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Passive Radar Tutorial

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Passive Radar signifying the localisation of a target by radar measurements without using own controlled emissions has been discussed, tried, reinvented, and matured within the last 80 years. Its advantages, like covert operation and saving the costs of a transmitter, are obvious. Military as well as civilian interests combined with the advances in technological developments have recently boosted research on passive radar and passive radar systems are currently approaching the market. This tutorial shall give an overview of the history, development, and processing in passive radar and enable the interested reader to further investigate the subject exploiting the presented material together with the cited references.

I. INTRODUCTION

Passive Coherent Location (PCL) systems have received significant interest in the academic and military communities. Since the end of World War II the interest in bistatic radars has been cyclic, with a periodicity of 15 to 20 years [1, Preface]. The most successful bistatic radar application since the mid-40s is the semiactive homing missiles. Interest in PCL is currently at a lasting peak, mainly due to rapidly emerging technology which has matured enough for the military to see PCL as a potential sensor for surveillance.

The attractive features of passive radar from a military point of view are its covertness (the ability to perform situational awareness without revealing the position of the sensor through emission of radar signals), and the fact that most of the potential illuminators of opportunity, namely broadcast transmitters, operate in the lower frequency bands (Very High Frequency (VHF) and Ultra High Frequency (UHF)) which provides some antistealth detection capability. Being completely passive, the deployment of the receiver does not require frequency allocation and thus allows operation in densely populated areas where electromagnetic "pollution" can be an issue.

The frequently quoted argument that PCL is cheaper than active radar is still to be proven; however, it surely needs less maintenance.

Passive radar consists of one or multiple transmitters of opportunity, and a network of one or more receivers. Since the transmitted waveforms of such transmitters of opportunity are normally not optimised for radar purposes, the receiver structure and receiver processing have to be specifically tailored to exploit such waveforms. Omnidirectional surveillance often requires multichannel array antennas of circular geometry spanning a relatively large bandwidth. Receiver channels in the in the UHF-region and below allow digitization of the received signals close to the antenna elements and features software defined radar where all the processing happens in the digital domain. This leaves the Analog-Digital (AD) converter as the decisive element. Powerful Central Processing Units (CPUs) and even Graphics Processing Units (GPUs) are available today to support the required radar processing (e.g., cross-correlation, beam forming, direct signal suppression, and direct signal reconstruction in the case of digital waveforms).

Such advanced signal processing approaches have been reported in the literature and at conferences in increasing numbers in recent years, and indicate that the main driver for most research and development has been the military air surveillance application. However, niche applications have also been addressed in the civilian world, taking advantage of the already available illuminations and thus avoiding further cluttering of the spectrum.

A. STRUCTURE OF THE TUTORIAL

The tutorial has been structured in the following way: After a brief introduction, an excursion into the history of passive radar and the basic principle of passive radar leads to a survey of the most frequently used illuminators of opportunity and their properties.

Since passive radar is inherently bi- or multistatic, a major section of the tutorial deals with the features and constraints of bistatic radar, ranging from bistatic geometry and the bistatic radar equation to the bistatic ambiguity function.

The tutorial then describes the processing steps typically performed in passive radar systems, starting with the cross-correlation of the surveillance and reference channels, all the way through to the tracking of targets in Cartesian space.

An outlook to future perspectives in processing and technology and a list of recent major publications related to the subject of passive radar finishes the tutorial.

II. NOMENCLATURE AND DEFINITIONS

As of today, a generally accepted definition of a passive radar system does not exist, nor a unified name for such systems. This chapter provides some of the published definitions and their interpretations.

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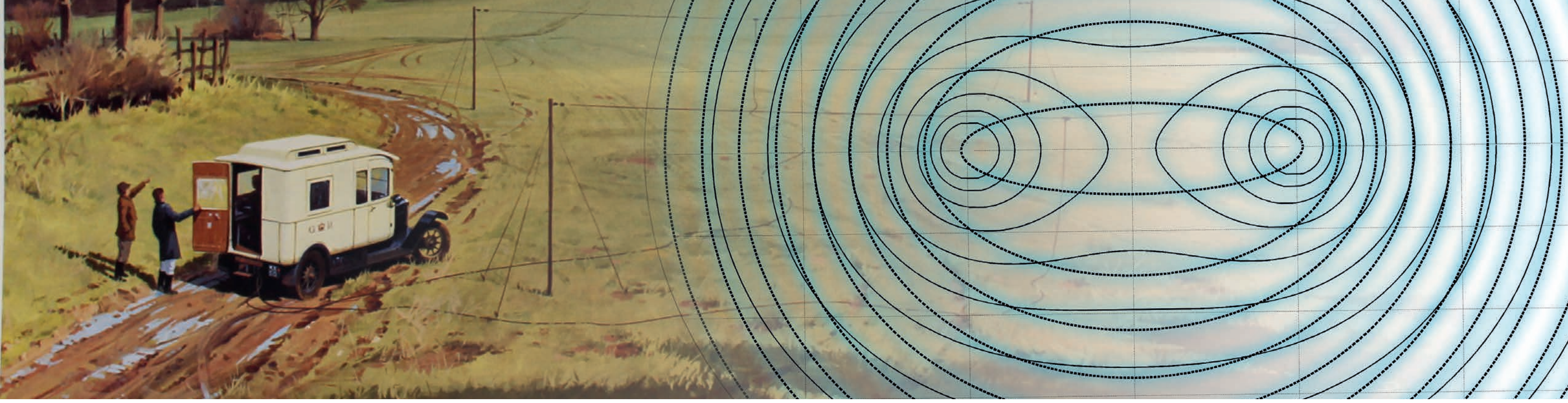

PCL, Passive Covert Radar (PCR), Passive Bistatic Radar (PBR), passive radar, multistatic radar, parasitic radar, commensal radar, symbiotic radar, and hitchhiking radar are all common names for passive radar systems exploiting cooperative, noncooperative transmitters, or transmitters of opportunity, [1, p. 3]. A recent review of the various names resulted in the compromise PBR, [2, p. 248]. However, it should be noted that the PCL name is still being used for full systems like Lockheed Martin's Silent Sentry® [3], [4], Thales' Home Alerter 100 [5], and HENSOLDT "Passive Radar" [6], [7]. The PCL-systems may be considered as systems of PBR systems. This work will focus on the system perspective of the technology, i.e., PCL, while relying on the technical depths of the PBR technology.

In 1990 Willis wrote the Bistatic Radar chapter in Skolnik's Radar Handbook [8]. Willis defined a bistatic radar to be a radar that employs two sites, transmit and receive, which are separated by a

ACRONYMS

AD	Analog-Digital	**IEEE**	Institute of Electrical and Electronics Engineers
ADS	Automatic Dependent Surveillance	**IMM**	Interacting Multiple Model
AWGN	Additive White Gaussian Noise	**IO**	Illuminators of Opportunity
BBC	British Broadcasting Corporation	**ISAR**	Inverse Synthetic Aperture Radar
CFAR	Constant False Alarm Rate	**LEO**	Low Earth Orbit
CORA	COvert RAdar	**LORA**	Linear array cOvert RAdar
CPI	Coherent Processing Interval	**LTE**	Long Term Evolution
CPU	Central Processing Unit	**MFN**	Multiple Frequency Network
DAB	Digital Audio Broadcast	**MHT**	Multi Hypothesis Tracker
DELIA	Dab Experimental radar with Linear Array	**MIMO**	Multiple In Multiple Out
DOA	Direction of Arrival	**NCTR**	Non Cooperative Target Recognition
DRG	Defence Research Group	**OFDM**	Orthogonal Frequency Division Modulation
DVB-T	Digital Video Broadcast - Terrestrial	**ONERA**	Office National d'Etudes et Recherches Aérospatiales
DVB-S	Digital Video Broadcast - Satellite	**OTH**	Over The Horizon
DVB-SH	Digital Video Broadcast - Satellite Handheld	**PARADE**	Passive Radar Demonstration
EIRP	Equivalent Isotropically Radiated Power	**PBR**	Passive Bistatic Radar
ERP	Equivalent Radiated Power	**PCL**	Passive Coherent Location
FFI	Forsvarets forskningsinstitutt	**PCR**	Passive Covert Radar
FFT	Fast Fourier Transform	**PDF**	Probability Density Function
FGAN	Forschungsgesellschaft für Angewandte Naturwissenschaften	**PETRA**	Passive Experimental Tv RAdar Plans and Programmes
FHR	Fraunhofer-Institut für Hochfrequenzphysik und Radartechnik	**RCS**	Radar Cross Section
FM	Frequency Modulation	**RF**	Radio Frequency
GPS	Global Positioning System	**SAR**	Synthetic Aperture Radar
GLONASS	GLObal NAvigation Satellite System	**SFN**	Single Frequency Network
GMTI	Ground Moving Target Indicator	**SNR**	Signal to Noise Ratio
GNN	Global Nearest Neighbor	**TDOA**	Time Difference of Arrival
GNSS	Global Navigation Satellite System	**UCL**	University College London
GPU	Graphics Processing Unit	**UHF**	Ultra High Frequency
GSM	Global System for Mobile communications	**VHF**	Very High Frequency
HiperLAN	High Performance Radio LAN	**WiFi**	Wireless Fidelity
HRR	High Range Resolution	**WiMAX**	Worldwide Interoperability for Microwave access

considerable distance, a statement he never clarified even though he mentioned two examples to clarify it: 1) A radar using different transmit and receive antennas at a single site should be considered monostatic. 2) An Over the Horizon radar's transmitter and receiver could be separated by 100 km or more, and still be considered monostatic when the target location is thousands of kilometres.

In Bistatic Radar [9] Willis uses the Institute of Electrical and Electronics Engineers (IEEE) bistatic radar definition: Bistatic radar is defined as a radar that uses antennas at different locations for transmission and reception. Willis points out that the IEEE definition does not specify how far the transmitting and receiving sites must be separated. Attempts to quantify this separation have been made by both Skolnik [8] and Blake [10], [11].

Figure 1.
Artist impression of Daventry experiment. Courtesy of BAE-Systems.

Willis writes that Skolnik (1990) [8] defined the separation as "a considerable distance," while he earlier [12] considered considerable distance as "comparable with the target distance," a definition which principally applies to forward-scatter fences. Willis also claims that Skolnik in the same paper defined the separation such that "… the echo signal does not travel over the same [total] path as the transmitted signal."

