AN INTRODUCTION TO PASSIVE RADAR SYSTEMS

A test and measurement perspective

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- R&S®FSW signal and spectrum analyzer
- R&S®RTP high-performance oscilloscope
- R&S®SGT100A SGMA vector RF source
- R&S®SMW200A vector signal generator
- R&S®ZNA vector network analyzer

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1 OVERVIEW

In this white paper, we introduce the concept and operating principles of passive radar systems. We review the basics of bistatic radars and introduce the concept of emitters of opportunity (EoO) and their ideal qualities. We discuss how satellites can be used as EoOs and evaluate the role of satellite illumination and forward scattering. We also consider how passive radar can be applied to stealth technologies and highlight examples of operational passive radar systems. The white paper concludes with a review of technologies that can be used during research, development, testing and evaluation (RDT&E) of passive radar systems.

2 PASSIVE RADAR INTRODUCTION

The idea of a passive radar has been in existence for almost the same length of time as the concept of radar itself. In many regards, it is very similar to a bistatic radar. The defining difference is that a passive radar system has no inherent transmitter, but uses transmissions from so-called emitters of opportunity (EoO). These are often referred to as signals of opportunity (SoO) or illuminators of opportunity (IoO). They are non-cooperative and thus unsynchronized emitters that are available in the operational environment. Commercial services used for this purpose typically include terrestrial television transmitters, FM radio transmitters, digital audio broadcasting, cellular base stations and satellites.

Over the last three decades, passive coherent radars (PCR) have enjoyed a renaissance due to certain technical and operational advantages, such as:

- Lower procurement, operation and maintenance costs
- Covert operation
- Small physical size
- High update rate
- Difficulty of jamming
- Resilience to anti-radiation missiles
- Improved ability to detect stealthy objects

In the early years, especially the low cost and covert operation were factors that drove the development of military passive radars. With the rise of stealth technology, unmanned aerial vehicles (UAV) and a new generation of missile systems, the potential for improved detection of these targets came to prominence.

On the other hand, in contrast to their rather simple hardware design (compared to active radar), there are several system limitations and challenges that are encountered when developing or deploying a PCR:

- Reliance on third-party EoO
- Complexity of deployment
- Mostly 2D operation
- Complexity of digital signal processing (DSP) required to implement a useful system
- Insufficient resolution to be used as fire control radars

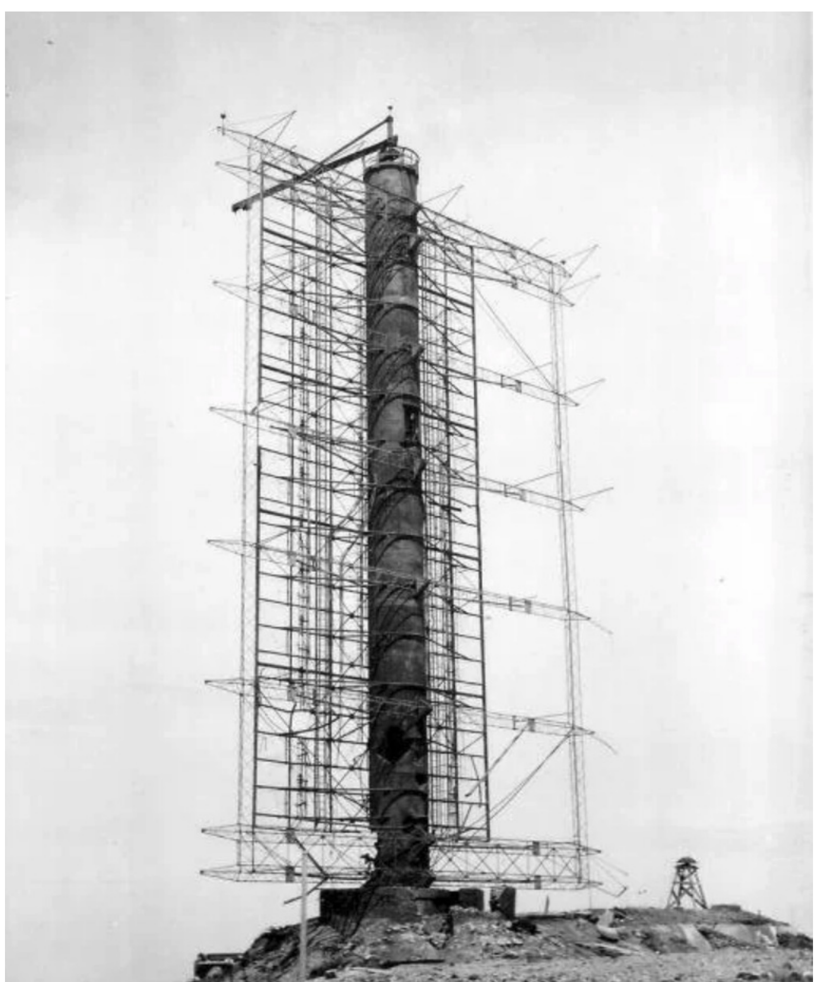
The PCR can also be found in the scientific community and in research. The availability of commercial software defined radios (SDR), a wide selection of software toolboxes for processing, and the potential coverage with different radio services in urban environments make this sensor technology easily accessible.

2.1 Passive radar history

The history of passive radar measurements to detect aircraft targets dates back to 1935 when Sir Robert Watson-Watt conducted an experiment that utilized the illumination from a commercial shortwave transmitter operating at a wavelength of 49 m, located in Daventry, UK, to detect a Heyford aircraft bomber at a range of about 13 km and an altitude of 1800 m. The Heyford was an advantageous target given its large wingspan of 23 m and overall dimensions of about ¼ wavelength of the Daventry transmission. The detector utilized a large antenna and an experimental high-speed oscilloscope that was loaned from the National Physical Laboratory (NPL) in London. As the Heyford flew overhead, the signal of the transmitter which was being received and displayed on the oscilloscope began to fluctuate, indicating that a variable and measurable amount of radio signal was being reflected from the passing Heyford aircraft.

The first operational passive radar is thought to be the German "Klein Heidelberg" receivers that utilized emissions from the British Chain Home radar to illuminate allied forces planes flying into German occupied territory during World War II in the period from 1943 to 1944. While the Chain Home radars were active radars operating with an initial transmission power of 350 kW (later increased to 750 kW) at a frequency of 20 MHz to 30 MHz, on the German side passive radars were installed along the continental channel coast of France. The German Klein Heidelberg receivers (antenna shown in Figure 1) exploited the emissions from the British Chain Home radars to detect incoming aircraft. The principle advantage of the Klein Heidelberg radar was its resistance to British jamming, when compared with the German active radars in use at the time, such as Freya, Mammut, Wasserman and Würzburg.

Figure 1: Klein Heidelberg passive radar antenna (photo: Jeroen Rijpsma)



The invention of the duplexer in 1936 led to the rapid development of the operationally more convenient, single-site, monostatic radar, and interest in passive radar waned. Radar development turned towards low probability of intercept (LPI) radars and the investigation of electronic counter-countermeasures (ECCM) to cope with jamming.

In the 1980s, several European countries developed a renewed interest in passive location. This refers to the use of passive emitter tracking (PET) and passive jammer location, but also included a passive radar receiver concept hitchhiking on the emissions from conventional airport surveillance radar (ASR).

A further revival of PCR occurred in the 1990s when the NATO Defense Research Group (DRG) launched a study on passive and noise radar. In addition to the pulse-chasing concept, broadcast transmitters were uncovered as potential sources for PCR. Besides the covert nature of passive radar, the inherent anti-stealth capability has been a key driver in the era of stealthy planes.

2.2 Examples of modern PCRs

Modern PCR systems, as shown in Figure 2, normally exploit existing VHF and UHF transmissions from analog and digital radios as well as television and are able to process multiple FM/DAB/DVB-T broadcasts simultaneously. This enables them to detect and track aerial targets covertly. Modes of operation like multi-angle target detection in a cluster of interconnected sensors improve the detection of targets with reduced radar cross section. Normally, those systems improve the direct emitter location systems that make them immune to self-screening jamming.

