PCL Waveforms

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Introduction

Passive radar uses transmitters of opportunity that illuminate a target or targets and capture the scattered radiation using a receiver placed remotely from the transmitter. The essential components of a passive radar system are illustrated in Figure 1. The point at which a target crosses the baseline between a transmitter and a receiver, it is said to be the 'forward scatter' geometry. In the forward scatter geometry there are a number of significant differences from the bistatic and monostatic cases. Here, we examine those differences and how they may be exploited to best effect [1, 2], and in the context of passive radar networks.

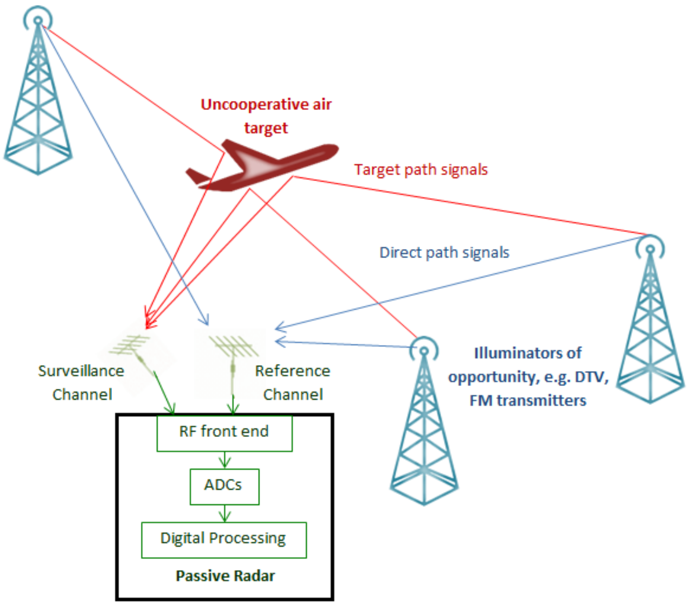

Figure 1: An example of a passive radar geometry.

Historical background

The first known operational use of forward scatter radar systems were as 'fences' designed to detect the passage of aircraft crossing a transmit-receive baseline. In this region, as will be seen shortly, the target's radar cross section (RCS) is significantly enhanced. Around 200 such fences were employed by Japan, France, the USA and the Soviet Union for aircraft detection around the end of the second world-war. There are also reports [3, 4] of three forward scatter, Over-the-Horizon (OTH) fences deployed in the mid 1960s to detect missiles launched from the Soviet Union. The OTH forward scatter systems, operating at frequencies in the range 3 to 30 MHz, proved to be effective over large surveillance areas and this helped to minimise the number of transmitting and receiving sites. Three transmitters were deployed in Taiwan, Japan and the Philippines the three receivers were located in Italy, Germany and the UK. The system detected a high percentage of known single events.

Forward scatter systems operating at higher frequencies, were less effective as aircraft rapidly flew out of the coverage range of a single fence and thus could not be detected and tracked across a network. Further, it was only when adjacent, orthogonally placed baselines were used that aircraft velocity and position be estimated and then only with limited accuracies. As a consequence, these higher frequency systems were abandoned. However, forward scatter has been revisited periodically with systems such as the US 'Fluttar' being developed in the 1950s for long range early warning and was deployed for a period of 5 years [5].

All of these early systems used a dedicated transmitter and receiver and would not fall under the definition of a passive radar. More recently a new wave of interest has emerged in forward scatter radar. In part, this has been driven the introduction of 'stealth' targets. Such targets have a significantly reduced RCS due to a combination of shaping, materials and coatings that, collectively, greatly suppress backscattering. However, the objective of stealth technology was to defeat monostatic radar and hence there is a great motivation for the target RCS enhancement that occurs at the forward scatter bistatic geometry. Secondly, interest in FSR has increased recently because of the establishment of *passive radar concepts* where illuminators of opportunity are used to form a network of bistatic radars and the forward scatter geometry is a natural part of such systems. It happens that many of the suitable transmitters are readily available in large numbers and are geographically dispersed, making forward scatter a natural mode of operation of a passive radar network.

Forward Scatter

The forward scatter geometry is shown in more detail in figure 2. As a target approaches the baseline between the transmitter and the receiver, the bistatic angle, β, increases, eventually reaching a maximum of 180^0. Under this condition, the ability to measure range and Doppler resolution is lost. At angles close to but less than 180^0, there are small components of range and Doppler that exist which can be exploited as part of a forward scatter mode of operation. According to Babinet's principle, the signal diffracted around a target of a given silhouette area will be equal and opposite to that diffracted through an equivalent target-shaped hole in an infinite screen perpendicular to the path between transmitter and receiver [6].

