IET Radar, Sonar and Navigation* on EMRS DTC, Vol.1, No.6, pp447-458, December 2007.
8. Colone, F., Cardinali, R. and Lombardo, P., 'Cancellation of clutter and multipath in passive radar using a sequential approach', *IEEE 2006 Radar Conference*, Verona (NY), USA, pp393-399, 24–27 April 2006.
9. Crispin, J.W., Goodrich, R.F. and Siegel, K.M., 'A theoretical method for the calculation of the radar cross sections of aircraft and missiles', University of Michigan report 2591-1-1-M, AF 19(604)-1949, AFCRC-TN-59-774, 1959.
10. Cuomo, K.M., Piou, J.E. and Mayhan, J.T., 'Ultra-wideband coherent processing', Special issue of *The Lincoln Laboratory Journal* on Superresolution, Vol. 10, No.2, pp203-221, 1997.
11. Davies, D.E.N., 'Use of bistatic radar techniques to improve resolution in the vertical plane', *Electronics Letters*., Vol.4, pp170-171, 1968.
12. Drabowitch, S., Papiernik, A., Griffiths, H.D., Encinas, J. and Smith, B.L., *Modern Antennas*, Chapman & Hall / IEEE MTT, ISBN 0 412 57910 3, 1997.
13. Dunsmore, M.R.B., 'Bistatic radars', chapter 11 in *Advanced Radar Techniques and Systems* (G. Galati ed.), Peter Peregrinus, 1993.
14. Ertan, S., Wicks, M.C., Antonik, P., Adve, R., Weiner, D., Griffiths, H.D. and Fotinopoulos, I., 'Bistatic denial by spatial waveform diversity', Proc. *RADAR 2002* Conference, Edinburgh; IEE Conf. Publ. No.490, pp17-21, 15 – 17 October 2002.
15. ETSI EN 300 910, 'Digital cellular telecommunications system (Phase 2+); radio transmission and reception'. GSM 05.05 version 8.5.1 Release 1999, November 2000.
16. Ewell, G.W., 'Bistatic radar cross section measurements', chapter 7 in *Techniques of Radar Reflectivity Measurement*, (N.C. Currie ed.), Artech House, 1989.
17. Farina, A. and D'Addio, E., 'Overview of detection theory in multistatic radar', *IEE Proc.*, Vol.133, Pt.F., No.7, pp613-623, December 1986.
18. Fawcette, J., 'Vulnerable radars seek a safe sanctuary', *Microwave Systems News*, April 1980, pp45-50.
19. Griffiths, H.D., Forrest, J.R., Williams, A.D. and Pell, C., 'Digital beamforming for bistatic radar receiver'; *Proc. 3rd IEE Intl. Conference on Antennas and Propagation*, Norwich; IEE Conf. Publ. No. 219 Part I, pp80–84, 12–15 April 1983.
20. Griffiths, H.D. and Carter, S.M., 'Provision of moving target indication in an independent bistatic radar receiver', *The Radio and Electronic Engineer*, Vol.54, No.7/8, pp336-342, July/August 1984.

