Chapter 24
Electronic Counter-Countermeasures

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Analysis of Integrated Systems
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24.1 INTRODUCTION

Since World War II, both radar and electronic warfare (EW)* have achieved a very high state of performance.[1,2] Modern military forces depend heavily on electromagnetic (EM) systems for surveillance, weapon control, communication, and navigation; thus access to, and control of, the EM spectrum is vital. Electronic countermeasures (ECM) are likely to be taken by hostile forces to degrade the effectiveness of EM systems.[3–7] As a direct consequence, EM systems are more and more frequently equipped with so-called electronic counter-countermeasures (ECCM) to ensure effective use of the EM spectrum despite an enemy's use of EW actions.

This chapter is devoted to the description of the ECCM techniques and design principles to be used in radar systems when they are subject to an ECM threat. Section 24.2 starts with a recall of the definitions pertaining to EW and ECCM. The topic of radar signals interception by EW devices is introduced in Section 24.3; the first strategy to be adopted by radar designers is to try to avoid interception by the opponent electronic devices. Section 24.4 is dedicated entirely to the analysis of the major ECM techniques and strategies. It is important to understand the ECM threat to a radar system in order to be able to efficiently react to it. To facilitate the description of the crowded family of ECCM techniques (Sections 24.6 through 24.10), a classification is attempted in Section 24.5. Then, the techniques are introduced according to their use in the various sections of radar, namely, antenna, transmitter, receiver, and signal processing. A key role is also played by those ECCM techniques that cannot be classified as electronic, such as human factors, methods of radar operation, and radar deployment tactics (Section 24.10).

The ensuing Section 24.11 shows the application of the aforementioned techniques to the most common radar families, namely, surveillance, tracking, multifunctional, phased-array, imaging, and over-the-horizon radars. The main design principles (e.g., selection of transmitter power, frequency, waveform, and antenna gain) as dictated by the ECM threat are also discussed in some detail.

* A list of acronyms is at the end of the chapter before the list of references.

The chapter ends with an approach to the problem of evaluating the efficacy of ECCM and ECM techniques (Section 24.12). There is a lack of theory to properly quantify the endless battle between ECCM and ECM techniques. Nevertheless, a commonly adopted approach to determine the ECM effect on a radar system is based on evaluation of the radar range under jamming conditions. The advantage of using specific ECCM techniques can be taken into account by calculating the radar range recovery.

A list of acronyms used in the chapter and the references appear at the end of the chapter.

24.2 TERMINOLOGY

EW is defined as a military action involving the use of EM energy to determine, exploit, reduce, or prevent radar use of the EM spectrum.[8–11] The operational employment of EW relies upon the capture of radar EM emissions using electronic intelligence (ELINT) devices, collating the information in support databases that are then used to interpret EM emission data, to understand the radar system functions, and to program reactions against the radar. EW is organized into two major categories: electronic warfare support measures (ESM) and ECM. Basically, the EW community takes as its job the degradation of radar capability. The radar community takes as its job the successful application of radar in spite of what the EW community does; the goal is pursued by means of ECCM techniques. The definitions of ESM, ECM, and ECCM are listed below.[8,11,12†]

ESM is that division of EW involving actions taken to search for, intercept, locate, record, and analyze radiated EM energy for the purpose of exploiting such radiations in the support of military operations. Thus, ESM provides a source of EW information required to conduct ECM, threat detection, warning, and avoidance. ECM is that division of EW involving actions taken to prevent or reduce a radar's effective use of the EM spectrum. ECCM comprises those radar actions taken to ensure effective use of the EM spectrum despite the enemy's use of EW.

The topic of EW is extremely rich in terms, some of which are also in general use in other electronic fields. A complete glossary of terms in use in the ECM and ECCM fields is found in the literature.[8,11,13]

24.3 ELECTRONIC WARFARE SUPPORT MEASURES

ESM usually consists of several detection and measurement receivers and real time processor boards dedicated to the interception of radar emissions. The identification of specific emitters is based on comparison with tactical or strategic ELINT.[9,14–17] Emitter location can be additionally provided through several methods such as triangulation

† Since the publication of the second edition of this Handbook, the U.S. Air Force changed some of the EW terms we have gotten used to over these many years. ECM is now Electronic Attack (EA), ECCM is Electronic Protection (EP), and ESM is Electronic Support (ES). These terms are not used in this chapter because they are seldom used by the radar community who seem to prefer retaining the more familiar expressions ECM, ECCM, and ESM.

from remote systems or single platform sequential bearing measurements, difference time of arrival (DToA) or hyperbolation, and Phase Difference Rate (PDR). Modern digital receiver technology, coupled with state-of-the-art deinterleaving signal processing to cleanly isolate and identify individual EM emitters, will enhance situation awareness. Using techniques such as time and frequency difference of arrival will improve single and multiple platform spatial location; this will allow EW to be used to cue targeting systems.

Radar interception, which is of particular interest in this section, is based on the reception and measurements of the signals transmitted by radar systems whether pulse or Continuous Wave (CW). The operational scenario in which ESM should operate is generally crowded with pulsed radar signals: figures of 500,000 to 1 million pulses per second are frequently quoted in the literature.[9] The center frequency, amplitude, pulse width, time of arrival (ToA), and bearing of each detected pulse are measured, converted in digital format, and packed into a pulse descriptor word (PDW). The train of PDWs are sent to a pulse-sort processor that deinterleaves the sequences belonging to different emitters and identifies Pulse Repetition Interval (PRI) values and modulation laws (random jitter, stagger, switching). Further comparison against an emitter database, which contains the range of characteristic parameters (frequency, pulse width, PRI), the related pattern of agility (random, stagger, etc.) for each emitter, the type of antenna scanning pattern and periods permits the generation of an emitter list with an identification score. The ESM receiver is used to control the deployment and operation of ECM; the link between ESM and ECM is often automatic.

A single received radar pulse is characterized by a number of measurable parameters. The availability, resolution, and accuracy of these measurements must all be taken into account when designing the deinterleaving system because the approach used depends on the parameter data set available. Obviously, the better the resolution and accuracy of any parameter measurement, the more efficiently the pulse-sort processor can carry out its task. However, there are limitations on the measurement process from outside the ESM system (e.g., multipath), from inside the system (e.g., timing constraints, dead time during reception), and from cost-effectiveness considerations. Angle of arrival is the most important sorting parameter available to the deinterleaving process since the target bearing does not vary from pulse to pulse. Therefore, amplitude comparison monopulse antennas or multiple base interferometric (phase comparison) systems are often used in order to warrant both 360° spatial coverage and pulse-based angle of arrival measurement. Monopulse rotating antennas can also be used when the time to intercept is not critical (this is the ELINT case), and it is possible to scan sequentially the operational scenario.

The carrier frequency is the next most important pulse parameter for deinterleaving. A common method of frequency measurement is to use a scanning superheterodyne receiver that has the advantage of high sensitivity, good frequency resolution, and immunity with respect to the interference of nearby emitters.[9] Unfortunately, this type of receiver has a poor probability of intercept for the same reasons as the rotating bearing measurement system. The situation is much worse if the emitter is also frequency-agile (random variation) or frequency-hopping (systematic variation). A common method to allow for wideband frequency measurements is based on interferometric devices that provide instantaneous frequency measurement with good accuracy and are able to reject signal interference with lower intensity. The higher sensitivity and probability of interception are provided by wide instantaneous band superheterodyne receivers followed by banks of contiguous receiver channels.

Several technologies have been proposed in the past such as surface acoustic wave (SAW) filters and Bragg cells.[9] The preferred approach is based on digital receivers that integrate wideband spectral analysis and several post-detection functions, such as intrapulse modulation measurement and waveform code reconnaissance.

Pulse width is an unreliable sorting parameter because of the high degree of corruption resulting from multipath transmission. Multipath effects can severely distort the pulse envelope, for example, by creating a long tail to the pulse and even displacing the position of the peak.

The ToA of the pulse can be taken as the instant that a threshold is crossed, but in the presence of noise and distortion, this becomes a variable measurement. Nevertheless, the ToA is used for deriving the PRI of the radar. The amplitude of the pulse is taken as the peak value. Dynamic-range considerations must take into account at least some three orders of magnitude for range variation and three orders of magnitude for scan pattern variations. In practice, 60 dB instantaneous dynamic range sounds like a minimum value; in many applications, it should be larger. The amplitude measurement is used (along with ToA) for deriving the scan pattern of the emitter.[9]

The classification of radar interception systems is based on the type of representation they provide of the electronic environment. A radar warning receiver (RWR) in an airborne installation provides alerts of the presence of threats such as radar on a missile, supplying the relative bearing on a cockpit-based display. Search radars are not the primary target for these systems, though range advantage due to one-way propagation with respect to two-way propagation allows radar interception at farther range than own platform detection. Required sensitivity values range from –38 dBm (dB milliWatt with respect to the isotropic) to –60 dBm. ESM is the most complex system and usually comprises the capability to produce a picture of the complete electronic order of battle in its deployment area and alert function. This kind of system is able to detect and analyze emitter waveforms and scanning patterns. The reaction time for the reconnaissance of the operational environment may be less than 10 s, though dangerous emitters and alert functions call for tighter constraints. Required sensitivity ranges from –55 dBm to better than –80 dBm. ELINT systems are similar to ESM, but may not require 100% probability of intercept. The reaction time may be minutes or hours. The purpose is not to detect emitters as soon as they switch on in the operational environment, but to provide detailed characteristics of emitters to allow the generation of an identification database for RWR and ESM systems. ELINT system sensitivity may reach –90 dBm, but they don't need to provide 360° surveillance, and they can reach such performance by means of several directive antennas.

The range at which a radar emission is detected by an RWR depends primarily on the sensitivity of the receiver and the radiated power of the victim radar. The calculation of the warning range can be obtained by the basic *one-way beacon equation*, which provides the signal-to-noise ratio (SNR) at the RWR:

$$\left(\frac{S}{N}\right)_{\text{at RWR}} = \left(\frac{P}{4\pi R^2}\right) G_t \left(\frac{G_r \lambda^2}{4\pi}\right)\left(\frac{1}{kT_S B}\right)\frac{1}{L} \tag{24.1}$$

where P is the radar radiated power; R is the range from the RWR to the radar; G_t is the transmitting-antenna gain of the radar; G_r is the receiving-antenna gain of the RWR; λ is the radar wavelength; the quantity kT_sB is the total system noise power of the RWR; and L is the losses.

Equation 24.1 is the basis of performance calculation for an RWR. It is noted that the RWR detection performance is inversely proportional to R^2 rather than to R^4 of the radar target detection equation. For this reason, the RWR can detect a radiating radar at distances far beyond those of a radar's own target detection capability. The radar-versus-interceptor problem is a battle in which the radar's advantage lies in the use of matched filtering, which cannot be duplicated by the interceptor (it does not know the exact radar waveform), while the interceptor's advantage lies in the fundamental R^2 advantage of one-way versus two-way radar propagation.[15–18] Low probability of intercept (LPI) techniques are applied to radar to win the battle of "to see and not to be seen": see Schleher[19] and references therein.

24.4 ELECTRONIC COUNTERMEASURES

The objectives of an ECM system are to deny information (detection, position, track initiation, track update, and classification of one or more targets) that the radar seeks or to surround desired radar echoes with so many false targets that the true information cannot be extracted.[3–7]

ECM tactics and techniques may be classified in a number of ways, i.e., by main purpose, whether active or passive, by deployment, by platform, by victim radar, or by a combination of these.[13–16,20] An encyclopedia of ECM tactics and techniques can be found in the literature.[3,13] Here description is limited to the most common types of ECM.

ECM includes both jamming and deception. *Jamming* is the intentional and deliberate transmission or retransmission of amplitude, frequency, phase, or otherwise modulated intermittent, CW, or noise-like signals for the purpose of interfering with, disturbing, exploiting, deceiving, masking, or otherwise degrading the reception of other signals that are used by radar systems.[3–13] A jammer is any ECM device that transmits a signal of any duty cycle for the sole or partial purpose of jamming a radar system.[3–13]

Radio signals by special transmitters intended for interfering with or precluding the normal operation of a victim radar system are called *active jamming*. They produce at the input of a victim system a background that impedes the detection and recognition of useful signals and determination of their parameters. The most common forms of active noise jamming are spot, swept, and barrage noises. Spot noise is used when the center frequency and bandwidth of the victim system to be jammed are known and confined to a narrow band. However, many radars are frequency-agile over a wideband as an ECCM against spot jamming. If the rate of frequency agility is slow enough, the jammer can follow the frequency changes and maintain the effect of spot jamming. Barrage or broadband jamming is simultaneously radiated across the entire band of the radar spectrum of interest. This method is used against frequency-agile systems whose rates are too fast to follow or when the victim's frequency parameters are imprecisely known.

Jammer *size* is characterized by the *effective radiated power*; ERP = G_jP_j, where G_j is the transmit antenna gain of the jammer and P_j is the jammer power.

Passive ECM is synonymous with chaff, decoys, and other reflectors that require no prime power. The chaff is made of elemental passive reflectors that can be floated or otherwise suspended in the atmosphere or exoatmosphere for the purpose of confusing, screening, or otherwise adversely affecting the victim electronic system. Examples are metal foils, metal-coated dielectrics (aluminum, silver, or zinc over fiberglass or nylon being the most common), string balls, rope, and semiconductors.[3,13] Chaff consists of dipoles cut to approximately a half wavelength of the radar frequency. It is suitably packaged to contain a broad range of dipole lengths designed to be effective over a wide frequency band. The basic properties of chaff are effective scatter area, the character and time of development of a chaff cloud, the spectra of the signals reflected by the cloud, and the width of the band that conceals the target.[3,9,21,22] From a radar viewpoint, the properties of chaff are very similar to those of weather clutter, except that its broadband in frequency can extend down to VHF. The mean doppler frequency of the chaff spectrum is determined by the mean wind velocity, while the spectrum spread is determined by wind turbulence and a shearing effect due to different wind velocities as a function of altitude.[3]

Decoys, which are another type of passive ECM, are a class of physically small radar targets whose radar cross sections (RCS) are generally enhanced by using reflectors or a Luneburg lens to simulate fighter or bomber aircraft. The objective of decoys is to cause a dilution of the assets of the defensive system, thereby increasing the survivability of the penetrating aircraft. However, when the decoys grow too large, they have to be engaged if they are thought large enough to carry a weapon.

Penetration Aid (Penaids) could be used by incoming ballistic missiles (BMs).[23] Penaid decoys are only one of several possible penaids. A decoy provides another target that the defense has to handle if the defense cannot distinguish a decoy from a re-entry vehicle.

The other major type of active jammer is deceptive ECM (DECM). *Deception* is the intentional and deliberate transmission or retransmission of amplitude, frequency, phase, or otherwise modulated intermittent or CW signals for the purpose of misleading in the interpretation or use of information by electronic systems.[3,13] The categories of deception are manipulative and imitative. *Manipulative* implies the alteration of friendly EM signals to accomplish deception, whereas *imitative* consists of introducing radiation into radar channels that imitates a hostile emission. DECM is also divided into *transponders* and *repeaters*.[3] Transponders generate noncoherent signals that emulate the temporal characteristics of the actual radar return. Repeaters generate coherent returns that attempt to emulate the amplitude, frequency, and temporal characteristics of the actual radar return. Repeaters usually require some form of memory for microwave signals to allow anticipatory returns to be generated; this is usually implemented by using a microwave acoustic memory or a digital RF memory (DRFM).[3]

In a DRFM system, the input RF signal is generally first down-shifted in frequency and then sampled with a high-speed analogue-to-digital converter (ADC). The samples, stored in memory, can be manipulated in amplitude, frequency, and phase to generate a wide range of jamming signals. The stored samples are later recalled, processed by the digital-to-analogue converter (DAC), up converted, and transmitted back to the victim radar.[24] The information content of an intercepted radar signal is mainly carried in the phase of the signal, and then the amplitude is usually discarded and only the phase contribution is quantized and processed.[25] The phase quantization is performed by the DRFM by means of M bits into $N = 2^M$ levels. After the phase quantization, introduced on the signal by the DRFM, the jamming signal is transmitted back to the victim radar with an increasing delay with respect to the received radar signal. This delay is quantized by a range gate pull off (RGPO) device. A range gate stealer system linearly delays the quantized signal in order to generate a constant range-rate false target. The joint effect of phase and delay quantization in DRFM can be analyzed as reported in Greco, Gini, and Farina.[26] Other artifacts in the deception signals can be introduced by imperfections in the down-up conversion and demodulation/modulation of the signal performed in the DRFM device. A detailed analysis of this kind of errors is in Berger.[27]

The DRFM is the principal means to implement a deception jammer; the range-gate stealer pulls the radar-tracking gate from the target position through the introduction of a false target into the radar's range-tracking circuits. A repeater jammer sends back an amplified version of the signal received from the radar. The deception signal, being stronger than the radar's return signal, captures the range-tracking circuits. The deception signal is then progressively delayed by using the DRFM, thereby "walking" the range gate off the actual target (RGPO technique). When the range gate is sufficiently removed from the actual target, the deception jammer is turned off, forcing the tracking radar into a target reacquisition mode.[3] Another form of deception is the velocity gate pull off (VGPO); a combination of RGPO and VGPO is also possible.

Another DECM technique is called *inverse-gain jamming*; it is used to capture the angle-tracking circuits of a conical-scan tracking radar.[3,13] This technique repeats a replica of the received signal with an induced amplitude modulation that is the inverse of the victim radar's combined transmitting and receiving antenna scan patterns. Against a conically scanning tracking radar, an inverse-gain repeater jammer has the effect of causing positive feedback, which pushes the tracking-radar antenna away from the target rather than toward the target. Inverse-gain jamming and RGPO are combined in many cases to counter conical-scan tracking radars.[3] The vulnerability of conical scan to such countermeasures motivates the use of monopulse trackers that are almost always used in military tracking radars.

A different form of DECM used against the main beam of surveillance radar attempts to cover the target's skin return with a wide pulse in order to confuse the radar's signal-processing circuitry into suppressing the actual target return.

What the radar can do against DECM is discussed later; see Section 24.11.

In the deployment of ECM, several classes can be singled out.[3] In the *stand-off jammer* (SOJ) case, the jamming platform remains close to but outside the lethal range of enemy weapon systems and jams these systems to protect the attacking vehicles. Stand-off ECM systems employ high-power noise jamming that must penetrate through the radar antenna receiving sidelobes at long ranges. *Escort jamming* is another ECM tactic in which the jamming platform accompanies the strike vehicles and jams radars to protect the strike vehicles.

Mutual-support, or *cooperative*, ECM involves the coordinated conduct of ECM by combat elements against acquisition and weapon control radars. One advantage of mutual-support jamming is the greater ERP available from a collection of platforms in contrast with a single platform. However, the real value of mutual-support jamming is in the coordinated tactics that can be employed. A favorite tactic employed against tracking radars, for example, is to switch between jammers located on separate aircraft within the radar's beamwidth. This blinking has the effect of introducing artificial glint into the radar tracking circuits, which, if introduced at the proper rate (typically 0.1 to 10 Hz), can cause the radar to break angle track. In addition, blinking has the desirable effect of confusing radiation homing missiles that might be directed against the jammer radiations.[3]

Stand-forward jamming is an ECM tactic in which the jamming platform is located between the weapon systems and the strike vehicles and jams the radars to protect the strike vehicles. The stand-forward jammer is usually within the lethal range of defensive weapon systems for a considerable time. Therefore, only the use of relatively low-cost remotely piloted vehicles might be practical; they can assist strike aircraft or missiles in penetrating radar-defended areas by jamming, ejecting chaff, dropping expendable jammers or decoys, acting as decoys themselves, and performing other related ECM tasks.