Figure 2: Early shot from Hensoldt's TwinVis [2] PCR system (photo: Matti Blume) and the Vera-NG [3] system from ERA (photo: Bin im Garten)

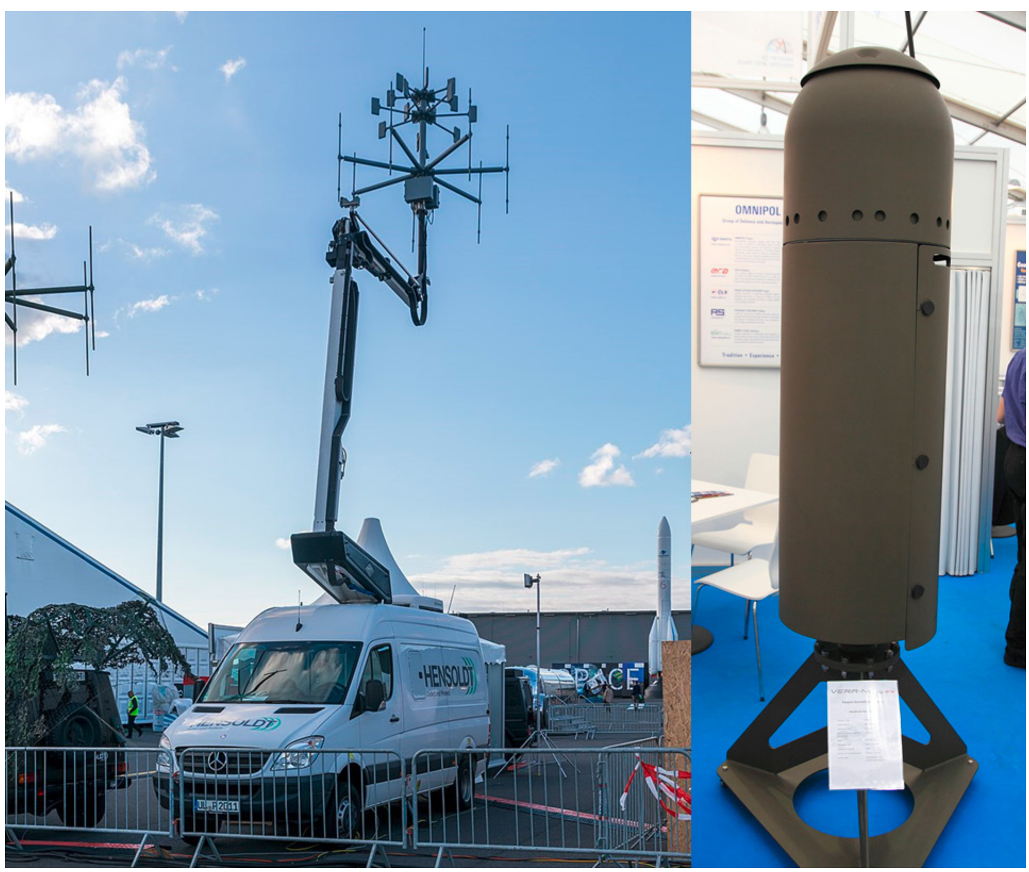


Figure 3 shows the Maverick S-Series PCR that is part of the Oculus Observatory in South Australia. It is designed to detect and track small objects in low earth orbit using satellite based transmissions. These examples are not exhaustive, but they do provide an overview of the state of the art at the time of drafting this white paper.

Figure 3: Silentium Defence Maverick S-series [1] air and space search radar (photo: Graeme Naylor)

3 PRINCIPLE OF OPERATION OF PASSIVE RADARS

The easiest way to understand PCR's principle of operation is by direct comparison with active radars.

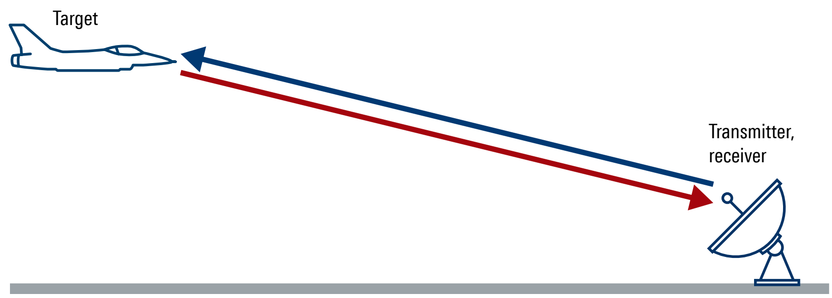
Passive radars are a class of bistatic radar systems that do not use a dedicated transmitter. Instead, they exploit transmissions from other sources for the purpose of illuminating their targets. Such sources are usually referred to as emitters of opportunity (EoO) and can include other radars, communications systems, broadcast systems, etc. EoOs are said to be "non-cooperative" because the PCR operator does not have any control over their transmissions and does not need their cooperation in order to utilize them.

3.1 Monostatic radar

In a monostatic radar, both the transmitter and receiver share a common antenna and are co-located as shown in Figure 4. In a monostatic architecture, the emitter is cooperative. Thus, the transmitted waveform is fully known and its transmission and reception are synchronized in time (to the point of phase coherence for most radars). Having a common aperture high-power transmit signal and a low-power receive signal makes isolation of the two paths very important. This can be implemented either in time via a pulsed waveform and blind times, or by means of sufficient physical isolation to allow full-duplex operation.

Figure 4: Monostatic architecture

Transmitter and receiver of a radar system are co-located and synchronized.



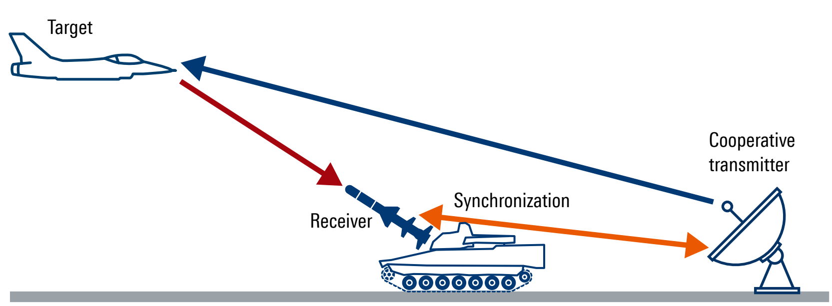
The operational drawback of this architecture is that the radar can be identified and isolated based on the transmitted waveform and emitter location systems can provide an exact location. Consequently, this opens the door for directed jamming and exploitation of kinetic effects to counter the operation of a monostatic radar.

3.2 Bistatic radar

A bistatic radar consists of separate transmitting and receiving sites as shown in Figure 5. A bistatic radar utilizes the forward scattering of the transmitted energy. The main implementation complexity in a bistatic radar is related to the requirement to maintain tight time synchronization between the transmitter and receiver, which are physically separated. However, this also provides several advantages with the most obvious being improved isolation. This enables full-duplex operation, which is the reason why this architecture is mainly used in weather radars and multi-satellite earth observation. In military systems, bistatic architectures can be found most often in anti-aircraft missiles. In a semi-active missile control system, only the receiver has to be integrated into the missile's airframe, which makes design easier in a limited size, weight and power (SWaP) environment. In other military applications, pure bistatic radars are used rarely.

Figure 5: Bistatic architecture

In this example, the radar transmitter is dislocated from the receiver in the missile, but a synchronization signal is distributed.



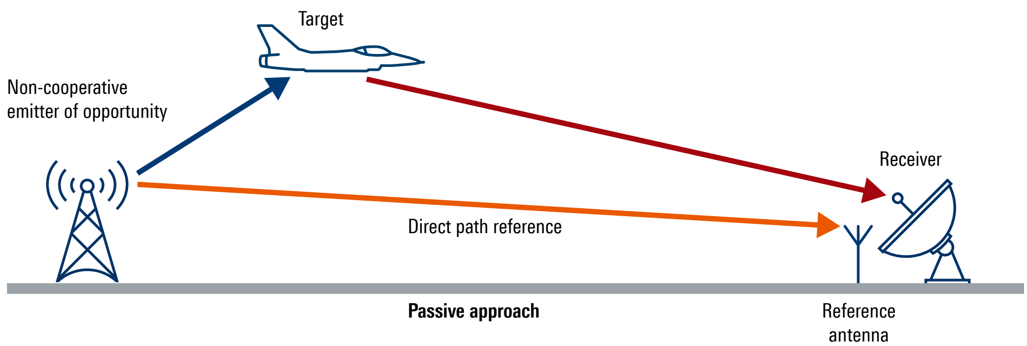
Some of the advantages of a PCR that are discussed later also apply to an active bi- or multistatic architecture. However, the synchronization necessary for high-accuracy detection is still a challenge. Countermeasures are difficult to deploy against a bistatic radar due to the passive nature of the receiver, which means that jamming needs to be spread in both azimuth and slant angle. In addition, an anti-radiation missile will be ineffective against the receiver since it does not emit any RF signals. However, the transmitter is still an active system and therefore its operation is not covert. Moreover, this system has higher operational costs due to the separate transmitting and receiving sites and the greater complexity of target detection and localization.

Examples of bistatic radar include:
- ▶ Weather radars
- ▶ Semi-active or track via missile (TVM) missile control systems
- ▶ PCR systems

3.3 Passive radar
As mentioned previously, a passive radar, or more correctly a PCR, is a form of bistatic radar in which the transmitter and receiver of the system are physically separated. The defining difference is that the illumination signal is non-cooperative, or in other words, not a deterministic part of the radar system. The EoO is used to illuminate the target, so the direction or angle of arrival (AoA) of the reflected energy can be extracted using well-known principles such as interferometry. This of course requires multiple receive antennas and parallel receiver paths for coherent signal processing.

Figure 6: Passive radar architecture

PCR normally uses a separate receive antenna for the reference signal, which has very high power compared to the reflection.