Blake [10], [11] defines two conditions for separation of transmitter and receiver by demanding *either* "… the *directions* of the transmitter and receiver [from the target] differ by an angle that is comparable to or greater than either beamwidth" *or* "… the *distances* from the target to the transmitter [R_T] and receiver [R_R] differ by an amount that is a significant fraction of either distance."

These definitions apply to all bistatic configurations, including forward-scatter fences, but they do not provide a measurable quantity due to the terms "comparable" and "significant fraction." The Radar Technology Encyclopedia [13] by Barton and Leonov uses the definition of Willis: "A bistatic radar, by definition, is one in which the transmitter and receiver sites are separated by a significant distance."

The IEEE [14] defines a bistatic radar as: "A radar using antennas for transmission and reception at sufficiently different locations that the angles or ranges from those locations to the target are significantly different."

Willis [9] defines a radar multistatic when "… two or more receiving sites with common (or overlapping) spatial coverage are employed, and data from targets in the common coverage area are combined at a central location." The Radar Technology Encyclopedia [13] defines multistatic radar as a radar in which information on a target is obtained by means of simultaneous processing of signals of several spatially separated transmitting, receiving or transceiving positions. And to sum it up, a multistatic radar is defined according to IEEE [14]: "A radar system having two or more transmitting or receiving antennas with all antennas separated by large distances when compared to the antenna sizes."

III. HISTORY OF PASSIVE RADAR

The history of passive radar measurements with the aim of detecting aircraft targets dates back to 1935, when Sir Robert Watson-Watt conducted the Daventry experiment. More than 80 years of development in passive radar followed. The milestones achieved during those 80 years are illuminated in this chapter and indicate that the renewed interest in recent years is correlated to the technological development in computing power.

In the Daventry experiment, Sir Robert Watson-Watt used the illumination from the shortwave (49 m wavelength) British Broadcasting Corporation (BBC) Empire transmitter at Daventry to detect a Heyford bomber aircraft at short distance (8 km) [15], [16]. Fig. 1 shows a sketch of the Daventry experiment. The Heyford was flown on a path between Weedon and the BBC transmitter at Daventry. Later, Sir Robert Watson-Watts' research led to the installation of a chain of radars along the south and east coast of England, known as the Chain Home radars [17]. While the Chain Home radars were active radars operating with a transmitting power of 350 kW (later 750 kW) at a frequency of 20–30 MHz, on the German side passive radars were installed along the continental Channel coast. Since 1943, the German "Klein Heidelberg" receivers located near the Channel coast line exploited the emissions of the British "Chain

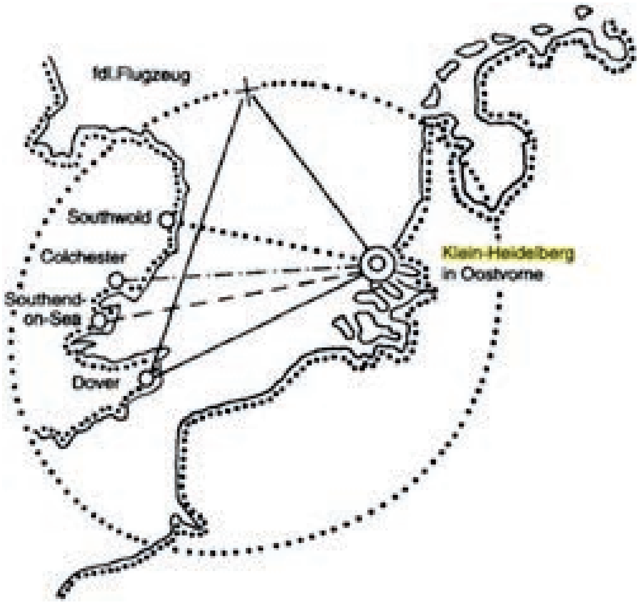

Figure 2.
Klein Heidelberg receiver and Chain Home radars.

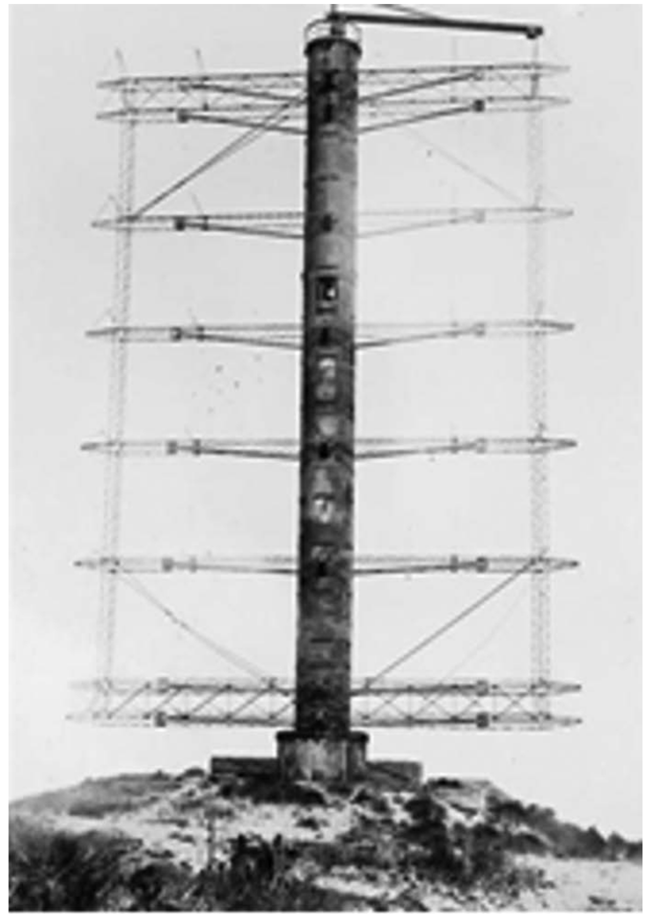

Figure 3.
Klein Heidelberg antenna.

Home" radars to detect in-coming aircraft [18]. These were the first operational passive radars. Resistance to the British jammers was the main advantage of the passive Klein Heidelberg receivers over the German active radars Freya, Mammut, Wasserman, and Würzburg. After preliminary trials at "mount couple" between Calais and Boulogne, four Klein Heidelberg receivers were set into operation during the summer of 1944 at Oostvoorne, den Haan, Boulogne, and Abbeville. Fig. 2 shows the location of the Oostvoorne station and the illuminating Chain Home radars.

A picture of the Klein Heidelberg antenna based on a 40 m Wasserman S tower is shown in Fig. 3. The main antenna consisted of 18 dipole elements in front of a reflector plane positioned in three column arrays of six elements each. It spanned a beamwidth of 45 degrees in azimuth and provided an angular measurement accuracy of about 5 degrees. An additional dipole antenna at 15 m height received the direct transmitted signal.

With the invention of the duplexer in 1936, which permitted the rapid development of the operationally more convenient, single-site, monostatic radar, interest in passive radar was temporarily lost.

A further revival of PCR, or equivalently PCL, occurred in the 1990s when the North Atlantic Treaty Organization Defence Research Group launched a study on passive and noise radar that was concluded by a symposium [19]. In addition to the pulse-chasing principle, which applies to the exploitation of noncooperative pulsed radar signals as the illumination, broadcast transmitters were discovered as potential sources for PCR. The new motivation for passive radar was, in addition to its covertness, the system's inherent antistealth capability. Since stealth technology primarily aims at the reduction of an aircraft's Radar Cross Section (RCS) with respect to mono-static radars at operational radar frequencies from L[1]- to X-band[2], the bi- or multistatic geometry of passive radars and their predominant VHF/UHF illuminators successfully counter stealth. PCL studies were conducted at University College London (UCL), where Griffiths and Long investigated the use of analogue television (TV) transmissions from Crystal Palace for the detection of aircraft targets [20]. Additionally, Howland utilised the analogue TV video carrier, again from the venerable Crystal Palace transmitter, to detect and track air-liners to ranges of up to 260 km. These studies demonstrated the feasibility of the principle of PCL technology. At the same time, Thales in France obtained a patent on a method which exploits the spectral shift of the TV-carrier and the line synchronisation pulses of a moving target echo versus the direct signal for passive target detection ranging. A demonstration of passive radar target detection using the illumination of a Russian type P18 VHF-surveillance radar was conducted under the name of Passive Radar Demonstration in 2001 by Forschungsgesellschaft für Angewandte Naturwissenschaften (FGAN)-Fraunhofer-Institut für Hochfrequenzphysik und Radartechnik (FHR) in cooperation with the Hungarian Technology agency. As a further source of illumination being available in almost all parts of the world, Frequency Modulation (FM)-radio signals were exploited in many PCR system designs. The first commercial PCR prototype using FM-radio broadcast emissions was developed by Lockheed-Martin [21] and is referred to as "Silent Sentry" (see Fig. 4), thus underlining the sensor's covertness. In France, a small company Communication et Téléphonie developed a system called

[1] L-band: 1–2 GHz
[2] X-band: 8–12 GHz

Figure 4.
Silent Sentry 3 setup (courtesy of Lockheed-Martin) .

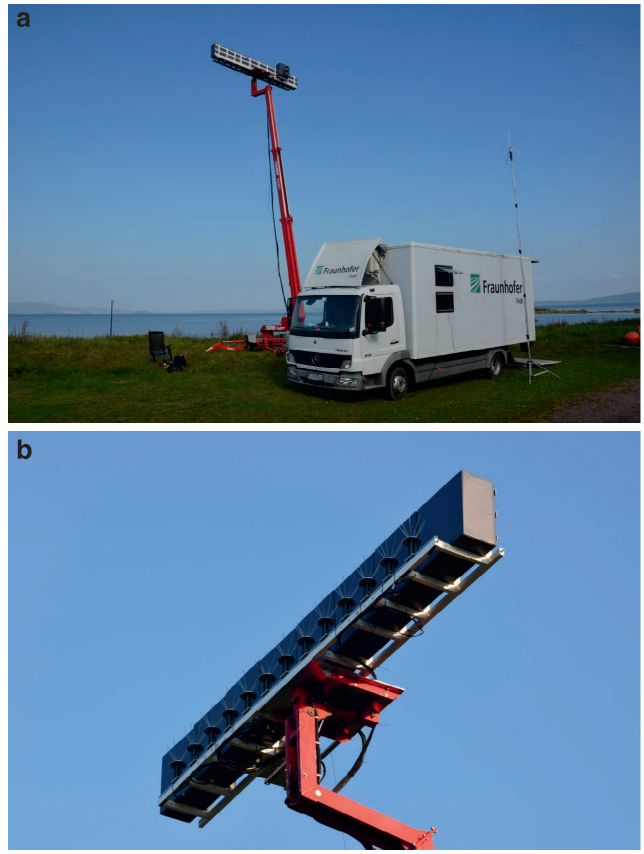

Figure 5.
LORA11 DVB-T PCL-System of FHR and FFI with linear array antenna.