A *self-screening jammer* (SSJ) is used to protect the carrying vehicle. This situation stresses the capability of an ECM system relating to its power, signal-processing, and ESM capabilities.

Self-protection (SP) decoy jamming is an off-board technique intended to create angle deception by causing a missile seeker to transfer angle track from the target to a decoy. Consequently, the missile guides toward the decoy and away from the target. A self-protection decoy is most likely to be used by large fighter/attack and bomber aircraft. The SP decoys are expendable or towed. Expendable decoys are ejected (or dropped) from the aircraft whereas towed decoys are tethered behind the aircraft. Expendable decoys contain miniature jamming systems that are small enough to fit into a standard chaff/flare dispenser. The decoy orients itself to the air stream by deploying low-drag aerodynamic fins sufficient to maintain stable flight. The decoy diverges from the velocity vector of the launch aircraft by natural deceleration as a result of air stream and falling due to gravity. The decoy typically starts radiating jamming signals toward the missile seeker immediately after ejection from the aircraft and continues radiation throughout its flight. Decoy ejection is typically commenced when the RWR detects incoming radar-guided missiles. Multiple decoys are sometimes dispensed at predetermined rates in order to improve the cumulative probability of aircraft survival.

A *towed decoy* is a small aerodynamically stable body that houses a miniature jammer. The decoy is deployed by reeling it out on a cable behind the aircraft to a fixed distance or offset. This offset is chosen such that even if a missile hits the decoy, the aircraft will not be damaged. The decoy can either be powered by the aircraft via the cable or be self powered. Besides providing power to the decoy, the cable can also be used as a data link to control jammer operation. Once deployed, the towed decoy can begin radiating jamming signals toward the missile seeker. When the towed decoy is no longer needed, it is either reeled in or jettisoned. The major drawback with towed decoys is that they might severely degrade aircraft maneuverability.

According to the platform, the jammer can be classified as airborne, missile-borne, naval-based, or ground-based.

A special class of missile-borne threat is the anti-radiation missile (ARM), having the objective of homing on and destroying the victim radar. The sorting and acquisition of radar signals is preliminarily made by an ESM system; afterward it cues the ARM, which continues homing on the victim radar by means of its own antenna, receiver, and signal processor. Acquisition depends on the direction of arrival (DoA), operating band, carrier frequency, pulse width, PRI, scan rate, and other parameters of the victim radar. An ARM homes on the continuous radiation from the radar sidelobes or on the flash of energy from the main beam. ARM benefits from the one-way-only radar signal attenuation. However, ARM receiver sensitivity is affected by mismatching losses; accuracy in locating the victim radar is affected by the limited dimension of the ARM antenna.

24.5 OBJECTIVES AND TAXONOMY OF ECCM TECHNIQUES

The primary objective of ECCM techniques when applied to a radar system is to allow the accomplishment of the radar intended mission while countering the effects of the enemy's ECM. In greater detail, the benefits of using ECCM techniques may be summarized as follows: (1) prevention of radar saturation, (2) enhancement of the signal-to-jamming ratio, (3) discrimination of directional interference, (4) rejection of false targets, (5) maintenance of target tracks, (6) counteraction of ESM, and (7) radar system survivability.[3]

There are two broad classes of ECCM: electronic techniques (Section 24.6–24.9) and operational doctrines (Section 24.10). Specific electronic techniques take place in the main radar subsystems, namely, the antenna, transmitter, receiver, and signal processor. Table 24.1 shows a categorization of some ECCM techniques along with the ECM techniques that are used to counter.[5,28] Suitable blending of these ECCM techniques can be implemented in the various types of radars, as discussed in Section 24.11.

The ensuing description is limited to the major ECCM techniques; the reader should be aware that an alphabetically listed collection of 150 ECCM techniques and an encyclopedia of ECCM tactics and techniques can be found in the literature.[8,29] Many other references describe the ECCM problem, among which Slocumb and West,[5] Maksimov et al.,[21] Gros et al.,[30] and Johnson and Stoner[31] are worth noting.

TABLE 24.1 ECCM Techniques Versus ECM Technique Countered (*Reproduced with permission from Slocumb and West*[5] *© Artech House 2000 and G. V. Morris*[28])

		ECM Technique Category Countered				
Radar Subsystem	ECCM Technique	Noise	False Target	Range Gate Pull Off	Velocity Gate Pull Off	Angle
Antenna related	Low or ultra-low sidelobes	×	×			
	Monopulse angle tracking					×
	Low cross-polarized response					×
	SLB (sidelobe blanking)	×	×			
	SLC (sidelobe canceler)	×				
	Electronic scan		×	×		×
	Adaptive receive polarization					×
	Cross polarization cancellation					×
Transmitter related	Low cross-polarized antenna					×
	High power	×				
	Pulse compression	×				
	Frequency diversity	×				
	Frequency agility	×	×			
	PRF jitter		×	×		
Receiver related	RGPO memory nulling			×		
	Bandwidth expansion		×		×	
	Beat frequency detector	×		×		
	Cover pulse channel processing		×			
	Home-on-jam	×				
	Leading/trailing edge track			×		
	Narrowband doppler noise detector	×	×			
	Velocity guard gates		×		×	
Signal processing related	VGPO reset		×		×	
	Signal realism		×	×	×	
	Acceleration limiting		×	×	×	
	Censored or ordered statistic CFAR	×	×			
	Doppler/range rate comparison			×	×	
	Time average CFAR	×				
	Total energy test	×				

24.6 ANTENNA-RELATED ECCM

Because the antenna represents the transducer between the radar and the environment, it is the first line of defense against jamming. The directivity of the antenna in the transmission and reception phases allows space discrimination to be used as an ECCM strategy. Techniques for space discrimination include antenna coverage and scan control, reduction of main-beam width, low sidelobes, sidelobe blanking, sidelobe cancelers, and adaptive array systems. Some of these techniques are useful during transmission, whereas others operate in the reception phase. Additionally, some are active against main-beam jammers, and others provide benefits against sidelobe jammers.

Blanking or turning off the receiver while the radar is scanning across the azimuth sector containing the jammer or reducing the scan sector covered are means to prevent the radar from looking at the jammer. Certain deception jammers depend on anticipation of the beam scan or on knowledge or measurement of the antenna scan rate. Random electronic scanning effectively prevents these deception jammers from synchronizing to the antenna scan rate, thus defeating this type of jammer. A high-gain antenna can be employed to spotlight a target and burn through the jammers. An antenna having multiple beams can also be used to allow deletion of the beam containing the jammer and still maintain detection capabilities with the remaining beams. Although they add complexity, cost, and possibly weight to the antenna, reduction of main-beam width and control of coverage and scan are valuable and worthwhile ECCM features of all radars.

If an air defense radar operates in a severe ECM environment, the detection range can be degraded because of jamming entering the sidelobes. On transmit, the energy radiated into spatial regions outside of the main beam is subject to being received by enemy RWRs or ARMs. For these reasons, low sidelobes are desirable on both receive and transmit (see Schrank,[32] Patton,[33] and Chapter 2 in Farina[34]). Sometimes the increase in main-beam width that results from low sidelobes worsens the problem of main-beam jamming; this consequence should be carefully considered in specifying the antenna radiation pattern.

Usually, specification of the sidelobes as a single number (e.g., −30 dB) means that the peak of the highest sidelobe is 30 dB below the peak of the main beam. The average, or root-mean-square (rms), sidelobe level is often more important. For example, if 10% of the radiated power is in the sidelobes, the average sidelobe level is −10 dB, where dB refers to the number of decibels by which the average sidelobe level is below the gain of an isotropic (ideal) radiator. In theory, extremely low sidelobes can be achieved with aperture illumination functions that are appropriately tapered. This leads to the well-known tradeoffs among gain, beamwidth, and sidelobe level.[35] In order to keep the beamwidth small with low sidelobes, a larger and costly (the cost could not be that large unless the radar uses an active aperture) antenna is needed. The chief problem with the low sidelobe antenna in its early days was that it had more mechanical problems because it was a waveguide array and not a reflector. Other design principles involved in low antenna sidelobes are the use of radar-absorbent material about the antenna structure, the use of a fence on ground installations, and the use of polarization screens and reflectors. This means that very low sidelobe antennas are costly in terms of size and complexity when compared with conventional antennas of similar gain and beamwidth characteristics. Second, as the design sidelobes are pushed lower and lower, a point is reached where minor error contributions to scattered energy (random errors) or misdirected radiation (systematic errors) become significant. In practice, peak sidelobe levels as low as −30 to −35 dB (average level, −5 to −20 dB) can be readily realized with phased-array antennas that electronically scan. To obtain sidelobes at levels −45 dB down from the main beam (average level, below −20 dB), the total phase-error budget is required to be in the order of 5° rms or less. This is difficult in arrays that electronically scan: the errors induced by phase shifters, active components, and feed elements must be included in this budget. Arrays have been realized in practice that have peak sidelobes in the vicinity of the −45 dB level; however, these are generally mechanically scanned, and the low error budgets are achieved by using all-passive feed components. Phased-array developments, which do scan electronically, also foresee fairly good sidelobe performance; see the following references[36–40] for a view of relevant developments.

Two additional techniques to prevent jamming from entering through the radar's sidelobes are the so-called sidelobe blanking (SLB) and sidelobe canceler (SLC). An example of the practical effectiveness of the SLB and SLC devices is presented in the literature, where the plan position indicator (PPI) display is shown for a radar, subject to an ECM, equipped with and without the SLB and SLC systems.[31]

Other discrimination means are based on polarization. The polarization characteristics of a radar can be exploited as ECCM techniques in two ways. First, the cross-polarized pattern (i.e., the orthogonal polarization to the main plane of polarization) of a radar antenna should be kept as low as possible consistent with radar system cost. Ratios of copolarized main-beam peak gain to cross-polarized gain anywhere in the antenna pattern should be greater than 25 dB to provide protection against common cross-polarized jamming. This is thought of as an ECCM technique, but it is really no more than good antenna design. The cross-polarized jamming in this case attacks a design deficiency in the radar. The requirement for good cross-polarization design practice in a radar antenna system extends to any auxiliary ECCM antennas as well. If their cross-polarized gains are high, ECCM techniques such as SLC and SLB may not be effective against cross-polarized noise or repeater jammers.[29]

In the second use of polarization, the radar antenna system purposely receives the cross-polarization component of the radar wave in addition to the copolarized component. The two orthogonally polarized components can be used to discriminate the useful target from chaff and jammer on the basis of their different polarizations.[41] However, limited benefits (a few decibels of cancellation ratio) can be obtained at the expense of a more complex antenna system (consider, for example, a phased-array with radiating elements able to separately receive and possibly transmit the two orthogonal components of a radar wave) and of a duplication of the receiver and signal processing.

Sidelobe Blanking (SLB) System. The purpose of an SLB system is to prevent the detection of strong targets and interference pulses (as they might appear after pulse compression) entering the radar receiver via the antenna sidelobes. Thus, SLB is mainly used to eliminate interference from other pulse transmissions and deliberate pulse-like jamming. Also, SLB is effective against coherent repeater interference (CRI); here "coherent" means that the interference tries to mimic the coded waveform radiated by the radar appearing as a spike signal after pulse compression.[42–45,34] A method of achieving this is to employ an auxiliary antenna coupled to a parallel receiving channel so that two signals from a single source are available for comparison.

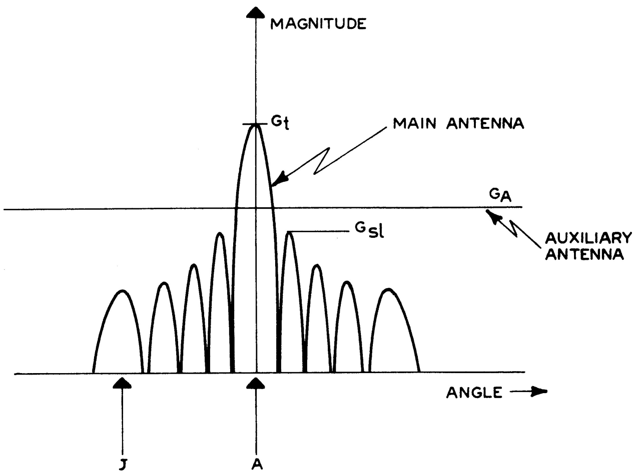

FIGURE 24.1*a* Main and auxiliary antenna patterns for the SLB (*after L. Maisel*[42] *© IEEE 1968*)

By suitable choice of the antenna gains, one may distinguish signals entering the sidelobes from those entering the main beam, and the former may be suppressed. Figure 24.1*a* illustrates the radiation pattern of the main antenna together with a low-gain auxiliary antenna. An implementation of the SLB processor is shown in Figure 24.1*b*, where the square-law-detected outputs of the two channels, ideally identical except for the antenna patterns, are compared. The comparison is made at each range bin for each pulse received and processed by the two parallel channels. Thus, the SLB decides whether or not to blank the main channel on a single-sweep basis and for each range bin. A target A in the main beam will result in a large signal in the main receiving channel and a small signal in the auxiliary receiving channel. A proper blanking logic allows this signal to pass. Targets and/or jammers J situated in the sidelobes give small main but large auxiliary signals so that these targets are suppressed by the blanking logic. It is assumed that the gain G_A of the auxiliary antenna is higher than the maximum gain G_{sl} of the sidelobes of the radar antenna.

The performance of the SLB may be analyzed by looking at the different outcomes obtained as a consequence of the pair (u, v) of the processed signals (see Figure 24.1*b*).

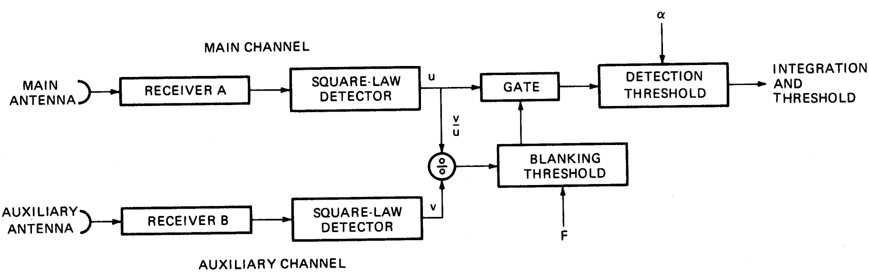

FIGURE 24.1*b* Scheme of sidelobe-blanking system (*after L. Maisel*[42] *© IEEE 1968*)

Three hypotheses have to be tested: (1) the null hypothesis H_0 corresponding to the presence of noise in the two channels, (2) the H_1 hypothesis pertaining to the target in the main beam, and (3) the H_2 hypothesis corresponding to target or interference signal in the sidelobe region. The null and H_1 hypotheses correspond to the usual decisions of "no detection" and "target detection," respectively. The blanking command is delivered when H_2 is detected.

SLB performance can be expressed in terms of the following probabilities: (i) The probability P_B of blanking a jammer in the radar sidelobes, which is the probability of associating the received signals (u, v) with H_2 when the same hypothesis is true; P_B is a function of the jammer-to-noise ratio (JNR) value, the blanking threshold F, and the gain margin $\beta = G_A/G_{\mathrm{sl}}$ of the auxiliary antenna with respect to the radar antenna sidelobes. (ii) The probability P_{FA} of false alarm, which is the probability of associating the received signals (u, v) with the hypothesis H_1 when the true hypothesis is H_0; P_{FA} is a function of the detection threshold α normalized to the noise power level and of the blanking threshold F. (iii) The probability P_D of detecting a target in the main beam, which is the probability of associating the received signal (u, v) with H_1 when the same hypothesis is true; P_D depends, among other things, on the signal-to-noise power ratio SNR, P_{FA}, and the blanking threshold F. (iv) The probability P_{FT} of detecting a false target produced by a jammer entering through the radar sidelobes. P_{FT} is the probability of associating (u, v) with H_1 when H_2 is true; it is a function of JNR, the thresholds α and F, and the gain margin β. (v) The probability P_{TB} of blanking a target received in the main beam. This is the probability of associating (u, v) with H_2 when H_1 is the true hypothesis. P_{TB} is related to SNR, F, and the auxiliary gain $w = G_A/G_t$ normalized to the gain G_t of the main beam. To complete the list of parameters needed to describe the SLB performance, the last figure to consider is the detection loss L on the main-beam target. This can be found by comparing the SNR values required to achieve a specified P_D value for the radar system with and without the SLB. L is a function of many parameters such as P_D, P_{FA}, F, G_A, JNR, and β. A numerical evaluation of these performance parameters can be found in the literature (specifically Chapter 3 of Farina,[34] among others[42–50]).

The SLB design requires the selection of suitable values for the following parameters (Chapter 3 of Farina,[34]): (i) the gain margin β and then the gain G_A of the auxiliary antenna, (ii) the blanking threshold F, and the normalized detection threshold α. The a priori known parameters are hypothesized to be the radar sidelobe level G_{sl} and the values of SNR and JNR. The design parameters can be selected by trying to maximize the detection probability P_D while keeping at prescribed values the probabilities P_B and P_{FA} and trying to minimize P_{FT}, P_{TB}, and L. The choice of the position of the auxiliary antenna has an impact on SLB performance in presence, for instance, of multipath; to avoid its effect, the phase centers of main and auxiliary antennas should be positioned at the same height with respect to the terrain surface.

In modern radar, the blanking of sidelobe impulsive interference may be achieved by the comparison of signals, pertaining to the same cells of the range-filter map (RFM) of main beam and SLB channels. The RFM is a two-dimensional map collecting the radar echoes of all range cells (after pulse compression) and all doppler filters of a radar burst. The two RFMs are independently generated for the main and auxiliary signals and the testing of the main and auxiliary received power values is performed for all range cells and all doppler filters. This is different from a conventional SLB approach (such as the one illustrated in Figure 24.1) operating so that if interfering/repeater jammer power is detected at a particular range cell, then that range cell has to be effectively blanked. The RFM-based SLB logic greatly reduces the risk of successfully emulating a useful target because a repeater has to appear in the same target range cell and has to emulate the same target doppler.

Sidelobe Canceler (SLC) System. The objective of the SLC is to suppress high duty cycle or even continuous noise-like interferences (NLI) (e.g., SOJ) received through the sidelobes of the radar. This is accomplished by equipping the radar with an array of auxiliary antennas used to adaptively estimate the DoA and the power of the jammers and, subsequently, to modify the receiving pattern of the radar antenna to place nulls in the jammers' directions. The SLC was invented by P. Howells and S. Applebaum.[51–52] A sample of subsequent references on SLC are also in the literature.[34,53–55]

The conceptual scheme of an SLC system is shown in Figure 24.2. The auxiliary antennas provide replicas of the jamming signals in the radar antenna sidelobes. To this end, the auxiliary patterns approximate the average sidelobe level of the radar receiving pattern. In addition, the auxiliaries are placed sufficiently close to the phase center of the radar antenna to ensure that the samples of the interference that they obtain are statistically correlated with the radar jamming signal. It is also noted that as many auxiliary antennas are needed as there are jamming signals to be suppressed. In fact, at least *N* auxiliary patterns properly controlled in amplitude

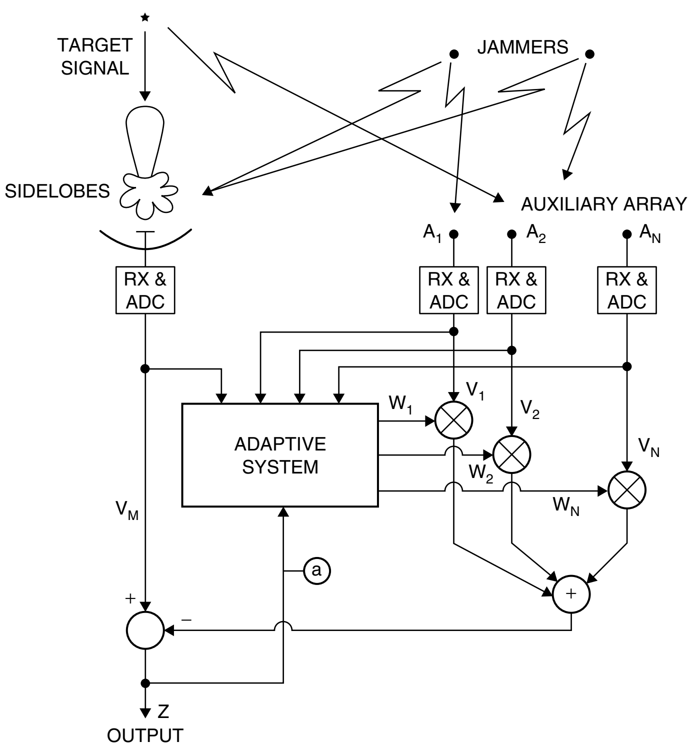

FIGURE 24.2 Principle of SLC operation (connection *a* only in the closed-loop implementation techniques); RX: receiver

and phase are needed to force to zero the main antenna receiving pattern in N given directions. The auxiliaries may be individual antennas or groups of receiving elements of a phased-array antenna.