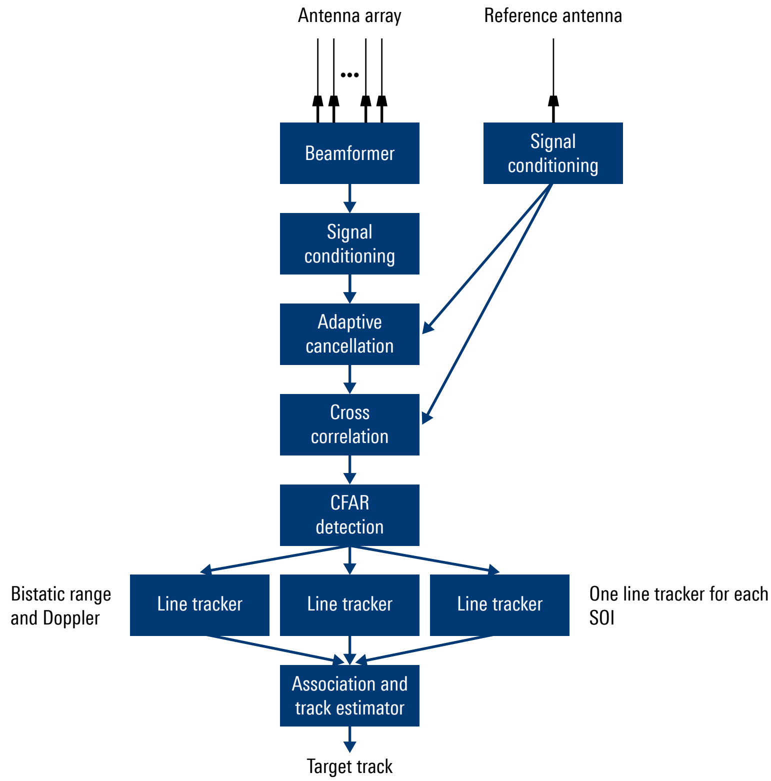
In contrast to an active radar, PCR does not have a deterministic reference of the transmitted waveform for matched filtering. For range processing, an additional step is necessary. With a separate but co-located antenna, the reference signal needs to be received directly from the EoO. This implies that the reference antenna has line of sight to the EoO. This signal sample is used for real-time correlation with the same signal traveling the indirect path (reflection of the target) as shown in Figure 6. With a known bistatic geometry between the PCR receiver and the EoO and the calculated time difference between the direct and reflected signals, the range of the target can be calculated.

3.4 Distinction between a PCR and an emitter location system
Emitter location systems (ELS) and passive radars commonly use the same principle to derive AoA, i.e. interferometric processing. Both make use of wideband receiver architectures that are flexible enough to operate with different kinds of emitters and waveforms. The main difference is that a PCR uses a third-party illuminator to receive a reflection from the target, whereas an ELS uses emissions directly from the target. Additionally, an ELS does not utilize a reference channel and cannot extract the emitter range directly as a result of a correlation process. For the purpose of locating an emitter, it uses spatial processing such as triangulation, which is relatively slow in comparison.

3.5 Passive radar block diagram

The classic passive radar block diagram is shown in Figure 7 and discussed in detail below.

Figure 7: Example of processing architecture for a passive radar



A passive radar typically utilizes the following processing steps:

Receiver

One challenge for a passive radar is related to the requirement to detect low-amplitude target returns, given the typically low power of the transmitter when compared to a traditional radar transmitter. These small signals are also subject to continuous background interference from other RF sources. The design requirements for the RF frontend receiver include low noise figure, wide dynamic range and high linearity. Even with an ideal receiver, the target returns are often below the noise floor.

Beamforming

A passive radar typically uses multiple antennas in traditional beamforming/direction finding configurations. There may also be several groups of antennas to accommodate different frequencies of interest. Traditional beamforming techniques, including amplitude monopulse and adaptive beamforming, are used to determine AoA of reflected signals from the target(s).

Signal conditioning

Signal conditioning may include low-noise amplification, tunable analog bandpass filters, channel equalization and demodulation of digital signals to improve radar ambiguity functions.

Adaptive filtering/cancellation

As previously mentioned, the signal-to-noise ratio of returned signals is typically very low. An adaptive filter can be used to remove the direct signal in a method akin to active noise control. This is necessary to ensure that the range/Doppler sidelobes of the EoO do not mask the echoes during cross-correlation processing. This may not be a concern if the EoO transmitters are not in line of sight (LoS) of the passive radar receiving antennas.

Cross-correlation

The core of a passive radar is the cross-correlator, which acts as a matched filter and also provides an estimate of the bistatic range and Doppler shift of each echo. One challenge is that many digitally modulated transmissions are similar to broadband noise in structure. As a result, they only tend to strongly correlate with themselves. To counter this with moving targets (which present a series of Doppler shifts), the cross-correlator must use a set of matched filter banks with filter banks that correspond to the Doppler shift. Cross-correlators often use discrete FFTs and are especially useful in OFDM waveforms. OFDM waveforms are commonly found in digital radio, satellite radio and digital video broadcasting. Signal processing gain is a function of the waveform bandwidth and integration length and can be as high as 50 dB. Integration times are limited by the motion of the target since they are smeared in both range and Doppler during the integration period.

Target detection

Targets are flagged by applying an adaptive threshold above the cross-correlation surface and tagging those that are above this surface as targets. A cell-averaging constant false alarm rate (CFAR) can be used to reject false alarms.

Line tracking

Line tracking is the function of tracking target returns from individual targets over time in range and Doppler that are produced during cross-correlation. A Kalman filter can be employed to enhance false alarm rejection.

Target tracking

The location of the target in a bistatic case can be determined by calculating the point of intersection of the bearing with the bistatic range ellipse. However, the utility of this approach tends to be limited due to errors in bearing and range. Improvements can be made in the estimation of the target location, heading and velocity by using a nonlinear filter such as extended or unscented Kalman against the full measurement data set of bistatic range, bearing and Doppler.

When employing multiple EoOs, the target can potentially be detected by every transmitter that is in line of sight. The returns from this target will appear at a different bistatic range and Doppler shift to each transmitter. Thus, it is necessary to ascertain which target return from each transmitter corresponds with those of the other transmitters. Having associated these returns, the point at which the bistatic range ellipses from each transmitter intersect is the location of the target, improving the overall accuracy of target location.

Performance

Passive radars can yield performance comparable to conventional short- and medium-range radar systems. The detection range is still subject to the limitations expressed by the standard radar range equation and further limited by external noise and interference and enhanced by signal processing gain. An FM transmitter is typically useful out to a range of 150 km and an ATSC HDTV transmitter may be usable out to 300 km. Passive radar accuracy is strongly predicated by the deployment geometry and the diversity of both the EoO and the number of receiver channels.

4 BISTATIC RADAR MATH

In general, the radar equation for a bistatic architecture is very similar to the **monostatic** definition of the maximum range R_{max} between the active radar and the reflection target:

$$R_{max} = \sqrt[4]{\frac{P_T \cdot G^2 \cdot \lambda^2 \cdot \sigma \cdot G_P}{(4\pi)^3 \cdot kTB \cdot F_n \cdot SNR_{min} \cdot Loss}}$$

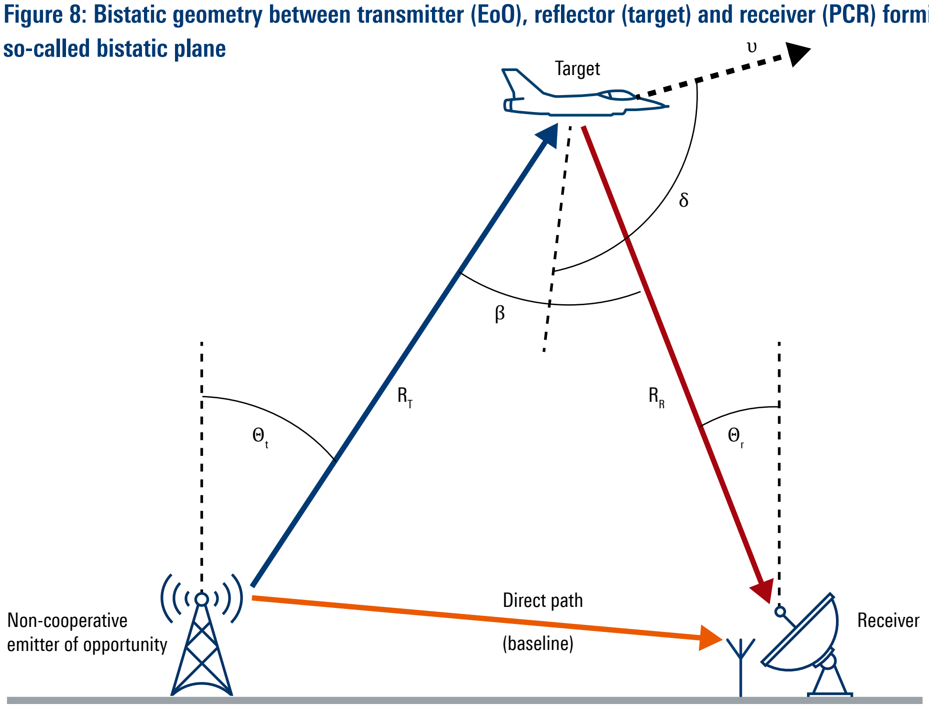
P_T	Transmit power
G	Gain of monostatic antenna
λ	Wavelength of transmitted RF
σ	Monostatic radar cross-section (RCS)
G_P	Processing gain (e.g. matched filter, integration)
kTB	Thermal noise
F_n	Noise figure of receiving system
SNR_{min}	Receiver sensitivity
$Loss$	Sum of all losses (system, path etc.)