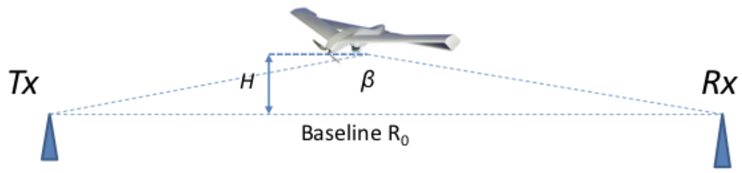

Figure 2. The forward scatter geometry

In other words, Babinet's principle tells us that we get exactly the same scattering from a perfectly-absorbing target as we would from a target-shaped hole in an infinite perfectly-conducting sheet. A signal that is diffracted through an aperture of a given shape and area can be readily calculated, allowing the forward scatter RCS to be determined directly. For a target of silhouette area, *A* and linear dimension *d*, the forward scatter RCS is:

$$\sigma_{FS} = \frac{4\pi A^2}{\lambda^2} (\text{m}^2) \qquad (1)$$

and the angular width of the forward scatter is:

$$\theta_B \approx \frac{\lambda}{d} \text{ (radians)} \qquad (2)$$

Equations (1) and (2) are plotted in Figure 3 for a target where, A = 10 m^2 and d = 10 m (say, a medium-sized aircraft). It is instructive to note that equations (1) and (2) are the equations for antenna gain and beam width respectively. The typical large central peak of an antenna beam pattern is responsible for the large RCS enhancement in forward scatter. From figure 3, it can be seen that the forward scatter RCS may be substantially greater than the equivalent monostatic RCS (which for this target might be of the order of 10 dBm^2). However, it can also be appreciated that whilst this geometry may give good detection performance, the target location accuracy will be poor, since the range and Doppler resolution will both be poor when the target is near the baseline. In other words, when the time when target is exactly between the transmitter and receiver is known but not how far the target is from the transmitter (or receiver). Figure 3 also shows that as the frequency of illumination increases, the RCS increases but the range of angles over which it can be observed decreases.

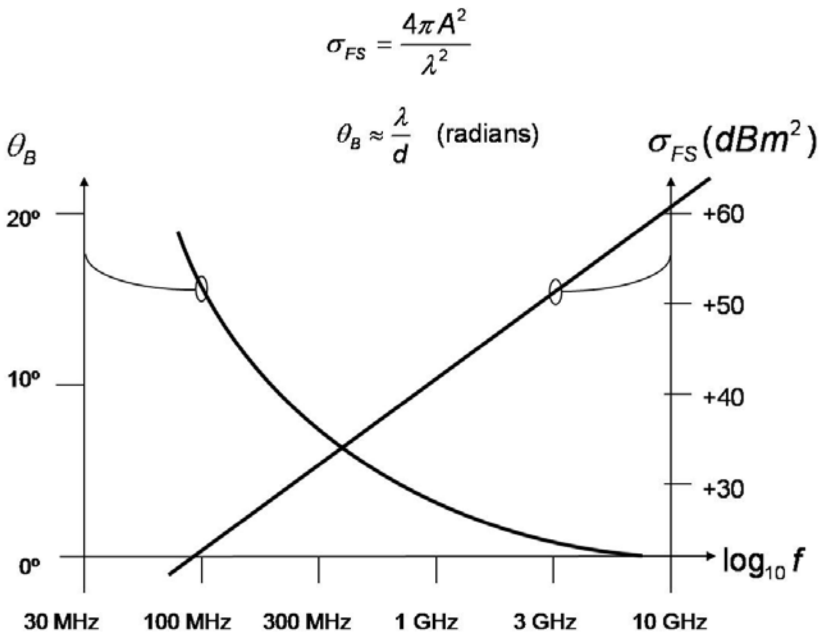

Figure 3: Forward scatter RCS σ_{FS} and angular width of scatter θ_B for an idealised medium aircraft target with A = 10 m^2 and d = 10 m.

Therefore, the optimum frequency that provides a large RCS over a reasonably broad a range of viewing angles is a little above 300 MHz, right in the middle of the UHF DTV band. Thus, for aircraft sized targets, the UHF band makes an excellent choice for a happy medium between coverage and RCS value. Indeed, the large numbers of high power DTV transmitters makes a comprehensive forward scatter network a natural part of a passive radar network. However, it should be noted that Figure 3 is constructed from a very simple representation of forward scatter and in practice, the RCS enhancement can be observed over a broad range of frequencies and transmitter choice will be chiefly governed by application. As passive radar typically consists of a number of bistatic pairs, the likelihood of targets crossing baselines would seem to be quite high. However, this has to be considered carefully for any given set of locations of transmitter and receiver, together with likely trajectories of a target. Consider an example with a ground-based transmitter operating at a frequency of 350 MHz and ground-based receiver separated by a baseline of 50 km. An aircraft at a cruising altitude of 10 km crosses the baseline halfway between the transmitter and the receiver. When the aircraft crosses the baseline, it will make an angle of over 20° as seen by the receiver. This places it outside of the observable region as indicated by Figure 3. Thus, forward scatter using ground-based transmitters and receivers might be better suited to the detection of low flying aircraft only, which may be of high interest in defence or security applications. Equally, it may also have a role detecting ground targets from ships, to vehicles to personnel, again making it attractive for military and security applications. This is especially so, given the potential for a significant RCS enhancement that could defeat otherwise stealthy targets.

Not only is forward scatter radar well suited to robust detection of small or stealthy targets, but with recent advances is also showing real promise for tracking and classification. Long integration times provide for improved detection and excellent Doppler resolution and of course, forward scatter radar can operate in all environments on a 24-hour basis. Recent work on tracking has used coherent processing to estimate motion parameters in forward scatter radar networks building a sequence of observations as a target propagates through a series of differently orientated baselines. Forward scatter classification can use statistical approaches that derive features from the target Doppler signatures and/or it can use profile reconstruction by inverting the problem of Fresnel diffraction of a moving target. It comes as no surprise that forward scatter has great potential as a core component of a passive radar network.