21. Griffiths, H. D., and Long, N. R W., 'Television-based bistatic radar', *IEE Proceedings*, Vol. 133, Part F, No.7, pp649-657, December 1986.
22. Griffiths, H.D., Garnett, A.J., Baker, C.J. and Keaveney, S., 'Bistatic radar using satellite-borne illuminators of opportunity', Proc. *RADAR-92* Conference, Brighton; IEE Conf. Publ. No.365, pp276-279, 12-13 October 1992.
23. Griffiths, H. D., Baker, C. J., Baubert, J., Kitchen, N. and Treagust, M., 'Bistatic radar using spaceborne illuminator of opportunity', Proc. *RADAR 2002* Conference, Edinburgh; IEE Conf. Publ. No.490, pp1–5, 15–17 October 2002.
24. Griffiths, H.D., Baker, C.J., Ghaleb, H., Ramakrishnan, R. and Willman, E., 'Measurement and analysis of ambiguity functions of off-air signals for passive coherent location', *Electronics Letters*, Vol.39, No.13, pp1005-1007, 26 June 2003.
25. Griffiths, H.D. 'From a different perspective: principles, practice and potential of bistatic radar', Proc. International Conference *RADAR 2003*, Adelaide, Australia, pp1–7, 3–5 September 2003.
26. Griffiths, H.D., Wicks, M.C., Weiner, D., Adve, R., Antonik, P.A. and Fotinopoulos, I., 'Denial of bistatic hosting by spatial-temporal waveform design', *IEE Proc. Radar, Sonar and Navigation*, Vol.152, No.2, pp81–88, April 2005.
27. Griffiths, H.D. and Baker, C.J., 'Measurement and analysis of ambiguity functions of passive radar transmissions', Proc. *RADAR 2005* Conference, Washington DC, IEEE Publ. No. 05CH37628, pp321–325, 9–12 May 2005.
28. Griffiths, H.D. and Baker, C.J., 'Passive Coherent Radar systems - part I: performance prediction', Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, pp153–159, June 2005.
29. Griffiths, H.D. and Baker, C.J., 'The signal and interference environment in Passive Bistatic Radar', Information, Decision and Control Symposium, Adelaide, 12–14 February 2007.
30. Horne, A.M. and Yates, G.A., 'Bistatic synthetic aperture radar', Proc. *RADAR 2002* Conference, Edinburgh; IEE Conf. Publ. No.490, pp22–25, 15–17 October 2002.
31. Howland, P.E., 'Target tracking using television-based bistatic radar', *IEE Proc. Radar Sonar and Navigation*, Vol. 146, No.3, June 1999, pp166-174.
32. Howland, P.E., Griffiths, H.D. and Baker, C.J., 'Passive Bistatic Radar', chapter in *Bistatic Radar: Emerging Technology* (M. Cherniakov ed.), Wiley, ISBN 0470026308, 2008.
33. Howland, P.E. (ed), Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, June 2005.
34. Howland, P.E., Maksimiuk, D. and Reitsma, G., 'FM radio based bistatic radar', Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, pp107–115, June 2005.
35. Jackson, M.C., 'The geometry of bistatic radar systems' *IEE* Proc., Vol.133, Part F., No.7, pp604-612, December 1986.
36. Kell, R.E., 'On the derivation of bistatic RCS from monostatic measurements', *Proc. IEEE*, Vol.53, pp983-988, 1965.
37. Koch, V. and Westphal, R., 'A new approach to a multistatic passive radar sensor for air defense', Proc. IEEE International Radar Conference *RADAR 2000*, Washington DC, IEEE Conf. Publ No.95CH3571-0, pp22-28, 8-11 May 1995.
38. Martinsek, D. and Goldstein, R., 'Bistatic radar experiment', Proc. *EUSAR '98*, European Conference on Synthetic Aperture Radar, Berlin, Germany, pp31-34, 1998.
39. Ogrodnik, R.F., 'Broad area surveillance exploiting ambient signals via coherent techniques', Proc. IEEE International Conference on Multisensor Fusion and Integration, pp421-429, 2004.
40. Ogrodnik, R.F., 'Bistatic laptop radar: an affordable, silent radar alternative', Proc. IEEE National Radar Conference, Ann Arbor, MI, pp369-373, 1996.
41. Ogrodnik, R.F., Wolf, W.E., Schneible, R., McNamara, J., Clancy, J. and Tomlinson, P.G., 'Bistatic variants of space-based radar', Proc. IEEE Aerospace Conference, Vol.2, pp159-169, 1997.
42. Pell, C. and Hanle, E. (eds), Special Issue of *IEE Proceedings Part F*. on Bistatic Radar, *IEE Proc.*, Vol.133, Pt.F., No.7, December 1986.