Occiu [22], which consisted of an 8-element antenna array, an off-the-shelf computer, sophisticated signal processing, and a mission planning software "Aneth." Other European industries like Thales and European Aeronautic Defence and Space Company (EADS) among others became interested in the new sensor approach. In retrospect, Occiu can be considered the predecessor to HA100 by Thales. The name HA100, standing for Homeland Alerter with about 100 km detection range, suggests the role foreseen for this type of sensor. Later, other industries like Leonardo, HENSOLDT, and ERA as well as research institutions like NC3A [9], Warsaw University of Technology, and Office National d'Etudes et Recherches Aérospatiales (ONERA) joined in with experimental systems or demonstrators. Fraunhofer FHR during that period had developed and operated a number of experimental systems like COvert RAdar (CORA), Passive Experimental Tv RAdar (PETRA), and Dab Experimental radar with Linear Array (DELIA) [23], leading to a demonstrator for Digital Video Broadcast—Terrestrial (DVB-T) PCL, Linear array cOvert RAdar (LORA)11 [24] (Fig. 5), the use of which was shared with Forsvarets forskningsinstitutt (FFI) of Norway. The handling of vast amounts of data at reasonable processing times was facilitated by technological development. Direct Radio Frequency (RF)-signal digitisation and applying the "software defined radar" principle further supported the applicability of passive radar for military and civil security purposes.

IV. PASSIVE RADAR PRINCIPLE OF OPERATION

The expression "passive radar systems" indicates a class of bistatic radar systems that do not transmit a dedicated electromagnetic signal, but instead exploit electromagnetic signals emitted by other sources for other purposes. Such sources are usually referred to as "illuminators of opportunity" and examples include other radars, communication systems, and broadcast systems for public utility.

Since the illuminating signal is not a priori known to the passive radar receiver, it has to measure both the signal to be exploited as well as the signal reflected off the target. Further, the radar has to preprocess the two signals, cross-correlate them, detect the targets, and finally track the targets. This section will elaborate on the basic principles of passive radar.

The principle of operation of passive radar is based on cross-correlating the signal received directly from a transmitter with its reflections from a target. A typical geometry is sketched in Fig. 6.

A. TIME DIFFERENCE OF ARRIVAL MEASUREMENT

The PCL receiver measures the Time Difference of Arrival (TDOA) between the direct signal and the reflected echo. The bistatic range measurement is retrieved from a TDOA measurement considering the electromagnetic wave propagation speed. Cross-correlation between the direct reference signal and the reflected echo results in the two-dimensional range-Doppler matrix. This means that different possible Doppler modulated replicas of the direct signal are cross-correlated with the echo signals. As a consequence, a PCL radar system is also able to estimate the bistatic Doppler frequency (which is equivalent to the bistatic range rate). It is well known that a bistatic range measurement locates the target onto an ellipsoid that has the transmitter and the receiver located at its foci.

Target positions are obtained by either using multiple transmitters or receivers to determine the ellipsoid intersections, or by mea-

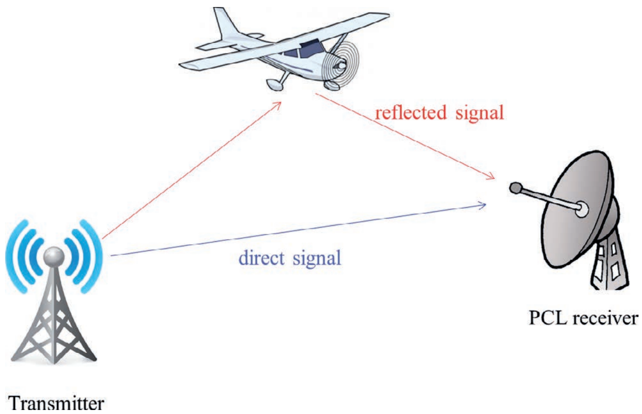

Figure 6.
Sketch of the PCL geometry.

suring the target direction and its intersection with the ellipsoid. The accuracy of the target position strongly depends on the bandwidth of the utilised signal and the receiver antenna beam-width, and is often considered a criterion for determining the suitability of passive radar systems for particular applications.

B. DOPPLER PROCESSING

On the other hand, if a single bistatic pair is considered, the bistatic Doppler information cannot be used to locate the target since the target direction of motion is unknown. The PCL Doppler resolution is usually very high since long integration times are exploited. This simple principle of operation conceals various important issues that characterize the performance of PCL systems, and that drive the corresponding research activities. First of all, the transmitted signal is not known a priori, and its characteristics are not under the control of the radar designer. This requires ad hoc hardware and signal processing to retrieve a copy or replica of the signal that is being transmitted. Moreover, the transmitted signal usually has spectral characteristics that do not match the needs of a radar, since it is designed for other purposes.

The main consequences are that the signal bandwidth is typically limited (not allowing high resolution radar capability), and its frequency is usually below that of conventional active radars. However, the signal bandwidth is highly dependent on the exploited illuminators of opportunity, and there exist several illuminators of opportunity providing signal bandwidths adequate for radar purposes (such as air target detection). The lower signal frequency is not necessarily a drawback in PCL systems, since it offers the possibility to measure target RCS signatures at different frequencies, which might help towards target identification and classification approaches and bears antistealth capabilities.

C. PROCESSING SCHEMES

As seen from the sketched geometry in Fig. 6, it can be expected that the echo signal reflected from the target will be masked by the direct signal unless it is separated by Doppler. The direct signal travels a shorter distance and it is not further attenuated by the reflection process at the target. Thus, in order to be able to detect low Doppler targets, additional processing is required to suppress the contribution of the direct signal. A block diagram of the basic signal processing steps foreseen in a PCL radar system is reported in Fig. 7. In general, two channels are required, one dedicated to the collection of the direct signal and referred to as "reference receiver" (e.g., this receiving channel will be connected to an antenna pointing directly toward the transmitter of opportunity), and a "surveillance receiver" whose aim is the collection of target echoes signals. Eventually, the surveillance receiver can be multi-channel, thus increasing the overall capabilities of the PCL system.

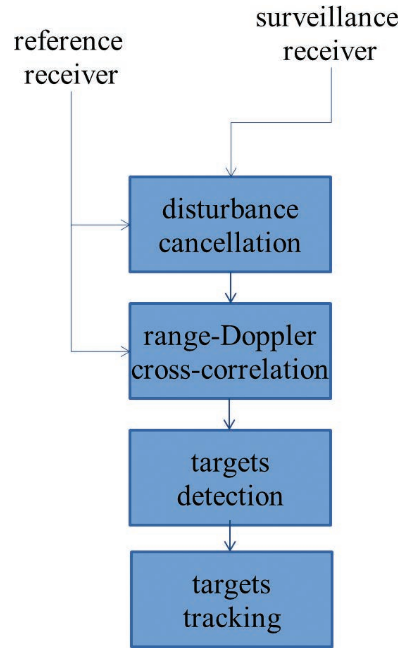

Figure 7.
Basic analogue PCL signal processing.

On the other hand, the reference receiver is usually single channel. It is clear that a dedicated reference receiver channel is required because the transmitted signal is not known a priori. Basically, it is important to receive the reference signal as clean as possible, which generally requires a line-of-sight to the transmitter and a highly directional antenna in order to avoid multipath. This is a particularly important requirement when analogue (broadcast) signals are exploited, which do not offer the possibility of reconstructing the transmitted signal from signal synchronization features. Fig. 7 shows the general analogue processing chain which starts with cross-correlating the reference channel with the surveillance channel and ends with tracking detected targets in the Cartesian domain. One of the most important steps in the processing chain is the suppression of the direct signal since its correlation sidelobes might mask weak target echoes. The direct signal suppression can be achieved by filtering the received signal spatially (e.g., by pointing a minimum of the receiver antenna diagram towards the transmitter), or in the time domain (e.g., by coherently subtracting the direct signal contribution from the surveillance channel). In the following sections, deeper insights into these approaches are presented.

This basic processing scheme can be refined if a digital transmission of opportunity is exploited (see Fig. 8). In fact, as mentioned above, the direct signal is likely to be the strongest signal contribution in the "surveillance channel." As a consequence, after

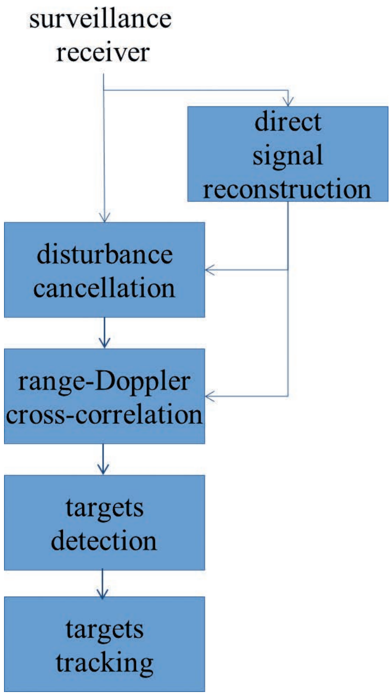

Figure 8.
Basic PCL signal processing using digital transmitter.

proper synchronization and by knowing the transmission standard, it is possible to decode the transmitted stream of bits, and then re-code this stream to reconstruct the original transmitted signal. This operation can be done using a single channel surveillance receiver, with significant reduction of costs and system complexity. If this second approach is followed, the block diagram in Fig. 7 would be modified to the one depicted in Fig. 8. In both cases, a cleaned version of the transmitted signal is used to remove the direct signal contribution together with eventual multipaths components from the surveillance channel. This step is labeled "disturbance cancellation." After direct signal removal, the "cleaned" surveillance signal is cross-correlated with the "cleaned" reference signal to produce one range-Doppler map per Coherent Processing Interval (CPI). Over each range-Doppler map target detection is performed (for instance resorting to Constant False Alarm Rate approaches). Detections collected from multiple CPIs can be further processed to produce tracks of detected targets. Target tracking can be performed in the range-Doppler domain, or in Cartesian coordinates if target geo-localization is available. It can be shown that two-stage tracking (both in range-Doppler and in Cartesian coordinates) might drastically reduce the resulting number of false alarms.