The Forward Scatter Signal

In bistatic radar, the signal re-radiated by a target is measured while the direct path (leakage) signal, is unwanted and has to be supressed. In fact, the leakage signal can be a fundamental limitation for passive radar. The forward scatter signature is a result of self-mixing and can be thought of as an ‘interference beat signal’ that occurs at the output of the receiver. It arises due to the interference of the direct path signal and the signal scattered by the target. In a perfect forward scatter geometry (i.e., with a bistatic angle of 180), the signal received is a target ‘shadow’. The strong direct path signal is the signal that travels directly from the transmitter to the receiver. The shadow signal is the much weaker forward scatter signal and this modulates the leakage signal. The forward scatter signal has a pattern equivalent to that of an antenna with an aperture equivalent to the target shadow silhouette, but with a negative gain.

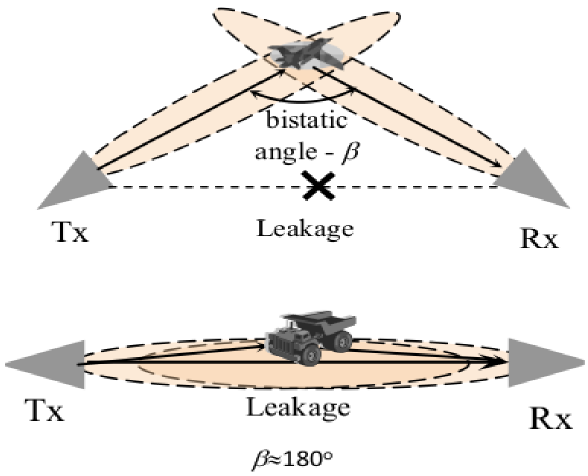

Figure 4: A comparison of bistatic and forward scattering

In a typical monostatic radar, the target echo signal strength is specified by its RCS. In forward scatter radar there is a similar parameter which specifies the signal strength at the receiver, the forward scatter cross section (FSCS), also measured in m^2 or dBm^2. The FSCS pattern in the Mie and optical region for a target of three-dimensional shape can be calculated using an appropriate plane shape as defined by the outline of the target. This is then replaced by a complimentary aperture antenna which has a negative gain, because the signal from such an antenna reduces the incident field strength rather than increase it. This replacement is equivalent to applying Babinet's principle. The full FSCS pattern (as opposed to just the main lobe) can be viewed and analysed as the radiation pattern of the secondary planar antenna using standard equations for far-field computation as shown in (3) below.

$$\sigma_{fs}(\vec{r}_0) = \lim_{R\to\infty} 4\pi R^2 \left(\left| E_{sh} \right|^2 / \left| E_{inc} \right|^2 \right) = \frac{4\pi}{\lambda^2} \left| \int_{A_{SH}} e^{j\left(\frac{2\pi}{\lambda}\right)\vec{\rho}\vec{r}_0} dS \right|^2 \quad (3)$$

Where E_{SH} is the electric field intensity of the shadow field
E_{INC} is the electric field intensity of the incident field
dS is the surface element of the co-phasal aperture
R is the target range
λ is the illumination wavelength

Equation (3) describes the pattern of the shadow aperture of the target. The shadow aperture can be thought of as 'black body' radiation, i.e. radiation of an object which absorbs an incident EM wave. For a bistatic angle of 180^0, this reverts to the simple expression represented by equation 1 that was introduced earlier, where A is the projected area of the target

. This is why the forward scatter geometry is ideal for detecting stealth targets. As a simple example, if the target had a square shape, it can be thought of as a planar, square shaped antenna with negative gain. It is well-known that the beam pattern for such an antenna is given by a Sinc function. Figure 5 shows beam pattern for an arbitrary but squarish shaped target. As might be expected there is a strong central lobe on the axis of the baseline surrounded by sidelobes of lesser gain. This provides a clear relationship between the shape of the target and the measured far-field pattern such that measurement of one can be inverted to reveal the other.

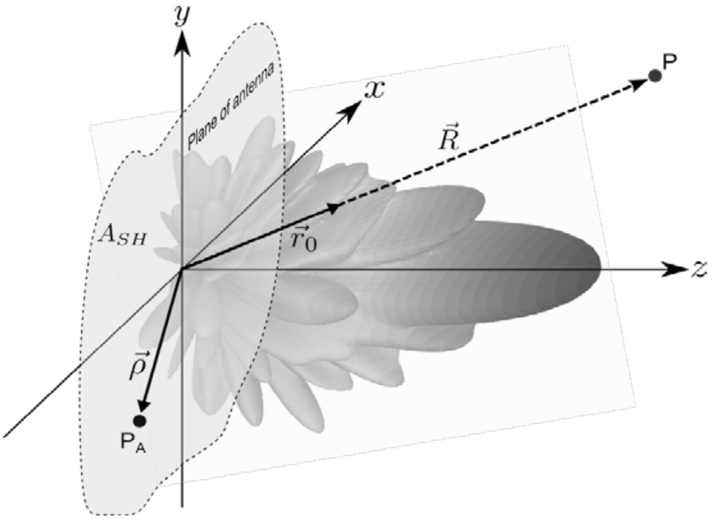

Figure 5: The 3-D 'beam pattern' for an arbitrary shaped target as seen along and just away from the baseline of a forward scatter radar

A further measurement of interest that can help with detection, tracking and classification is Doppler. Figure 6. shows the form of the Doppler signature as a target crosses the baseline in a forward scatter geometry.