The amplitude and phase of the signals delivered by the N auxiliaries are controlled by a set of suitable weights: denote the set with the N-dimensional vector $\mathbf{W} = (W_1, W_2, \ldots, W_N)$. The jamming signal is canceled by a linear combination of the signals from the auxiliaries and the main antenna. The problem is to find a suitable means of controlling the weights $\mathbf{W}$ of the linear combination so that the maximum possible cancellation is achieved. Owing to the stochastic nature of the jamming signals in the radar and in the auxiliary channels and to the hypothesized linear combination of signals, it is advisable to resort to the techniques of linear prediction theory for stochastic processes. Denote with V_M, the radar signal at a certain range bin and with $\mathbf{V} = (V_1, V_2, \ldots, V_N)$ the N-dimensional vector containing the set of signals, at the same range bin, from the N auxiliary antennas. It is assumed that all the signals have bandpass frequency spectra; therefore, the signals can be represented by their complex envelopes, which modulate a common carrier frequency that does not appear explicitly. The jamming signals in the channels may be regarded as samples of a stochastic process having zero mean value and a certain time autocorrelation function. For linear prediction problems, the set of samples $\mathbf{V}$ is completely described by its N-dimensional covariance matrix $\mathbf{M} = \mathrm{E}(\mathbf{V}^*\mathbf{V}^T)$, where $E(\cdot)$ denotes the statistical expectation, the asterisk $(\cdot)^*$ indicates the complex conjugate, and $\mathbf{V}^T$ is the transpose vector of $\mathbf{V}$. The statistical relationship between V_M and $\mathbf{V}$ is mathematically represented by the N-dimensional covariance vector $\mathbf{R} = E(V_M\mathbf{V}^*)$. The optimum weight vector $\hat{\mathbf{W}}$ is determined by minimizing the mean square prediction error, which equals the output residual power:

$$P_Z = E\{|Z|^2\} = E\{|V_M - \hat{\mathbf{W}}^T\mathbf{V}|^2\} \tag{24.2}$$

where Z is the system output. It is found that the following fundamental equation applies:

$$\hat{\mathbf{W}} = \mu\mathbf{M}^{-1}\mathbf{R} \tag{24.3}$$

where μ is an arbitrary constant value. The benefit of using the SLC can be measured by introducing the jammer cancellation ratio (JCR), defined as the ratio of the output noise power without and with the SLC:

$$JCR = \frac{E\{|V_M|^2\}}{E\{|V_M - \hat{\mathbf{W}}^T\mathbf{V}|^2\}} = \frac{E\{|V_M|^2\}}{E\{|V_M|^2\} - \mathbf{R}^T\mathbf{M}^{-1}\mathbf{R}*} \tag{24.4}$$

By applying Eqs. 24.3 and 24.4 to the simple case of one auxiliary antenna and one jammer, the following results are found:

$$\hat{\mathbf{W}} = \frac{E\{V_M V_A*\}}{E\{|V_A|^2\}} \triangleq \rho \qquad JCR = \frac{1}{1 - |\rho|^2} \tag{24.5}$$

It is noted that the optimum weight is related to the correlation coefficient ρ between the main signal, V_M, and the auxiliary signal, V_A; high values of the correlation coefficient provide high values of JCR.

The problem of implementing the optimum-weight set (Eq. 24.3) is essentially related to the real-time estimation of $\mathbf{M}$ and $\mathbf{R}$ and to the inversion of $\mathbf{M}$. Several processing schemes have been conceived that may be classified in two main categories: (1) closed-loop techniques, in which the output residue (connection a in Figure 24.2) is fed back into the adaptive system; and (2) direct-solution methods, often referred to as *open-loop*, which operate just on the incoming signals V_M and $\mathbf{V}$. Broadly speaking, closed-loop methods are cheaper and simpler to implement than direct-solution methods; one of several practical implementations is described in Griffiths.[56] By virtue of their self-correcting nature, they do not require components that have a wide dynamic range or a high degree of linearity, and so they are well suited to analogue implementation. However, closed-loop methods suffer from the fundamental limitation that their speed of response must be restricted in order to achieve a stable and not noisy steady state. Direct-solution methods, on the other hand, do not suffer from problems of slow convergence but, in general, require components of such high accuracy and wide dynamic range that they can only be realized by digital means. Of course, closed-loop methods can also be implemented by using digital circuitry; in which case, the constraints on numerical accuracy are greatly relaxed, and the total number of arithmetic operations is much reduced by comparison with direct-solution methods. The majority of implementations has become open loop with digital technology.

Practical considerations (see Chapter 4 of Farina[34] for a detailed analysis) often limit the SLC nulling capabilities to a *JCR* of about 30 to 40 dB, but their theoretical performance is potentially much higher. Adequate cancellation of the directional interference is obtained if the receiving channels are properly matched in amplitude and phase across the radar receiving bandwidth. This condition is necessary to attribute the amplitude and phase differences measured across the channels only to the nature (power and DoA) of the impinging interference. There are several sources of mismatching; the imperfect matching of the analogue receiving channels is one of the main limitations to the interference cancellation. The effect of this mismatch on the *JCR* has been studied in the literature; see Farina[57] and references therein.

For contemporary presence of amplitude and phase mismatches, the JCR has an expression that is derived in Appendix 2.[57] A numerical application of this equation is shown in Figure 24.3; the parameter values of the study case are quoted in Farina.[57] Figure 24.3 shows the JCR contour curves versus the normalized amplitude a_n and the phase b (degrees) mismatches of the analogue receiving channels (see Farina[57] for the precise definition of these parameters).

It is seen that to have 40 dB of *JCR*, one needs to specify tight requirements for both amplitude (below 1%) and phase (below 0.7°) mismatches. This figure motivates the need to resort to equalization digital filters to compensate for the mismatches of the auxiliary channels (in their analogue part) with respect to the main channel. This subject is covered in Farina[57] and references therein. Examples of other possible limitations to cancellation are listed below[34,53,58,59]:

1. Mismatch between the main and auxiliary signals including the propagation paths, the patterns of the main and auxiliary antennas, the paths internal to the system up to the cancellation point, and the crosstalk between the channels[60–62]
2. The limited number of auxiliary channels adopted in a practical system as compared with the number of jamming signals
3. Aperture-frequency dispersion, often expressed in terms of aperture-bandwidth product[37,59,63]
4. The limited bandwidth of the majority of the schemes implementing Eq. 24.3, as compared with the wideband of a barrage jammer that can be regarded as a cluster, spread in angle, of narrowband jammers
5. Quadrature errors in synchronous (i.e., I, Q) detectors[64–66]

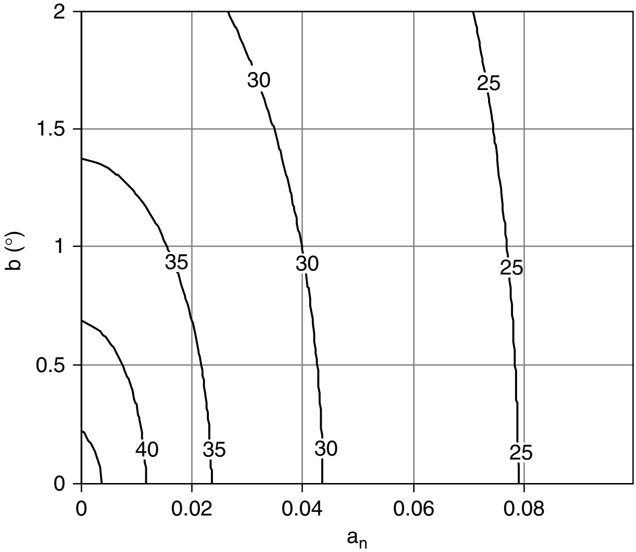

FIGURE 24.3 Contour curve of *JCR* (dB) versus the amplitude (in natural number, along the horizontal axis) and phase (in degrees, along the vertical axis) mismatches of the analogue receiving channels

6. Digital receiver channel errors such as ADC quantization, sample/hold jitter, and digital converter offset[67,68]
7. The pulse width that limits the reaction time of the adaptive system, in order to avoid the cancellation of target signal
8. The target signal in the auxiliary array that may result in nonnegligible steering of the auxiliaries toward the main-beam direction
9. Multipath delay, often expressed in terms of delay-bandwidth product[69–70]
10. The presence of clutter that, if not properly removed, may capture the adaptive system, giving rise to nulls along directions different from those of the jammers[37,71]
11. The tradeoff that has to be sought between the accuracy of weights estimation and the reaction time of the adaptive system
12. The limited number of time samples available to estimate the jammer covariance matrix; usually 3N sample should be available if N is the number of adaptive channels[101]
13. The antenna rotation rate that might produce a fast time varying power and jammer DoA[101]

Joint SLB and SLC. SLB is effective against spiky signal after pulse compression (like CRI), whereas SLC combats the continuous NLI. As previously stated, both techniques combat the interferences impinging on the main antenna sidelobes. The two techniques can be jointly used against the simultaneous presence of CRI and NLI. An approach is to cascade the SLC and SLB techniques as shown in Figure 24.4. The scheme depicts three receiving channels, each one having an antenna, a receiver, and an ADC; they provide three signals labeled, respectively, as *SLC, MAIN*, and *SLB*. The left-hand side antenna is a low-gain auxiliary performing the SLC processing in

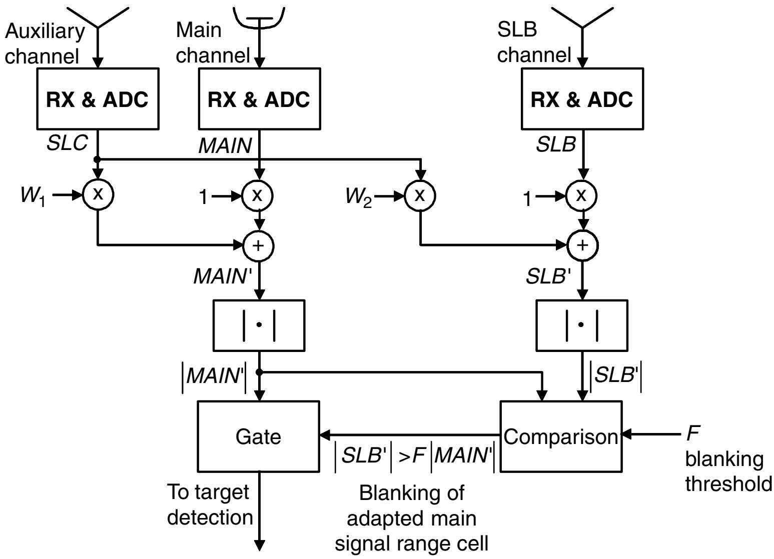

FIGURE 24.4 A processing scheme incorporating SLC and SLB devices

the main and sidelobe blanking channels. The center antenna is the high-gain radar antenna to detect targets notwithstanding impulsive and noise-like interferences. The right-hand side antenna is a low-gain auxiliary that is used for SLB processing in the main channel. The adaptive cancellation of NLI received by the main antenna is achieved by the linear combination of the *SLC* and *MAIN* signals with the adaptive weights W_1 and 1, respectively; the resulting adapted signal *MAIN*' doesn't contain the NLI. Similarly, the adaptive cancellation of NLI received by the rhs auxiliary antenna is reached by the linear combination of the *SLC* and *SLB* signals with the adaptive weights W_2 and 1, respectively; the adapted signal *SLB*' doesn't contain the NLI. Once the NLI is removed from the two channels, then the classic SLB logic can be applied against the CRI by comparing the amplitude $|MAIN'|$ of the main channel with that $|SLB'|$ of the blanking channel, which are both NLI free.[72]

Because the phase centers of the three antennas (the main and the two auxiliaries) are spaced, in general, more than 0.5 λ (where λ is the length of the radiated EM wave), the adapted patterns of the main and SLB channels fluctuate around average curves due to the presence of grating lobes.[72] Nevertheless, a reasonable gain margin is present between the pattern of the adapted SLB and the sidelobes of the adapted main antenna; thus, an adequate probability of blanking the CRI in the presence of adaptively nulled NLI should be expected. In order to improve the above gain margin and, consequently, the blanking probability of CRI, the following processing strategies are suggested[72,73]: spatial and frequency diversity.

Spatial Diversity. The rationale is to use two low-gain auxiliaries (instead of one, as shown in Figure 24.4) for the SLB; because their phase centers will be different, the grating lobes affecting the adapted patterns of the two SLB antennas will be different too. Taking the greater of the two adapted SLB signals, the gain margin between the SLB and the main antenna sidelobes will increase with a consequent improvement of the performance of the blanking logic.

Frequency Diversity. Another technique to improve the blanking performance is to resort to the diversity of the radar carrier frequency; in this case, we need just one low-gain antenna (as shown in Figure 24.4) for the SLB. The radar operates in frequency diversity mode, i.e., it radiates a burst of L pulses (T seconds apart) with slightly different carrier frequencies.[73] The grating lobes in the adapted main and the L SLB patterns will change as a function of the carrier frequency. Taking the max of the output of the L SLB signals is equivalent to a smoothing of the grating lobes. In a specific example presented in Farina and Timmoneri,[73] two carrier frequencies are used and the values of d/λ (where "d" is the inter-element distance) for the array of receiving elements are respectively 0.5 and 0.55. The blanking is separately applied on the received data at the two carrier frequencies; subsequently, the separate blanking bits are processed by a logic OR (the global blanking logic). The ensuing Figure 24.5 displays the blanking curves for the two separate carrier frequencies and for the logic OR. It is noted that the frequency diversity and the logic OR provide an improvement of the blanking probability; this is due to the different shapes of the antenna patterns at the two slightly different carrier frequencies. Figure 24.5 also presents the probability of blanking a useful target (P_{TB}) received by the main antenna beam. The probabilities are estimated via 200 independent Monte Carlo simulations. The target SNR is 20 dB; the JNR is 20 dB; the target DoA is assumed to be evenly distributed in the main-beam angular interval [–4°, 4°]; details on the numerical parameters used in the study case are in the reference.[73] It is noted that P_{TB} is negligible for $F = 0$ dB, while $P_B \geq 0.9$.

After a careful performance evaluation of the system depicted in Figure 24.4, it might be necessary to always resort to either spatial or frequency diversity to improve the SLB performance. The selection of one of the two diversity techniques depends on overall system considerations related to the impact of adding more auxiliaries and/or radiating, with the radar, proper carrier frequencies. Furthermore, if compact and high-speed processing are requested, spatial and frequency diversity techniques can be fruitfully implemented resorting to systolic schemes.

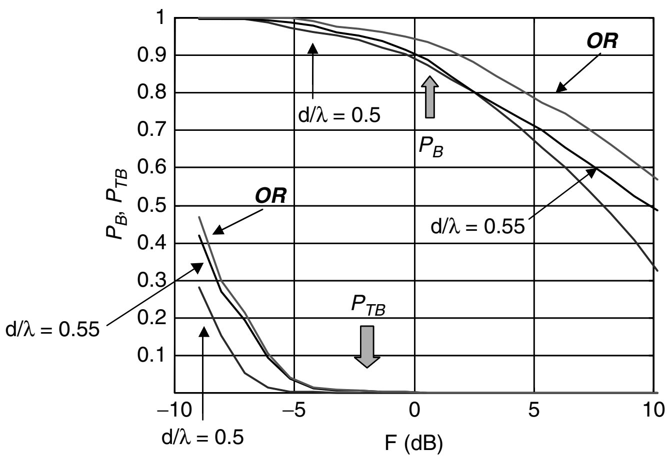

FIGURE 24.5 Blanking probability (P_B) and target blanking probability (P_{TB}) versus the blanking threshold F (in dB) for the frequency diversity scheme

Systolic Schemes for SLB and SLC. In the quest for efficient parallel processing, the systolic schemes come into the scene; their use has been described for the implementation of SLC and more general adaptive array problems in the literature[34,74,75] The rationale and the use of a systolic array that processes the signals received by SLC and main channel is reported on pages 146–156 of Farina[34] and in Farina and Timmoneri.[73] Figures 1 to 4[73] depict the use of a systolic processing scheme that incorporates the SLB and SLC. The advantage of these schemes resides in the decomposition of the complex processing for adaptive cancellation of the NLI into a network of simple processing elements that can be conveniently mapped onto a parallel processing architecture based either on Commercial off the Shelf (COTS) technology or custom Very Large Scale Integration (VLSI) devices. In the literature[76–80] it has been shown that a wide spectrum of technologies can be used like Field Programmable Gate Arrays (FPGA), Coordinate Rotation Digital Computer (CORDIC) implemented with VLSI and optical computers. Pioneering work on the use of CORDIC for adaptive nulling dates back to C. Rader at MIT-Lincoln Laboratory.[81,82] The advantage of systolic implementation is high processing speed and compact, low weight, low power consumption hardware.

