Passive Coherent Location (PCL)
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.
3. PERFORMANCE PREDICTION

The starting point for prediction of PBR performance is the bistatic radar equation:

\[ P_r = \frac{P_t G_t}{4\pi r_1^2} \cdot \sigma_b \cdot \frac{1}{4\pi r_2^2} \cdot \frac{G_r \lambda^2}{4\pi} \]

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
- \( \sigma_b \) is the target bistatic radar cross-section
- \( r_2 \) is the target-to-receiver range
- \( G_r \) is the receive antenna gain
- \( \lambda \) is the radar wavelength
The very earliest radar systems were bistatic, with the transmitter and receiver at separate locations. The advent of the duplexer has meant that transmitting and receiving through the same antenna (monostatic radar) has since dominated radar design.

**Advantages Of bistatic passive over Monostatic Active Radar:**
1. It is cheap and undetectable because of the lack of the transmitter.
2. It has also potential capability of detecting “stealth” targets due to bistatic geometry and low operating frequency.

**Disadvantages Of Passive Radar:**
1) lack of control over transmitter and its parameters
2) sophisticated signal processing
3) general immaturity of the technology
**PCL radar** are bistatic or multistatic radar that do not contain transmitters, but use other emitters such as:

- other radars
- Analogue Television signals
- FM Radio signals
- cell phone signals.
- Digital Radio and TV
## Signal Parameters For A Range Of Passive Radar Illumination Sources

<table>
<thead>
<tr>
<th>Transmission</th>
<th>Frequency</th>
<th>Modulation, bandwidth</th>
<th>$P_iG_t$ (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF broadcast</td>
<td>10 – 30 MHz</td>
<td>DSB AM, 9 kHz DRM, 10 kHz</td>
<td>50 MW</td>
</tr>
<tr>
<td>VHF FM (analogue)</td>
<td>~ 100 MHz</td>
<td>FM, 50 kHz</td>
<td>250 kW</td>
</tr>
<tr>
<td>UHF TV (analogue)</td>
<td>~ 550 MHz</td>
<td>vestigial-sideband AM (vision); FM (sound), 5.5 MHz</td>
<td>1 MW</td>
</tr>
<tr>
<td>Digital Audio Broadcast</td>
<td>~ 220 MHz</td>
<td>digital, COFDM 220 kHz</td>
<td>10 kW</td>
</tr>
<tr>
<td>Digital TV</td>
<td>~750 MHz</td>
<td>digital, 6 MHz</td>
<td>8 kW</td>
</tr>
<tr>
<td>Cell-phone Networks (GSM)</td>
<td>900 MHz, 1.8 GHz</td>
<td>GMSK, FDM/TDMA/FDD 200 kHz</td>
<td>100 W</td>
</tr>
<tr>
<td>Cell-phone Networks (3G)</td>
<td>~2 GHz</td>
<td>CDMA, 3.84 MHz</td>
<td>100 W</td>
</tr>
</tbody>
</table>
- High availability of at one FM broadcast stations.
- Wide-area coverage.
- Comparatively high ERP.
- RCS returns are higher in the FM band.
- Most absorber material used for stealth applications is not optimized for irradiation by lower frequency intercepts.
- More immune to Anti Radiation Missiles. This fact is due to practical accuracy problems in calculation of the exact location of a low frequency radar site.
- Ambiguity function of FM approaches that of the ideal "thumb-tack" response.
- Diffraction Effects at these frequencies allow the detection of hidden targets through forests or behind smooth objects.
Figure 2. Ambiguity functions for three typical FM radio stations: (a) BBC Radio 4 (speech); (b) Jazz FM (fast tempo jazz) and (c) Choice FM (reggae music).
Figure 2: Variation in range resolution as a function of time for seven types of VHF FM radio modulation over a two-second interval (after [4]).
Disadvantage Of FM Broadcast Signal

- **Low bandwidth waveform**: poor range resolution
  Allowable channel bandwidth of 150 kHz modulation bandwidth can provide 1km range resolution. At best case in FM, 30 kHz modulation bandwidth is achieved, which results in 5km range resolution.