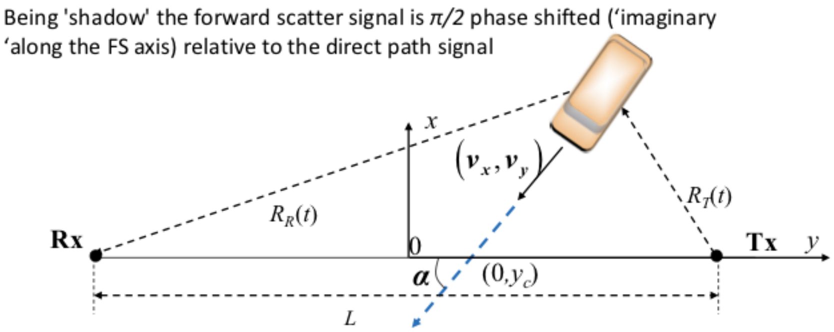

Figure 6: The forward scatter Doppler geometry

The received signal is again made up from the interference of the directly received and shadow signals with a phase determined by the relative positions of the target, transmitter and receiver as shown in equation (4) below.

$$f_D(t) = -\frac{1}{\lambda}\frac{d[R_T(t) + R_R(t)]}{dt} \qquad (4)$$

It can be seen from equation (4) that there is no Doppler if the range sum is invariant. This is the case for any target moving along or at the baseline. Equally a target moving around an ellipse with the transmitter and receiver as foci will also have zero Doppler. If a target transitions across the baseline following an orthogonal trajectory it will map out a quadratic phase response (i.e., a linear frequency modulation) assuming the velocity in the narrow forward scatter region to be a constant. This modulation with time can be used for (i) locating the position of the target, (ii) estimating target velocity for tracking and (iii) imaging and computation of target shape profile leading to classification.

Forward Scatter Detection

The first requirement of any forward scatter radar system is to be able to detect a target crossing the baseline. As with any other type of radar this is mainly determined by the signal to interference plus noise ratio. In the forward scatter geometry, a target can be considered as an obstacle in the way of the wave travelling from the transmitter to the receiver. As has just been seen, the diffraction pattern depends on the relative positions of the transmitter, receiver and target and is determined by the size, shape and orientation of the target as well as the illuminating wavelength. In order to detect the presence of both the leakage and the scattered signal, the target-radar topology should satisfy the far-field condition as this ensures a maximum forward scatter signal.

As an example, figure 7. shows the measured signatures of targets with different sizes that, in turn, define different diffraction cases. In figure 7, the baseline is 300m and the far-field condition parameter, S = $D^2/4\lambda$, is displayed for each of the targets. In figure 7 (a), S = 60 m, and the far-field condition can be easily met. In figure 7 (b), S = 160m which places the target in the transition region between the near and far-fields. In figure 7 (c), S = 630 m which places the target very much in the near-field.

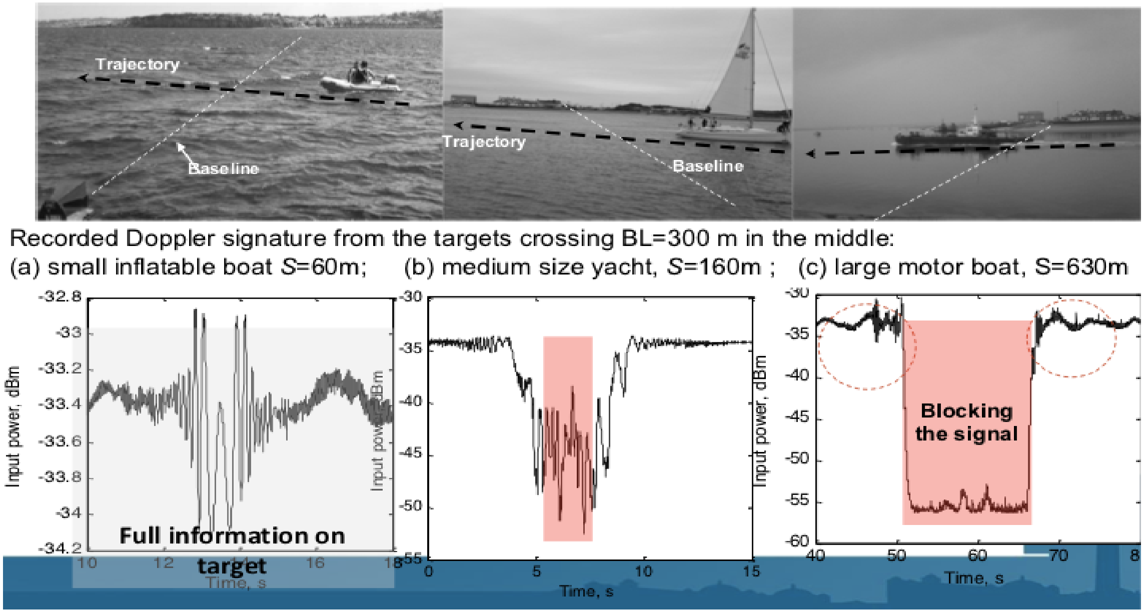

Figure 7. The effects of different sized targets and the resulting diffraction

Figure 7 (a) shows the Fraunhofer (far-field) diffraction pattern from a small inflatable boat of approximate size 2.9 m x 1 m (length and height above the sea surface). Because the far-field condition is satisfied there is a full representation of the changing target signatures as it crosses the baseline. In this way the information regarding the target is complete and there will be a strong central lobe maximising detection performance. This may be contrasted with the case shown in figure 7 (c) where the target is a much larger ship and the far-field condition is no longer satisfied. Here, the sheer size of the target acts to block the illuminating radiation from being received for almost the whole of the forward scatter zone and as a consequence very little information can be derived. However, detection is still possible based upon the change in signal as the target crosses the baseline. Figure 7 (b) shows the intermediate case where the size of the target is such that this case is in the transition zone between the Fresnel and Fraunhofer conditions (near-field and far-field). Here, a signature can be observed with evidence of some blocking. However, it may not necessarily preclude detection. Overall, though, the design of the system should aim to satisfy the forward scatter far-field criterion.