43. Poullin, D., ‘Passive detection using digital broadcasters (DAB, DVB) with COFDM modulation’, Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, pp143–152, June 2005.
44. Ringer, M.A.. Frazer, G.J. and Anderson, S.J., ‘Waveform analysis of transmissions of opportunity for passive radar’, Proc. *ISSPA’99*, Brisbane, pp511-514, 22-25 August 1999.
45. Rittenbach, O.E. and Fishbein, W., ‘Semi-active correlation radar employing satellite-borne illumination’, *IRE Transaction on Military Electronics*, pp268–269, April–July 1960.
46. Sahr, J.D. and Lind, F.D., ‘The Manastash Ridge radar: a passive bistatic radar for upper atmospheric radio science’, *Radio Science*, Vol.32, No.6, pp2345-2358, 1977.
47. Schoenenberger, J.G. and Forrest, J.R., ‘Principles of independent receivers for use with co-operative radar transmitters’, *The Radio and Electronic Engineer*, Vol.52, No.2, pp93-101, February 1982.
48. Sollom, P.W., ‘A little flutter on VHF’, *RSGB Bulletin*, pp709–728, November 1966; pp794-824, December 1966.
49. Tan, D.K.P., Sun, H., Lu, Y., Lesturgie, M. and Chan, H.L., ‘Passive radar using Global System for Mobile communication signal: theory, implementation, and measurements’, Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, pp116–123, June 2005.
50. Thomas, J.M., Griffiths, H.D. and Baker, C.J., ‘Ambiguity function analysis of Digital Radio Mondiale signals for HF passive bistatic radar applications’, *Electronics Letters*, Vol.42, No 25, pp1482–1483, 7 December 2006.
51. Tsao, T., Slamani, M., Varshney, P., Weiner, D., Schwarzlander, H. and Borek, S., ‘Ambiguity function for a bistatic radar’, *IEEE Trans. Aerospace and Electronic Systems*, Vol.33, No.3, pp1041-1051, July 1997.
52. Walke, B., *Mobile Radio Networks; Networking, Protocols and Traffic Performance*, John Wiley, 1998.
53. Walke, B., Seidenberg, P. and Althoff, M.P., *UMTS: the Fundamentals*, John Wiley, 2003.
54. Whitewood, A.P., ‘Bistatic radar using a spaceborne illuminator’, PhD thesis, University College London, June 2006.
55. Willis, N.J., ‘Bistatic radar’, chapter 25 in *Radar Handbook* (second edition), (M.I. Skolnik ed.), McGraw-Hill, 1990.
56. Willis, N.J., *Bistatic Radar*, Artech House, 1991.
57. Willis, N.J., *Bistatic radars and their third resurgence: passive coherent location*, IEEE Radar Conference, Long Beach, USA, 24 April 2002.
58. Willis, N.J. and Griffiths, H.D. (eds), *Advances in Bistatic Radar*, SciTech Publishing Inc., Raleigh, NC, ISBN 1891121480, 2007.
59. Woodward, P.M., *Probability and Information Theory, with Applications to Radar*, Pergamon Press, 1953; reprinted by Artech House, 1980.
60. http://www.scitechpublishing.com
61. http://www.sitefinder.radio.gov.uk

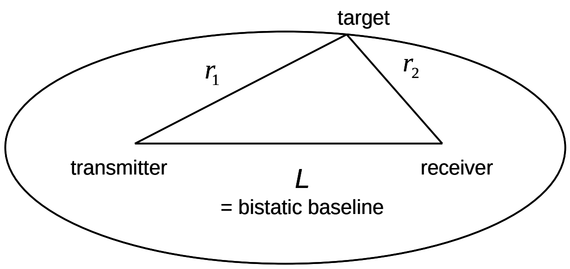


Figure 1: Bistatic geometry [35].

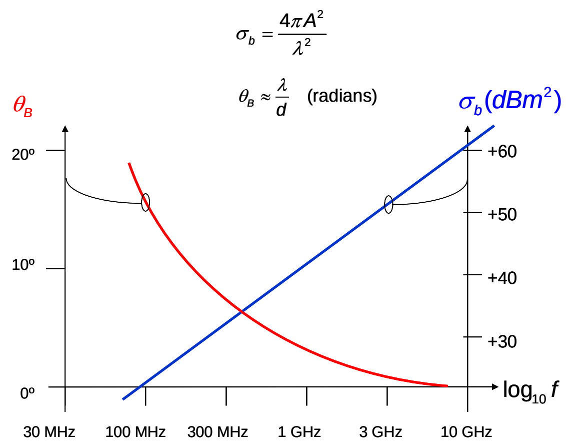


Figure 2: Forward scatter RCS σ_b and angular width θ_F of scatter for a typical small aircraft target ($A = 10m^2$, $d = 10m$).