- **Low carrier frequency**:  
  - It is not practical to build highly directional antennas:  
    - Single PCL receiver can measure only range and range-rate.  
    - To determine bearing, multiple receiver are needed.  
  - To reach good Doppler frequency resolution, one must use long processing intervals places a computational burden on signal processor of PCL.
Apply an adaptive filter to reject the unwanted transmitter signal in two surveillance channels.

- Using cross-correlator to generate two amplitude–range–Doppler (ARD) surfaces.
- Apply CFAR detection to each ARD surface to determine the range and Doppler of each target.
- Estimate the target bearing in direction finding processor.
- Associate range–Doppler–bearing data with individual targets in “Plot-to-target association” box.
- Determine the target’s location, speed and heading by nonlinear filter in “target state estimation” box.
Although the cross-correlation processing between the reference and surveillance channels causes any unwanted reference signal in the surveillance channel to be confined to the zero-Doppler and zero-range bin, the range and Doppler sidelobes of this autocorrelation function remain significant, therefore, it is therefore critical that the direct signal and clutter is removed from the surveillance channels before cross-correlation processing is attempted.
To act as a matched filter for the radar system and provide the necessary signal processing gain to allow detection of the target echo.

To estimate the bistatic range and Doppler shift of the target.

\[
|\Psi(\tau, \nu)| = \left| \sum_{n=0}^{N-1} e(n)d^*(n-\tau)e^{j2\pi\nu n/N} \right|
\]

- \( s(n) \): filtered echo signal.
- \( d(n) \): reference signal.
- \( \tau \): TDOA
- \( \nu \): Doppler shift of interest

Cross-correlation concept
Simplest algorithm for Range Doppler Processing is:

- rotate the elements of $d(n)$ and conjugate to obtain the required time delay, $d^*(n - \tau)$
- multiply the rotated $d(n)$ and $e(n)$
- calculate the FFT of $e(n)d^*(n - \tau)$
- discard data from Doppler bins not of interest

Example results of cross-correlation processing
Δφ = 2π \frac{dsinθ}{λ}

اختلاف فاز بین دو کانال است (اختلاف فاز بین دو مقدار FFT در سلول مشابه در دو کانال)
4. PROCESSING

4.1 Suppression of Direct Signals, Multipath and Interference

Various techniques have been reported to suppress this radio frequency interference. First, and most attractive due to effectiveness, simplicity and cost, is to site the receive antenna so that it is physically shielded from the direct path signal, using topography, buildings or shrouds. This technique alone can often provide adequate suppression, but in turn limits the receive antenna’s field of view (FOV). In some cases this trade-off is entirely acceptable. But for air surveillance, terrain blockage of the receiver’s FOV is nearly always unacceptable, especially for low altitude spatial cancellation of the direct path signal is a second principal option. An array antenna at the receiver can be configured to steer a null at the direct path signal, and null depths of several tens of dB are achievable. Howland used this technique in his 2000 FM radio-based bistatic radar trials [24, 9] to achieve ~15 dB of cancellation. The radiation pattern nulls should ideally be broadband, so that multiple signals from a given transmitter may be suppressed by a single null.

To add additional complexity, if the environment is non-stationary adaptive control of the antenna array is required. Adaptive arrays and null steering techniques have been studied and developed extensively over several decades, both for mobile and personal communications and for radar applications. The first of these (in the 1970s and early 1980s) were analogue, but these were soon overtaken by digital approaches as fast analogue-to-digital converters and processing power became readily available.

Spectral cancellation of the direct path signal is a third principal option. Howland succinctly detailed this problem and then his solution [22]:
The transmitted signal:
~30 kW isotropic radiated power

The direct-path signal $x[]$

Cascade mountains block direct-path transmission

The scattered signal $y[]$
It is clear that a combination of techniques will often be needed to achieve adequate direct path suppression, and even then (as has already been noted) the achieved value of receiver noise figure is unlikely to be better than about 25 dB.