Adaptive Arrays. An adaptive array (Figure 24.6) is a collection of N antennas with their own receivers (RX) and ADC, feeding a weighting and summing network, with automatic signal-dependent weight adjustment to reduce the effect of unwanted

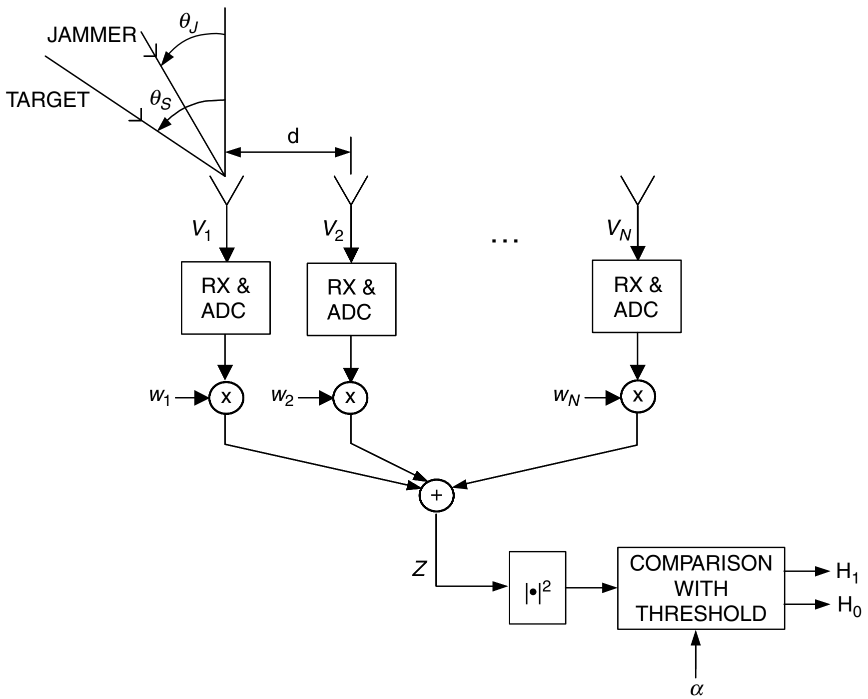

FIGURE 24.6 The adaptive array scheme

signals and/or to emphasize the desired signal or signals in the summing network output. Output signal Z is envelope-detected and compared with a suitable threshold α to detect the presence of a useful target (see Chapter 5 in Farina[34] and other sources.[53–57,83,84]) The adaptive array is a generalization of the SLC described in the preceding subsection. The basic theory of jammer cancellation and target enhancement is considered first; attention is then focused on the following topics: main-beam jammer cancellation, target DoA estimation in presence of jammer, two-dimensional adaptive processing for joint clutter and jammer cancellation, adaptivity at the subarray level, and superresolution. The implementation of the adaptive array concept is more and more related to digital beamforming[85–87] and to digital array radar (DAR) technologies.[88,89]

Jammer Cancellation and Target Signal Enhancement. Adaptive array principles have found a thorough mathematical treatment since the late 1960s[83,84]; for a brief history of adaptive arrays, see Reed[90]; for an overview of least squares adaptive processing in military applications with celebration of B. Franklin medal to B. Widrow for pioneering work on adaptive signal processing, see Etter et al.[91] The theory and application of adaptive array principles to radar is well established; for a look to popular publications see, for instance, Haykin and Steinhardt,[92] Smith,[93] and Farina et al.[94] The basic result is given by the expression of the optimum set of weights:

$$\hat{\mathbf{W}} = \mu \mathbf{M}^{-1}\mathbf{S}^* \tag{24.6}$$

where $\mathbf{M} = E(\mathbf{V}^*\mathbf{V}^T)$ is the N-dimensional covariance matrix of the overall disturbance (noise and jammer) $\mathbf{V}$ received by the array, and $\mathbf{S}$ is the N-dimensional vector containing the expected signal samples in the array from a target along a certain direction of arrival. The similarity of Eq. 24.6 to Eq. 24.3 governing the SLC is immediately recognized.

With respect to SLC, adaptive array techniques offer the capability of enhancing the target signal while canceling the disturbance. The adaptive system allocates in an optimum fashion its degrees of freedom to the enhancement of the target signal and to the cancellation of jammer.

Several generalizations of the basic theory have been considered, including: (i) the target model $\mathbf{S}$ is not known a priori, as it is assumed in deriving Eq. 24.6; (ii) in addition to spatial filtering, doppler filtering is performed to cancel clutter and chaff; and (iii) the radar platform is moving as in shipborne, airborne, or even spaceborne applications. A relevant advancement of the adaptive array concept is space-time adaptive processing (STAP).[95–98]

STAP may be thought of as a two-dimensional adaptive filter that combines receive beamforming and doppler filtering. A basic illustration of STAP is given in Figure 1 of Ward[95] where a pictorial view of the interference environment seen by an airborne radar and the corresponding adapted two-dimensional filter response are shown. The power spectral density resulting from jammer and clutter is depicted as a function of the spatial (i.e., the sin(angle)) and the temporal (i.e., doppler) frequencies. Barrage noise jamming appears as a wall localized in angle and distributed all over doppler frequencies. The clutter echo from a single ground patch has a doppler frequency that depends on the angle between the clutter patch and the platform flight direction; clutter from all angles lies on a diagonal ridge across the space-time frequency plane. A main-beam target competes with both main-beam and sidelobe clutter as well as jamming.

The STAP generates a space-time filtering response with a main beam along the expected doppler frequency and angle of arrival of target and deep nulls along the jammer wall and the clutter ridge. To perform STAP, the radar should have an array of N antennas, each with their own receiving channel and ADC. Each channel receives M echoes from a transmitted train of M coherent pulses. Adaptivity involves the NM echoes.

The detection probability P_D for the optimum filter of Eq. 24.6 is for a constant cross section target model[84]:

$$P_D = Q\left(\sqrt{2 \bullet \mathbf{S}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{S}^{*}},\ \sqrt{2\ln(1/P_{\mathrm{FA}})}\right) \tag{24.7}$$

where Q (. , .) is the Marcum Q function‡ and P_{FA} is the prescribed probability of false alarm. It is also shown that the set of weights of Eq. 24.6 provides the maximum value of the improvement factor I_f, which is defined as follows:

$$I_f = \frac{\text{signal–to–interference plus noise power ratio at the output}}{\text{signal–to–interference plus noise power ratio at the input}} \tag{24.8}$$

The I_f value corresponding to the optimum set of weights of Eq. 24.6 is[84]

$$\mathrm{I}_f = \frac{\mathbf{S}^T\mathbf{M}^{-1}\mathbf{S}^*}{(SINR)_I} \tag{24.9}$$

The signal-to-interference plus noise power ratio $(SINR)_I$ is measured at the input of a receiving element of the array and refers to one echo pulse. The I_f represents the performance of the adaptive array: it accounts for the target signal integration and the interference cancellation. Practical applications of the equation above are, for instance, in Chapter 5 of Farina.[34] Crucial for the understanding of the adapted array pattern is the concept of eigenvalue-eigenvector decomposition of the interference covariance matrix **M**: see again Chapter 5 of Farina[34] and Testa and Vannicola.[99] An important technique that mitigates the deleterious effects of the noise eigenvectors, thus continuing to maintain a prescribed level of low sidelobes in the adapted array pattern is the so-called diagonal loading.[100,101]

Adaptive arrays came about after the successful application of SLC, the application of Eq. 24.6, and of more general and powerful adaptive array concepts (e.g., GSLC: generalized SLC[34]). Clearly the efficiency of the adaptive array depends on the number of degrees of freedom (dof) and the accuracy of receiving channels (e.g., degrees of matching). There is some trade-off between accuracy and number of channels; a system with one dof is less efficient (and requires maximum accuracy) than a system with, say, four dof. An adaptive system with N dof can theoretically suppress (N – 1) jammers, realistically—as a rule of thumb—N/2 or N/3. If the number of jammers is higher, the adaptive array is still useful because some jammer suppression is achieved with an accordingly reduced detection range.

‡ The Marcum Q function is defined as

$$Q(a,b) = \int_b^\infty x \exp\left\{-\frac{x^2+a^2}{2}\right\} I_o(ax)dx$$

where $I_o(\cdot)$ is the modified Bessel function of order 0.

Concerning the comparison between adaptive beamforming and a very low sidelobe antenna, it is in the important case of close to main-beam jamming where adaptive beamforming is superior. On the other hand, the adaptive array allows one to obtain certain lowered sidelobes simultaneously to jamming nulling. Concerning the practical applicability of adaptive arrays some considerations follow. A number of operational radar systems are adaptive; they are described in the technical literature.[38–40,102] A modern radar with digital processing already has at least four digital channels (sum, difference in azimuth, difference in elevation, and guard). In general, the number of implemented receiving channels is mainly a matter of cost. It has been argued that radar systems with a number of adaptive dof of a few tens are already in operation in the microwave band; the number of adaptive dof may be more in the over-the-horizon (OTH) radar.

For the foreseeable future, the fully adaptive array (i.e., with adaptivity at receiving element level) has only theoretical value for antennas with a thousand elements. There are radars that are fully adaptive, but they have only a limited number of elements that can be economically handled in an adaptive array. Arrays with a large number of receiving elements need some form of processing reduction. One method of partial adaptivity is to arrange the array elements in subgroups that form the inputs of the adaptive processor. Careful selection of the subgroup elements is necessary to avoid grating lobes; this topic is discussed in a following section. Another simplification of the fully adaptive array is the deterministic spatial filtering, where a fixed reduction of the sidelobes is operated in those directions or solid angles from which the interferences are expected to come. As an example, a probable region with interferences is the horizon or part of it because jammers are mostly ground-based or at long range. The weights are computed offline, by assuming an a priori known covariance matrix **M**, and stored in a memory where a "menu" of weights is available to an operator or an automatic decision system (pp. 277–283 of Farina[34]).

Main Beam Cancellation (MBC) Systems. The objective of the MBC is to suppress high duty cycle and NLI received through the main beam of the radar. The conceptual scheme of MBC is analogous to the scheme of SLC; however, high gain beams are employed in lieu of low gain auxiliary antennas. Jamming is cancelled by a linear combination of the signals from the high gain beams and the main antenna. The weights to be applied can be computed by Eq. 24.3. The capability to cancel a certain number of main-beam interferences depends on the available number of high gain beams. A so-called four-lobed pattern can be used for main-beam interference cancellation.[103,104] The use of low-gain auxiliary antennas joined to high gain beams allows the contemporaneous cancellation of sidelobe and main-beam interferences.

Target DoA Estimation in Presence of Sidelobe and Main-Beam Interferences. Phased-array radars are required to detect, locate, and track targets in the presence of natural interference and jamming. Monopulse is the technique of choice to determine the target angular coordinates when ECM is encountered since it is much harder to deceive than a conical scan. However, the application of adaptive beamforming (to better mitigate the presence of an intense jammer) with the related distortion of sum and difference beam shapes may introduce errors in the conventional monopulse technique, in particular, if the jammer is close to the main beam[105]; thus, the conventional monopulse technique cannot be applied.[106] A Maximum Likelihood (ML) approach for target DoA estimation is considered, which generalizes the monopulse concept.[107–114,104]

The target angular coordinates—azimuth and elevation (θ, ϕ)—can be estimated by ML, also in the presence of main-beam and sidelobe jamming, by processing the data received by a set of low and high gain beams. The set of received radar echoes, $\mathbf{V} \equiv b\mathbf{S}(\theta_T, \phi_T) + \mathbf{d}$, depends on the angular coordinates of the target, (θ_T, ϕ_T), the complex target amplitude b, and white gaussian zero mean noise plus jamming disturbance $\mathbf{d}$. $\mathbf{S}$ is a vector containing the values of the patterns of high and low gain antennas in a certain direction (θ, ϕ). The data $\mathbf{V}$ are characterized by a gaussian probability density function conditioned to the target unknown parameters, i.e., $p_v(\mathbf{V}/b, \theta_T, \phi_T)$. The ML estimation of the target's unknown parameters is obtained as follows:

$$(\hat{b},\hat{\theta}_T,\hat{\phi}_T) = \arg\min_{b,\theta,\phi}\left\{\left[\mathbf{V} - b\mathbf{S}(\theta,\phi)\right]^H \mathbf{M}_d^{-1}\left[\mathbf{V} - b\mathbf{S}(\theta,\phi)\right]\right\} = \arg\min_{b,\theta,\phi}\left\{F(b,\theta,\phi)\right\} \tag{24.10}$$

where $\mathbf{M}_d$ is the disturbance covariance matrix, $\mathbf{M}_d = \sigma_n^2 \cdot [\mathbf{I} + JNR \bullet \mathbf{S}(\theta_J, \phi_J) \bullet \mathbf{S}(\theta_J, \phi_J)^H]$, depending on the angular coordinates of the jamming (θ_J, ϕ_J)[§] and on the jamming-to-noise power ratio, $JNR = P_J/\sigma_n^2$; in Eq. 24.10, $(\cdot)^H$ stands for the complex conjugate transpose operation. The amplitude b can be separately estimated by nulling the first derivative of the function to be minimized. By replacing the amplitude estimation $\hat{b}$ into the function to be minimized, the following DoA estimator is obtained:

$$(\hat{\theta}_T,\hat{\phi}_T) = \text{argmax}_{\theta,\phi}\{U(\theta,\phi)\} = \text{argmax}_{\theta,\phi}\left\{\frac{\left|\mathrm{S}^H(\theta,\phi) \bullet \mathbf{M}_d^{-1} \bullet \mathbf{V}\right|^2}{\mathrm{S}^H(\theta,\phi) \bullet \mathbf{M}_d^{-1} \bullet \mathrm{S}(\theta,\phi)}\right\} \tag{24.11}$$

It can be noted that the numerator of the functional U(θ, ϕ) is the squared adapted output ($|S^H(\theta,\phi) \bullet \mathbf{M}_d^{-1} \bullet \mathbf{V}|^2$) of a generalized array of high and low gain antenna patterns; the denominator $[\mathbf{S}^H(\theta,\phi) \bullet \mathbf{M}_d^{-1} \bullet S(\theta,\phi)]$ is a normalizing term that, as we will see in a moment, plays a key role. The U function for a certain pair of angles (θ, ϕ) determines, after comparison with a suitable threshold, if a target is detected. The same U functional when scanned across a suitable set of (θ, ϕ) angle values provides, by means of Eq. 24.11, the target DoA estimate. We refer to Eq. 24.11 and its practical implementation as the *generalized monopulse technique*.

The algorithm needs the estimation of the disturbance covariance matrix $\mathbf{M}_d$, which is obtained by the radar echoes corresponding to range cells adjacent to the cell under test where a potential target is sought. The maximum of the U functional can be estimated by an exhaustive search in the range of values of interest of (θ, ϕ) or by using a fast recursive algorithm.[114] The recursion can be initialized with the angular coordinates of the main-beam pointing. By replacing the estimated disturbance covariance matrix into the U functional, a Constant False Alarm Rate (CFAR) detector is obtained.[115] Thus, the comparison of the U functional with a suitable threshold permits the target detection maintaining the prescribed CFAR. Only for the range cell in which the detection occurred, the radar signals are taken and further processed by the ML algorithm to produce the target DoA estimate.

The performance of the ML estimation algorithm of target DoA can be studied by resorting to the Cramer-Rao Lower Bound (CRLB) analysis and Monte Carlo simulations.[104,107–109,113,114] In these studies, it is shown that the shape of the U functional

[§] Here, just one jammer is considered; but the mathematical approach is easily extended to more than one jammer.

depicts the presence of the target as well as of the jamming. It has been demonstrated that Monte Carlo simulation is in close agreement with CRLB analysis. It has been found that the use of the four-lobed antenna pattern in addition to the conventional monopulse beams (sum, difference in azimuth, and elevation) can improve the estimation of the target DoA in presence of a jammer.

Joint Adaptive Jammer and Clutter Cancellation. Clutter, always present in a radar, negatively affects the performance of the adaptive jammer cancellation; therefore, means have to be adopted to effectively contrast the contemporaneous presence of clutter and jammer. When heavy clutter is present, the SLC and adaptive array will attempt to minimize the power in the adapted output without differentiating between clutter and other forms of interference. In other words, the adapted pattern will contain nulls steered in the direction of the main-beam antenna. A number of techniques may be used to avoid the problems raised by the presence of clutter. A technique, particularly suitable for low-PRF (Pulse Repetition Frequency) radar, avoids the influence of close-in clutter returns on adaptive weights by simply selecting for adaptation the clutter-free ranges at the end of each PRI. This technique does not apply to radars operating in high-PRF range-ambiguous modes with significant clutter in all range cells. If the clutter and jammer cannot be separated, either in range or doppler domains, then a two-dimensional (in doppler frequency and angle) adaptive filter might be required; this is particularly true when the statistical features of clutter and jammer are not known a priori. In fact, when either the jamming or clutter statistics cannot be estimated independently of one another, it becomes difficult to design an effective spatial adaptive filter for jamming rejection or a temporal adaptive filter for clutter mitigation since the presence of one contaminates the estimation process for the other.[116] This problem is most accentuated when the clutter-to-jamming ratio approaches unity; in which case, the cascade of a spatial and a temporal adaptive processors may perform poorly. In such situations, a joint two-dimensional adaptive filtering in doppler and angle domains represents a means to cancel the composite disturbance (i.e., the superposition of jamming and clutter) jointly rather than sequentially.[117] The performance advantages of two-dimensional adaptivity shall be traded-off with the computational cost. To reduce the computational load, different computational strategies may be devised, for example, by calculating the adapted two-dimensional weights at a rate lower than the input data and applying them to the radar snapshots at their natural rate. An efficient algorithmic procedure to extract the weights, named Inverse *QR*, is detailed in Bollini et al.[75] Other possibilities are to use modern computing technologies like the FPGA, Power PC, or high-speed optical processor to support the two-dimensional adaptive processing.[80]

Adaptivity at the Sub-Array Level. For an operational phased-array radar (PAR) with thousands of elements, it is not possible to adapt directly the signals from each radiating element. It is necessary to reduce the system complexity by using sub-arrays. A sub-array is an aggregation of antenna elementary radiators; the whole antenna can be considered as an array of these super elements. Adaptive processing can be applied at the output signals of each sub-array, thus reducing the system complexity. Provided that the sub-arrays are configured reasonably, the number of sub-arrays and the receiving channel errors (e.g, channel mismatching) determine the cancellation performance. Thus, the number of sub-arrays is a trade-off between hardware complexity, cost, and achievable performance.

It is highly desirable in PAR to have low sidelobes; this is obtained by (i) fixed weighting layer with analogue technology (i.e., at the microwave element stage) to reduce the sidelobe level everywhere; (ii) fixed weights at the digital sub-array level to reach a prescribed peak-to-sidelobe ratio (PSLR); and (iii) an adaptive weighting layer with digital technology to put nulls along the jammer DoA of high directional beams (sum, difference, cluster of high gain patterns) and low gain, possibly omnidirectional, beams (e.g., guard channel: Ω). Figure 24.7 presents a simplified scheme of a modern PAR.

Formation of Sum and Difference Patterns. Consider the problem of how to form sum and difference beams with prescribed low sidelobes in a PAR with sub-arrays. A strategy is to apply a tapering at element level (i.e., in the analogue receiving section where one attenuator is generally available per element; thus one taper function is available to achieve reasonable low sidelobes for both sum and difference beams). Subsequently a fixed digital taper, after the formation of sub-arrays, is applied with a set of weights for the sum and a different set of weights for each difference channel. This is schematically illustrated in Figure 24.8 for a uniform linear array (ULA) that generates a sum and a difference channel. The figure depicts a ULA with 24 receiving elements clustered into four not overlapping and not regular sub-arrays.[118]

The calculation of analogue taper is made by resorting to the nulling of fictitious wide angle jamming, which occupies the whole angular sector where sidelobes of sum and difference beams have to be kept low. In Farina et al.,[118] it was found that the analogue tapering is a compromise between the Taylor (which is the best taper for the sum beam) and the Bayliss (which is the best taper for the difference beam), the degree of compromise being regulated by amount of fictitious JNR selected for the sum and difference beams. A numerical example, reported in Farina et al.[118], for a ULA of $N = 24$ elements and a uniform distribution of the fictitious jammer out of the main beams of the sum and difference beams, gives a PSLR of 17.5 dB and 16.5 dB for the sum and difference beams, respectively.