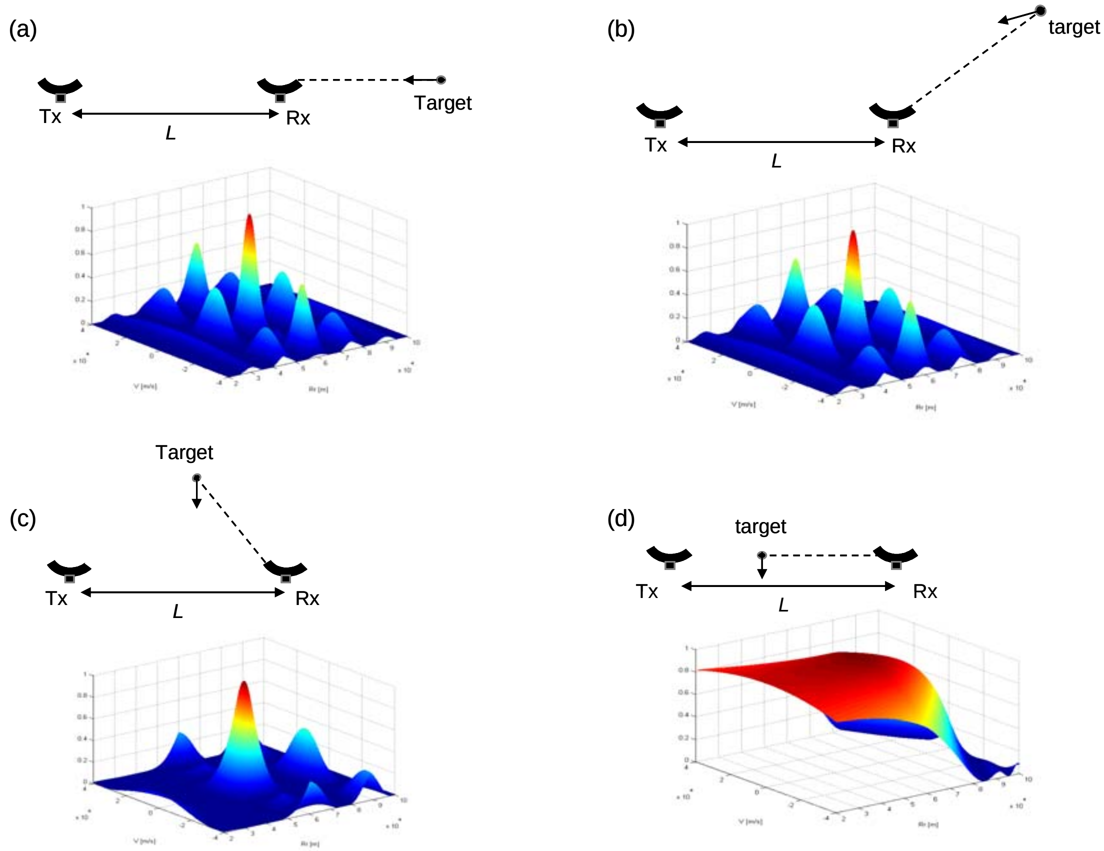
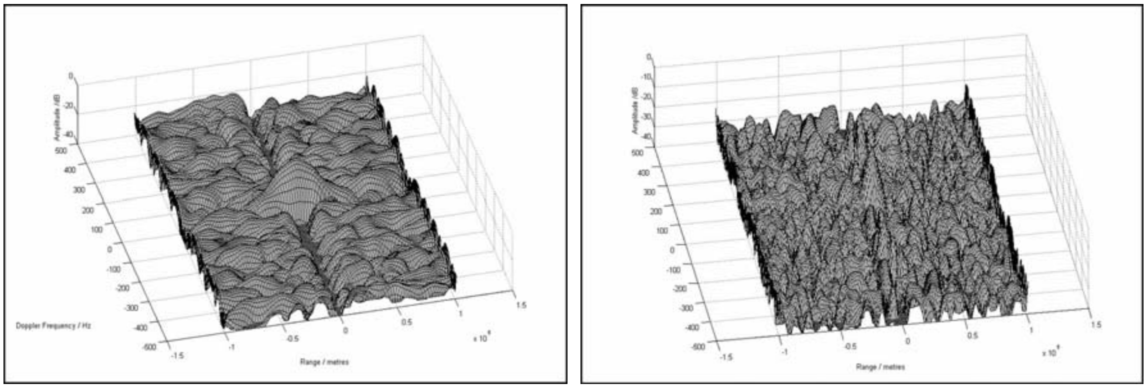


Figure 3: Bistatic ambiguity functions for four different target locations and directions of motion.



(a) (b)

Figure 4: Typical off-air ambiguity functions from (a) speech (BBC Radio 4), and (b) fast-tempo jazz music (Jazz FM).