V. ILLUMINATORS OF OPPORTUNITY

The passive radar relies on transmitters of opportunity which have primary functions other than to serve as radar illuminators. This section will explain what types of illuminators are available and how their specific properties impact on passive radar processing requirements. After generally classifying the transmitters of opportunity into space borne and terrestrial, a focus will be placed on waveforms, antenna design and network concepts for terrestrial broadcast services.

A. CLASSES OF ILLUMINATORS

There are multiple possible classification criteria for illuminators that one might choose, like signal modulation or purpose of transmission. However, dividing them into terrestrial and space borne classes indicates what is primarily used today and what probably will be desired in the future.

Illuminators of Opportunity (IO) belonging to the terrestrial class are:

- other radars: for example, radars used for air traffic control or for maritime coastal monitoring;
- mobile communication systems: base stations for Global System for Mobile communications (GSM), Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE); access points for Wireless Fidelity (WiFi), Worldwide Interoperability for Microwave access (WiMAX), High Performance Radio LAN (HiperLAN);
- broadcast systems for public utility: FM and Digital Audio Broadcast (DAB) radio (analogue and digital, respectively); analogue TV and DVB-T (also known as digital TV).

Illuminators of opportunity belonging to the space borne class are:

- other radars: for example, radars used for Earth monitoring and remote sensing applications;
- broadcast systems for public utility: such as Digital Video Broadcast—Satellite (DVB-S) (also known as digital satellite TV), and its handheld variation Digital Video Broadcast—Satellite Handheld (DVB-SH);
- mobile communication systems: like Globalstar, Iridium, and Orbcomm;
- geolocalization system: transmitters like Global Positioning System (GPS), GLObal NAvigation Satellite System, and the future GALILEO.

Among these different possibilities, a good IO for PCL should provide a reliable continuous transmitted signal over time, with a strong Equivalent Isotropically Radiated Power (EIRP), possibly over a wide area. For this last reason, other radars are usually excluded from the analysis.

B. MODULATION PROPERTIES

As briefly discussed before, the transmitted signal characteristics should be as uniform as possible. For this reason, digital transmissions are generally more favourable with respect to analogue transmissions. An example is represented by FM radio. Given its wide availability and reasonable transmit power, FM radio has been largely exploited for PCL purposes in the early years of the 21st century. However, FM radio modulation is analogue, which means that the effective instantaneous signal bandwidth is highly dependent on the program content being broadcasted. Specifically, rock music seems to be most advantageous due to a comparably large constant bandwidth, while oral contributions like news are the least favourable (an explanatory example of PCL performance for different transmitted FM radio signals can be observed by comparing the ambiguity functions in Figs. 7.10 and 7.11 in [23]). Careful selection of the transmitter to be used is therefore required for optimum performance. For this reason, the exploitation of FM radio started to rapidly diminish as other digital broadcast services entered into operation, such as DAB and DVB-T. DAB and DVB-T (namely terrestrial digital radio and television, respectively) use an Orthogonal Frequency Division Modulation (OFDM) scheme which guarantees constant signal features, namely constant bandwidth, and (predictable) range/Doppler/sidelobe characteristics of the auto-ambiguity function. However, digital modulation schemes also present drawbacks mainly related to periodicities in the signal structure.

Considerations relating to FM, DAB, and DVB-T Illuminators of Opportunity

	FM	DAB	DVB-T
Frequency band (MHz)	88-108	174-240	470-862
Network	MFN	SFN	SFN
Single channel BW	150 kHz (max.)	1.536 MHz	7.612 MHz
Typical ERP (kW)	2-250	0.5-10	1-100
Power density (Φ) at target in example scenarios	ERP = 100 kW; target at 50 km; Φ = -55 dBW/m^2	ERP = 5 kW; target at 30 km; Φ = -64 dBW/m^2	ERP = 50 kW; target at 50 km; Φ = -58 dBW/m^2
Range-cell width (ΔR) and its dependencies	1-3 km depending on instantaneous BW, bistatic angle	approx. 100 m depending on bistatic angle	approx. 20 m depending on bistatic angle
Typical integration times (s)	1	0.5	0.5

FM, frequency modulation; DAB, digital audio broadcast; DVB-T, digital video broadcast-terrestrial; MFN, multiple frequency network; SFN, single frequency network; ERP, effective radiated power

Figure 9.
Brief comparison of FM radio, DAB radio, and DVB-T.

These periodicities in the transmitted signal are introduced for different reasons (e.g., for synchronization purposes), but they also introduce artefacts in the passive radar processing that result in potential false alarms if not properly compensated for. WiFi, WiMAX, and the least popular HiperLAN are also digital transmissions based on OFDM. Their availability is marginal (WiMAX and HiperLAN) or reduced to very short ranges (WiFi). Nevertheless, the possibility to exploit WiFi signals for indoor PCL and short-range surveillance has been demonstrated [24], [25].

Cellular phone networks like GSM (but also LTE) offer a wide coverage, and are good candidates as illuminator of opportunities for PCL [26]. DAB is also a good candidate, but its exploitation is highly dependent on the availability of digital radio services. In fact, only some countries in Europe offer these services. On the other hand, DVB-T currently represents the most used IO for PCL. This can be contributed to the facts that DVB-T is now available in most countries, it uses OFDM modulation, it has adequate signal bandwidth for most PCL radar applications, and it has adequate EIRP values. An undesired peculiarity of DAB and DVB-T is that they usually operate in a so-called SFN. In a SFN, all transmitters belonging to the network simultaneously transmit the same signal at the same frequencies. From a PCL point of view, this means that multiple replicas of the direct signal will be collected at the receiver (i.e., multipaths), and that a single target might generate multiple echoes at the receiver (one for each nearby transmitter). As a consequence, the PCL system might not only suffer from multipath target detection (due to strong multipath effects), but might also experience ambiguous association between echoes and the transmitter that generated the echo (making target geolocalization more complicated). Even in the presence of these drawbacks, PCL experimental and operational systems based on DVB-T have been largely developed. Fig. 9 reports a comparative overview of FM radio, DAB, and DVB-T.

Considering the satellite class of illuminators of opportunity, Global Navigation Satellite System (GNSS) systems clearly offer a wide coverage; however, the EIRP is usually not enough for applicability in PCL systems, and the received signals are strongly attenuated due to long baselines between transmitters and the receiver. Nevertheless, PCL experiments have been successfully conducted in past years using GNSS systems as illuminators of opportunity [27], [28]. An exception is represented by DVB-SH satellites. The near future intention of these satellites is to provide high quality digital broadcast services to handheld devices such as smartphones and tablets. In this case, given the poor receiving antenna characteristics of the handheld devices, high EIRP values are foreseen which make such transmitters, together with the previously mentioned OFDM signal characteristics, appealing illuminators of opportunity for PCL [29]. The actual commercial success of these services will likely drive their availability (or not) in the near future. Recent fast emerging concurrent standards like LTE might obscure DVB-SH.

C. ANTENNA ELEVATION CHARACTERISTICS

One of the primary objectives in broadcast engineering is to achieve wide-area coverage with adequate field intensity so that users can receive the transmissions of interest. The “users” in terms of broadcast engineering usually refer to ground-based receivers for such services as FM radio, TV, DAB, DVB-T, GSM, etc. In the case of commonly used illuminators of opportunity for passive radar purposes, namely FM, DAB, and DVB-T, the field strength produced by a station depends, among other things, on Equivalent Radiated Power (ERP), antenna heights, local terrain, and tropospheric scattering conditions. The antenna systems usually consist of several individual radiating bays fed as a phased array. Their radiation characteristics concentrate the energy in the horizontal plane towards the population to be served, mini-

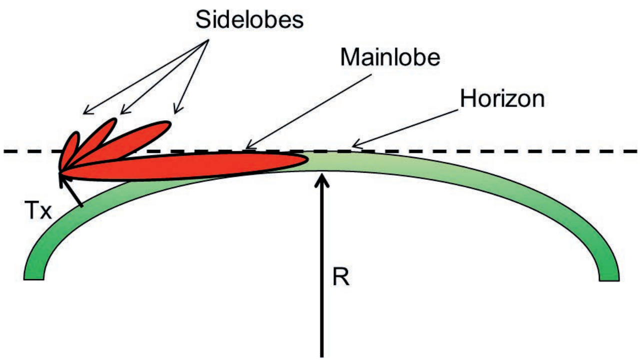

Figure 10.
Illustration of the elevation beam pattern tilted below the horizontal.

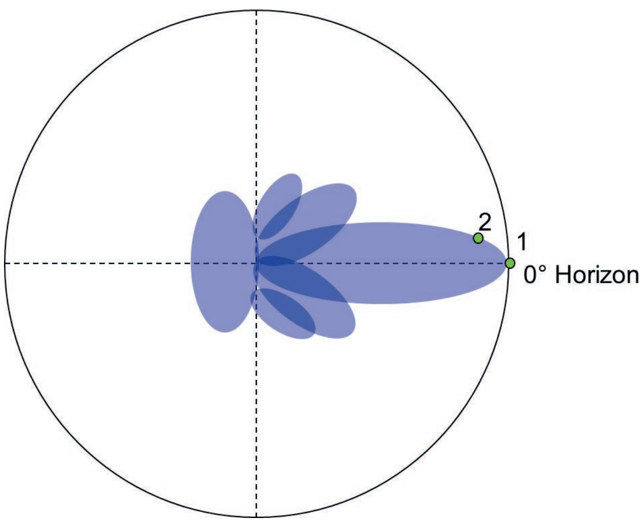

Figure 11.
Representation of antenna elevation pattern in polar coordinates.

mising the radiation out into space. Minimising the radiation out into space (i.e., beyond the horizon) requires the vertical plane radiation pattern to be tilted slightly below the horizontal. This is a common procedure in broadcast engineering and is referred to as beam-tilt. The beam-tilt principle is illustrated in Fig. 10. Fig. 11 is a representation of an antenna elevation pattern in polar coordinates. Point 1 in Fig. 11 indicates the peak of the beam at the horizon (the illustration does not depict beam-tilt). The ERP refers to the effective power output from the antenna in a specified direction and includes the transmitter power output, transmission-line losses, and antenna power gain. The maximum ERP occurs at the peak of the beam where the beamwidth is narrowest. Point 2 refers to the maximum field pattern (equivalent to the -3 dB beamwidth). The strength of the main lobe falls off increasingly as the angle from the centre of the beam increases. It is conventional to consider the -3 dB beamwidth to determine the size of the antennas frontal area (aperture).