The next step is to derive the fixed tapers at a digital level for sum and difference beams; a suitable technique is described in Nickel.[119,120] The rationale of the approach

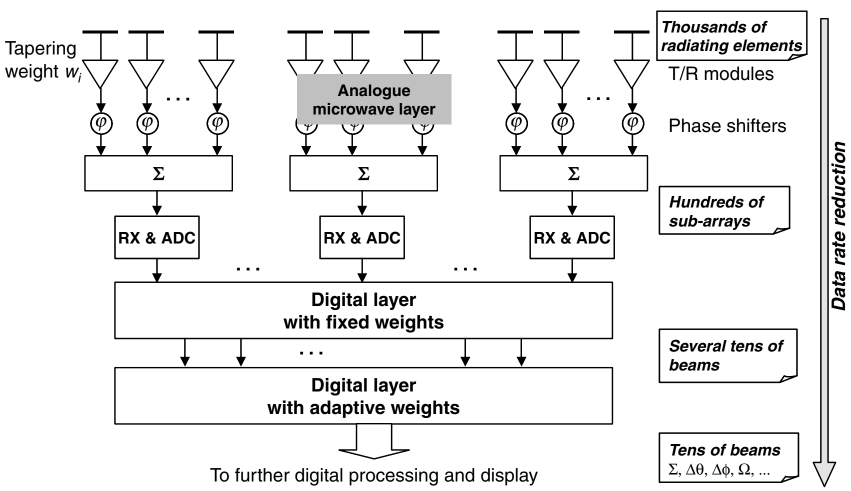

FIGURE 24.7 Scheme of a PAR

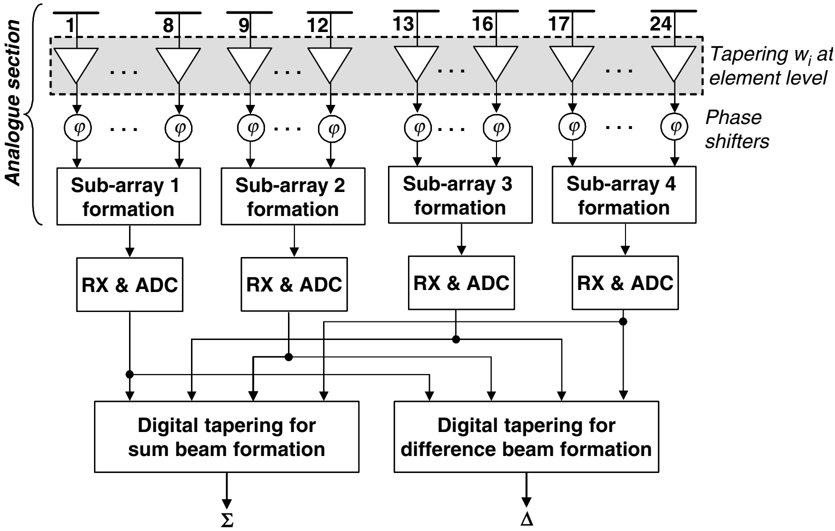

FIGURE 24.8 Example of a ULA with sub-arrays that generate sum and difference channels

is to obtain the sum beam by compensating, at the sub-array level, the analogue taper at the element level to achieve an overall taper more similar to the Taylor one; this is obtained by increasing the contribution of central sub-array weights (i.e., the sub-arrays 2 and 3 shown in Figure 24.8) with respect to the weights of the side sub-arrays 1 and 4. To obtain the difference beam, the analogue tapering at the element level is compensated, at the sub-array level, to achieve an overall taper function more similar to the Bayliss one; this is obtained by decreasing the contribution of the central sub-arrays 2 and 3.

A numerical example is reported in Farina et al.[118] with an ULA of $N = 24$ elements and $M = 4$ sub-arrays. The chosen weight is a Taylor tapering with 30 dB of PSLR. There are only 4 digital degrees of freedom; this means that marginal improvement of performance in terms of PSLR can be achieved. Nevertheless, a PSLR of 25 dB was obtained for the combination of 24 analogue weights and 4 digital weights. For the same ULA about 20 dB of PSLR was obtained for the difference channel.

Considerations Related to Sub-array Adaptivity. Tapering at the array element level produces unequal noise power at sub-array outputs because of the different number of elements in each sub-array. Adaptivity would try to equalize the noise between channels, thus negating the tapering effect.[119] The transformation $\mathbf{T}$ that encodes the sub-array architecture* should be such that $\mathbf{T}^H\mathbf{T} = \mathbf{I}$. In this way, the noise power at sub-array outputs is equal; subsequently the missing taper weights are applied digitally at sub-array outputs (weight rescaling).[119] As an example consider a linear array of 12 elements and raised cosine tapering. Figure 24.9 depicts the following. Continuous curve: pattern of array

* The sub-arrays architecture can be represented by a matrix $\mathbf{T}$; having a number M of columns equal to the number of sub-arrays and a number N of rows equal to the number of elementary radiators. The element t_{ij} of the matrix is defined either as w_i if the i-th elementary radiator belongs to the j-th sub-array or as 0 if the i-th elementary radiator does not belong to the j-th sub-array, where w_i is the tapering weight in the analogue layer of Figure 24.8.

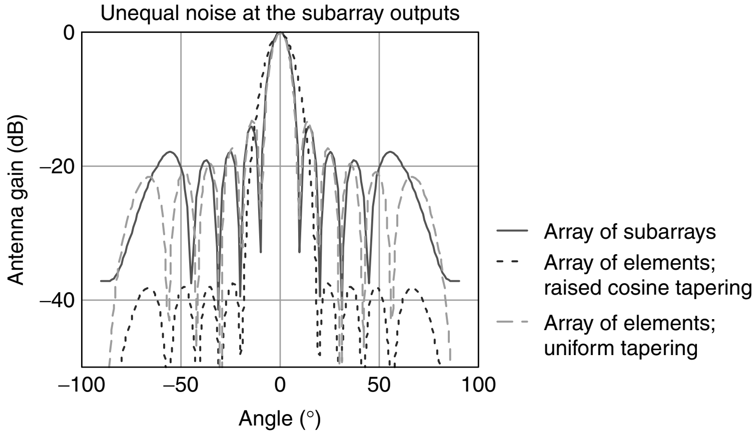

FIGURE 24.9 Examples of the antenna patterns achieved in several cases

of sub-arrays without noise normalization at the output of sub-arrays; it approximately follows the uniform tapering (dashed line). Dotted line: pattern of array of elements and of array of sub-arrays after noise normalization and weight rescaling.

The numerical example follows with Figure 24.10, which portrays the cancellation of a jammer with the DoA = –50° and a JNR of 30 dB. The continuous line refers to an unadapted pattern, tapered at the element level, whereas the dotted line pertains to the adapted pattern at the sub-array level.

Sub-arrays are, in general, chosen to be irregular in their shape and position to avoid grating lobes. If a jammer impinges on a grating lobe, the jammer will be nulled by distorting the grating lobe and, as a consequence, the array main beam (grating notch). For example, consider a ULA with $N = 12$ elements; then, form two types of not overlapping sub-array configurations both having $M = 6$ sub-arrays.

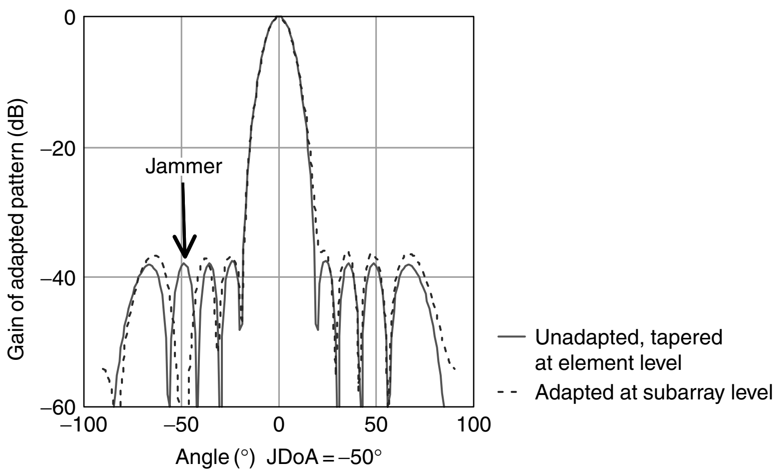

FIGURE 24.10 Jammer cancellation at sub-array level

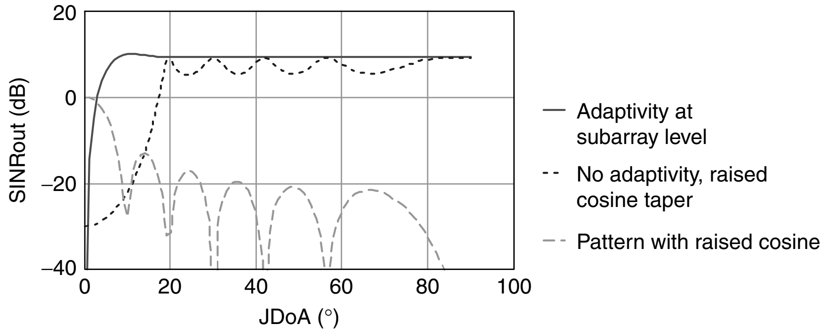

FIGURE 24.11 SINR versus the jammer DoA (JDoA)

The first configuration is regular with two elements for each sub-array. The second configuration is irregular with 2, 1, 4, 2, 1, and 2 elements, respectively. Figure 24.11 shows the SINR at the output of the array versus the jammer DoA. The target DoA is at 0°, the SNR is 0 dB, the JNR is 30 dB. Three curves summarize the system performance. The dashed line is the array pattern with raised cosine taper: this is shown for the sake of comparison with the other two curves of the SINR. The dotted line is the SINR for the quiescent (absence of adaptivity) pattern: it mimics the reciprocal of the sidelobe and main-beam pattern. The continuous line is the SINR for the adaptive irregular sub-array architecture; the maximum value of the SINR is ($10\log_{10}12$ – *tapering losses*).

Figure 24.12 depicts the SINR for the regular array configuration and absence of tapering. It is noted that when the jammer DoA is around 80°, the SINR decreases; this is because of the grating lobe. The maximum value of SINR is 10.79 dB = $10\log_{10}12$, because there are no tapering losses.

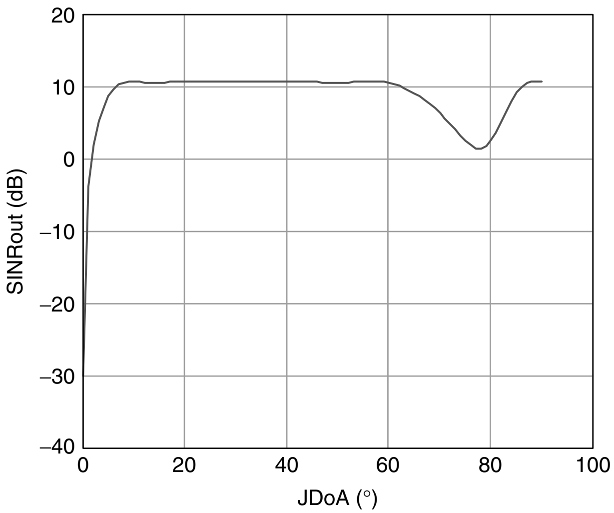

FIGURE 24.12 SINR versus the JDoA for a regular sub-array architecture and no tapering

Superresolution. The resolution of a conventional antenna is limited by the well-known Rayleigh criterion, which states that two equal-amplitude noise sources can be resolved if they are separated in angle by 0.8 λ/L, in radians, where λ is the wavelength and L is the aperture length. When the incident wave is received with a high JNR, an adaptive array antenna may—in principle—achieve a narrower *adaptive beamwidth*, giving a sharper bearing estimation of the incident wave. If accurate strobes of the jammers can be obtained, these can be exploited to form beams in the jammer directions, which are used as auxiliary channels for adaptive interference suppression.[121] The interference directions can also be used for deterministic nulling, which is of interest for main-beam nulling.[122] In addition to the interference source directions and source strengths, this technique can provide other information as to the number of sources and any cross correlations (coherence) between the sources. Such information can be used to track and catalogue the interference sources in order to properly react to them; the jammer mapping—a function running in the background—is useful to select the modes (e.g., admissible pointing directions and waveforms) of multifunction radar and for general situation awareness. Superresolution might be able to resolve multiple independent sources; due to sidelobe superposition and masking problems, superresolution might be vital for jammer mapping in case of multiple jammers. Superresolution is also of interest as an ECCM to counter cross-eye jamming in seeker head applications: see Section 12.1 of Wirth.[102]

The superresolution concept was mainly developed and analyzed by W. F. Gabriel[123] at the Naval Research Laboratory (U.S.). Different methods for bearing estimation were described by Gabriel and, subsequently, by other authors.[34,124–130] One is the maximum-entropy method (MEM) invented by J. P. Burg. It works well with a Howells-Applebaum adaptive beamformer, which has an omnidirectional receiving pattern except where jammers are present. The presence of jammers is indicated by nulls in the receiving pattern. Because nulls are always sharper than antenna lobes, jammer bearings can be obtained more accurately from the adaptive beam pattern, and superresolution is the result. The desired spatial spectrum pattern is obtained as simply the inverse of the adapted pattern. As Gabriel pointed out, there is not a true antenna pattern because there is no linear combination of the signals from an array that could produce such a peaked spatial pattern. It is simply a function computed from the reciprocal of a true adapted antenna pattern. Superresolution and adaptive antennas for jammer cancellation are intimately related. Roughly speaking, the difference is that one produces a pattern with the nulls down (adaptive antenna for jammer cancellation) and the other with the nulls up, i.e., peaks (superresolution of jammers).

One limiting factor of superresolution techniques is that they often require the received signals to obey accurate models of the array manifold. This can be violated due to propagation effects (e.g., spatial spreading and nonstationarity) as well as instrumental effects (e.g., channel mismatch). These factors also affect the performance of adaptive antennas for jammer cancellation, but model mismatches can degrade the performance of superresolution techniques more severely. The higher performance of the superresolution techniques is often obtained at the expense of requiring a stricter adherence to the assumed model; if the model is inaccurate, these techniques—which rely on its heavy exploitation—subsequently become the most sensitive and more prone to perform badly.

For efficient superresolution, an array with a reasonable number of sub-arrays is required; this may be the reason for the lack of application of this technique to practical radar systems except for experimental purposes. Superresolution based on a small

SLC configuration is not efficient, because this leads to the maximum entropy or autoregressive methods that, being nonlinear processing, have a high probability of spurious peaks.

Practical experiences indicate that the resolution limit is determined rather more by implementation and environmental factors than by the pure JNR considerations.

24.7 TRANSMITTER-RELATED ECCM

The different types of ECCM are related to the proper use and control of the power, frequency, and waveform of the radiated signal. One brute-force approach to defeat noise jamming is to increase the radar's transmitter power. This technique, when coupled with "spotlighting" the radar antenna on the target, results in an increase of the radar's detection range. Spotlighting or burnthrough modes might be effective, but a price must be paid. As the radar dwells in a particular direction, it is not looking elsewhere—where it is supposed to look. In addition, the burnthrough mode is not effective against chaff, decoys, repeaters, spoofers, and so on.

More effective is the use of complex, variable, and dissimilar transmitted signals that place a maximum burden on ESM and ECM. Different ways of operation refer to the change of the transmitted frequency in frequency-agility or frequency-diversity modes or to the use of wide instantaneous bandwidth.[131–133] *Frequency agility* usually refers to the radar's ability to change the transmitter frequency on a pulse-to-pulse or a batch-to-batch basis. The batch-to-batch approach allows doppler processing, which is not compatible with frequency agility on a pulse-to-pulse basis. In a waveform with pulse-to-pulse frequency agility, the center frequency of each transmitted pulse is moved, in either a random or a programmed schedule, between a large number of center frequencies. The frequency of the next pulse cannot generally be predicted from the frequency of the current pulse.[134] *Frequency diversity* refers to the use of several complementary radar transmissions at different frequencies, either from a single radar (e.g., a radar having stacked beams in elevation by employing different frequencies on each elevation beam[38]) or from several radars. The objective of frequency agility and diversity is to force the jammer to spread its energy over the entire agile bandwidth of the radar; this corresponds to a reduction of the jammer density and resulting ECM effectiveness.[29]

A good example of the use of the frequency domain for purpose of ECCM is the Senrad, an experimental long-range air-surveillance radar built and tested at the Naval Research Laboratory (U.S.)[135] Senrad was an example of how to build a radar so as to force the jammer to dilute its radiated energy per unit bandwidth; it includes both frequency agility and frequency diversity. This radar shows that its unusually wide bandwidth allows a reduction of the effectiveness of the noise jammer that can seriously degrade more narrowband radars.

Frequency agility, diversity, and instantaneous wideband techniques represent a form of ECCM in which the information-carrying signal is spread over as wide a frequency (or space or time) region as possible to reduce detectability by ESM and/or ARM and make jamming more difficult. This ECCM technique pertains to the realm of waveform coding.[3,136–137]

The ambiguity function (AF) is the tool to characterize waveform coding in terms of resolution, sidelobe level, and ambiguity.[137] In selecting a waveform for a given radar application, the AF should be tested against the environment in which the radar will be expected to operate. The so-called environmental diagram depicts spectral, spatial, and amplitude characteristics of the radar environment (clutter, ECM such as chaff, intentional interferences, and—perhaps—interferences from neighboring EM apparatuses) and is used to assist the radar waveform design. An example of an environmental diagram is on p. 15 of Levanon and Mozeson[137]: on the range-doppler plane are shown the regions in which several types of clutter and high altitude chaff are expected. On the same diagram are superimposed the expected target trajectories and the AF contour of a, say, pulse-burst waveform. As the target follows a particular trajectory, the AF will move accordingly and the spurious AF peaks will slide across the clutter and chaff regions determining the intensity and features of the radar echoes.

Waveform coding includes PRF jitter and PRF stagger, which are helpful for some deception jammer but don't help against noise jammer. Waveform coding makes deception jamming or spoofing of the radar difficult, since the enemy should not know or anticipate the fine structure of the transmitted waveform; as a consequence, it gives assurance of maximum range performance against such types of jamming. Intrapulse coding to achieve pulse compression may be particularly effective in improving target detection capability by radiation of enough average radar power without exceeding peak power limitations within the radar and by improving range resolution (larger bandwidth), which, in turn, reduces chaff returns and resolves targets to a higher degree.

Some advantage can be gained by including the capability to examine the jammer signals, find holes in their transmitted spectra, and select the radar frequency with the lowest level of jamming. This approach is particularly useful against pulsed ECM, spot noise, and nonuniform barrage noise; its effectiveness depends primarily on the extent of the radar agile bandwidth and the acquisition speed and frequency tracking of an "intelligent" jammer. A technique suited to this purpose is referred to as *automatic frequency selection* (AFS).[133,138]

Another method to reduce the effect of main-beam noise jamming is to increase the transmitter frequency (as an alternative means to the use of a larger antenna) in order to narrow the antenna's beamwidth. This restricts the sector that is blanked by main-beam jamming and also provides a strobe in the direction of the jammer. Strobes from a few spatially separated radars allow the jammer to be located.

The availability of solid-state transmitter technology[36–40] allows the generation of high duty cycle waveforms, which may be of some help to realize LPI radar.

As a general remark, one of the factors preventing good ECCM is the reduction of EM spectrum allocated to radar. As discussed, operating over a wide spectral range has important advantages for ECCM, but the civilian and commercial telecommunication systems erode more and more portions of the spectrum at the expense of military ECCM capability.

24.8 RECEIVER-RELATED ECCM

Jamming signals that survive the antenna ECCM expedients can, if large enough, saturate the radar processing chain. Wide dynamic range receivers need to be used to avoid saturation.

A logarithmic (log) receiver might help against noise jamming, but it has detrimental effects against clutter when doppler processing is used. A log receiver is a device whose video output is proportional to the logarithm of the envelope of the RF input signal over a specified range. It might be useful in preventing receiver saturation in the presence of variable intensities of jamming noise. By comparison with a linear receiver of low dynamic range, moderate jamming noise levels will normally cause the computer to saturate so that the target signal will not be detected. The main disadvantage is that a log characteristic causes spectral spreading of the received echoes. It would not be possible to maintain clutter rejection in an MTI or pulse doppler radar if the spectrum of clutter echoes were to spread into the spectral region in which target returns were expected.[21, 29]

The main message is that the dynamic range problem is important for the rejection of jammer as well as clutter, the latter always present in a radar. Thus, the recommendation is to implement, in a modern radar, a receiver with a wide linear dynamic range (e.g., 100 dB). This wide dynamic range needs to be maintained also in the ADC devices with a suitable number of bits; as a rule of thumb, each bit adds 6 dB to the dynamic range count.