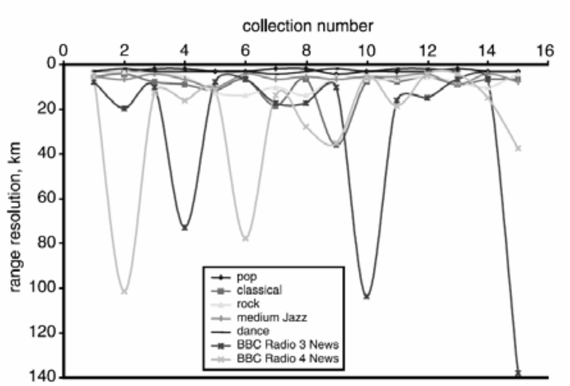


Figure 5: Variation in range resolution as a function of time for seven types of VHF FM radio modulation over a two-second interval (after [*]).

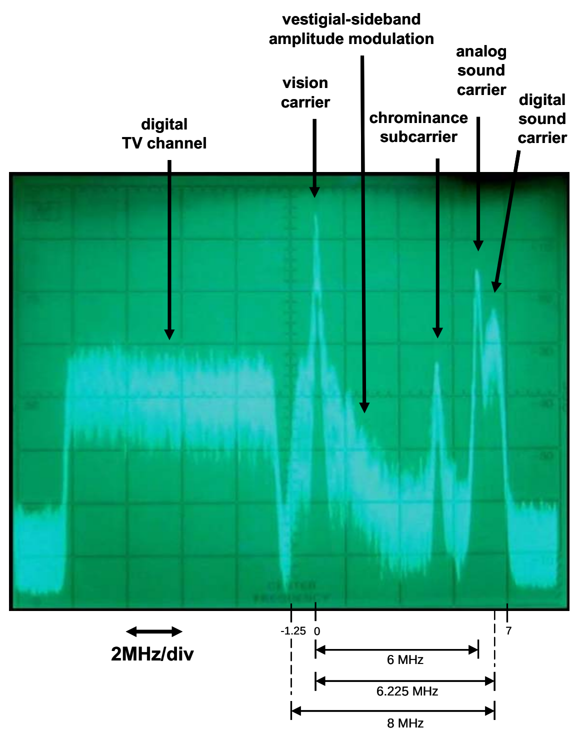
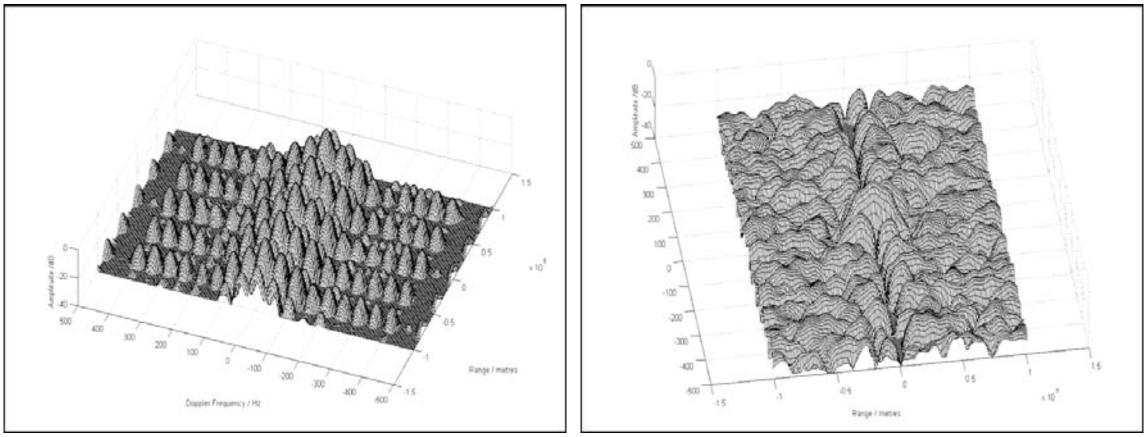


Figure 6: Spectrum of typical PAL analogue TV signal (right of centre) and digital TV signal (left of centre). Horizontal scale 501–521 MHz; vertical scale 10 dB/division.



(a) (b)

Figure 7: Ambiguity functions for components of analogue TV signal (a) chrominance subcarrier, (b) FM sound carrier.