If we consider the **bistatic** geometry in Figure 8, some of the necessary changes become obvious. The antennas for transmission and reception are separate entities with different gains. Moreover, the target range is not derived from the traveling time due to the two-way trip from transmitter to target, but rather the sum $R_T + R_R$. The bistatic radar equation (using the Cassini oval to solve SNR) for calculation of the maximum target range is as follows:

$$R_{Rmax} = \sqrt{\frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2 \cdot \sigma_B \cdot G_P}{(4\pi)^3 \cdot R_T^2 \cdot kTB \cdot F_n \cdot SNR_{min} \cdot Loss}}$$

G_T	Gain of transmit antenna
G_R	Gain of receive antenna
σ_B	Bistatic RCS
R_T	Distance between transmitter and target
R_R	Distance between target and receiver

Figure 8: Bistatic geometry between transmitter (EoO), reflector (target) and receiver (PCR) forming the so-called bistatic plane



It can be seen that the maximum distance between PCR and target is dependent on the distance from the EoO as well as the target. It may therefore be preferable to write the equation in the following form:

$$R_T R_R = \sqrt{\frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2 \cdot \sigma_B \cdot G_P}{(4\pi)^3 \cdot kTB \cdot F_n \cdot SNR_{min} \cdot Loss}}$$

This can be directly interpreted as Cassini ovals that define a contour with constant range product from two points that are located at a distance L (from transmitter to receiver, also known as the baseline). For a given SNR, a constant range product contour can be calculated. These contours are typically not co-centric with the results of the isorange processing, leading to a variation in SNR along a constant range contour. This calculation is important when it comes to deployment of a PCR since it influences the sensor coverage as well as the selection of suitable transmitter(s).

The range resolution of a bistatic architecture is very similar to the monostatic case since it is derived from the time-bandwidth product of the transmitted waveform. However, without processing the AoA, different targets on the same isorange contour cannot be resolved on range alone. With a known geometry and the targets in the bistatic region, the range resolution can be expressed as:

$$\Delta r = \frac{c}{2\cos\left(\frac{\beta}{2}\right) \cdot B}$$

c_T	Speed of light (vacuum)
$\beta/2$	Bistatic bisector
B	Signal bandwidth

Additionally for a given range resolution, a closest range ellipsoid can be drawn for which targets inside this bistatic range cannot be separated in range from the direct signal. This is due to the small difference in distance traveled by the reflected signal relative to the direct transmission. This region is sometimes called the blind zone or "evil eye". Theoretically, super-resolution algorithms, like the relatively simple multiple signal classification (MUSIC), offer resolutions (e.g. in range and angle) that exceed the physical limits. However, they require good a priori knowledge of the scenery and are normally quite processing intensive.

Calculation of the Doppler shift in a bistatic architecture must reflect the fact that several relative motions contribute to the measured frequency shift on the PCR. In general, this can be described by:

$$f_d = \frac{-\frac{d}{d_t}(R_T + R_R)}{\lambda}$$

However, assuming a situation where both the receiver and transmitter are stationary and the Doppler shift depends on the target motion only, this simplifies to:

$$f_d = \frac{2v}{\lambda} \cos\delta \cos\frac{\beta}{2}$$

v	Absolute velocity of target
δ	Target trajectory relative to bistatic plane

Doppler resolution is limited by the cross-correlation between the signals from direct to reflected path and therefore by the ambiguity function of the emitter of opportunity.

5 EMITTERS OF OPPORTUNITY

The performance of a PCR is largely dependent on the waveform of the illuminating signal and the position and aperture of the corresponding transmitter. For any given area of interest, the potential candidates may vary tremendously. As shown in Figure 9, EoOs can be broadly classified into terrestrial and space based emitters. Terrestrial emitters include FM radio, digital audio broadcast (DAB), digital video broadcast terrestrial (DVB-T), cellular base stations and air traffic control (ATC) radar. When a PCR uses another radar system's waveform for illumination, the term parasitic radar is often applied. Space based emitters include variants of GNSS such as GPS, Galileo etc., satellite digital video broadcast (DVB-S) and large low earth orbit constellations such as Starlink, Telesat Lightspeed, OneWeb and Amazon Kuiper.

Figure 9: Example of EoO taxonomy

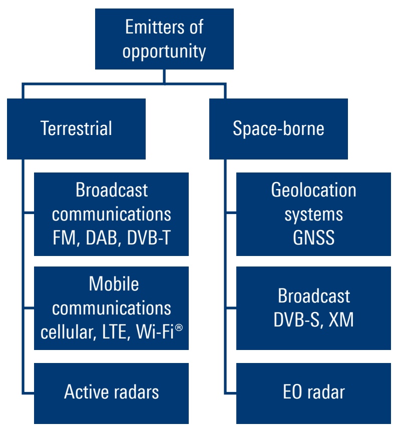


Table 1 lists commonly used radio services, but is not exhaustive. This brings up the question of the general signal qualities that define the resulting PCR performance. According to [1], there are many illuminators within an urban environment, some of which are suitable for PCR while others are not. Each has its own advantages for detecting targets, although all of them have limitations.

Table 1: Summary of attributes for common EoOs

Emitter	RF	Modulation, EIRP	Advantages	Disadvantages
FM radio	approx. 0.1 GHz	FM, 50 kHz, 250 kW	High power levels and wide area coverage	Low resolution; thus, low RCS targets are difficult to detect
DAB	approx. 0.2 GHz	OFDM, 220 kHz, 10 kW	Good ambiguity function	Strong direct signal interference (DSI) from multiple transmitters
DVB-T	approx. 0.6 GHz	COFDM, 6 MHz, 8 kW	Ambiguity function independent of data transmitted	Deterministic components cause peaks of ambiguity function
LTE base stations	2 GHz	CDMA, 5 MHz, 100 W	Excellent ambiguity function	Limited to only low-altitude targets
GNSS	1.2 GHz, 1.5 GHz	BPSK, approx. 15 MHz, approx. 100 W	Global coverage and availability of multiple sources	No continuous signal from a single satellite
ATC radar	e.g. 1.3 GHz	NLFM, 1 MHz, e.g. 60 kW	Constant and controlled coverage	Inconsistent RCS (material dependent) and low RCS targets, such as a drone
DVB-S2 satellite	10 GHz to 14 GHz	PSK, 4 GHz/40 MHz, approx. 500 kW	Global coverage and availability of multiple sources	Math can be complicated

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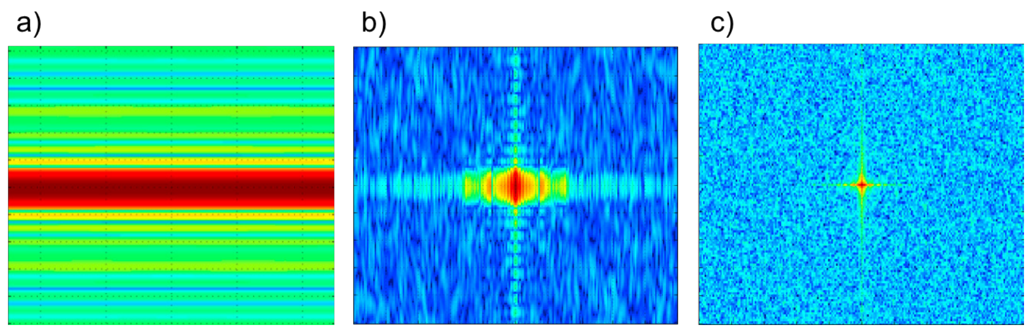
The most obvious parameter to consider is the transmit power P_T of the transmitter since it directly defines the maximum range for target detection and therefore the coverage of a PCR system. Similar to a monostatic architecture, the full ERIP defined by $P_T \cdot G_T$ only applies if the target is inside the transmitter's 3 dB beamwidth. As a non-cooperative emitter, the PCR has no control over the beam steering of the transmitter, making correct geographical placement a desirable attribute. This coverage or availability is one of the main reasons why satellites, even with their relatively low transmit power, are so attractive as an EoO for PCR.

Figure 10: Comparison of the ambiguity function

a) Analog TV station, b) DVB-T signal and c) DVB-S signal [2]



For the range resolution, the same principle applies as in the case of active radars, namely a favorable time-bandwidth product. Since almost all EoOs are communications services and therefore pseudo-CW, bandwidth alone defines the range resolution. Figure 10 a) shows the ambiguity function for an analog TV broadcast signal. It is obvious that in the zero Doppler slice $\chi(\tau,0)$, the range resolution of this waveform is very poor. Theoretically, a signal bandwidth of 7 MHz should provide an improved resolution, but due to aliasing of the dominant carriers and various signal peaks from other channels, the performance is degraded. This shows the performance of a real-life scenario within a dense spectral environment.