Hard or soft limiters can also be used to counter jamming signals. They are nonlinear memoryless devices that cut jamming signals having wide amplitudes. The Dicke-Fix receiver counters high rates of swept-frequency CW jamming and swept spot noise jammers.[29,139] In a radar receiver, the Dicke-Fix uses a wideband intermediate-frequency (IF) amplifier and a limiter ahead of the narrow-bandwidth IF amplifier. The wideband amplifier allows a rapid recovery time from the effects of the swept jammer, and the limiter cuts the jamming signal. The narrowband target signal, after transit through the wideband amplifier and the limiter without remarkable degradation, is integrated by the narrowband filter matched to the signal. The word *Fix* in the Dicke-Fix was put there many years ago to indicate it was a "fix" for a problem that occurred at the time and was to be replaced by something better. It was usually installed with a switch to turn it off, if necessary. Today Dicke-Fix is not used in a modern radar, especially one that employs doppler processing; thus, it is no longer of interest in many radar applications.

Other special processing circuits can be used in the radar to avoid saturation, i.e., fast-time-constant (FTC) devices (perhaps of little use in modern radar), automatic gain control (AGC), and CFAR.[8,29,31] However, they cannot be said to be ECCM techniques. For example, FTC allows the detection of signals that are greater than clutter by preventing the clutter from saturating the computer. FTC does not provide subclutter visibility. AGC keeps the radar receiver operating within its dynamic range, preventing system overload and providing proper normalization so as to furnish signals of standardized amplitude to radar range, velocity, and angle processing-tracking circuits. In conclusion, these devices have a place in the radar but not as means for fighting the ECM battle.

In summary, there isn't much that has been done in the receiver to combat ECM other than to insure there is a good receiver that does its job. Today, modern phased-array multi-channel radar are going to adopt fully digital, software controlled receivers, as in the DAR case; here, the expected advantages are the wider linear dynamic range and the within-band calibration of the receivers that will support the adaptivity on several tens of channels: a distinctive advantage against directional noise jammers.

24.9 SIGNAL-PROCESSING-RELATED ECCM

Digital coherent signal processing greatly alleviates the effects of clutter and chaff.[3,140] This is motivated by the use of coherent doppler processing techniques such as fixed, adaptive MTI, or optimum pulse-doppler processing. Noncoherent devices are also required because of the limited degree of clutter, chaff, and jammer suppression practically achieved by coherent devices, so that the cancellation residue may still be a significant source of false alarm. Among the noncoherent devices, it is worth mentioning the CFAR detector[141–145] and the pulse-width discriminator, this latter being effective against pulsed jammers. The pulse-width discrimination circuit measures the width of each received pulse. If the received pulse is not of approximately the same width as the transmitted pulse, it is rejected. A pulse-width discrimination technique can help in rejecting chaff; in fact, echo returns from chaff corridors are much wider than the transmitted pulse. However, if a target is within the chaff corridor the pulse width discriminator might also eliminate the target.

Coherent Processing. The most effective anti-chaff technique available to radar is the use of doppler filtering, which exploits the different motion characteristics of the target and the chaff.[3] The characteristics of chaff are similar to those of weather clutter, except that the chaff-scattering elements are cut to respond to a broad spectrum of radar frequencies. Weather clutter and chaff differ from ground clutter in that both the mean doppler shift and the spread are determined by wind velocity and wind shear, the latter arising from the variation of wind velocity with height. Chaff moves with the local wind, and there are ways (adaptive MTI and optimum doppler processing[†]) to make an MTI null out both moving and stationary unwanted echoes.[55,136,146] There are two basic doppler filtering techniques that are used. The first is the MTI, which employs a PRF that provides unambiguous range coverage while using a comb doppler filter whose nulls are tuned to the average radial speed of chaff.[3] The second is the pulse doppler, which can use a high PRF to provide unambiguous doppler coverage in conjunction with a doppler filter bank, allowing separation of target from the chaff.[3] A problem with chaff might be when there is a significant wind shear in the atmosphere. With wind shear, the doppler spectrum from chaff can have a wide spectral width (unless the elevation beamwidth is very narrow as might occur with tri-dimensional radar with stacked beams in elevation[38]) so that it is difficult to cancel moving chaff echoes. A pulse doppler radar has a better chance, but it has problems of its own because of the foldover of the clutter that might occupy a large range extent.

Coherent doppler processors might require relatively large amounts of pulses (e.g., more than 10), which must be transmitted at a stable frequency and PRF. A responsive jammer could measure the frequency of the first transmitted pulse and then center the jammer to spot-jam the following pulses. Also, the requirement for a stable PRF precludes the use of pulse-to-pulse jitter, which is one of the most effective techniques against deception jammers that rely on anticipating the radar transmitter pulse. Coherent doppler processors are also generally vulnerable to impulsive radio frequency interference, especially in radars with a limited number of coherent bursts on target.[147]

Another ECCM technique to be considered is pulse compression by matched filtering; it is intimately related to the waveform coding discussed in Section 24.7. Pulse compression[136,137,141] is a pulse radar technique in which long pulses are transmitted to increase the energy on the target while still retaining the target range resolution of a short pulse transmission. It is almost always used in radar for achieving

† The adaptive MTI estimates the mean doppler frequency of a moving clutter source and places the null of, say, a binomial MTI. Optimum doppler processing estimates the whole spectrum of clutter and shapes, by means of the inverse of the clutter covariance matrix, the cancellation filter accordingly; furthermore, with a doppler filter bank, it integrates the echo signal from moving targets. The optimum filter weights are calculated by an equation similar to Eq. 24.6 applied to the radar echoes received by a coherent pulse train transmitted by the radar.

high range resolution or reducing the peak power. Pulse compression offers some ECCM advantage that is discussed hereafter.[3,148] When the pulse compression search radar is compared, from an ESM standpoint, with a conventional search radar with the same wide pulse, the enemy receiver on a jamming platform will not know (in the general case) the pulse compression reference code and will be at a disadvantage. Compared with a radar that uses an uncompressed wide pulse, the pulse compression technique increases the radar's capability against extended signal returns like chaff and clutter. In addition, noise from a jammer does not pulse-compress. Extended clutter tends to be noise like and will not pulse-compress, which keeps down interference displayed to operators.[29] The disadvantages of pulse compression are related to the long duration of the coded pulse, which gives more time for the ECM equipment to process the pulse. In many cases, pulse compression can provide the means for easy radar jamming for the enemy ECM operator. Pulse compression is also vulnerable to cover-pulse jamming, in which the ECM pulse is returned to the radar with a high JNR such that the normal target return is covered by the jamming pulse. The width of the ECM pulse is normally wider than the radar skin return.[13] This type of deception can be counteracted by an ECCM technique such as the cover-pulse channel, where the tracking is on the ECM transmission rather than on the skin return from the target.[29]

The digital coherent implementation of the Dicke-Fix receiver concept requires the use of a coherent hard limiter that preserves the phase of the signal while keeping the amplitude at a constant value.[‡] The coherent limiter is inserted upstream of the pulse compression filter in a radar that uses phase-coded signals. In reception, the jammer and target signals are cut in amplitude. The preservation of the target signal phase coding allows the integration of target energy by means of the pulse compression filter matched to the phase code. The Dicke-Fix processing scheme suffers from three limitations. The first is related to the detection loss experienced when the target does not compete with the jammer. The second disadvantage refers to the masking effect of a weak target signal sufficiently close in range (compared with the spatial extension of the code) to a strong target. Furthermore, it cannot be used in conjunction with doppler processing.

CFAR. CFAR is a technique made necessary to prevent the computer from being overloaded by false alarms, which reduce the capability of the radar to detect desired targets.[141] This processing also plays a role as ECCM; there are three motivations for this.

First, the scope of ECM techniques, in a broad sense, is to impair the target detection and tracking performance of a radar system. Detection performance is measured by the probability of detection; tracking performance is determined by the probability of detection and the probability of false alarm as well. Conventional (cell averaging) CFAR raises the threshold in the presence of noise jamming and reduces the number of targets detected. However, the targets that survive can be effectively tracked because the probability of false alarm has been maintained at sufficiently low levels. Without CFAR and appropriate threshold adjustments, perhaps no targets will be tracked due to the very large number of false peaks (detections on the jammer), making it through to saturate the tracker. Conventional CFAR is not really removing the interference: it is just "hiding" it from the radar operator. However, it is allowing the tracker to operate

‡ This is used with Barker codes, for instance, where the amplitude limitation doesn't impair the phase code.

effectively for the targets that survive, and so in this way, it can prevent the overall failure of the radar. In the limit of no targets being detected (i.e., a very powerful jammer), then it could still be argued that no tracks are better than many false tracks.

Second, not all jammers are noise jammers. Some indeed have a structure in range-doppler space, and CFAR techniques can potentially be used to lower these unwanted signals beneath the detection threshold, once again preventing the detection of false tracks, which—from a tactical perspective—can cause serious dilemmas for a radar operator.

Third, there are the adaptive CFAR detectors (AMF, or adaptive matched filter, for example[115]) that really are ECCM techniques in the sense that they enhance the probability of detection against structured interferences (in space and/or time) while maintaining the constant false alarm rate property that allows these detected targets to be effectively tracked, rather than being seduced by a high number of false detections. This type of processing—or similarly derived from the generalized likelihood ratio test (GLRT)—has been used in some practical radar.

Furthermore, any self-respecting radar system should make the operator aware of higher noise levels due to jamming even though they may not be visible on the CFAR display; the act of performing CFAR should not exclude the operator from knowing that jamming is present and that the detection threshold has been raised.

24.10 OPERATIONAL-DEPLOYMENT TECHNIQUES

To this point in the chapter, only electronic ECCM techniques have been considered. However, radar operational philosophy and deployment tactics may also have a significant effect on the radar's resistance to ECM, ESM, and ARM. This group of techniques can be subdivided into those involving the operator, the methods of operation, the radar deployment tactics, and the friend ESM in support to ECCM.[8] An operational technique against ECM is to use missiles with home on jam (HOJ) guidance to intercept noise jammers. HOJ is a means whereby a missile guidance receiver utilizes the self-screening target jamming signal to develop angular steering information so the missile can home on that target.

The role of the operator in the ECCM chain pertains to the more general topic of *human-factor* ECCM.[29] This is a generic ECCM technique that covers the ability of an air defense officer, a radar operator, a commanding officer, and/or any other air defense associated personnel to recognize the various kinds of ECM, to analyze the effect of the ECM, to decide what the appropriate ECCM should be, and/or to take the necessary ECCM action within the framework of the person's command structure. However, the human operator is less effective against a simultaneous attack of many enemy vehicles supported by a strong ECM force. An operator confronted with a large mix of ECM types and a large number of ECCM techniques is likely to do the wrong thing and/or react too slowly. In this situation, it might be proper to resort to automatically applied ECCM techniques; this is the tendency today. However, a possible concern is that this could, sometimes, hurt the ECCM capability of the radar since a well-trained operator can often figure out what is happening; but the automatic processor can only make decisions based on preprogrammed logics installed in its computer and might not recognize when something unusual (as in jamming) occurs. This is a possible adverse effect of the absence of a decision-making operator.

The operational methods include emission control (EMCON), the appropriate assignment of operating frequencies to various radars, the use of combined ECCMs to meet combined ECMs, the use of dummy transmitters to draw ECM to other frequencies, and so on. EMCON is a technique for the management of all EM radiations of a friendly system, force, or complex to obtain maximum advantages in the areas of intelligence data reception, detection, identification, navigation, missile guidance, etc., over the enemy in a given situation. EMCON permits essential operations while minimizing the disclosure of location, identification, force level, or operational intentions to enemy intelligence receptors. It includes the authorization to radiate, the control of radiation parameters such as amplitude, frequency, phase, direction, and time, the prohibition of radiation, and the scheduling of such actions for all units and equipment of a complex.[29] The on-off scheduling of the radar's operation, to include only those time intervals when surveillance is required, can reduce the probability of the radar location being found by direction finding (DF) equipment or radar homing and warning receivers. Radar blinking (using multiple radars with coordinated on-off times) can confuse an ARM seeker and guidance or a DF receiver. Decoy transmitters, radiating from antennas not located at the radar, may also be employed to confuse DF receivers and ARMs; these decoys can also operate in conjunction with the radars in a blinking mode.

Proper site selection for ground-based radars in fixed installations can provide a degree of natural signal masking to prevent, for example, detection by ground-based ESM equipment. A high degree of mobility for tactical systems allows "radiate and run" operations, which are designed to prevent the radar from being engaged by DF location techniques and associated weapons.[3] The deployment of a radar network with overlapping coverage could provide some ECCM benefits. In the netted monostatic case, the radars have different frequencies for interference reduction purposes; consequently, the ECM has to consider jamming all radars in the overlapping zone, thus reducing its efficacy. This is the kind of frequency diversity discussed in Section 24.7.

Finally, it is worth noting that friendly ESM can support ECCM action by warning of possible hostile activity, providing angular locations of hostile jammers and information characteristics of jammers. This information is helpful in the selection of a suitable ECCM action.

24.11 APPLICATION OF ECCM TECHNIQUES

This section shows the application of the previously described ECCM techniques to surveillance, tracking, phased-array, imaging, and over-the-horizon radars. The use of ECCM techniques in other types of radars such as mortar location radars, missile guidance radars, and navigation radars is considered in the literature.[3]

Surveillance Radars. The function of a surveillance radar is to search a large volume of space and locate the position of targets within the search coverage. The radar range and the azimuth-elevation coverage depend on the specific radar applications. The target reports generated by a surveillance radar are processed to form target tracks. The key features of a surveillance radar are the detection range in clear, clutter, and jamming environments, the accuracy and rate of the extracted data, and the false-alarm rate. In the ensuing discussion, the design principles, driven by the requirements forced by the threat, are mainly addressed.[3]

Detection in a clear environment is a feature of early-warning radars,[§] which look primarily for high-altitude targets at long ranges beyond the surface horizon, where the effects of clutter can be ignored. Under these conditions, a simplified analysis states that radar performance is relatively insensitive to transmitter frequency and waveform shape; in practice, the lower microwave frequencies are preferred because it is easier to obtain large antenna and high average power at lower frequencies, and rain clutter is not important. The maximum detection range on a target with a certain RCS (σ) in free space, for a surveillance radar that must uniformly search a specified volume in a given time period, depends on the product of the average transmitter power ($\bar{P}$) and the effective antenna aperture (A_r). It also depends on the inverse of the system noise temperature, but this is of little consequence since the noise temperature is not a major design issue anymore. The situation is more complex when the target to be detected is of the stealth type.[149]

Waveform design and operating frequency are relevant parameters in tactical and volume surveillance radars, which must be able to detect low-flying penetrating targets that attempt to use terrain-shielding effects to escape radar detection. In this case, the selection of waveform and frequency is made to tackle the problems of masking, multipath, chaff, clutter, and ECM.[134,138,150]

The major EW threats to a surveillance radar are (i) noise jamming, (ii) chaff, (iii) deception jamming, (iv) decoys and expendables, and (v) ARM.

Common types of jamming are main-beam noise jamming and sidelobe noise jamming. Against this threat, good radar ECCM performance is achieved by increasing the product ($\bar{P}A_r$) of average transmitter power by the effective antenna aperture. A military radar should always have 20 dB more power-aperture product than given by standard designs, yet this is seldom allowed. The request for a low sidelobe level has to be traded off with the corresponding degradation of the main-beam width; the widening of the main-beam width may make the radar more vulnerable to main-beam jamming.

The noise jammer situation is basically an energy battle between the radar and the jammer. In the main-beam noise-jamming situation, the advantage is with the jammer because the radar experiences a two-way propagation loss of its energy as contrasted with the one-way propagation loss between the jammer and the radar. With sidelobe jamming, the radar designer can reduce the jammer advantage by low sidelobe design coupled with the use of sidelobe cancellation techniques. With main-beam noise jamming, the radar can maximize the received target energy by transmitting more average power, dwelling longer on the target, or increasing the antenna gain. If the radar's data rate is fixed and a uniform angular search rate is dictated by mechanical or search strategy, then the only option for the radar is to increase its average transmitter power. The next option is to manage the data rate, thereby allowing a longer dwell time on the target (burnthrough mode) along specific spatial sectors where needed. The ability to vary the data rate in an optimal manner is one of the principal advantages of phased-array radars.[3]

Another principle of ECCM design against main-beam noise jamming is to minimize the amount of jamming energy accepted by the radar. This is accomplished by spreading the transmitted frequency range of the radar over as wide a band as possible, thus forcing the jammer into a barrage-jamming mode. This can be obtained by

[§] Of course, such radars have to see also targets at shorter ranges where clutter echoes can mask the target's echo; for this reason, all long range civil air traffic control radar employ doppler processing.

resorting to frequency agility and/or frequency diversity. Some radars incorporate an AFS device that allows the radar frequency to be tuned to that part of the spectrum containing the minimum jamming energy.[133,138]

In accordance with the search-radar equation (see Section 24.12), ECCM performance appears (explicitly) to be insensitive to frequency.* Increasing the radar frequency does not affect the signal-to-interference energy ratio within a radar resolution cell when the antenna aperture and the radar data rate are held constant. The increased frequency increases both the antenna gain and the number of radar resolution cells that must be searched by equivalent amounts; the net effect is that the target return power is increased by the same amount by which the target dwell time is decreased, thereby holding the target-to-jamming energy ratio constant. Nevertheless, in practice, the effect of main-beam noise jamming can be reduced with high radar frequency. Higher frequency radars tend to have narrower antenna beamwidths and larger operating frequency bandwidths (5 to 10 percent of radar center frequency) than lower frequency radars. Thus, main-beam jammers will blank smaller sectors of high frequency radars than of low frequency radars. In addition, main-beam jamming of a narrow beam radar tends to provide a strobe in the direction of the jammer, which can be used to triangulate and reveal the jammer location. Wider radar bandwidth, with appropriate coding, forces the jammer to spread its energy over a wider band, thereby diluting the effective jamming energy.[3]

ECCM design principles for main-beam noise jamming also apply to sidelobe noise jamming, with the addition that the sidelobe response in the direction of the jammer must be minimized. Ultralow sidelobes in the order of, say, 45 dB below the antenna's main-beam peak response are feasible by using advanced technology. Sometimes the control of sidelobe noise jamming by using ultralow-sidelobe antennas is not proper; this is true because the main-beam width might be increased two to three times. In addition, most operational radars do not use ultralow (less than –40 dB) or low (–30 to –40 dB) sidelobe antennas and have antenna sidelobes in the –20 to –30 dB region with average sidelobes of 0 to 5 dB below isotropic. SLC has the potential of reducing noise jamming through the antenna sidelobes, and it is used for this purpose in operational radars.[3]

As explained in Section 24.9, ECCM techniques against chaff are mainly those based on coherent doppler processing.[3,152] In particular, the reference[152] describes a comparison of fixed and adaptive doppler cancelers applied to chaff data recorded by a multifunctional phased-array radar operating at S band. Both cancelers process an 8 pulse coherent burst. The fixed (i.e., nonadaptive) processing is a Dolph-Chebyshev filter with 60 dB of sidelobe attenuation with respect to peak. The adaptive filter, based on the optimum doppler filtering (see Section 24.9 and the literature[55,136,146]) has the weights built around the estimation and inversion of the disturbance (chaff and noise) covariance matrix. The target detectability is evaluated against a dense chaff cloud. For the particular set of recorded measurements, it has been shown a substantially enhanced performance of the adaptive filter over the nonadaptive filter.