D. DIFFERENCES BETWEEN MFN AND SFN

Considering the price of broadcasting licences, operating a network where the ratio between spectrum and bandwidth is optimized becomes important. Based on OFDM modulation proper-

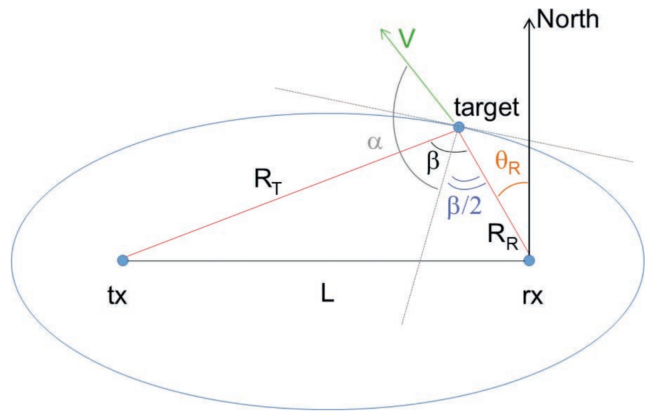

Figure 12.
Sketch of the bistatic geometry in two-dimensional Cartesian coordinates.

ties, the DVB consortium introduced SFN as a way to optimize spectrum and bandwidth for DVB-T broadcast. SFN topology differs from MFN topology, where all the transmitters broadcast at different frequencies. In a SFN, all transmitters of one SFN cell broadcast at the same frequency, enabling spectrum and bandwidth optimization. For example, in a MFN a common service area is illuminated with three different broadcast frequencies occupying 24 MHz bandwidth, while in a SFN approach with bandwidth optimization, only 8 MHz are occupied. An SFN requires that all transmitters are coherently transmitting the same signal at the same time. For that purpose, GPS disciplined oscillators are generally used on transmission. Likewise using GPS-locked oscillators on receive can provide a synchronisation advantage for PCL systems using SFN illumination.

VI. BISTATIC RADAR

Since passive radar is inherently bistatic or even multistatic, an excursion to the basics of bistatic radar is considered helpful for the understanding of passive radar processing. Based on the bistatic geometry with separated locations for transmitter and receiver, the bistatic radar equation is introduced, leading to the location dependent range and Doppler resolution. With the curves of constant signal to noise ratio (Ovals of Cassini) and the ellipsoids of constant target echo delay, the key differences between mono- and bistatic radar are addressed leading to the various schemes of geolocation in multistatic configurations.

A. BISTATIC GEOMETRY

A two-dimensional sketch of the bistatic geometry of a PCL radar system in Cartesian coordinates is depicted in Fig. 12. The location of the transmitter is labeled as “tx”, the receiver as “rx”, and the target as “tgt”. The plane containing the transmitter, the receiver, and the target is called bistatic plane. Please note that in the usual case of ground-based transmitter/receiver and airborne target, the bistatic plane is not parallel to the Earth surface. The line between the transmitter and the receiver is denoted as the baseline, L. The range from the transmitter to the target is R_T, while the

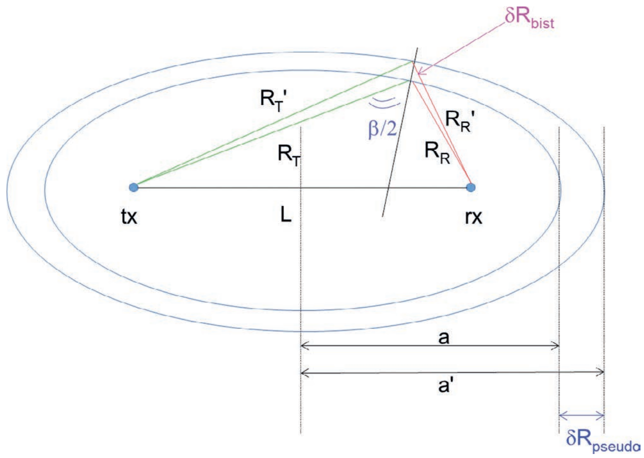

Figure 13.
Sketch of the bistatic range resolution.

range from the target to the receiver is R_R. The angle between the transmitter and the receiver with vertex at the target is denoted as the bistatic angle β. The bistatic range R_{bist} is calculated through TDOA measurements corresponding to $R_{bist} = R_T + R_R - L$. The locus of points at constant bistatic range define iso-range lines, that are represented by ellipses in the bistatic plane of Fig. 12 (in a three-dimensional representation they are ellipsoids) where the transmitter and the receiver are located at the foci. The sum $R_T + R_R$ equals twice the semimajor axis of the corresponding ellipse. An important property is that the bisector of the bistatic angle is always orthogonal to the tangent of the iso-range contour in any point of the ellipse.

B. BISTATIC RANGE RESOLUTION

The range resolution in the monostatic case is defined as the minimum distance between two targets that still allows the radar to distinguish the corresponding returns. In meters, this corresponds to the well-known formula $\delta R_{mono} = c\tau/2$, where c is the speed of light in vacuum, and τ is the temporal duration of the pulse (if range compression is applied, $\tau = 1/B$ where B is the processed transmitted signal bandwidth). In other words, in the monostatic case δR_{mono} is defined as the difference of two concentric circles having a difference in radius of $c/2B$. An extension of this concept in the bistatic case is possible. To do that, let us define a pseudo-monostatic range resolution δR_{pseudo} as the separation between two concentric iso-range ellipses having the semi major axis a and a′, where $\delta R_{pseudo} = a - a' = c/2B$. The two aforementioned concentric ellipses are shown in Fig. 13. From Fig. 13 it is clear that the bistatic range resolution δR_{bist} not only depends on δR_{pseudo}, but also on the specific position within the ellipse. By explicating this latter dependence in terms of the bistatic angle β, one can approximate the bistatic range resolution as $\delta R_{bist} \approx c/(2B\cos(\beta/2))$ [9].

C. BISTATIC DOPPLER

The bistatic Doppler is defined as the bistatic range rate R_{bist} over time normalized by the carrier wavelength λ [9]. That is,

$$f_{bist} = \frac{1}{\lambda}\left[\frac{\partial}{\partial t}R_{bist(t)}\right] = \frac{1}{\lambda}\left[\frac{\partial}{\partial t}R_T(t) + \frac{\partial}{\partial t}R_R(t)\right]. \quad (1)$$

As is apparent, the bistatic Doppler is comprised of two contributions, the first due to the relative radial motion between transmitter and target, and the second due to the relative motion between target and receiver. In the usual PCL radar case the transmitter and receiver are stationary, therefore the measured bistatic Doppler only depends on the target motion. In this particular case, the bistatic Doppler frequency can be expressed as

$$f_{bist} = \frac{V}{\lambda}\left[\cos(\alpha - \beta/2) + \cos(\alpha + \beta/2)\right] = \frac{2V}{\lambda}\cos\alpha\cos(\beta/2) \quad (2)$$

where V is the modulus of the target velocity vector and α is the orientation of V with respect to the bisector of the bistatic angle (see Fig. 12). It is important to note that any target moving along the baseline between the transmitter and the receiver will have a zero bistatic Doppler frequency, since the two terms in (1) cancel out each other. On the other hand, in the extended baseline case (i.e., when $\beta = 0$) the bistatic Doppler reduces to the monostatic Doppler. By observing (1), it is also important to notice that the bistatic Doppler will be zero for all targets moving along the bistatic iso-range; that is, the bistatic range $R_{bist}(t)$ does not change over time. Therefore, targets moving on such trajectories would not be detectable in such a bistatic geometry, as the corresponding echo returns will exhibit zero-Doppler, exactly the same as the strong clutter returns. In this case, the exploitation of a multistatic configuration would provide geometry diversity gain, thus allowing for detection of all possible motions. In other words, when multiple Tx-Rx bistatic pairs are possible they can be defined such that blind motions in one bistatic configuration are not blind in other configurations. This means that targets are always detectable regardless of their motion, with an evident improvement of the overall situational awareness over the observed area. This idea has been firstly introduced in a simultaneous monostatic and bistatic Ground Moving Target Indicator configuration in [30], but it can be easily extended to the multistatic PCL case. In the following we will analyze the simplest multi-static configuration with two transmitters T_1 and T_2 and one receiver; however, the analysis can be easily extended to more than two transmitters and more receivers readily. By properly defining the receiver position R, targets moving along the first bistatic iso-range will exhibit a Doppler modulation in the second bistatic dataset, and vice versa.

D. BISTATIC RADAR EQUATION

The bistatic radar equation defines the basis for a detection performance analysis of a PCL radar system. Specifically, it allows calculation of the expected Signal to Noise Ratio (SNR) as a function of target position and RCS, as well as transmitter and receiver characteristics (like transmitted power and antenna diagrams). It also allows estimation of the maximum detection range of the radar system once the desired detection and false alarm probabilities are defined together with target fluctuation models. For PCL systems exploiting SFN transmitters, the target echo signal always competes with a strong direct signal. With respect to thermal noise, the target echo signal is increased by the processing gain resulting from the correlation process G_{corr}. Thus, in many situations, specifically when transmitters are close to the receiver, the limiting factor is not thermal noise but rather the correlation side lobes of the closest or strongest transmitter in the net. A quantitative comparison between direct signal interference and thermal noise level can be found in [23, Ch.7.2.3]. In order to determine the detection range capability and thus the bi- or multistatic coverage of a PCL radar receiver, the power level of the direct transmitter signals at the location of the receiver has to be known. Let S_{d_i} be the power density of the ith transmitter at the location of the receiver,

$$S_{d_i} = \frac{P_{T_i} G_{T_i} F_i}{4\pi L_i^2} \tag{3}$$

where P_{T_i} is the transmitted power of the ith transmitter, G_{T_i} is the gain of the ith transmitter in the direction to the receiver, F_i is the propagation factor on the path from the ith transmitter to the receiver, and L_i is the ith transmitter to receiver baseline. The received power in the passive radar receiver with an antenna gain of G_{R_i} in the direction of the ith transmitter is then given by:

$$P_{d_i} = S_{d_i} A_R = \frac{P_{T_i} G_{T_i} F_{T_i}}{4\pi L_i^2} \frac{\lambda^2 G_{R_i}}{4\pi}. \tag{4}$$