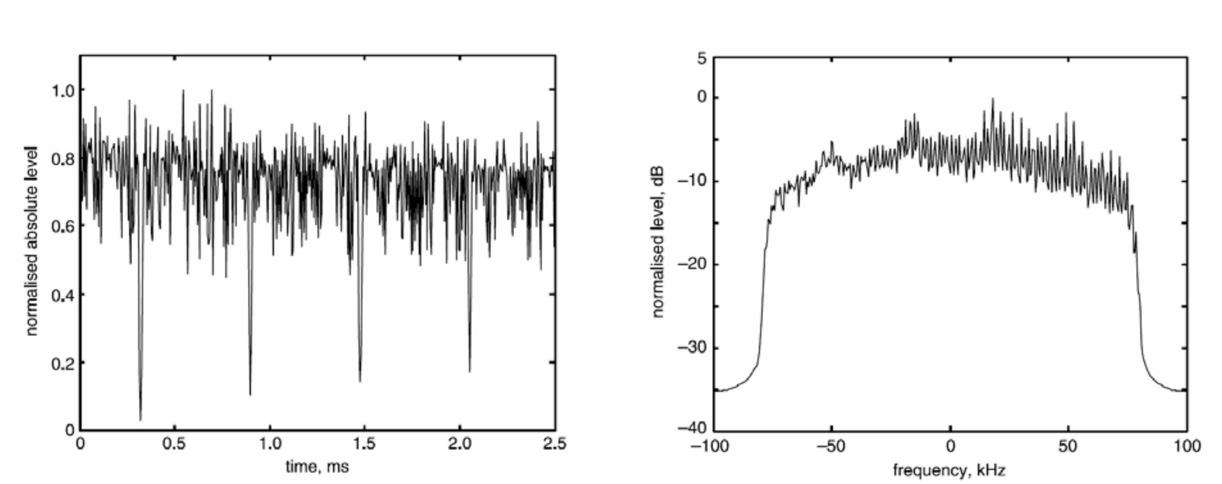
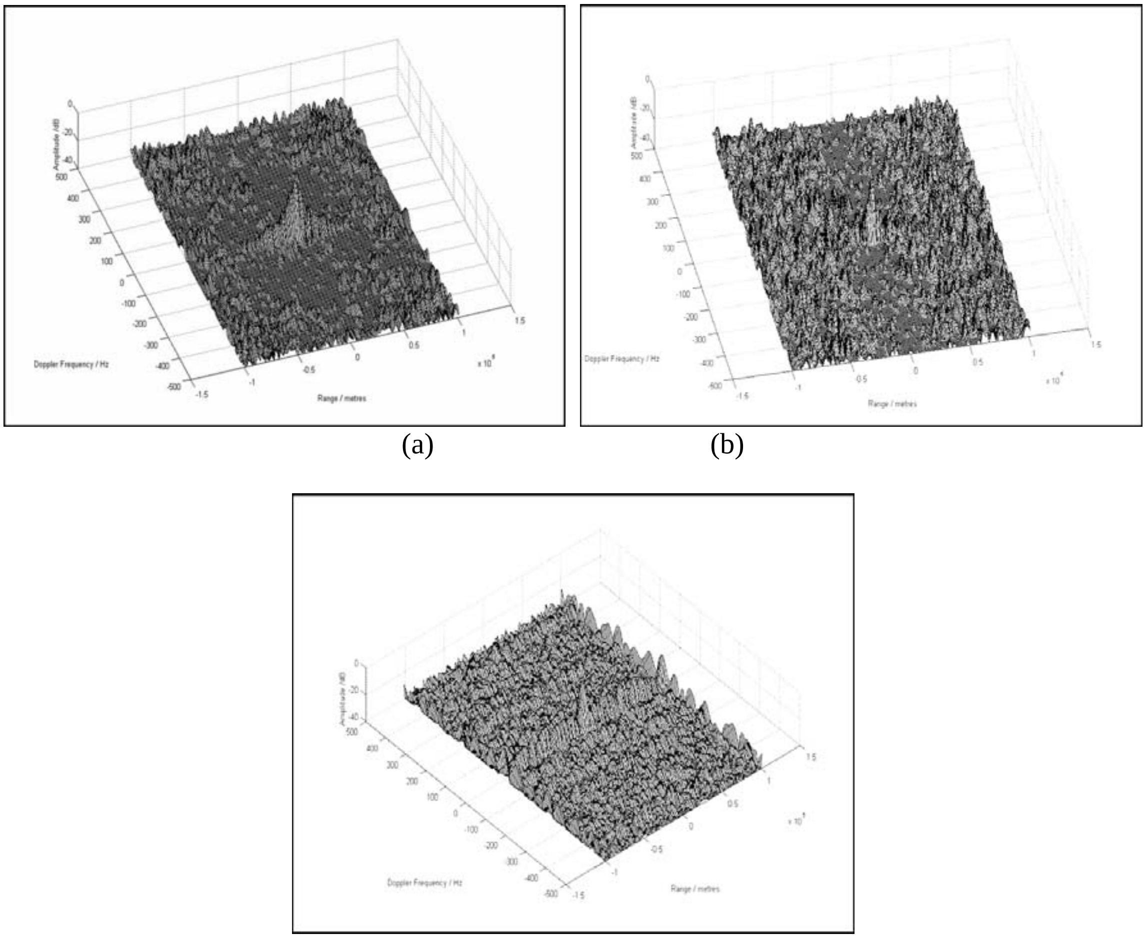