* As mentioned previously, the lower frequencies might be preferred for long-range surveillance because the usual radar equation does not include all the pertinent factors. In the jamming case, one should take account that the jamming antenna on an aircraft has a lower gain at lower frequencies so the jamming power density might be less at the lower frequencies. Also, when multipath is important, by selecting the radar frequency properly, one might reduce the jamming power received by being in a null of the jammer transmitting antenna. Chaff might not be as easy to deploy at the lower frequencies.[151] In conclusion, the lower radar frequencies might not be as vulnerable as one might think by examining the traditional radar equation.

Another class of ECCM techniques is aimed to contrast the deceptive ECM. Deception jammers have a number of specific characteristics that can be used by radars to identify their presence. The most prominent is that false-target returns must usually follow the return from the jammer-carrying target and must all lie in the same direction within a radar PRI. If the deception jammer uses a delay that is greater than a PRI period to generate an anticipatory false-target return, then pulse-to-pulse PRI jitter identifies the false-target returns. The generation of false targets in directions different from that of the jammer-carrying aircraft requires injecting pulse-jamming signals into the radar's sidelobes. Many radars employ the SLB (see Section 24.6) to defeat this type of ECM.

True-target returns tend to fluctuate from scan to scan with fixed-frequency radars and from pulse to pulse with frequency-agility radars. Transponder jammers generally send the same amplitude reply to all signals they receive above a threshold and, therefore, do not simulate actual target fluctuation responses. In addition, they usually appear wider in azimuth than real targets owing to the modulation effect of the radar scanning antenna's response on the real target. Repeater jammers can be made to simulate the actual amplitude response of real targets and, hence, are more effective over transponder-type jammers from an ECM viewpoint. An operating mode to be included in a radar to distinguish useful targets from transponder and repeater jammers is based on a doppler spectrum analysis provided enough time on target is available. Additional expensive techniques against deceptive jamming can be based on the measurement and analysis of the angular and polarization signatures of the echo signals.

The same ECCM considerations apply with decoy targets that have the general attributes of real targets and are very difficult to identify as false targets. A method sometimes employed is to test the scintillation characteristics of the detected targets to determine whether or not they follow those of real targets. Expendables that tend to be designed under stringent economic constraints often return only a steady signal to the radar. With doppler spectrum analysis, it is possible to look for returns from rotating components of the target that any form of powered target must possess. Examples are jet engine or propeller modulation returns associated with aircraft targets.

ARMs pose a serious threat to a surveillance radar. The survivability of a surveillance radar to an ARM attack relies upon waveform coding (to dilute the energy in the frequency range), the management of radiated energy in time and along the angular sectors, and the adoption of low sidelobes in transmission. These actions make it more difficult for an ARM to home on radar. When an ARM attack is detected, it may be useful to turn on spatially remote decoy transmitters to draw the ARM away from the radar site. Blinking with a network of radars achieves better results. The ARM trajectory is usually selected to attack the radar through the zenith hole region above the radar, where its detection capability is minimal. Thus, a supplemental radar that provides a high probability of detection in the zenith hole region is required. There are certain advantages in choosing a low transmitting frequency (UHF or VHF) for the supplemental radar. The RCS of the ARM becomes greater as the wavelength of the radar approaches the missile dimensions, causing a resonance effect.[3] A low-frequency radar is somewhat less vulnerable to an ARM attack owing to the difficulty of implementing a low-frequency antenna with the limited aperture available in the missile.[151] However, low-frequency radar has poor angular resolution.

Tracking Radars. Tracking radars provide good resolution and precise measurement of the kinematic parameters (position, velocity, and acceleration) of targets. The estimation, updated with measurements, and prediction of the kinematic parameters as the time runs are the processing steps used to build up the tracks of targets. Tracks allow guidance and control of friendly forces, threat assessment, and enemy target engagement by weapons. Tracking can be accomplished in four ways: (i) The dedicated radar tracker (sometimes called a *single target tracker* and denoted STT) continuously points its antenna at a single target by sensing errors from the true target position and correcting these errors by a servo control system. Then there are two different types of radars called, in the past, *track-while-scan*. (ii) One is a limited angle scan as in some air-defense radars and aircraft landing radars, which search a limited angular sector at a rapid rate (e.g., 10 or 20 times a second). (iii) The other type of track while scan (TWS) was what is now called automatic detection and tracking (ADT). The ADT system generates tracks of more than one target by using a series of scan-to-scan target measurements taken as the antenna samples the target paths. (iv) The multifunctional phased-array radar tracks multiple targets by multiple independent beams, formed by the same array aperture, that are allotted to different targets. This subsection is limited to the design principles, driven by the threat requirements, of the dedicated radar tracker.[3,153] The ensuing subsection will refer to multifunctional phased-array radar.

Good ECCM performance is achieved by radiating as large an average transmitter power at the highest transmitter frequency practicable, coupled with as low a sidelobe level as achievable. Increasing the transmitter frequency, for a fixed antenna size, increases the antenna gain G_t, which, in turn, increases the received target power as G_t^2. For main-beam noise jamming, the received jamming power increases directly as G_t, resulting in a net increase in signal-to-jamming power by a factor proportional to the antenna gain G_t. Here, it is noted a basic difference between surveillance and tracking radar: the detection range of a tracking radar improves as the frequency is increased for a fixed-size antenna. The reason for this improvement is that the antenna gain is directly increased with frequency, thereby focusing more power on the target. This increased power is integrated for a time, which is inversely proportional to the bandwidth of the servo control loop. For a surveillance radar, this increased power is collected for a proportionally shorter time, since the radar must search more cells in the same time because of the narrower antenna beamwidth.

With sidelobe jamming, the received jamming power is proportional to the sidelobe antenna gain, (G_{sl}) resulting in a net increase in signal-to-jamming power ratio by the factor $G_t G_{sl}^{-1}$. As with surveillance radars, sidelobe noise jamming and deception can be further attenuated by the use of SLC in conjunction with SLB, as described in Section 24.6.

The use of higher transmission frequencies for tracking radars generally make them less susceptible to noise jamming than surveillance radars. In addition, tactical tracking radars may track the noise jammer in angle. Tracking a noise jammer in angle from two spatially separated radars provides enough information to locate a jammer with sufficient accuracy.

A more threatening ECM against tracking radars is DECM. These threats require considerably less energy than noise jamming (a feature particularly important on tactical aircraft, where available space is limited). Nevertheless, they are very effective in capturing and deceiving the range gate (with the RGPO technique), the velocity gate (with the VGPO technique), and the angle-tracking circuits. A primary ECCM defense against RGPO is the use of a leading-edge range tracker. The assumption is that the deception jammer needs time to react and that the leading edge of the return pulse will not be covered by the jammer. PRI jitter and frequency agility both help to ensure that the jammer will not be able to anticipate the radar pulse and lead the actual skin interval. Alternatively, the tracking radar might employ a multigate range-tracking system to simultaneously track both the skin and false-target returns. This approach utilizes the fact that both the jamming signals and the target return come from the same angular direction, so that the radar's angle-tracking circuits are always locked onto the real target.[3]

The methodology of introducing VGPO into the radar's tracking circuits is analogous to the method used with RGPO. The frequency shift is initially programmed so that the repeated signal is within the passband of the doppler filter containing the target return. This is needed to capture the doppler filter containing the target, through the radar's AGC action. The repeater jammer signal is then further shifted in frequency to the maximum expected doppler frequency of the radar. The repeated signal is then switched off, forcing the victim radar to reacquire the target.[3] Coherent tracking radars can check the radial velocity derived from doppler measurements with that derived from differentiated range data. Anomalous differences provide a warning of the probable presence of a deception jammer. When RGPO and VGPO operate simultaneously, the best defense is the contemporary tracking of true and false targets in both range and doppler dimensions. The use of multimode (high, low, and medium PRF) radars can also be an effective ECCM measure helping to counter range-gate and velocity-gate stealers by switching radar modes.

Angle-gate stealing is particularly effective against conical-scanning or sequential-lobing tracking radars. It is for this reason that such trackers cannot be used in military applications. The fundamental problem with these radars is that angle tracking is accomplished by demodulating the amplitude modulation imposed on the target return pulses over a complete scanning or lobing cycle. To jam this type of radar effectively, the radar's angle-tracking-error-sensing circuits must be captured with a false amplitude-modulated signal, at the scanning or lobing rate, which is significantly out of phase with that from the target return. When the conical-scan or lobing modulation is imposed on both the transmitter and the receiver beams, it is relatively simple for a jammer to synthesize the appropriate jamming signal by inverting and repeating the transmitter modulation (inverse-gain repeater).[154] This can be partially overcome by a conical scan-on-receiver only (COSRO) system, where the tracking radar radiates a nonscanning transmitting beam but receives with a conical-scan beam. The jammer then has no knowledge of the phase of the conically scanned receiving beam and must adopt a trial-and-error method of scanning the jamming modulation until a noticeable reaction occurs in the tracking radar beam. (This jamming technique is called jog *detection*.[13]) A sequential lobing-on-receive only (LORO) system conceals the lobing rate from a potential jammer.[3] Conical scan and sequential lobing are going to be replaced by the monopulse technique; thus, COSRO and LORO are becoming obsolete.

Monopulse tracking is inherently insensitive to angle deceptive jamming from a single point source. This is a result of the monopulse angle-error-sensing mechanism that forms an error proportional to the angle between the target and the antenna's boresight on each return pulse. This is accomplished by comparing signals received simultaneously in two or more antenna beams, as distinguished from techniques such as lobe switching or conical scanning, in which angle information requires multiple pulses. Effective monopulse jamming techniques generally attempt to exploit the monopulse radar's susceptibility to target glint or multipath signals.[13]

One jamming approach, known as *cross-eye*, used against monopulse radars generates artificial glint into the monopulse tracking loop.[13] The inventors of the cross-eye technique are B. Lewis (NRL, USA) and D. Howard; see their patent[155] originally filed the 1958. Cross-eye is basically a two-source interferometer whose antennas usually are mounted on the aircraft's wingtip as far apart as possible. The signals received in each wingtip antenna are repeated in the opposite wingtip antenna, except for a 180° phase shift, which is inserted in one line to direct an interferometric null toward the victim radar. In effect, this creates an apparent change of target direction as viewed from the radar. A large repeater gain is required to generate a high jammer-to-signal ratio; otherwise, the skin echo will overwhelm the jamming signals in the interferometer pattern nulls. The maximum effectiveness of the technique implies a considerable delay (on the order of 100 ns) in the repeated signal, owing to the transmission line and amplifier between the receiver and transmitter antennas. Thus, leading-edge or multigate range tracking should be an effective ECCM technique against cross-eye jamming.[3,13]

Terrain-bounce jamming or terrain scattered interference (TSI) or hot clutter is another monopulse jamming technique that is used against semiactive missile seekers and airborne tracking radars. With this technique, the jammer aircraft illuminates the Earth's surface in front of and below it, so that the semiactive missile homes on the illuminated ground spot and not on the jammer aircraft. The uncertainty of the terrain scattering parameters and the possible depolarizing effects of surface reflection are some of the problems associated with this technique.[3]

The TSI against airborne radar and the corresponding mitigation techniques are described in detail in the literature[156–158] TSI is a significant problem to military airborne radar; in fact, an often weak target signal in the main beam has to compete with jammer that propagates not only via direct-path but also via multipath from the underlying terrain. Mitigation techniques have been focused on estimating the direct jammer signal, estimating the linear system created by the multipath, and removing an estimate of the reflected jammer signal from the main received radar signal[158]; this is also allowed by using reference beams pointed at hot clutter.[157] Adaptive cancellation techniques have to be able to account for the doppler induced by relative motion between airborne radar and jammer platforms and the jammer signal nonstationarity that is produced from such a bistatic geometry. TSI mitigation for over-the-horizon (OTH) radar is described in Abramovich et al.[159]

Monopulse radars that use parabolic reflector antennas are susceptible to jamming through cross-polarization lobes generated by the reflector surface.[3,13] This occurs because the angle-error-sensing discriminator has an inverse slope for a cross-polarized signal, which causes the angle-tracking servo to have positive feedback instead of the negative feedback required for tracking. Monopulse estimates with planar array antennas usually have a high resistance to cross-polarization jamming (see Section 11.5 of Wirth[102]). With array antennas—in contrast to reflector antennas—all the single antenna elements have the same polarization-dependent pattern. This is multiplied with the array factor and also applies for the sum and difference patterns. The resultant form of the beam pattern will thus be independent of polarization. Therefore, the monopulse operation will also not be disturbed.[102]

Phased-Array Radars. In this subsection, we illustrate, by a numerical example, the role played by the scheduler in a multifunctional PAR to combat ECM. To this end, we resort to a benchmark study described in the literature, which defines typical ECM threats, operational scenarios, and phased-array performance mainly in terms of target tracking under ECM. The simulation benchmark[160] includes two types of ECM, namely SOJ and RGPO. The SOJ, mounted on an aircraft, transmits broadband noise toward the radar. The SOJ flies an oval (race course) holding pattern in a clockwise direction at an altitude of 3050 m and a speed of 168 m/s; it is approximately

150 km from the radar. The two circular turns are performed at an acceleration of 1.5 g. The transmitted SOJ noise impacts the radar with power γ_0 not exceeding eight times the receiver noise power. Thus, a SOJ will not completely hide a target, and it can be defeated with a higher energy waveform. In RGPO, the target under track repeats with delay and amplification the radar pulse so as to pull the radar range gate off the target. The time delay is controlled so the false target is separated from the true one with either linear or quadratic motion. For the linear case, the range of the false target R_k^{ft} is related to the range of the true target R_k^t via

$$R_k^{\mathrm{ft}} = R_k^t + v_{\mathrm{po}}(t_k - t_0) \tag{24.12}$$

where v_{po} is the pull-off rate, t_k is the time at which the target is being observed, and t_0 is the initial reference time of the RGPO false target. Alternatively, for the quadratic case

$$R_k^{\mathrm{ft}} = R_k^t + \frac{1}{2}a_{\mathrm{po}}(t_k - t_0)^2 \tag{24.13}$$

where a_{po} is the pull-off acceleration.

Radar Scheduling. The scheduling and the tracking functions closely cooperate; both interact to update, with current measurements, the target's state vector, and make the predictions necessary to point the radar beam at the target the next time it is observed, select the type of waveform to radiate, and select the threshold to apply for target detection. A conceptual scheme showing the interaction of scheduling and tracking is shown in Figure 24.13, where r_k, b_k, e_k are the range, bearing, and elevation measurements at t_k; SNR_k is the observed SNR at t_k; t_{k+1} is the commanded time for the next target observation; $r_{k+1|k}$, $b_{k+1|k}$, $e_{k+1|k}$ are the predicted range, bearing, and elevation for beam pointing control at t_{k+1}; W_{k+1} is the waveform selection at t_{k+1}; β_{k+1} is the detection threshold for the dwell set at t_{k+1}; and $\mathbf{X}_{k|k}$, $\mathbf{P}_{k|k}$ are the target filtered state estimate and covariance matrix at t_k given all the radar measurements up to t_k.

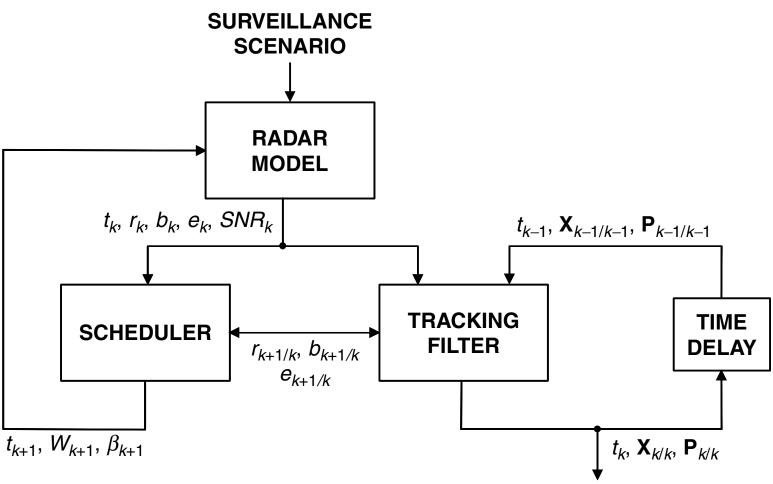

FIGURE 24.13 Interaction of radar scheduler and tracking filter

The scheme is built around two closed loops: (i) the loop encompassing the radar model, the tracking filter, and the scheduler, and (ii) the tracking filter loop. The scenario is observed by the radar at time t_k; the radar model provides the measurements r_k, b_k, e_k and SNR_k. The tracking filter updates the previous target state estimate $\mathbf{X}_{k-1|k-1}$, and its covariance matrix $\mathbf{P}_{k-1|k-1}$ at time t_k providing the new estimates $\mathbf{X}_{k|k}$ and $\mathbf{P}_{k|k}$ and the values $r_{k+1|k}$, $b_{k+1|k}$ and $e_{k+1|k}$ at the next time instant t_{k+1}. The scheduler provides the waveform to radiate W_{k+1} and the threshold β_{k+1} to apply for target detection at t_{k+1}.

Selection of the Sampling Period. The sampling period is chosen among a finite number of possible different values based on kinematic considerations on the target (estimated speed) as well as on whether missed detections have occurred. If there is no measurement to be associated to the target, the sampling period is set equal to $T_s = 0.1$ s and the waveform of highest energy is selected, so as to possibly avoid a second missed detection due to the possibly low target-RCS. Conversely, the sampling period is selected as follows:

- $T_s = 0.5$ s for targets with estimated speed greater than 400 m/s
- $T_s = 2$ s for targets with estimated speed between 100 and 400 m/s
- $T_s = 3$ s for targets with estimated speed less than 100 m/s

Even though the target may accelerate or maneuver, for the sake of simplicity, the sampling period is selected only on the basis of the target estimated speed.

Selection of the Detection Threshold. The presence of a jamming signal can increase the number of false alarms and wrong plot-track associations up to an unacceptable level, thus increasing significantly, the probability of loosing a target under track. It is, therefore, important that the radar receiver be equipped with a CFAR. Since the false alarm probability is related to the detection threshold, the latter should be adapted online based on the intensity of disturbances.

Selection of the Waveform. The benchmark[161] includes 8 waveforms, indexed by i and characterized by a different pulse width $\tau_e(i)$, so that the waveform can be selected in order to provide a SNR greater than the detection threshold and thus maintain an assigned probability of target detection. This can be accomplished by first estimating the average target RCS_{k}[†] at time t_k, and then computing for each waveform i, the predicted $SNR_k(i)$, and finally selecting the waveform index i such that the corresponding $SNR_{\mathrm{k}}(i)$ is just greater than the desired detection threshold plus a given tolerance.[161]

ECCM: A-SOJ and A-RGPO. Hereafter, specific *anti-SOJ* (A-SOJ) and *anti-RGPO* (A-RGPO) techniques will be described.

A-SOJ is based on estimating the jammer position and power level and then using such estimates to adapt the radar detection threshold online.

- *Jammer state estimation*. Whenever the radar operates in the passive mode, i.e., without emitting pulses, bearing b_k^j and elevation e_k^j of the jammer as well as the relative standard deviations σ_k^{jb} and σ_k^{je}, and the jammer-to-noise ratio ρ_k^j (in the following

[†] The RCS is certainly a fluctuating quantity versus time; it also depends upon the target aspect angle. However, if enough time-on-target is available, the RCS estimate can be sufficiently accurate.

expressed in dB) are measured. This allows the tracking filter to estimate the jammer state made up of four state components: the two angular positions (bearing and elevation) and the relative angular speeds. The jammer track is initialized by using the first two measurements provided by the radar.