The diffraction patterns also offer a means of determining target kinematics which can be deduced from the derived Doppler associated with the time varying phase functions. Figure 8. Show an example of how this can be achieved using spectrograms for the cases introduced in figure 7.

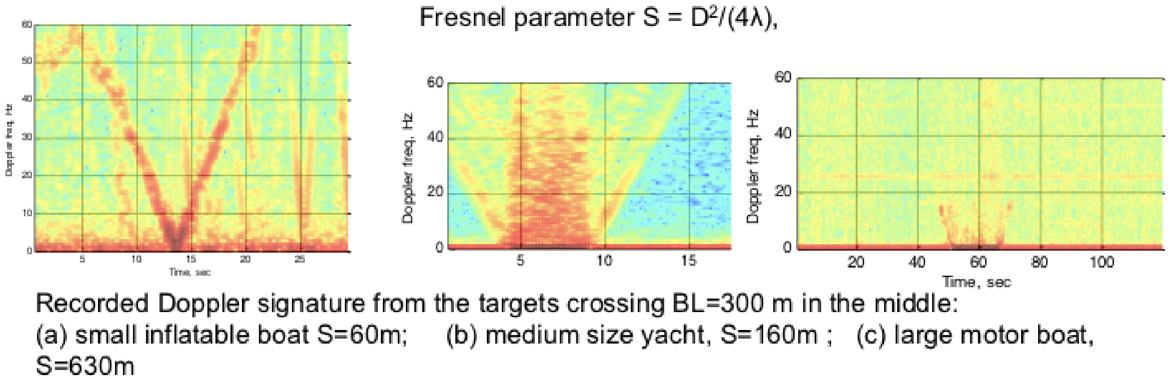

Figure 8: Spectrograms for the three different sized targets shown in figure 6.

The position in the spectrogram at which the Doppler velocity goes to zero is when the ideal forward scatter condition is met and the target is on the baseline. Thus, the time at which this occurs will be a known quantity. The slope of the Doppler gives a measure of the radial speed of the target allowing the target velocity to be deduced, assuming it to be a constant. However, the rate of Doppler shift will be higher the closer the target is to the receiver and hence exact velocity estimation can be difficult.

Figure 9. shows schematically, the steps leading to a detection decision. Firstly, the received signal is cross-correlated with a reference function for the target. This has the aim of maximising the signal to noise ratio (SNR) through matched filtering. In fact, a series of reference functions is used to find the closest match with the target velocity and trajectory. This is followed by application of a detection algorithm to determine the presence or absence of a target.

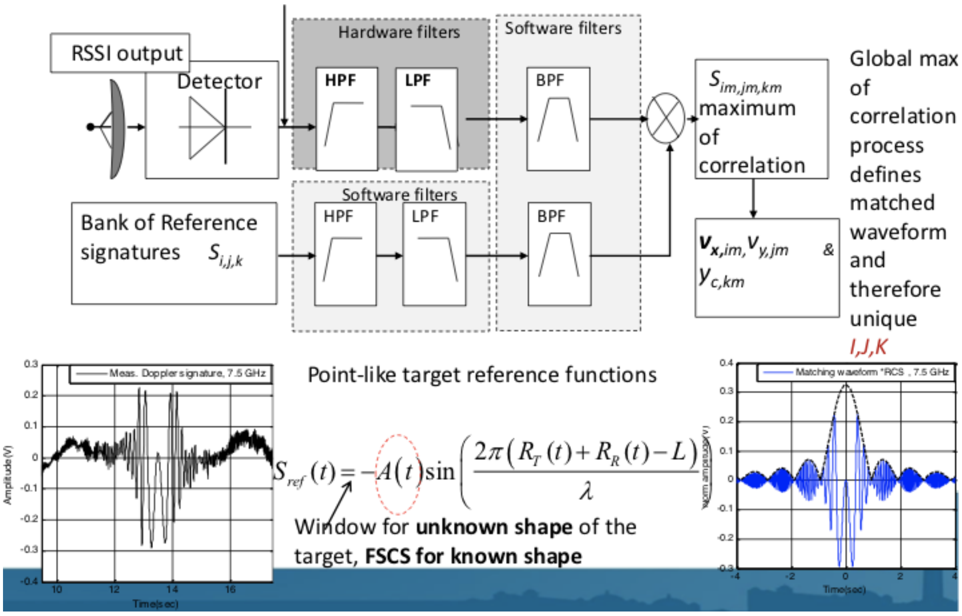

Figure 9: Match filtering of the quadratic phase function forward scatter signal

In figure 9.the received signal is first filtered to remove extraneous noise and unwanted signals. The next step is correlation followed by detection where a threshold is derived and applied to the measured data in order to make a decision as to whether a target is present or not. Figure 10 shows an example data set in which both a constant threshold and an adaptive threshold are applied. The adaptive threshold allows a constant false alarm rate (CFAR) that attempts to following the mean level of the noise thus controlling false alarms to a constant level.