Figure 8: (a) time-domain representation of part of one TDMA-modulated carrier of a GSM signal, showing the 577 µs slots; (b) frequency-domain representation, showing the 200 kHz channel (after Tan et al. [49]).



(a) (b)

(c)

Figure 9: Ambiguity functions for three digital transmissions: (a) digital audio broadcast (DAB) at 222.4 MHz; (b) Digital video broadcast (terrestrial DBV-T) at 505 MHz; (c) GSM900 at 944.6 MHz.

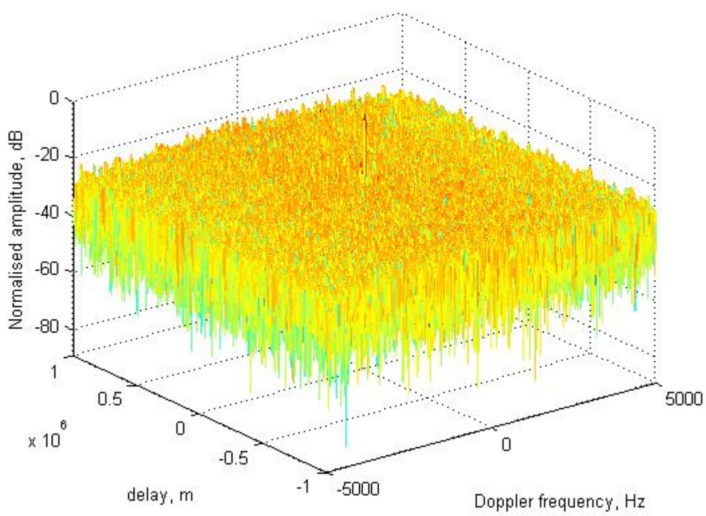


Figure 10: Normalised ambiguity function for DRM signal with 80ms integration time [50].

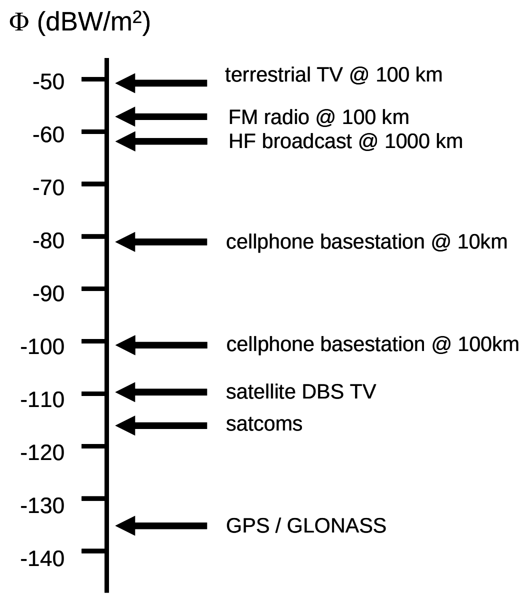


Figure 11: A 'league table' of some passive bistatic radar illumination sources, arranged in order of power density at the target. These power densities have been calculated on the basis of a single channel, full signal bandwidth, no processing gain and free space propagation (except for the HF broadcast signal, for which the propagation, and hence the power density, will depend on time of day, season and time of sunspot cycle).

Figure 12: Manastash Ridge Radar receiver, showing the simplicity of the digital receiver and GPS synchronisation hardware.