What can be deduced, however, is that the illuminator's waveforms need to produce an ambiguity function as close as possible to a thumbtack response. In other words, this involves the solution of the optimization to minimize the ambiguity function:

$$\chi(\tau, f) = \int_{-\infty}^{\infty} s(t)s^*(t-\tau)e^{j2\pi ft}dt$$

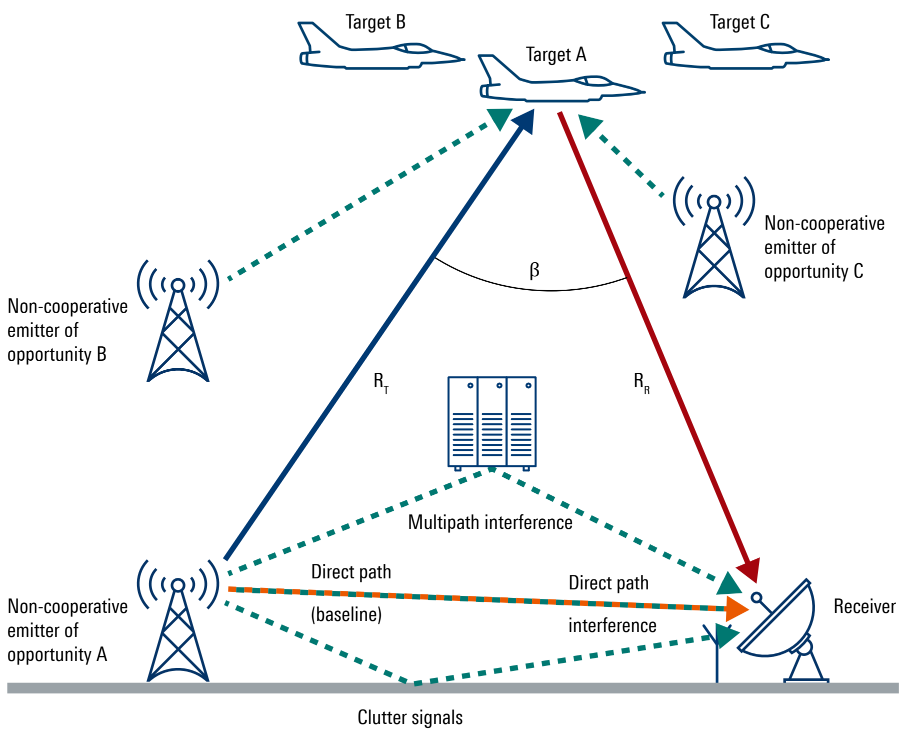
The ambiguity function in this regard is a two-dimensional autocorrelation of the function s with the time shift τ and the frequency shift f as variables. Figure 10 shows waveforms for several different EoOs along with usage of the ambiguity function to estimate both the range and Doppler resolution.

As the name implies, however, this function also provides information about ambiguities, e.g. several range-Doppler pairs that provide the same filter response and therefore false positives in detection. The ambiguity function is defined by the properties of the signal and the receiving filter and not by any particular target scenario.

6 CHALLENGES IN BISTATIC PROCESSING

Besides the signal properties of the EoO that are outside the control of the PCR operator, there are several factors that may impact sensing performance. These challenges mostly arise due to the fact that a PCR in reality is not operating in a dual situation (e.g. one emitter, one target and one receiver) or in a clean electromagnetic environment. The complexity of such a real-world spectral environment is depicted in Figure 11.

Figure 11: Example of the complexity of a real-world scenario

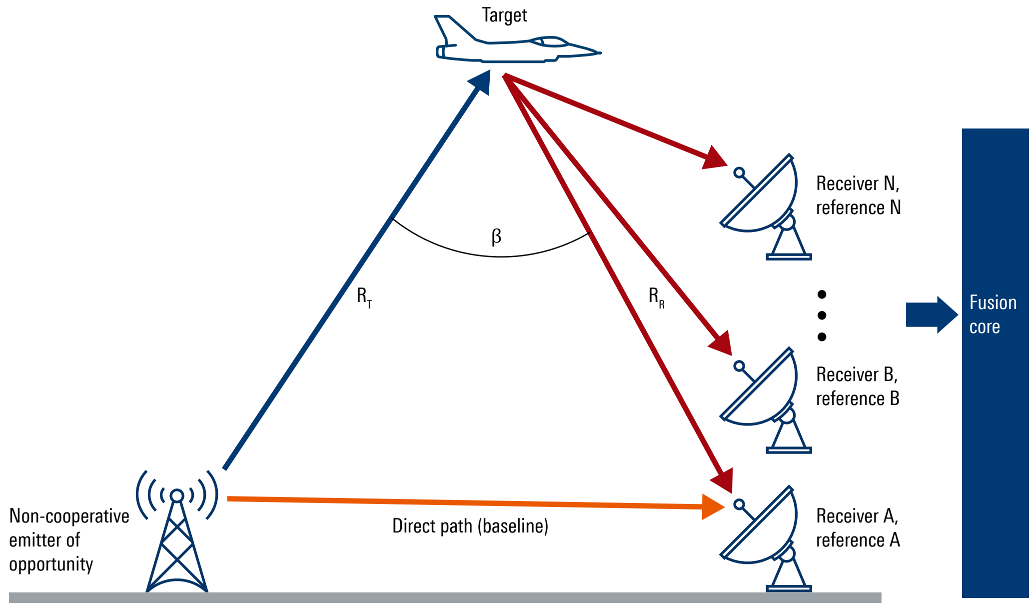


As mentioned before, EoOs are most often CW-like. The PCR needs to process the direct path transmission for the EoO as the reference in parallel to the reflection from the target using two decoupled antenna systems. The direct signal has much higher power when compared to the target reflection ($P_{Ref} \gg P_{Target}$) due to the shorter distance traveled (less propagation loss). When the reference signal is received by the main antenna system, this might cause direct signal interference (DSI). The dynamic range of the receiver may limit the sensitivity and reduce the probability of detection of the target reflection.

Clutter and multipathing of the reference signal may create similar issues, especially since separation of the PCR's reference and main antenna system beam pattern or sidelobe blanking has only limited use. Additionally, reception of the reference signal is also degraded by images of itself from clutter signals and multipath signals generated by other static reflectors, commonly known as multipath signal interference (MSI). These MSI signals normally have high power and a small time delay and can prevent accurate range processing of the reflected signal from the target (compare with Figure 7).

If there are other very similar EoOs in the detection range of the PCR, they may exhibit strong correlation with the reference signal. These transmitters may also include their own clutter and multipath signals, leading to a very complex and dense spectral environment. It is often desirable to use multiple EoOs to achieve improved coverage, probability of detection or accuracy. The necessary processing resources increase accordingly, especially as the number of potential targets increases.

Figure 12: Multistatic PCR approach and subsequent data fusion



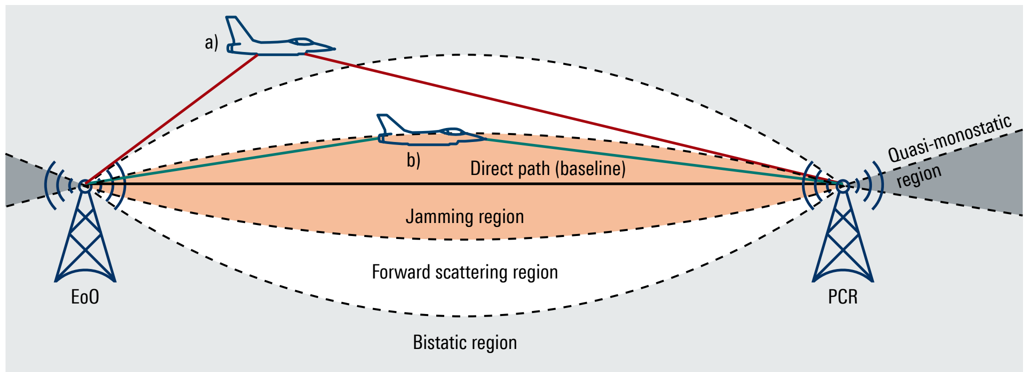
Multistatic approaches, as shown in Figure 12, have proven to be particularly useful for improving the area coverage and processing of the AoA. In this architecture, several PCR sites are connected and share either raw data or track list level via a centralized fusion core. In this example, each PCR extracts the reference signal and provides preprocessed data. However, approaches with a single common reference extraction are also possible.

Considering the discussion up to this point (e.g. correlation processing of reference and reflected signals, multidimensional FFTs for detection and measurement, super-resolution processing, sensor fusion), it is clear that the major bottleneck in PCR design is related to the availability of real-time capable processing resources. On the other hand, the decision as to which available EoO to use for an operational requirement, or the question of where to locate the PCR, mainly relies on the use of heuristics. On-site signal measurements combined with human expertise for a given use case are still a time-consuming but necessary process [3]. Application of artificial intelligence and machine learning to the operation of a PCR is an area of ongoing research.