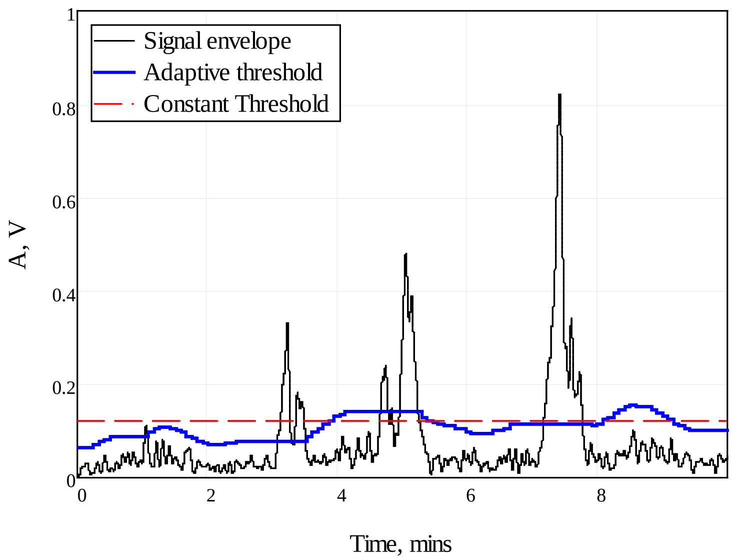

Figure 10: Constant and adaptive thresholding of the target signal for detection

In the example shown in figure 10, the signal has been non-coherently processed and the targets are people walking across the baseline, following each other with a separation of around 5m. The approach used is very similar to that used in conventional monostatic radar. The data can also be processed ‘pseudo-coherently’ using a reference waveform derived from another transmission close in frequency. Ultimately, best performance will be for fully coherent processing where both amplitude and phase are used. In the pseudo-coherent case the received signal is cross-correlated with another signal close in frequency but phase shifted to get a closer match. In the coherent case, conventional matched filtering is done using a replica of the transmitted signal. It is also perfectly possible to combine the three forms of detected output and this could be done on a majority vote basis.

Resolving multiple targets

As has already been seen, forward scatter radar, does not enable measurement of range and Doppler can only be measured over time as a target passes towards and beyond the transmitter-receiver baseline. The resolution of multiple targets with forward scatter radar has to be done in the Doppler domain and therefore uses Doppler to resolve targets. The received signal will consist of two superimposed signals from two targets can be written as:

$$S_r(t) = A_1(t)\sin[\psi_1(t)] + A_2(t)\sin[\psi_2(t)] \qquad (5)$$

Where A_1 is the amplitude of the signal from target 1
A_2 is the amplitude of the signal from target 2

$$\psi_1(t) = \omega_0 \frac{R_{1R}(t) + R_{1T}(t)}{c} \qquad (6)$$

$$\psi_2(t) = \omega_0 \frac{R_{2R}(t) + R_{2T}(t)}{c} \qquad (7)$$

Two targets moving with the same speed and direction but separated by some distance will have differential delay times. This means that when matched filter processing is applied, the differential delays will result in multiple separately observable targets. This approach employs the same principle that SAR imaging uses to resolve closely spaced stationary targets. The ‘resolution of targets depends on the relative spacing as a function of the illuminating wavelength. This can be seen in figure 11, which shows simulated signatures of two people walking at a speed of approximately 6 km/h in a direction perpendicular to a transmitter-receiver baseline distance of 100 m. The targets walk towards the centre of the baseline and are separated, one behind the other, by a distance of approximately 5 m. Figure 11 shows results for differing illumination frequencies.

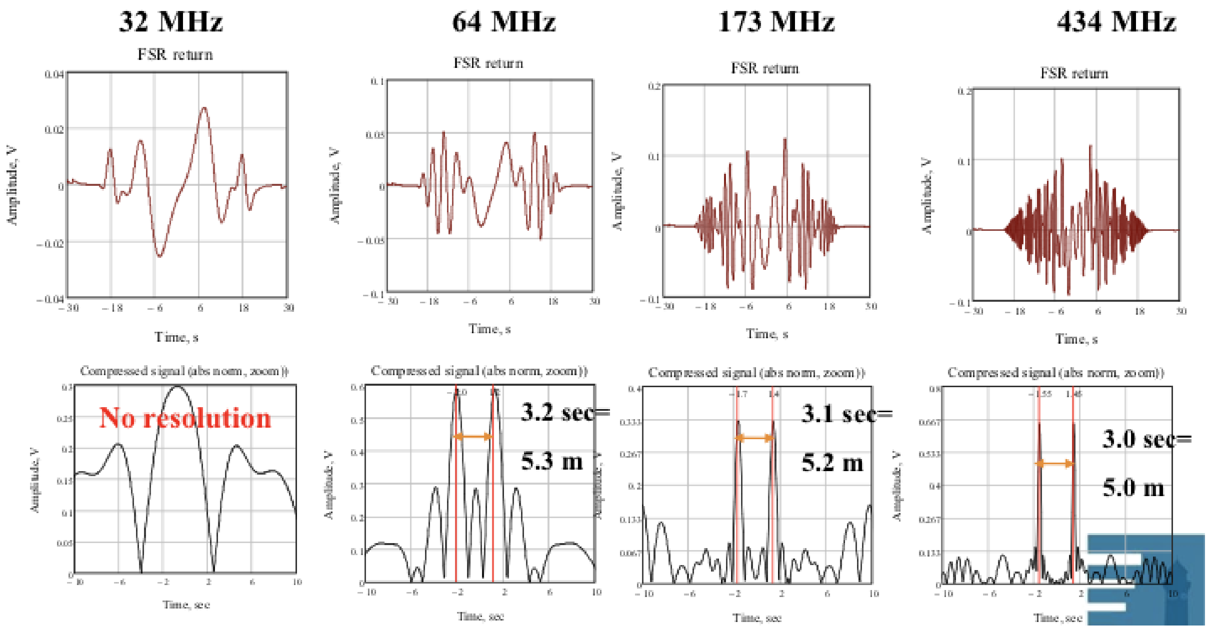

Figure 11: Two targets crossing a 100m baseline forward scatter radar with differing illumination frequencies.