4.2 Target Location and Tracking

The second issue is the means by which the quantities measured by the receiver(s) are used to locate and track targets. For each target a PBR system can measure: (i) bistatic range (from the delay difference between the direct signal and the targets echo), (ii) echo Doppler, and (iii) echo angle of arrival, from one or more transmissions, and at one or more receivers. There are essentially two approaches to this problem. The first is multilateration, in which each measurement of bistatic range from a transmitter-receiver pair will locate the target on an ellipse. A set of such measurements will yield a set of ellipses, whose intersection will yield the target location. The second is to set up a target state vector, and to use the measurements to give the best estimates of the vector components, in a similar manner to classical tracking theory. Space does not permit a full treatment of these techniques, but the reader is referred to [22] for details.
Target Association

Tracking targets is performed in the range–Doppler-bearing domain.

- association of returns from different transmitters of the same target (in a multistatic system)
- target state estimation
FM radio-based bistatic radar

FM radio-based bistatic radar, showing surveillance and direct signal antennas and digital receivers. Courtesy of Paul Howland and Darek Maksimiuk, NATO C3 Agency.
The accuracy of each of bistatic-range, bearing and Doppler, however, is quite different:

- Range and bearing are a factor of ten or so worse than a conventional microwave radar owing to the lower bandwidth of the FM radio signal.
- Doppler is two or three orders of magnitude more accurate (owing to the extended integration times possible with passive radar).
TV Based BPR
Analogue TV signals with a bandwidth of about 6.0 MHz are typically located in the several hundred MHz regions. In the frequency spectrum of analogue TV signals, two carriers are present, one for the visual and the other for sound signal. Typically a wideband spectral response provides good range resolution. However, the spectral shape of TV signals negates the advantages gained from its wideband spectrum. For example, the output of the filter matched to the TV signal has several strong recurrent lobs which produce several spurious. In addition, because of the periodic synchronization structure in the analogue TV signal, the unambiguous range is about order of 9 km.

Regarding all these facts, the TV signal is not a suitable choice for range measurement.

(وجود پالس های همزمان سازی و شباهت ذاتی سطرهای متوالی سازنده تصویر)
Figure 3: 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.
transmitter has a power of 500kW. If the modulation scheme used was double sideband amplitude modulation (DSB-AM) then it can be shown that 66% of the transmitted power would be in the carrier (assuming 100% modulation), and 16% in each sideband [15]. However, vestigial sideband modulation is used, in which the vision carrier is suppressed by 6dB and only a much reduced portion of the lower sideband is transmitted [16]. For the purposes of this calculation then, assume that no lower sideband will be (66*0.25):16. Thus approximately half the transmitted power is in the carrier, and so the TV vision carrier can be represented in the bistatic radar equation with a power of 250kW.
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 [21].

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 [21, 22].

**P.E. Howland et. Al.**

It is shown that targets can be detected and tracked over a large area. In the examples shown, targets were tracked at ranges of up to 260km from the radar receiver, using the Crystal Palace TV transmitter and a receiver located 156km away in Pershore, Worcestershire.
50m low loss coaxial cable → VHF/UHF down-convertor → HF digital receivers → Doppler & bearing processing → CFAR detection → Kalman filter plot association → Many tracks
\[ b = \sqrt{x^2 + (L-y)^2} \]

\[ a = \sqrt{x^2 + y^2} \]

arctan(x/y)
3.3.4 Measurement Equations

Consider the geometry shown in Figure 3.8. In a radar system the Doppler shift of an echo is directly proportional to the rate of change of total path length that the signal travels on from the transmitter to the target to the receiver. From Figure 3.8 it is clear that the total path length is given by the distance $a + b$, and so the Doppler shift will be given by:

$$F_d = -\frac{1}{\lambda} \left[ \frac{da}{dt} + \frac{db}{dt} \right] \quad (3.3)$$