7 BISTATIC VERSUS FORWARD SCATTERING

Up to this point, the implicit assumption for the processing was that the target was in the bistatic region (see target a) in Figure 13) of the geometry determined by the Cassini contours with a bistatic angle β ≫ 180°.

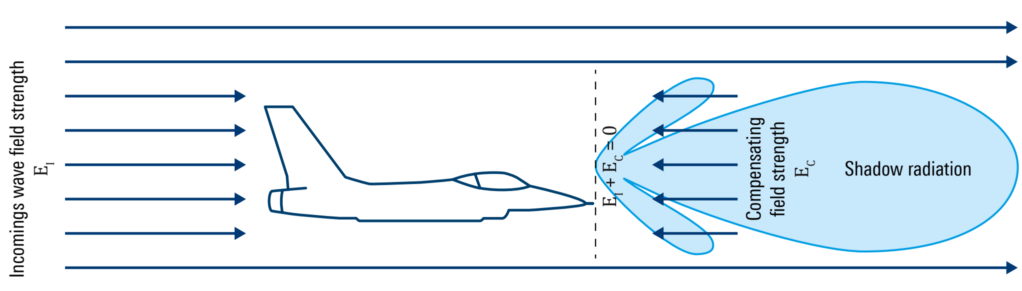
Figure 13: Definition of scattering regions with bistatic radar architectures



An interesting effect occurs when the target is within the forward scattering or jamming region (see target b) in Figure 13). With a bistatic angle 140° ≤ β ≤ 180°, the size of the range resolution cell approaches ∞. In addition, the echo from an object with an arbitrary velocity has zero Doppler shift. Therefore, the PCR is unable to measure the distance or velocity of the target without extensive processing effort.

The disadvantage of a forward scattering geometry is due to the fact that the bistatic range is much smaller than the actual distance to the target and the bistatic velocity is very low. In fact, it is much lower than the real target velocity. However, there is interest in forward scattering geometries because the bistatic RCS of a target is dependent on the frequency and bistatic angle. Moreover, for bistatic angles close to the baseline, the RCS increases by several orders of magnitude. For example, given a spherical object with a radius of 1 m at 3 GHz, the forward scattering RCS is about 26 dB higher than for a monostatic radar [4].

Figure 14: Behind the absorbing object, a shadow region is formed with the intensity of the electric field equal to zero

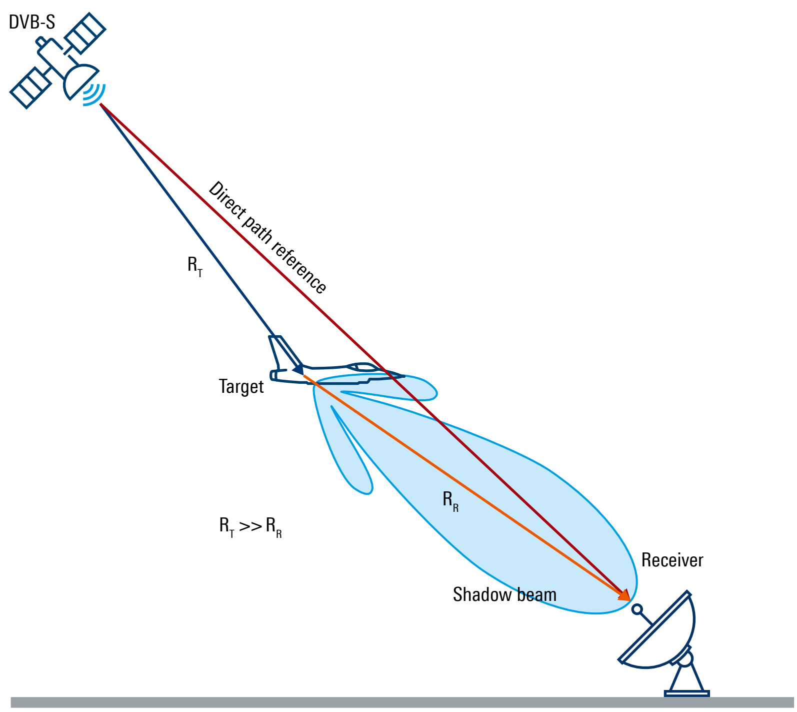


The enhancement of the target's RCS in the forward scatter region, and hence its extended detection range, is the main factor driving interest in forward scattering radar (FSR). The forward scatter effect is a result of co-phase perturbations of the waves in the object’s shadow (Figure 14). This interference causes focusing of the field on a line perpendicular to the target's shadow area. In effect, the object's shadow beam has a high directive gain on the non-illuminated side of the target. The narrow main lobe is inversely proportional to the dimensions of the object's shadow area. Moreover, neither use of an absorbing coating nor alteration of the target's 3D shape has any significant effect on the detection probability for a forward scatter radar.

8 SATELLITES AS EMITTERS OF OPPORTUNITY

The main advantage of utilizing a satellite as an EoO is that satellites are available in areas where there may be no viable terrestrial emitters, for example in the middle of the Pacific Ocean. Satellites typically make exemplary EoOs due to the wideband nature of most satellite transmissions and good autocorrelation properties. The PCR antenna system can be mounted on a moving platform, for example on a ship. Of course, the ego velocity of the platform with an additional Doppler component has to be considered when it comes to target extraction. As with other PCRs, there are two antennas: One always tracks the satellite, which is the direct path reference antenna, while the receiver looks in the direction of the target. In order to detect the target, a cross-correlation between the direct path signal and the echo of the target is necessary. Figure 15 shows a diagram of a typical satellite based PCR.

Figure 15: Satellite based forward scattering PCR



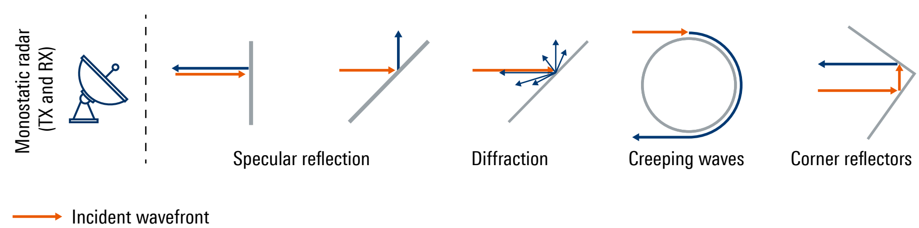
An additional advantage lies in the geometrical setup of the bistatic plane when using an EoO with large distance to target and receiver. In terrestrial configurations, it is very unlikely for a target to enter the forward scattering region. Therefore, the RCS of the target is comparatively low. With a satellite as an illuminator, the chance of the narrow shadow beam due to forward scattering pointing in the direction of the PCR main antenna system is much more likely, leading to all the previously mentioned advantages of an FSR.

9 PCR DETECTION OF STEALTH OBJECTS

One of the premises of PCR systems is an improved capability to detect stealth targets [5]. To understand why this is such a relevant topic, it is first necessary to understand the principles of stealth technology. Other spectral signatures, such as engine heat aside, avoidance of transmissions, or reduction of transmissions from the platform to the bare minimum, are also of concern. But when it comes to radar stealth, and therefore reduction of the platform's RCS, there are two main principles in design.

The first design goal is to prevent any surfaces of the platform from reflecting energy back towards the radar receiver. Figure 16 shows the sources of backscattered energy and explains the unusual design of stealthy objects. For example, a stealthy aircraft avoids any flat surfaces and sharp edges, or minimizes downfacing corner reflectors (like engine intakes or weapon bays), or uses a special surface treatment to avoid diffraction. The main reason why these stealth techniques have limited use against bistatic radar architectures in general is that the effects only reduce the backscattered energy. The energy does not simply vanish or get absorbed, but is redirected. A bistatic radar uses this redirected energy for detection.

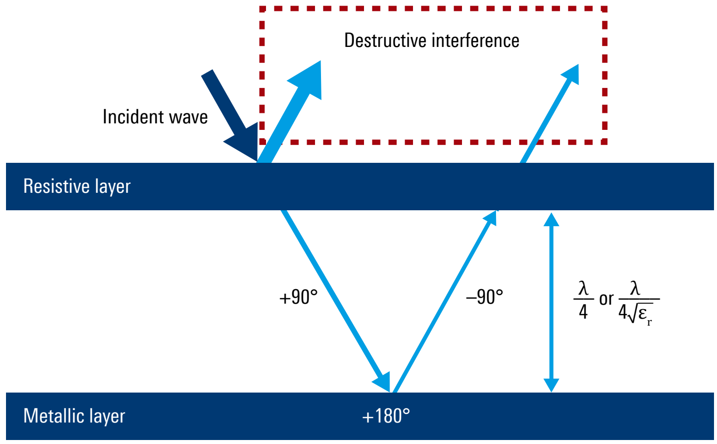
Figure 16: The geometry of stealthy design tries to avoid the backscattering of energy to its source – the monostatic radar system



Another aspect of reducing the RCS of a platform is dependent on the frequency of the incoming wavefront. Most straightforward is the avoidance of edged surfaces that could be resonant at that frequency. More complex and a wide field of study are radar absorbing materials (RAM), which either dissipate or absorb incoming electromagnetic energy.