The correlation side lobes of the ith direct signal, denoted as correlation noise N_{corr_i}, are reduced with respect to the correlation peak by the correlation gain G_{corr}. That is,

$$N_{corr_i} = \frac{P_{T_i} G_{T_i} F_{T_i}}{4\pi L_i^2} \frac{\lambda^2 G_{R_i}}{4\pi G_{corr}}. \tag{5}$$

The SNR of a target echo, competing with the correlation noise of the dominant (strongest, closest) transmitter N_{corr_D} in the net, depends on the targets RCS σ and the power of the illuminating transmitters, which can, under optimum conditions, be all transmitters in the net.

$$SNR = \frac{P_{T_i} G_{T_i} F_{T_i}}{4\pi R_{T_i}^2} \frac{\lambda^2 G_R}{4\pi} \frac{\sigma F_{R_i}}{4\pi R_{R_i}^2} \frac{1}{N_{corr_D}} \tag{6}$$

with F_{T_i} and F_{R_i} being the respective propagation factors on the path from the transmitter to the target then on to the receiver, and R_{T_i} and R_{R_i} being the respective distances. G_R and G_{T_i} denote the receiver and ith transmitter antenna gains respectively in the direction of the target. Inserting (5) into (6) results in

$$SNR = \frac{P_{T_i} G_{T_i} F_{T_i}}{R_{T_i}^2} \frac{\lambda^2 G_R}{4\pi} \frac{\sigma F_{R_i}}{R_{R_i}^2} \frac{L_D^2 G_{corr}}{P_{T_D} G_{T_D} F_{T_D} \lambda^2 G_{R_D}}. \tag{7}$$

For free space conditions, which lead to maximum detection ranges, F_T and F_R are 1. The receiver antenna is assumed to be omni directional (azimuth), and for simplicity we assume $G_R = G_{R_D}$. Solving (7) for $R_{T_i}^2 R_{R_i}^2$, which gives the equivalent monostatic range R_0, and selecting the dominant $i = D$ transmitter as the source of the correlation noise, we obtain:

$$R_0 = \sqrt[4]{\frac{P_{T_i} G_{T_i} \sigma L_D^2 G_{corr}}{4\pi P_{T_D} G_{T_D} F_D (SNR)}} \tag{8}$$

where L_D is the baseline to the dominant transmitter, F_D the corresponding propagation factor, and $P_{T_D} G_{T_D}$ are the power and gain of the dominant transmitter in the direction of the receiver. Hence, the measures to increase R_0, which can be influenced by the receiver either through the choice of location or processing, are:

- increase the distance to the dominant transmitter,
- increase the correlation gain and
- reduce the propagation factor.

E. OVALS OF CASSINI

The Ovals of Cassini [9] are contours where SNR and the range product $R_T R_R$ are held constant. The SNR is highest around the transmitter and receiver sites, dropping off as one gets further and further away from these. At a point in the middle of the baseline between the transmitter and receiver sites ($L/2$), the ovals break into two nonconnected ovals, one around the transmitter, and the other around the receiver. The point on the baseline [9] where this happens is called the *cusp*, and the curve is called a *lemniscate* (of two parts), and it looks like the infinity sign ∞. The Ovals of Cassini are shown as solid contour lines in Fig. 14 for a bistatic radar system where the baseline is 40 *km*. The lemniscate is not shown, but the cusp is at the origin and the behavior of the ovals are apparent. If the baseline is increased, the ovals will shrink towards a lemniscate, and finally collapse in a circle, one around the transmitter and one around the receiver [9].

For a monostatic radar the Ovals of Cassini collapse to circles of constant SNR with the radar in the center, and the constant range contours (circles) coincide with the constant SNR contours. For the bistatic case this is not true. Fig. 14 shows the Ovals of Cassini overlaid with isorange contours, the constant range ellipses, for a bistatic radar system. It is obvious from the figure that two targets (assumed to be equal) at different range profiles can result in the same SNR, or vice versa, that two equal targets at the same isorange contour can result in different SNR in the radar. Willis [9] has estimated the instantaneous SNR dynamic range for an isorange contour in a bistatic radar system as a function of the eccentricity e

$$\Delta \frac{S}{N} = \frac{4}{\left(1 + \cos\left(2\sin^{-1} e\right)\right)^2} \tag{9}$$

where the ratio of maximum to minimum target SNR on an isorange contour, defined as an ellipse of eccentricity, e. This shows that especially in forward scatter applications, the instantaneous dynamic range can be large, that is, eccentricity $e \rightarrow 1$. For the monostatic case, eccentricity $e = 0$, and the dynamic range difference

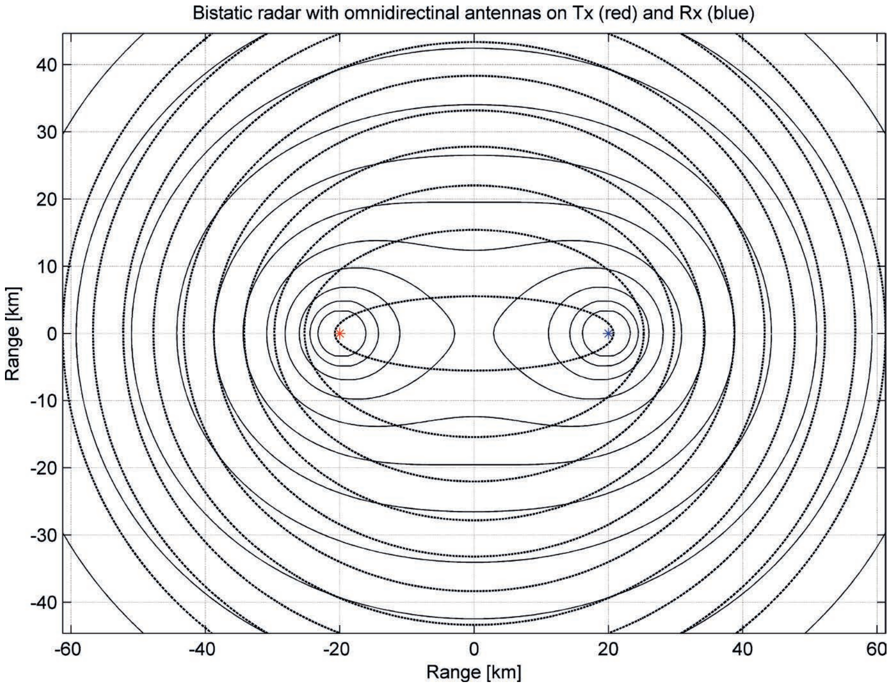

Figure 14.
The Ovals of Cassini (solid line), and the isorange contours (dotted lines).

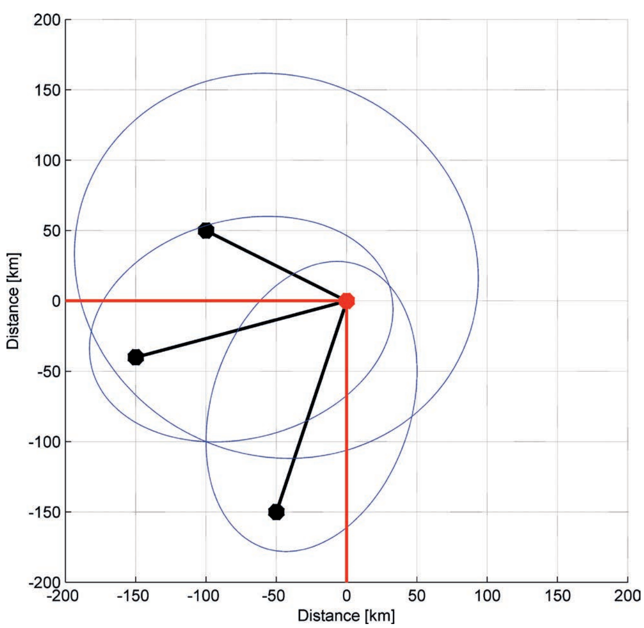

Figure 15.
The figure shows a multistatic radar system with three transmitters (black circles) and one receiver (red circle). In the scene there is one target present at position (–100 *km*, –100 *km*). The target's constant range profile is drawn for each of the three transmitter-receiver pairs (black lines), also showing three ghosts. The red lines indicate a quadrant with respect to the receiver, mimicking a coarse receiver antenna beamforming.

is zero as expected. For the bistatic case, as the target gets further and further away from the transmitter/receiver pair, the Ovals of Cassini will approach circles and the dynamic range difference will approach zero, i.e., the monostatic situation. However, going the other way and approaching the baseline, the effects of this might get quite severe as $e \to 0$, and thus $S/N \to \infty$ as seen in (9).

F. TARGET GEO-LOCALIZATION THROUGH ELLIPSOIDS INTERSECTION

Fig. 15 shows an illustration of a multistatic radar system. In the scene, three transmitters and one receiver, all with omni directional antennas, are assumed to see the target simultaneously. For each transmitter-receiver pair the target's constant range profile is drawn. From the illustration it is clear that the target is located at the intersection of the three ellipses. The rest of the intersections not corresponding to real targets are called ghosts and should be recognized as such in the signal processing. They can easily be found in Fig. 15, since this is an oversimplified situation used to illustrate the concept. In real life the number of transmitters can be more than three, the ellipses are actually ellipsoids, and the number of targets is usually higher than one. An example of such a situation from a real system is shown by Howland in [1, pp. 168, Figs. 6–42]. Howland [1, pp. 162] has developed a general expression for the maximum number of ghosts in the 2D situation, $f(M, T)$, generated by T targets and M transmit-receive pairs

$$f\left(M,T\right)=\left(2T^{2}-T\right)\left(M^{2}-M\right)\Big/2. \tag{10}$$

Table 1 shows the maximum number of intersections (or ghosts) as a function of M bistatic transmitter-receiver pairs and T targets present in the scene. It is seen that the number of ghosts increases rapidly as new transmitters and/or targets are added to the scene. For $M = 8$ transmitter-receiver pairs, and $T = 1$, the maximum number of ghosts is $f(8, 1) = 28$. The corresponding numbers for $T = 5$, and $T = 10$ are $f(8, 5) = 1{,}260$, and $f(8, 10) = 5{,}320$, respectively. In order to reduce the number of ghosts an indication of target direction might be very efficient. If the receiver is able to determine in which quadrant the target is, the maximum number of intersections is drastically reduced. This spatial discrimination will also reduce the number of targets generating constant range ellipses, and thus also the number of ghosts. This is exemplified with two red lines in Fig. 15, where the number of candidates is reduced from four to two. This rough direction/quadrant estimate is normally achieved by the receiver antenna beamforming.