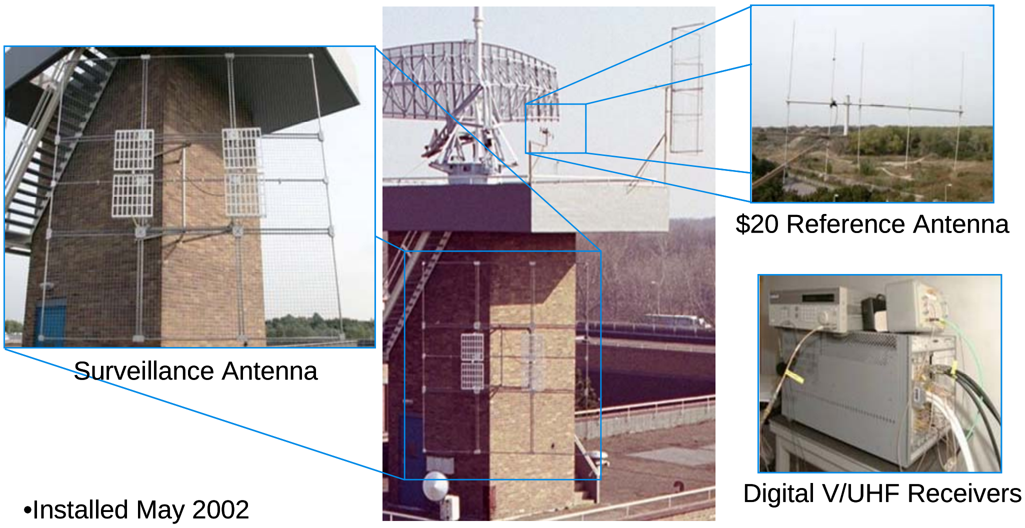


Figure 13: FM radio-based bistatic radar, showing surveillance and direct signal antennas and digital receivers [34]. Courtesy of Paul Howland and Darek Maksimiuk, NATO C3 Agency.

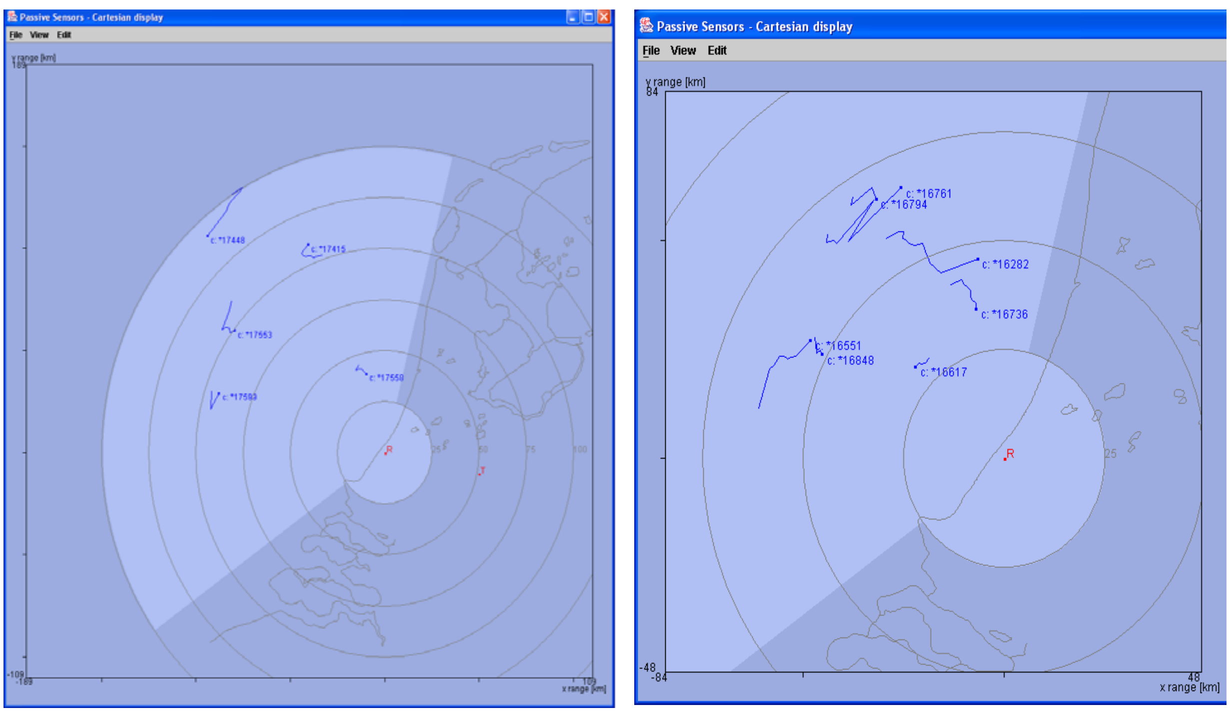


Figure 14: Examples of tracks of aircraft over the North Sea obtained with PBR system located at The Hague [34]. Courtesy of Paul Howland and Darek Maksimiuk, NATO C3 Agency.