The time dependent Doppler frequency, given by equation (4), shows that the total Doppler span will have an inverse dependency on the illuminating wavelength. Thus, as can be seen in figure 11, at an illuminating frequency of 32 MHz, the total bandwidth of the frequency spread is insufficient to allow resolution of the two targets. As the illuminating frequency is increased it becomes easier and easier to resolve the targets but, in this example, they can be resolved from a frequency of 64 MHz upwards. As the illuminating frequency increases, the resolution, shown by the width of the peaks, improves and the minimum spacing at which targets could still be resolved steadily reduces.

Classification

Forward scatter radar offers a rich source of disparate information which can be used to feed automatic classification algorithms. Classification can be split into a number of separate categories, each revealing more about a target. For example, classification, recognition and identification can be described as follows:

(i) *Target classification:* Separation of different targets into different classes (animals, personnel, cars, armed vehicles and tanks, trucks)

(ii) *Target recognition:* Separation of different targets within a single class (e.g., different types of cars)

(iii) *Target identification:* Separation of different targets of the same type (e.g. a particular type of car, different Honda CRVs etc.)

There are two main approaches to classification using forward scatter radar. The first is based on the Doppler signature and the is second based on shape recognition. The different types of information that can be extracted from forward scatter target signatures are:

(i) An approximate estimate of target speed and trajectory, obtained from a forward scatter network that has multiple baselines and crossing times.

(ii) More precise crossing times, crossing points and target speed through optimal signature compression.

(iii) Target RCS computed from the power budget equation for every baseline crossing.
(iv) Approximate target shape, via an inverse FFT of the far-field diffraction pattern.
(v) Exploitation of known landscape and environmental information.

Automatic target recognition techniques can be applied in the spectral domain. For example, techniques such as Principal Component Analysis (PCA), Multi-Layer Perceptron (MLP) or Maximum Likelihood Estimator (MLE) can all be used. The first step is to decide features that collectively represent a given target that are unique and different for the different targets of interest. This becomes a library set against which features derived from an unknown target are compared and the closest match providing the classification decision. Figure 12 shows an example of the essential steps that might be used to recognise three different types of vehicle.