Alternatively, in a pure bistatic situation target geo-localisation can be obtained by intersecting the direction of arrival of the target echo measured through antenna beamforming, with the ellipsoid determined by the time difference of arrival of the target echo signal with respect to the direct signal. In this case the radar resolution no longer depends only on the signal bandwidth, but also on the beamwidths of the receiver antenna. Unlike in monostatic radar,

Table 1.

Maximum Number of Ghosts Generated by T Targets for M Transmit-Receive Pairs [1]										
M* \ *T	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2	1	6	15	28	45	66	91	120	153	190
3	3	18	45	84	135	198	273	360	459	570
4	6	36	90	168	270	396	546	720	918	1,140
5	10	60	150	280	450	660	910	1,200	1,530	1,900
6	15	90	225	420	675	990	1,365	1,800	2,295	2,850
7	21	126	315	588	945	1,386	1,911	2,520	3,213	3,990
8	28	168	420	784	1,260	1,848	2,548	3,360	4,284	5,320

the size of the resolution cell does not only vary with range but also with the bistatic geometry.

VII. PASSIVE RADAR PROCESSING

The signals received by a passive radar contain the direct signal, reflections from moving objects, reflections from stationary objects, and noise. They are processed in various stages in order to discriminate the moving target from unwanted stationary returns in the presence of a dominant direct signal and to finally build a target track. These stages range from the cross-correlation of the direct signal with the echo signals, described by the ambiguity function, to detection schemes discriminating target echoes from noise, to tracking sequences of detections first in the range-Doppler domain and then in the Cartesian domain.

A. CROSS-CORRELATION

The cross-correlation between the direct signal and the echo signal (see Figs. 7 and 8), also referred to as range-Doppler correlation, is the key step of the PCL processing. The aim of this step is to recognize the weak target contributions, which are delayed and Doppler shifted in the received signal.

The performance of the cross-correlation with varying time-delay and Doppler shift strongly depends on the signal waveform and is generally described by the ambiguity function. In passive bistatic radar this ambiguity function does not only depend on the waveform, but in addition on the location of the target in a bistatic geometry. This variation is not respected in the cross-correlation processing, but has to be taken into account in the later stages like range-Doppler tracking.

The expression of the cross-correlation $\chi(\tau, f_D)$ is

$$\chi(\tau, f_D) = \int_{-\infty}^{+\infty} s_{surv}(t)\, s_{ref}^{*}(t-\tau)\, e^{-j2\pi f_D t}\, dt \tag{11}$$

where $s_{surv}(t)$ is the complex envelope of the signal received in the surveillance channel, $s_{ref}(t)$ is a (cleaned) replica of the transmitted signal, τ is the potential TDOA of the target echo signal, and f_D is the potential corresponding bistatic Doppler. Basically, due to the very poor Doppler robustness of the signals of opportunity used in PCL, the echo signal is correlated with Doppler-shifted replicas of the reference signal. This creates a bank of range compression filters, each one matched to a particular potential Doppler of the target. It allows the unambiguous estimation of the bistatic Doppler frequency in addition to the unambiguous bistatic target range measurement. The specific characteristics of the ambiguity function depend on the signal of opportunity that is being used. In general, signals having a thumbtack-shaped ambiguity function are preferred since a low constant side-lobe level over the range/Doppler plane diminishes the risk of strong targets masking the weak ones.

Due to the signal structure, digital transmissions like DVB-T have periodicities in both time and frequency. For the purpose of broadcasting they are used for receiver synchronization. Those periodicities usually appear in the ambiguity function in the form of sidelobes located at specific range/Doppler positions. Since a reduction of these undesired sidelobes through conventional tapering (like Hamming, Taylor, Chebyshev windowing) is not effective, other specific techniques such as those presented in [31], [32] have to be exploited. In digital processing, the ambiguity function (11) will be approximated by the sum over N samples

$$\chi[\tau, f_D] = \sum_{n=0}^{N-1} s_{surv}[nT_s]\, s_{ref}^{*}[nT_s - \tau]\, e^{-j2\pi f_D n T_s / N}. \tag{12}$$

The temporal integration interval is usually limited to the coherent integration time T_{int}. A reduction of the computational burden can be achieved by implementing the correlation in (12) in the frequency domain by means of a Fast Fourier Transform (FFT). The so-called Correlation FFT Algorithm [33] takes advantage of the fact that the samples along one Doppler bin are the cross-correlation between a Doppler shifted replica of the surveillance signal and the reference signal. This correlation becomes a multiplication in the frequency domain and the Doppler bin for the Doppler shift f_D can be calculated by

$$\chi[\tau]_{f_D} = IDFT\left\{ s_{surv, f_D}[k]\, s_{ref}^{*}[k] \right\}. \tag{13}$$

The Fourier transformation of the reference signal only needs to be calculated once for all Doppler bins. The same applies for the surveillance signal, if we take into account that the Doppler shifted replicas of the surveillance signal can be obtained by a circular shift of the samples in the frequency domain.

B. DETECTION IN PCL

The detection stage in PCL does not differ from that of other radar systems, being the decision process that determines whether a target is present in a given range/Doppler cell or not. The main issues which have to be considered are:

- statistical characteristics of the disturbance;
- occupation of a single target in terms of range/Doppler cells;
- residual unremoved clutter.

In PCL, the main disturbance source is the direct signal, and not the receiver thermal noise. As a consequence, one should make sure that the Additive White Gaussian Noise assumption holds, before calculating the detection threshold T. If this is not the case, the statistical model of the disturbance should be adequately modified, for instance by fitting other Probability Density Functions to the histogram of the interference, and then deriving the detection threshold accordingly. An erroneous modelling of the disturbance statistics may lead to a significant increase of false alarms.

The target dimension in the range/Doppler map depends highly on the physical target dimensions and on the PCL resolution in range and Doppler. While for FM radio-based PCL systems an air target is usually confined in one range gate, this does not necessarily apply for DVB-T based PCL due to the much better range resolution. Due to this, it can be useful to implement clustering algorithms. These algorithms group multiple adjacent range/Doppler cells where detections are declared, and group the different detections as coming from a single target. The use of clustering has significant effects in reducing the overall number of detections, where typical clustering techniques may be taken from image processing [34].

Clutter is usually present in PCL systems in terms of surveillance channel direct signal and multipath. Several techniques that exploit the temporal and spatial domains can be introduced for suppressing this interference. These clutter suppression techniques might not lead to an ideal cancellation of the interference, thus giving rise to residual unremoved clutter. Such residual unremoved disturbances, together with erroneous modelling of the disturbance statistics and imperfections in the clustering, may lead to an overall number of false alarms significantly greater than the desired value. This is one of the main issues of PCL systems that has to be dealt with in the tracking algorithms.

The tracker is usually implemented in two stages, first in the range/Doppler domain to reduce false alarms, and successively in the Cartesian domain to geo-localise the target and smooth the track.

C. TARGET RANGE/DOPPLER TRACKING

A first tracking stage in the range-Doppler domain is used to reduce false alarms. It handles clutter and missed detections by forming tracks directly in the range/range-rate domain, and leads to a reduced number of ellipsoid intersection tests and mitigates the ghost target phenomenon, greatly reducing the association problem for the Cartesian tracker.

The range/Doppler tracking algorithm might be based on a linear Kalman filter [35], [36] that exploits range-Doppler measurements returned by a clustering algorithm. Data association is then performed, and the track initiation, confirmation and cancellation are obtained by using a "m out of n" logic. Among all techniques, the Global Nearest Neighbor approach might be used to perform the data association, which attempts to find and to propagate the single most likely data association hypothesis at each scan. In detail, an ellipsoidal gate is used [35].

Every unassociated detection initiates a tentative track. If in the subsequent scans a tentative track is associated with a detection, which falls into its gate, a tentative track is promoted to a confirmed track. Otherwise, a tentative track is deleted. A confirmed track is deleted if it is not updated by detections over a given number of processing intervals or a certain period of time.

The target position and velocity estimate are initialized from the received detections.

D. TARGET GEO-LOCALIZATION THROUGH RANGE AND DOA MEASUREMENTS

In order to localize the target in Cartesian coordinates and enhance the signal to noise ratio, one approach is to measure the Direction of Arrival (DOA) of the echo signal in addition to measuring the range. An experimental PCL-system of Fraunhofer FHR utilises a uniformly spaced linearly array of 11 discone antennas and a spatial smoothing Bucci beamforming algorithm [37] for direction measurements. By using the range measurements and the estimated DOA it is possible to localize a target as the intersection of an iso-range contour (an ellipsoid with foci at the location of the transmitter and the receiver) and the DOA cone. In the particular case where the altitude of a target is unknown and consequently assumed to be zero, the DOA degenerates into a line and the ellipsoid into an ellipsis. Considering the low elevation illumination of broadcast transmitters, this can be considered a first order rough estimate. The iso-range contour and the DOA (θ_R) are shown in Fig. 12.

A target being tracked in the range/Doppler domain, as shown in Fig. 16, can now be tracked in the Cartesian domain as well. The Cartesian track is depicted in Fig. 17. In both figures the estimated tracks are represented in yellow and the GPS truth collected during the trial are represented in red. The offset between the GPS and the tracks is caused primarily by insufficient knowledge of the transmitter position.

E. TARGET GEO-LOCALIZATION THROUGH ELLIPSOIDS INTERSECTION

If a DOA estimation is not available, multiple transmitter-receiver pairs can be used to localize a target in Cartesian coordinates by calculating the intersection point of the ellipsoids using one transmitter and multiple receivers or multiple transmitters and one receiver as shown in Fig. 15.

One of the major challenges in target localization in PCL using single-frequency network transmitters is that the source of the measurements corresponding to different transmitters is unknown. Therefore, all combinations of the measurements need to be checked for ellipsoid intersection. When multiple measurements are present, this can lead to ghost targets which occur when intersections of ellipsoids of multiple transmitter-receiver pairs do not correspond with true target positions.

An additional challenge is that the number of possible measurement combinations grows rapidly with the number of the targets and transmitters. For this reason, it is desirable to use very fast algorithms for calculating the ellipsoids intersections, so that hundreds or thousands of combinations can be processed in real time.