As an example, Figure 17 shows a classic absorbing material called Salisbury Screen. This absorber consists basically of a resistive material positioned on a metal plate. There is a clear space between the resistive skin and the metal that can be filled by the support of absorbing materials called spacers. This technology aims at a defined phase shift between the reflected energy at the resistive and the metallic layer of 180°, thus producing destructive interference for both waves. Later approaches include the use of multilayered techniques or metamaterials as the RAM. However, a commonality between all these approaches is the high dependency on wavelength/frequency. Even modern tunable metamaterials are relatively narrowband and per design cover classical radar frequencies.

Figure 17: The Salisbury Screen, a rather simple RAM, uses destructive interference to reduce the energy of the backscattered wave



That is the reason for interest in VHF and UHF radar systems, but also for PCR. Most commercial radio services used as EoOs operate at relatively low frequencies that are much less affected by RAM. In fact, for RAM to be effective at longer wavelengths (i.e. lower frequencies than traditional radars), it would have to be much thicker and therefore heavier, which would be problematic.

The special benefits of FSR in detecting low RCS targets have been explained before. Nevertheless, the limitations of PCR systems in that regard are not negligible. The availability of EoOs and therefore the coverage is very limited, bringing a high uncertainty when it comes to critical operations. Moreover, the overall operational accuracy is comparable to a weak (low power) ATC radar, but is typically not sufficient for other operational uses, e.g. a fire control radar.

10 RESEARCH, DEVELOPMENT, TESTING AND EVALUATION OF PASSIVE RADAR

Taking the V-model as an example for the development process of a PCR (regardless of whether this model is actually used or not), the different stages and interdependencies of each step can be identified. Normally, specification begins on an abstract functional level based on operational requirements or corner use cases.

The level of abstraction increases from testing of physical RF parameters for R&D, up to full system integration testing and validation.

However, between PCR operators, primes and tier X suppliers, it is also necessary to have aligned methods of validation and verification to ensure that quality and design goals are met (e.g. site/field acceptance testing).

10.1 Hardware testing

From a hardware perspective, PCR involves synchronized multiple channel receivers. The challenge in the design of the analog frontend is mainly that a passive radar system must detect very small target returns in the presence of very strong, continuous interference (full duplex). This contrasts with a conventional radar that listens for echoes during the periods of silence between each pulse transmission. As a result, the receiver must have excellent channel isolation, low noise figure, wide dynamic range and high linearity. Nevertheless, the received echoes are normally well below the noise floor and the system tends to be externally noise limited. The objectives have to be achieved while covering the operating frequencies of several radio services, thus normally making a superheterodyne architecture necessary.

Regardless of the impact of these requirements on the actual system specifications, this translates in terms of T&M into more or less classical receiver testing with measurements typically used for component and sub-system tests, such as:

- Spurious measurements
- Dynamic range
- Compression point
- Gain/frequency response
- Noise figure
- Input/output impedance
- Load pull measurements
- Image rejection
- Receiver sensitivity
- IP2/IP3
- Quadrature error
- LO phase noise
- LO substitution
- LO leakage
- LO long-term stability
- Antenna radiation pattern

Instruments used to perform RDT&E include vector network analyzers (VNA), vector signal generators (VSG), vector signal analyzers (VSA) and analog signal generators. Time domain measurements are also performed using multi-channel oscilloscopes. Figure 18 and Figure 19 show some examples of receiver-related test setups.

Figure 18: Example of receiver-related test setup with the R&S®SMW200A and R&S®FSW

R&S®SMW200A vector signal generator and R&S®FSW signal and spectrum analyzer conducting linearity measurements on a cascaded RF FE (mixer, filter and power amplifier) [6]. Depicted are AM-AM and AM-PM and non-linear frequency response.

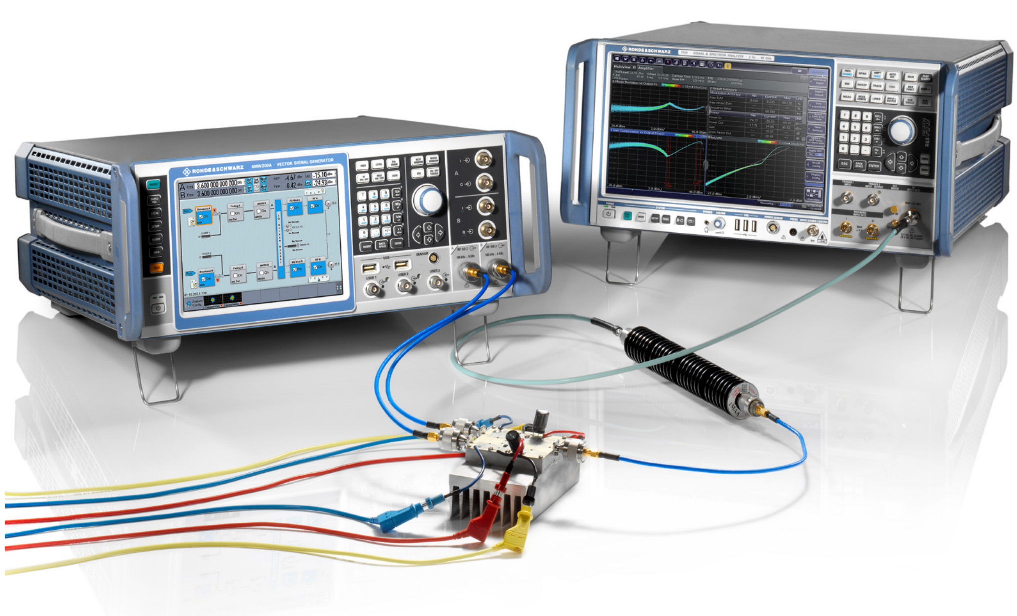


Figure 19: Example of receiver-related test setup with the R&S®ZNA

Fully calibrated R&S®ZNA vector signal analyzer setup for mixer measurement. Measurement of conversion loss, port matching and LO feedthrough parameters, all in the same channel. Four internal sources are used for intermodulation measurements.

An oscilloscope can be utilized for power supply characterization, digital bus analysis and signal integrity measurements. Mixed signal oscilloscopes (Figure 20) are hybrid test instruments that combine the measurement capabilities of digital oscilloscopes with the analysis capabilities of logic analyzers.

Oscilloscope based measurements include:

- Power/signal integrity
- LO/clock jitter
- Latency
- Timing
- EQ flatness
- ADC/DAC tests
  - Spurious free dynamic range (SFDR)
  - Effective number of bits (EnoB)
  - Speed
  - Quantization error
- EMI debugging
- FPGA tests
- DSP tests

Figure 20: R&S®RTP oscilloscope based mixed signal measurements

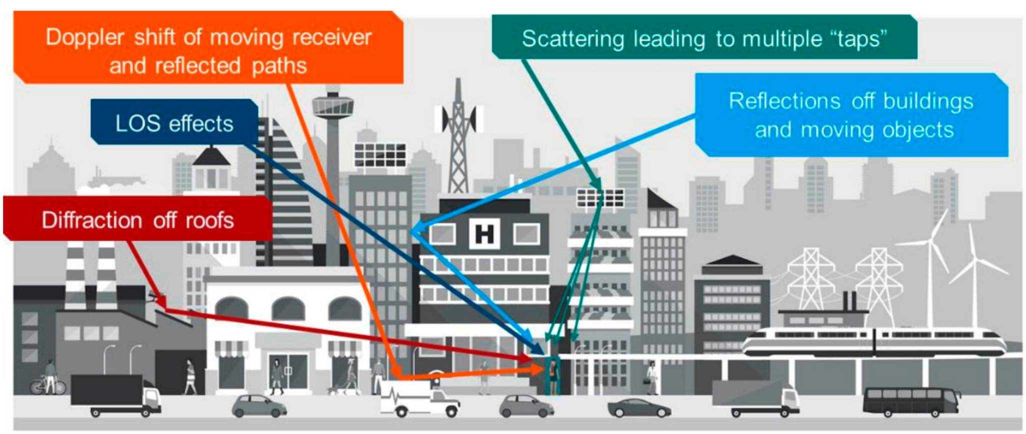
10.2 Modeling and measurement of channel impairments

For extraction of the reference signals, the conditions and disturbances are very similar to what is relevant in cellular tests. Outdoor scenarios typically simulate multipath, including:

- Scattering from rough surfaces
- Reflections from buildings
- Diffraction from walls and roofs
- Multiple Doppler shifts relative to the motion of vehicles, low-flying aircraft, etc.

Fading testing can account for the LoS signal, an interfering signal and a wide range of channel impairments such as reflection, diffraction, scattering, Doppler, shadow, refraction and absorption.