From Figure 3.8 it can be seen that:

$$a = \sqrt{x^2 + y^2} \quad (3.4)$$

$$b = \sqrt{x^2 + (L - y)^2} \quad (3.5)$$

and hence it is trivial to show that

$$F_d = -\frac{1}{\lambda} \left[ \frac{x\dot{x} + y\dot{y}}{\sqrt{x^2 + y^2}} + \frac{x\dot{x} + (L - y)\dot{y}}{\sqrt{x^2 + (L - y)^2}} \right] \quad (3.6)$$

where $\dot{x} = \frac{dx}{dt}$ and $\dot{y} = \frac{dy}{dt}$. 
\[ x(nT) = x_0 + n\dot{x}T \]
\[ y(nT) = y_0 + n\dot{y}T \]

Thus if \( x \) and \( y \) are replaced by the target state equations of section 3.3.3 then:

\[
F_d = -\frac{1}{\lambda} \left[ \frac{(x_0 + nT\dot{x})\dot{x} + (y_0 + nT\dot{y})\dot{y}}{\sqrt{(x_0 + nT\dot{x})^2 + (y_0 + nT\dot{y})^2}} + \frac{(x_0 + nT\dot{x})\dot{x} + (L - (y_0 + nT\dot{y}))\dot{y}}{\sqrt{(x_0 + nT\dot{x})^2 + (L - (y_0 + nT\dot{y}))^2}} \right]
\] (3.7)

By inspection of Figure 3.8 it is apparent that the direction of arrival of the echo is given by:

\[
\Phi = \tan^{-1} \left( \frac{x_0 + nT\dot{x}}{y_0 + nT\dot{y}} \right)
\] (3.8)

### 3.3.5 Inclusion of Target Altitude

Target altitude can be modelled by fairly minor alterations to equations 3.7 and 3.8 as shown below:

\[
F_d = -\frac{1}{\lambda} \left[ \frac{x\ddot{x} + y\ddot{y}}{\sqrt{x^2 + y^2 + z^2}} + \frac{x\ddot{x} + (L - y)\ddot{y}}{\sqrt{x^2 + (L - y)^2 + z^2}} \right]
\] (3.9)

\[
\Phi = \sin^{-1} \left( \frac{x}{\sqrt{x^2 + y^2 + z^2}} \right)
\] (3.10)

where \( z \) is the target altitude above the ground. These have been used to successfully
Many tracks

Track initialisation only

Track maintenance

Kalman filter association

Genetic algorithm

Modified Levenberg-Marquardt algorithm

Extended Kalman filter track estimation
where \( F(i) \) and \( \Psi(i) \) represent the \( i^{th} \) samples of Doppler and DOA respectively, and \( N \) is the number of samples of Doppler and DOA per batch.

The vector \( h(x) \) contains the measurement equations (Equations 3.7 and 3.8) that correspond to the measurements in the vector \( z \), so

\[
\begin{pmatrix}
F_d(0) \\
\Phi(0) \\
F_d(1) \\
\Phi(1) \\
\vdots \\
F_d(N - 1) \\
\Phi(N - 1)
\end{pmatrix}
\]
In terms of $h(x)$ and $z$ the algorithms attempt to minimise the cost function $J_{LS}$ defined as:

$$J_{LS} = \frac{1}{2} [z - h(x)]^T [z - h(x)]$$  \hspace{1cm} (5.3)

where the expression $z - h(x)$ is known as the residual.