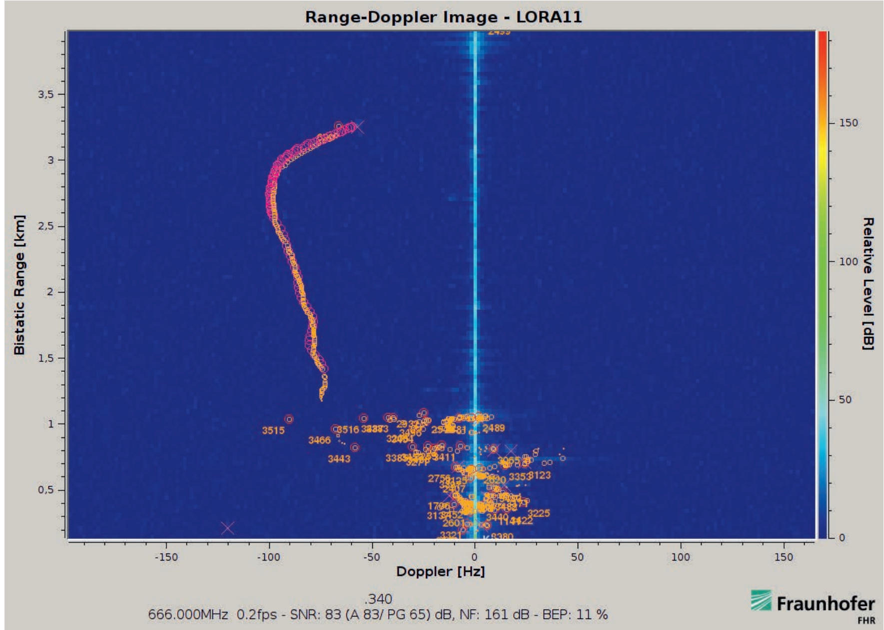

Figure 16.
Tracking of the airplane in the range-Doppler domain.

F. DIRECT CARTESIAN TRACKING

As an alternative approach the range-Doppler detections can directly fit into a tracking algorithm which pursues multi hypotheses of target motion, a Multi Hypothesis Tracker (MHT). This tracking could be more robust with respect to instabilities of range-Doppler tracks, and potentially apply more advanced motion models (for example an Interacting Multiple Model).

The MHT algorithm was originally developed by Reid [38]. The hypothesis oriented MHT presents an exhaustive method of enumerating all possible assignment track to measurement combinations.

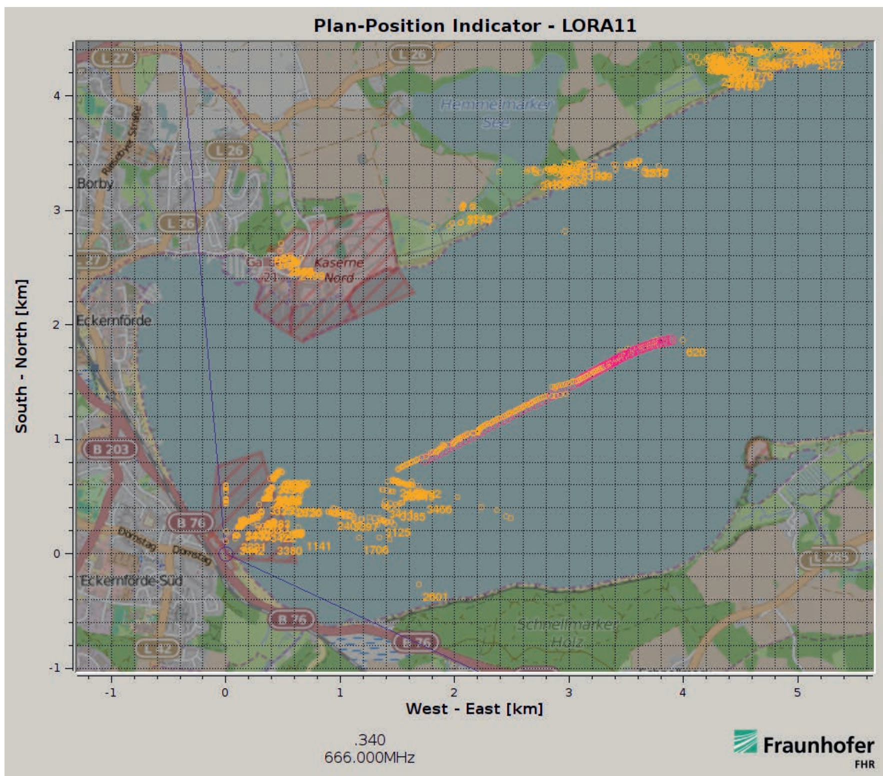

Figure 17.
Tracking of the airplane in the Cartesian domain.

VIII. PERSPECTIVES

Future trends in PCL will need to focus on overcoming deficiencies in illuminator waveforms, exploiting the potential of emerging technologies, and exploring new areas for the application of passive radar (e.g., PCL on mobile platforms).

A. DOPPLER ONLY TRACKING

Since signals like FM and GSM used in passive radars are relatively narrowband, the accuracy of range measurements is limited. Doppler resolution may be obtained through long integration times provided that a target remains in the resolution cell.

The bistatic velocity can be described as a sum of the values of velocity vector components towards the transmitter and towards the receiver. The idea of Doppler-only localization can be derived intuitively from the fact that for different target locations and velocities the measured set of the bistatic velocities will also be different. The mutual uniqueness between the bistatic velocities set and the target state obviously depends on the system geometry and the number of transmitters. Simulation results [39], [40] show that measurements of the Doppler shifts in passive radar systems can not only improve localization and tracking algorithms accuracy, but also provide sufficient information about the target position and velocity. That means that Doppler-based localization algorithms in PCL systems can be used to bypass the range resolution limitations of narrowband signals.

B. PCL ON MOBILE PLATFORMS

Early work pointed out the PBR potential of exploiting ground-based broadcasters for air-to-air surveillance [41], while the first published demonstrations were presented around 2010 [42], [43].

At UCL an FM-radio receiver was installed in a private aircraft and flown with the intention of detecting commercial airliners in the vicinity of London's Heathrow and Gatwick airports [42]. Detections of commercial airliners were demonstrated, and also verified from the Automatic Dependent Surveillance-data flight paths. Further encouraging results followed from a data collection campaign [44], [45]. Also, Warsaw University of Technology [43], [46] presented early demonstrations of an airborne PBR concept supported by real measurements. This work focused on the signal processing challenges of airborne PBR, and was also followed by further promising results [47]–[49].

A final observation from the perspective of airborne PBR would be the imaging of the ground/surface. The current status of the research field is elegantly represented in the Swedish work presented in [50].

Reference [51] proposes a new concept of Earth observation from space where ground-based DVB-T transmitters are illuminating the ground while the passive radar receiver is space borne on a satellite in Low Earth Orbit receiving the ground reflected energy and producing Synthetic Aperture Radar imagery of the ground. The concept is supported by proof-of-concept measurements obtained by a surface moving platform.

C. EMERGING TECHNOLOGY

CPU and GPU technological trends in combination with fast AD conversion at high dynamic ranges enable the processing of larger bandwidths, e.g., multiple DVB-T channels, and thus provide better range resolution.

With such improved range resolution, a radar sensor with high range and Doppler resolution as well as 100% time on target can be achieved. This will be a good starting point for creating bistatic High Range Resolution (HRR) profiles and bistatic Inverse Synthetic Aperture Radar (ISAR) images.

Work on exploiting more of the available energy has also been reported [52]–[55]. It has been demonstrated that combining DVB-T bands yields improved range resolution, while extending the coherent integration time yields finer Doppler resolution. This motivates classification approaches towards smaller and slower targets while also sub-target resolutions of larger targets might be achievable. The results offer the potential of Non-Cooperative Target Recognition through ISAR and/or HRR-capabilities in a PBR system based on DVB-T broadcasters.

Furthermore, even 3D ISAR imaging was demonstrated [56], and comprehensive theoretical work [57] and experiments on passive radar imaging were published [56], [58]–[63].

IX. CONCLUSION

With the development in signal processing and data processing technology in recent years, and advances in algorithmic development, PBR and PCL has reached a stage of maturity which has allowed industries to approach the market with demonstrator systems. The demonstrators are primarily aimed at the needs of the military for air surveillance, gap filling, and object protection.

In addition, research organisations, universities, and industries have proposed passive radar sensors for civilian applications [64]. Examples include traffic density monitoring, monitoring of private airfields, harbour traffic monitoring, and passive radar collision warning for wind turbines.

While the technology is ready and processing has demonstrated the capability to deal with current illuminator signals, the signal environment is constantly changing due to the changing needs of broadcast and communication networks. For example, analogue TV was replaced by digital TV (i.e., DVB-T), which is in turn being replaced by DVB-T2. FM-radio is gradually disappearing, partly being replaced by DAB. Mobile communications have developed from GSM to UMTS and LTE with the perspective of 5G. This constant changing requires high flexibility of the passive radar receiver which today can be best met with software defined radar concepts.

Such cost efficient concepts are based on digitising the received signals as close as possible to the receiver antenna elements and processing them in the digital domain. They are, however, limited by the capability of the AD conversion to span the required dynamic range.

Since the development of AD converters towards higher sampling rates and larger dynamic ranges is driven by the consumer market needs and has not kept pace with the development of computer processing power, lacking performance may still need the consideration of advanced solutions for the remaining analogue components, specifically the antenna.

Thus, for some applications, smart antenna concepts with sophisticated spatial and spectral performance in combination with flexible receiver front-ends are still a requirement and may be for some time.

X. RECOMMENDED FURTHER READING

For the interested reader the following sources are recommended:

Bistatic radar was for a long time described in the book of N. Willis [9]. Recent development and research has resulted in the newer major publications like N. Willis and H. Griffiths “Advances in Bistatic Radar” [1], H. Griffiths and C. Baker “An Introduction to Passive Radar” [65], M. Cherniakov “Bistatic Radar: Principles and Practice” [66], and “Bistatic Radar: Emerging Technology” [2].

Bistatic radar is also included with two full chapters (Chapter 44: *Bistatic radar*, and Chapter 45: *Distributed Radar and Multiple In Multiple Out (MIMO) radar*) in the third edition of Stimson's "Introduction to Airborne Radar" [67], while the second edition barely treated the subject. ❖

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