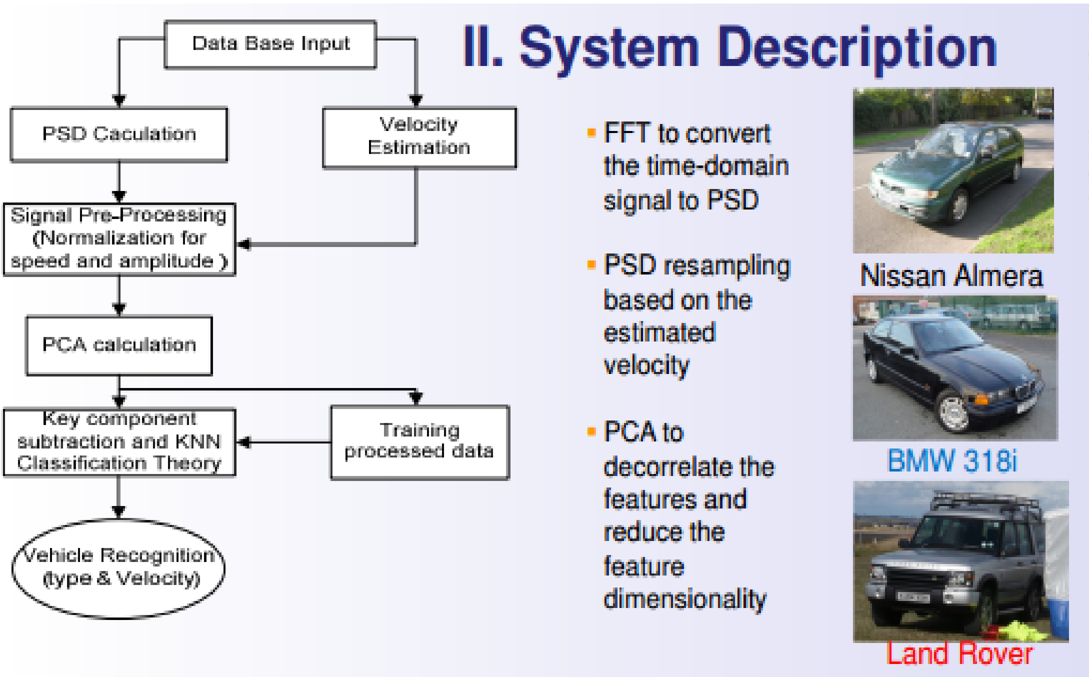

Figure 12. Target classification methodology

It may be recalled that, in forward scatter radar, the received signal is a result of interference of the scattered wave (secondary electromagnetic waves generated by the target aperture), with the direct path wave which is strictly coherent with the scattered wave. Thus, both amplitude and phase of the scattered field can be extracted providing information about the target. This method is sometimes referred to as an RF Hologram (RFH), similar to optical holographic imaging. RFH synthesis is possible if the target and the receiver have motion relative to one another. A Shadow Inverse Synthetic Aperture Radar algorithm (SISAR) is used to reconstruct the shadow profile of the target. This is essentially the same approach used to separate targets based on their differential Doppler signatures as discussed above. An exact knowledge of target motion parameters and the radar topology are needed to form focussed linear images. Another way of looking at this is through physical optics. Here a target is represented by a complimentary, transparent aperture. The Huygens-Fresnel principle and a discrete version of the Fresnel-Kirchhoff diffraction theory can then be used to quantitatively model the scattered signal. This is shown in schematic form in Figure 13.

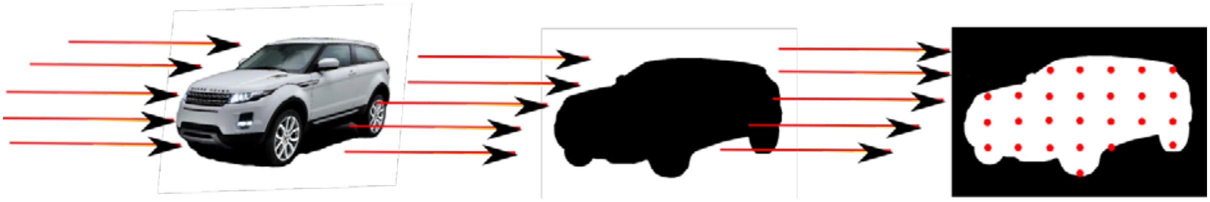

Figure 13: Target shape formation

In effect, inverting the measurement of the far-field radiation pattern of the silhouette of the target is a direct way of estimating target shape. This is the inverse of estimating the far-field pattern for an antenna of a given shape (at a given frequency). Figure 14 shows the signatures and the result of applying an inverse Fourier transform to the complex received signal to generate the target shape profile. This profile can then be used as a basis for classification using standard techniques using approaches such as template matching. The advantage of this approach is that the profile of a target is relatively stable and hence classification performance in forward scatter can high.

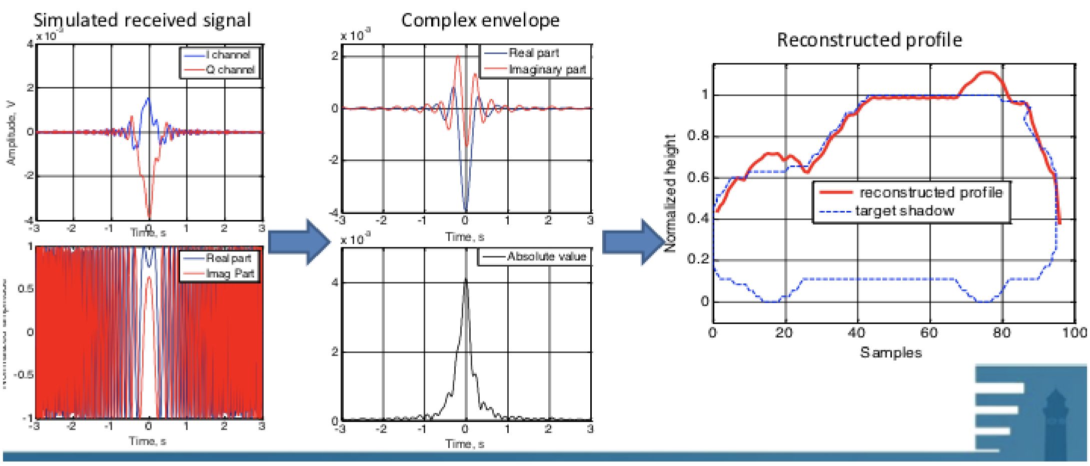

Figure 14: Generating target shape profiles from complex received data in forward scatter radar

Summary

Forward scatter radar and passive forward scatter radar allow target detection and target motion parameter estimation. Consequently, forward scatter radar can be thought of as an additional mode in passive radar, enhancing performance and enabling a richer source of data to be acquired helping with more complex tasks such as classification. Passive forward scatter radar can be realized by efficient and reliable techniques to provide multiple functionality such as 'electronic fences' for small target detection. Passive forward scatter classification is possible based on the unique signature of a target in measured over time frequency domain and it is possible to reconstruct a target's using its complex signature gathered over time.

The advantages for passive forward scatter radar include

- Enhanced RCS of conventional targets compared to monostatic and bistatic radar giving robustness to stealth technology.
- Long coherent integration times and hence excellent Doppler resolution

- Stable signatures
- An imaging modality that use a form of ISAR
- Easy to use non-cooperative transmitters
- Simple and cost-effective hardware
- Bolt on to passive radar

However, there are some potential characteristics that require a careful understanding before forwards scatter radar can be fully exploited, including some aspects yet to be explored in practical systems. These include:

- The operational area is along a narrow spatial angle making for a linear zone of use.
- There is no direct range resolution.
- Clutter
- Integration with passive radar yet to happen

The challenge is to integrate a forward scatter mode of operation into passive radar networks to provide seamless detection, tracking and classification with an overall performance level that exceed that of traditional passive radar alone.

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