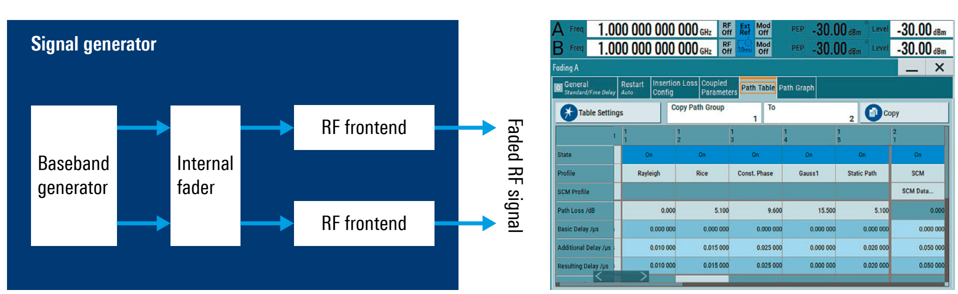
Figure 21: Channel impairments from the perspective of wireless communications testing



Test equipment and propagation models (dedicated to wireless communications) are readily available for such scenarios. The internal faders of the R&S®SMW200A can also be used with generic models to cover most transmission standards. While utilizing this tool, it is possible to test the cancellation algorithms for the reference channels of the PCR and the conditions for clutter, DSI and MSI.

The R&S®SMW200A supports multiple RF paths with optional integrated real-time baseband fading simulation of up to eight individual baseband signals in a single box, offering fading bandwidths up to 800 MHz. The maximum delay of this setup translates to a maximum path length of about 30 km.

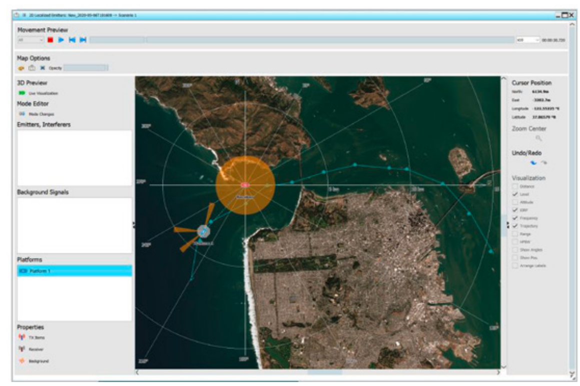
Figure 22: Basic principle of a VSG based fader and example of a generic propagation path configuration



10.3 PCR signal environment simulation

For validation of PCR system performance, the most straightforward approach would involve configuring the system within a real live environment. The major drawbacks of such an approach are that the possible influence on the scenario is minimal, reproducibility is unattainable, and the involved costs are high. In contrast, a conducted RF approach that simulates the signal environment offers the benefit of testing the whole signal chain under predetermined and repeatable conditions. R&S®Pulse Sequencer Software is commonly used for testing ESM receivers that rely on the actual emissions of a threat emitter. Nevertheless, it can be used to set up a scenario where all required signals, namely the direct path reference signal and the reflection from target, can be simulated including the different propagation delays. It is not limited to radar-like signals, but can include sample waveforms of communications signals as well. This software is thus perfectly suited for simulation of a PCR environment and tracking scenario.

Figure 23: Test system for scenario based four-channel AoA simulation using R&S®Pulse Sequencer Software

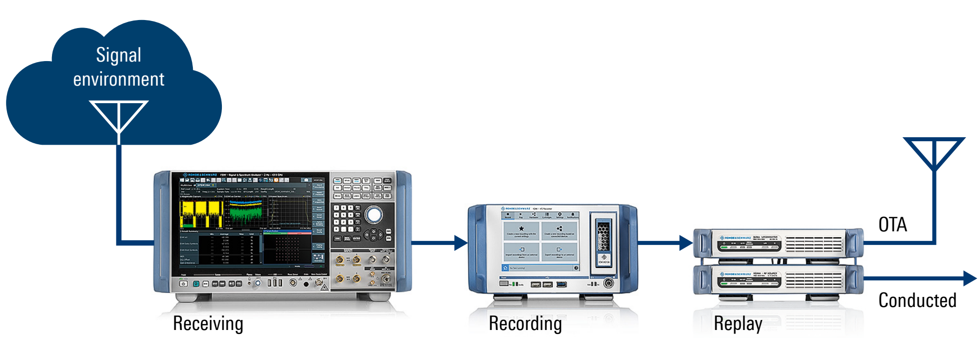


The pulse sequencer also includes simulation of AoA since the software can directly control a scalable number of signal generators (e.g. in Figure 23, there are two R&S®SMW200A instruments with two channels each). This includes automated control of phase, timing and amplitude per channel depending on the PCR main receiving antenna manifold. This setup is also suited for performing acceptance testing since it provides a common reference for the system manufacturer and the operator.

10.4 Utilizing live signals for laboratory validation

Another approach for using reproducible data for system validation is shown in Figure 24. No synthetic data is used here for the environmental simulation. Instead, the process is based on real data recordings of a complex RF environment captured by a receiver. Stored on a suitable device, this data can then be replayed in a controlled lab setting to a PCR under test. This is especially useful to provide realistic RF signals during algorithm development, regression testing and production testing.

Figure 24: Concept of an RF recording and playback system with multi-channel replay via R&S®SGT100A



In principle, this concept can also be used to stimulate multi-channel receivers for AoA testing if the recorded signal is replayed via several signal generators. However, the technique for inducing the appropriate phase, time and amplitude behavior is highly dependent on the signal generators that are used.

10.5 Creating your own emitter of opportunity

One of the biggest drawbacks of a PCR is its dependency on a suitable EoO. Without proper coverage, the detection or measurement performance of a passive radar may drop off tremendously. There can be many reasons for a lack of useful EoOs, such as:

- Simple absence of infrastructure in rural environments
- Irregular transmissions that may not be 24/7
- Content of transmission is unsuitable for correlation, e.g. FM transmission of talk shows with low modulation
- Transmitters are not aligned with PCR due to terrain obscuration (i.e. mountain shadows etc.)

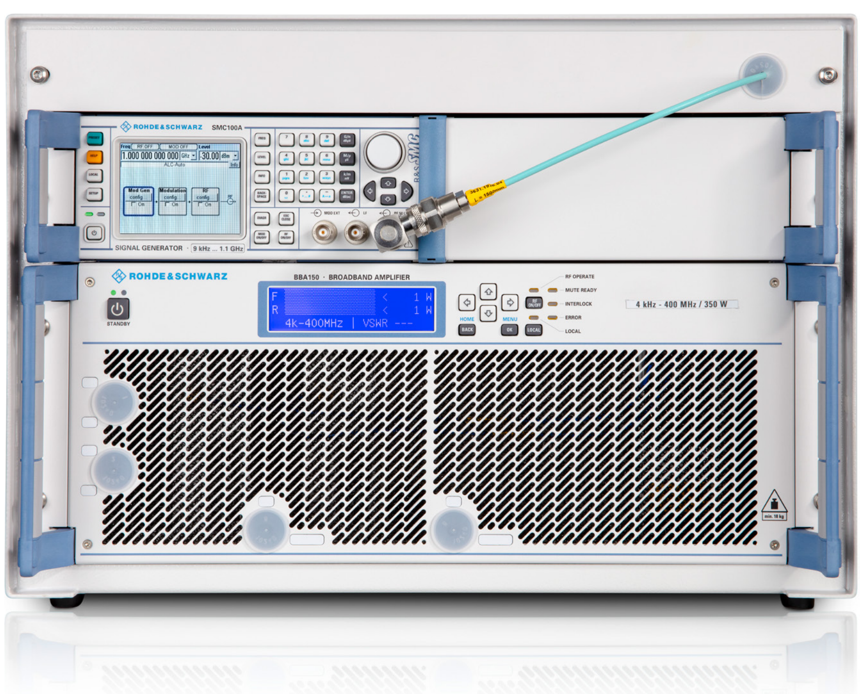
To improve the coverage and performance under such conditions, a PCR operator could set up its own transmitters. Of course, the transmitters have to adhere to the spectral footprint of a pseudo-commercial transmission in order to maintain covert operation.

Rohde & Schwarz offers a wide portfolio of broadcasting solutions. The most straightforward and cost-efficient approach would be to use commercial off-the-shelf (COTS) components. The building blocks of a very generic EoO, shown in Figure 25, can be constructed using:

- Signal generator to provide baseband signal, modulation and RF
- Broadband amplifier with output power derived from the operational requirements
- Transmit antenna (omnidirectional or directional)

Figure 25: Example of a very generic EoO

A low-cost solution for building a simple FM transmitter (RF up to 450 MHz at 350 W) using the R&S®BBA150 broadband amplifier and R&S®SMC100A signal generator. Other configurations could be used for more complex modulation, higher RF or transmit power.



11 CONCLUSION

Passive radar is gaining renewed interest due to the proliferation of stealth, UAV, force protection requirements, space situational awareness, and evolving hypersonic threats. Modern systems incorporate many elements, including passive modes of active radars, integration of ESM and passive radar technologies into a single system, networked passive radar sensors, and even offensive missile seekers utilizing passive techniques. PCR research started in the lab, but many companies are now fielding PCR systems that are used in operation environments. Finally, the proliferation of low earth orbit satellite constellations is opening up a large set of overhead space based illuminators that promise to make passive radar even more applicable in today's operational environments.

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