A necessary condition to find the minimum of $J_{LS}$ is for

$$\frac{\partial J_{LS}}{\partial x}(x) = 0$$  \hspace{1cm} (5.4)

$$\Rightarrow [z - h(\hat{x})]^T \frac{\partial h}{\partial x}(\hat{x}) = 0$$  \hspace{1cm} (5.5)

where $\hat{x}$ denotes the estimate of the state vector $x$. Rearranging this gives:

$$\left[ \frac{\partial h}{\partial x}(\hat{x}) \right]^T [z - h(\hat{x})] = 0$$  \hspace{1cm} (5.6)
estimation problem, however, $h(x)$ is highly non-linear (see equations 5.2, 3.7 and 3.8), and so equation 5.6 must be solved numerically to obtain the state vector estimate. This chapter addresses three such algorithms.

All three algorithms can be written in the following general form:

$$\hat{x} = x^* + \beta[z - h(x^*)]$$  \hspace{1cm} (5.7)

where $\hat{x}$ is the current estimate, $x^*$ is the previous estimate, and $\beta$ is a matrix quantity that can be regarded as a glorified proportionality constant that determines what to add to the previous state estimate to improve it. The fundamental difference in all three algorithms is their choice of $\beta$. 
Figure 3.3: VXI mounted radar receiver equipment
### Other Signals

<table>
<thead>
<tr>
<th>signal</th>
<th>frequency (MHz)</th>
<th>range resolution (km)</th>
<th>effective bandwidth (kHz)</th>
<th>peak range sidelobe level (dB)</th>
<th>peak Doppler sidelobe level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM radio: speech (BBC Radio 4)</td>
<td>93.5</td>
<td>16.5</td>
<td>9.1</td>
<td>−19.1</td>
<td>−46.5</td>
</tr>
<tr>
<td>FM radio: classical music</td>
<td>100.6</td>
<td>5.8</td>
<td>25.9</td>
<td>−23.9</td>
<td>−32.5</td>
</tr>
<tr>
<td>FM radio: rock music (XFM)</td>
<td>104.9</td>
<td>6.55</td>
<td>22.9</td>
<td>−12.0</td>
<td>−26.0</td>
</tr>
<tr>
<td>FM radio: reggae (Choice FM)</td>
<td>107.1</td>
<td>1.8</td>
<td>83.5</td>
<td>−27.0</td>
<td>−39.5</td>
</tr>
<tr>
<td>DAB</td>
<td>219.4</td>
<td>1.54</td>
<td>97.1</td>
<td>−11.7</td>
<td>−38.0</td>
</tr>
<tr>
<td>Analogue TV: chrominance sub-carrier</td>
<td>491.55</td>
<td>9.61</td>
<td>15.6</td>
<td>−0.2</td>
<td>−9.1</td>
</tr>
<tr>
<td>Digital TV (DVB-T)</td>
<td>505.0</td>
<td>1.72</td>
<td>87.1</td>
<td>−18.5</td>
<td>−34.6</td>
</tr>
<tr>
<td>GSM 900</td>
<td>944.6</td>
<td>1.8</td>
<td>83.3</td>
<td>−9.3</td>
<td>−46.7</td>
</tr>
<tr>
<td>GSM 1800</td>
<td>1833.6</td>
<td>2.62</td>
<td>57.2</td>
<td>−6.9</td>
<td>−43.8</td>
</tr>
</tbody>
</table>

Table 1. Properties of ambiguity functions of various types of broadcast and communications signals.
Figure 6: 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.
5. EXAMPLES OF PRACTICAL SYSTEMS

Also of great relevance and interest is Lockheed Martin’s Silent Sentry [3], which is one example of 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 is THALES’s Homeland Alerter 100 system. The publicity material for this states:

‘The Homeland Alerter is a passive radar that uses civil radio and TV wavebands to detect objects flying at a low altitude. The radar can locate them and measure their velocity. Designed mainly for coastal surveillance, protection of high value assets, airports and force projection missions, this discreet radar is fully interoperable with the highest level command systems.’

There has also been significant work on using HF transmissions for PBR purposes, giving potentially very long range performance, though subject to the diurnal, annual and sunspot cycle variations in ionospheric propagation. Notable among these is the NOSTRAMARINE system of Lesturgie and his co-workers [27].
6. 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 [18] 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