- *Jammer power level estimation*. An estimate of the power level can be obtained by the first-order linear filter initialized from $\gamma_0(t_1^j) = 1$ for a suitable filter coefficient $\alpha_j \in (0,1)$:

$$\gamma_o(t_k^j) = \alpha_j \cdot \gamma_o(t_{k-1}^j) + (1-\alpha_j) \cdot 10^{\rho_k^j/10} \tag{24.14}$$

- *Adaptation of the detection threshold*. For a given detection threshold β (in dB), the probability of false alarm turns out to be:

$$P_{\text{fa}} = \exp\left(-\frac{10^{\beta/10}}{\gamma_0 G_{\text{stc}}(R)(\Sigma_k^j)^2 + 1}\right) \tag{24.15}$$

Hence, the detection threshold can be selected at each time instant, t_k, in the following way:

$$\beta_k = \max\left\{9.64,\ 10\log_{10}\left[-\gamma_0(t_{k-1}^j) G_{\text{stc}}(r_{k/k})(\Sigma_k^j)^2 + 1\right]\ln P_{\text{fa}}\right\} \tag{24.16}$$

where $\gamma_0(t_{k-1}^j)$ is the most recent available estimate of the jammer power level; the value $\beta_k = 9.64$ dB is the one which allows, in the absence of jammers, the desired false alarm probability $P_{\text{fa}} = 10^{-4}$; $r_{k|k}$ is the filtered estimate of the target range; $G_{\text{stc}}(.)$ is the sensitivity time control gain; and Σ_k^j is the normalized antenna gain for the received signal computed in the radar active mode.[161]

Because the phased-array radar considered here is a multifunctional one, it has also a tracking mode that might be affected by the RGPO; for this reason, an A-RGPO is considered an ECCM technique. Whenever RGPO is active, two high-amplitude signals are received from the radar: the true target's echo and an RGPO-induced signal. Since the time at which the target under track activates RGPO is unknown to the tracking algorithm, the latter must first recognize that RGPO is active and then implement an appropriate A-RGPO technique. In order to establish whether RGPO is active, the following test can be adopted. Let N be the number of measurements exceeding the detection threshold of more than 3 dB. Then if $N < 2$, it is decided that RGPO is not active and no A-RGPO action is undertaken; otherwise, if $N = 2$, the A-RGPO ECCMs described below are applied. Notice that the test also aims at discriminating the type of ECM being active, i.e., SOJ or RGPO. In fact, whenever the noise jammer is in the antenna main beam many false measurements with high jammer-to-noise ratio are induced; in this case, it turns out that $N > 2$ and RGPO is declared inactive. Whenever the jammer is no longer in the target's line-of-sight, it may happen that multiple measurements exceed the detection threshold, but the condition that the excess is greater than 3 dB will be very unlikely to be fulfilled in practice. Once it has been established that RGPO is active, several devices can be adopted in order to prevent the loss of the target under track.

1. A first approach consists of maintaining two tracks until the RGPO is deactivated.
2. A second approach consists of penalizing, in the data association, the measurements whose range is greater than the average range of measurements with SNR higher than the detection threshold.[161]

3. A third, more drastic approach, consists of discarding the measurement with higher range among the two measurements that have exceeded the detection threshold of more than 3 dB.

It is important to guarantee, under RGPO, a very high SNR for the target. In fact, it might happen that the signal produced by the false target overcomes the detection threshold whereas the one from the true target does not, thus causing an association error with possible serious consequences in the target's tracking. Hence, whenever RGPO is active, a high energy waveform must be selected. A further precaution is the following: if there are missed detections for at least two out of the last three scans, an immediate revisit with sampling interval $T_s = 0.1$ s in search dwell mode is performed. In search mode, the range gate is 10 km instead of 1.5 km, so in this way, it is possible to obtain a new target measurement for updating the tracking filter and thus avoid the target's loss.

Simulation Results. Monte Carlo simulation experiments using the benchmark[160] have been carried out in order to assess the benefits of the above described ECCMs. More specifically, the adaptation of the detection threshold has been used as A-SOJ whereas the technique based on discarding the measurements with higher range has been adopted as A-RGPO. Three types of targets (numbered 1, 5, and 6) have been considered: target 1 represents a cargo aircraft while targets 5 and 6 represent fighter/attack aircrafts with a much higher degree of maneuverability. For each experiment, the following results are displayed: number of lost targets (over 50 Monte Carlo trials), T_s (radar sampling time), T_{ave} (average fraction of time required by the radar for target tracking), P_M (average power), position error, and velocity error. Table 24.2 shows simulation results for the Interacting Multiple Model (IMM) tracking[162] algorithm in the absence of ECMs. Tables 24.3 and 24.4 report the results in the presence of SOJ, without and respectively with A-SOJ. Similarly Tables 24.5 and 24.6 report the results in the presence of RGPO, without and respectively with A-RGPO. The examination of these tables reveals that the presence of ECMs considerably deteriorates the tracking performance if no appropriate ECCMs are undertaken. Conversely, the adoption of the above described A-SOJ and A-RGPO techniques allows the performance that would be attained in the absence of the corresponding ECMs to be restored.

TABLE 24.2 Simulation Results Without ECM

TARGET NO.	LOST TARGETS	T_s (s)	T_{ave} (s)	P_M (W)	POS ERR (m)	VEL ERR (m/s)
1	0	1.958	$0.5106\ 10^{-3}$	5.7985	116.8	65.26
5	1	0.6772	$1.477\ 10^{-3}$	68.898	95.39	61.29
6	1	1.112	$0.899\ 10^{-3}$	10.774	82.94	58.43

TABLE 24.3 Simulation Results With SOJ and Without A-SOJ

TARGET NO.	LOST TARGETS	T_s (s)	T_{ave} (s)	P_M (W)	POS ERR (m)	VEL ERR (m/s)
1	34	1.919	$0.521\ 10^{-3}$	6.6179	127.5	71.09
5	15	0.6923	$1.444\ 10^{-3}$	68.411	103	66.78
6	50					

TABLE 24.4 Simulation Results With SOJ and A-SOJ

TARGET NO.	LOST TARGETS	T_s (s)	T_{ave} (s)	P_M (W)	POS ERR (m)	VEL ERR (m/s)
1	1	1.944	$0.5144\ 10^{-3}$	6.6179	127.5	71.09
5	1	0.6888	$1.452\ 10^{-3}$	68.411	103	66.78
6	4	1.118	$0.8944\ 10^{-3}$	15.11	80.49	59.59

TABLE 24.5 Simulation Results With RGPO and Without A-RGPO

TARGET NO.	LOST TARGETS	T_s (s)	T_{ave} (s)	P_M (W)	POS ERR (m)	VEL ERR (m/s)
1	48	1.963	$0.5095\ 10^{-3}$	5.044	120.5	66.6
5	50					
6	50					

TABLE 24.6 Simulation Results With RGPO and A-RGPO

TARGET NO.	LOST TARGETS	T_s (s)	T_{ave} (s)	P_M (W)	POS ERR (m)	VEL ERR (m/s)
1	0	1.889	$0.5295\ 10^{-3}$	6.6179	127.5	71.09
5	1	0.7045	$1.419\ 10^{-3}$	68.411	103	66.78
6	0	1.156	$0.8651\ 10^{-3}$	15.586	124.9	80.26

Imaging Radar. There are two types of imaging radar that will be discussed: synthetic aperture radar (SAR) and inverse SAR (ISAR).

SAR. SAR allows us to have a high-resolution mapping of the EM backscatter from an observed scene. More precisely, the radar data is obtained in polar coordinates, i.e., slant range and azimuth, while a two-dimensional image in the rectangular coordinates (x, y) is provided. High resolution in slant-range is obtained by transmitting a coded waveform, with a large value of the time-bandwidth product, and coherently processing—in a filter matched to the waveform—the echo signals. High resolution along the transversal direction is achieved by forming a synthetic aperture. This requires (i) to put the radar onboard a moving platform, e.g., an aircraft or a satellite; (ii) to record the EM signals from each scatterer that is illuminated by the moving antenna beam in successive instants of time, and (iii) to coherently combine the signals—via a suitable azimuthal matched filter—thus focusing the sliding antenna pattern in a narrower synthetic beam. Radiometric resolution, another key parameter, is related to the capability of SAR of distinguishing different objects in the scene on the basis of their EM reflectivity. Radiometric resolution determines how fine a sensor can distinguish between objects with similar EM reflection properties. It is a parameter of great importance, especially for those applications oriented to extended target exploitation like polarimetry and classification. Thus, the radiometric resolution should be optimized mainly for good extended target interpretation, accounting for all kind of back-scatterers. Multilook processing is commonly used in SAR image formation in order to reduce the speckle noise. Traditional digital multilook processing consists of an incoherent addition of independent images (looks) of the same scene. The looks can be obtained by partitioning the available signal bandwidth (range and/or azimuth) and processing each look independently. The final image is produced by adding the looks incoherently, pixel by pixel. The direct trade-off between geometric and radiometric resolution must be considered when choosing the number of looks for processing. One-look processing means a fully coherent use of the bandwidth (best geometric resolution), and in this case, the speckle noise will obey an exponential distribution where the standard deviation is equal to the mean value in the intensity image (multiplicative characteristic). For multilook processing, the geometric resolution will degrade as the number of looks increases and the speckle statistics of the intensity image obey a gamma distribution, where the standard deviation decreases with the square root of the number of independent looks.[163]

SAR images are useful for surveillance and reconnaissance applications. However, jamming could make SAR images unusable. The use of ECCM is, therefore, essential to reducing the vulnerability of SAR to jammers. The susceptibility to intercept signals from SAR and vulnerability to jamming are described in Goj.[164] A simulated noise jamming produces stripes on the SAR images that demonstrate the effectiveness of jamming against targets like strong point scatterers such as electric power-line towers, as well as low-reflectivity agricultural patterns and desert land. The references[165,166] discuss the significant vulnerability to ECM of spaceborne SAR during maritime reconnaissance missions. In 1978, typical imagery from Seasat SAR showed several features that made the SAR a powerful maritime surveillance sensor. The ships and the wakes produced by the ship motion were imaged. The ship image (a blob) appeared displaced from its wake due to the doppler shift caused by the ship's motion relative to the spacecraft. However, the ship's position at the time of imaging and its course could be determined from the wake. The ship speed can be calculated too by the displacement of the ship from its wake. All this information is obtainable only if enough SNR is available for the identification of these image features either by a human operator or an automatic processor. There exists, therefore, a potential vulnerability to SAR in the maritime surveillance application if a high level of background noise causes degradations of the SAR image to an extent where ship and wake can no longer be identified in the image. In the literature[165,166] some critical aspects, in terms of jammer receiver sensitivity and transmitted power, for spot-noise jamming are considered and the system requirements are derived to determine the feasibility and practicality of such jammer. Results of a computer simulation of an engagement between SAR and representative jamming system are given to enable the effectiveness of ECM to be assessed.

The threats to a SAR are barrage jamming, spot jamming, random pulse jamming, and repeater jamming. Repeater/deception jamming is a major threat because it might not be recognizable, whereas the others are, at least in principle, recognizable. The impact of each threat and the possible countermeasures are described in the remaining part of this section.

- *Barrage jammer*. The disturbance noise extends over the entire swath of the SAR image, and it shows generally a uniform intensity. The radar image of barrage jammer noise will exhibit speckle, i.e., a brightness variation from one resolution cell to another. In addition, because a large number of noise samples are added noncoherently, the multiple looks of jammer noise tend to smooth out the intensity variation from pixel to pixel, just as in the case of thermal noise.

- *Spot jammer*. It also covers the entire swath and with uniform intensity disturbing noise as for the barrage jammer; however, its image will differ from the barrage noise because the Fourier transform of narrower band jammer noise will result in speckle size in the range dimension that is larger than that of thermal noise or clutter. The processed cross-range dimension is again equal to that of clutter or thermal noise. Spot jammer noise will appear to be stretched in range.
- *Random pulse jamming*. The jammer pulses may also be transmitted at random intervals, so that such noise pulses can appear in any part of the range swath. When observed over a sufficient number of samples, the noise pulses will occupy all parts of the range swath in one sample or another. The azimuth processor forms the sum of the noise power from all samples within one synthetic aperture length. That sum will be equal to the total noise power in the aperture, which is proportional to the average jammer noise power. Also, in this case, the speckle dimension will appear stretched in range, just as in the spot jammer case. However, the random pulse jammer speckle will exhibit more pronounced brightness variations than that from spot or barrage jamming, because fewer noise samples are added noncoherently, thereby reducing the smoothing effect of multiple looks.
- *Repeater jamming*.[167] The enemy may utilize the transmitting radar to send out a signal within the band of the SAR to confuse the SAR system receiver. The jamming signal causes the SAR to receive and process erroneous information that results in severe degradations in the SAR images and/or formation of the image of nonexistent targets. A deception jamming could be composed of manipulated replicas of the transmitted radar signals via DRFM. In Hyberg[168] the possibility of preventing SAR mapping through coherent DRFM jamming has been investigated. A software model has been developed and verified in several flight trials in the case of a ground-based DRFM jammer.

ECCM techniques for SAR can be divided into (i) antenna-based techniques (low sidelobes, adaptive arrays) and (ii) transmitter/receiver/processing–based techniques (frequency agility, pulse coding).

- *Low sidelobes*. SAR antennas with low sidelobes reduce the level of jamming power received and, in addition, reduce the probability of being intercepted by ECM stations (in the sidelobe region).[169] In relation to low sidelobes, the following comment is in order. In a conventional radar, the effect of low sidelobes is clear, but there is a difference in SAR because the beamwidth is much wider than in other radar applications. In principle, the finer the resolution the smaller the SAR physical antenna and the wider is its beamwidth. Thus, jamming in the main beam is more likely in a SAR than in other radars because of the wide main beam. To get false targets into the SAR, it would have to come from the main beam, so low sidelobes might not be much involved in deception jammer. Likewise, main-beam jamming may be more of a threat to SAR than sidelobe jamming.
- *Adaptive arrays*. The references[170–172] deal with the rejection of a barrage noise jamming using an adaptive spatial nulling. Equipping the SAR system with an antenna partitioned into several sub-apertures connected to parallel channels (i.e., multichannel SAR) allows spatial adaptive processing to suppress the interfering signal. In Farina and Lombardo,[170] the performance of such a technique is evaluated in terms of SAR impulse response, detection performance of point target, and radiometric resolution of an extended scene. In Ender[171] a SAR image, taken with an experimental four-channel SAR jammed by a small 1 watt

noise jammer leading to a JNR in the raw data of about 30 dB when the jammer passes the center of the main beam, is depicted. The de-jammed image by adaptive spatial suppression is also shown demonstrating the good performance of adaptive spatial cancellation. The reference[171] provides a comprehensive study of anti-jamming spatial adaptive techniques including also the space/slow-time anti-jamming filter with suitable image reconstruction algorithm. Results indicate that the slow-time STAP provides superior interference cancellation than spatial-only filtering. SAR usually involves wideband processing, requiring for adaptive nulling techniques, peculiar algorithms. Efficient broadband jammer nulling has to be countered with space/fast-time (i.e., range cell) processing.[172] The expected number of spatial dof is not higher; we have only to add the dof in time. The adaptive beamforming algorithms have to be implemented into the SAR processing which is always space-time processing (typically post-doppler). Rosenberg and Gray[173] tackle the problem of mitigating the effects of an airborne broadband jammer present in the main beam of a SAR. In addition to this, multipath reflections from the ground, known as hot-clutter, will add a nonstationary interference component to the image. The authors show the image degradation from hot-clutter, the limited restoration that multi-channel spatial imaging and slow-time STAP can provide, and how fast-time STAP can improve the final image quality.

- *Frequency agility*. SAR processing needs phase coherence for obtaining the synthetic aperture, thus frequency agility has to be used with care. Frequency changing during a synthetic aperture length time results in a change of focal length (different coefficient of the quadratic phase term) of the phase history of the illuminated targets that degrades the cross-range resolution. SAR operating in burst mode can change its central frequency from one look to another, without any degradation in image quality. Given the efficiency of simple broadband jamming and modern ESM, we need to conclude that frequency agility is not of great help in SAR ECCM.
- *Pulse coding*.[167] An effective ECCM against a DRFM repeat jammer is to change the radar transmitted pulse code from one PRI to another. The radar maintains the same carrier and bandwidth; however, the pulses are coded to be approximately orthogonal to each other (i.e., their cross-correlation is approximately equal to zero). Such a radar is less susceptible to a DRFM repeater because (i) the jammer cannot adapt easily since the radar signal is varying in the PRI domain, and (ii) the signal transmitted by a DRFM repeater jammer at a given PRI (i.e., the radar signal that is used by the SAR at the previous PRI) is approximately orthogonal to the radar signal that the SAR is utilizing at the current PRI, and thus, a matched filtering with the current PRI radar signal would weaken the DRFM repeater jammer signal. In Soumekh[167] a novel method is outlined that combines the above mentioned pulse diversity radar signaling with a new coherent two-dimensional processing of the measured data to effectively suppress a DRFM repeater jammer.

ISAR. The inverse SAR is a method of reconstructing a high-resolution two-dimensional EM intensity image of moving targets (e.g., ships, aircraft) in the range and cross-range (doppler) domains. ISAR imaging is important in military applications such as target recognition and classification (since it can usually recognize the class of target) that can also be used to cue weapon systems. The need for coherent countering of these imaging sensors is a high priority for EW. The references[174,175] present the design of a pipelined all-digital image synthesizer capable of generating false-target images from a series of intercepted ISAR chirp pulses, thus providing RF imaging decoy capability. The image synthesizer modulates the phase samples from a phase sampling DRFM that stores intercepted ISAR pulses. The image synthesizer must also synthesize the temporal lengthening and amplitude modulation caused by the many reflective surfaces of a target and must generate a realistic doppler profile for each surface. The position of a false target image in range can be controlled by delaying in time the read-out samples going to the image synthesizer. The range-doppler image of a ship with 32 range bins is synthesized as an example in Pace et al.[175] ECCM techniques to defeat this type of jamming signals are similar to those proposed for SAR.

Over-the-Horizon Radar. An important defense-related role of high frequency (HF) over-the-horizon (OTH) radar is to provide a capability for early warning detection and tracking of air and ship targets. By using the ionosphere as a propagation medium, *skywave* OTH radars can operate at very long distances to achieve detection and tracking at ranges of 500–3000 km. On the other hand, *surface-wave* OTH radars exploit vertically polarized HF signals (3–30 MHz) and the conductive properties of sea water to detect targets at ranges limited to about 250 km. This upper limit generally applies to large ships and frequencies in the lower HF band.[176,177]

ECM to OTH Radar. For both skywave and surface-wave OTH radar systems, the ionosphere also propagates unwanted interference signals to the radar site, particularly at night when the ionosphere is prone to propagating radio frequency interference (RFI) sources from very long distances. RFI can arise from unintentional and intentional anthropogenic emitters in the user-congested HF band, as well as jamming sources. Jamming sources may be located on the target platform itself (self-screening) and received by the main antenna beam or radiate from a separate location (stand-off) and be received mainly through the antenna beampattern sidelobes. The jamming signal may be incoherent with the radar waveform and operate in a "spot" or "barrage" fashion to raise the noise floor in both range and doppler search spaces to potentially impair detection performance, or it can be coherent with the radar waveform, as in the case of deception jamming, which may generate false targets and potentially impair the tracking system from following the true target.

Impact of Ionosphere. An important aspect that distinguishes OTH radar from line-of-sight systems is the impact of the ionospheric propagation medium on the characteristics of the received interference. The ionosphere is stratified with different reflecting layers, so a single interference source is often received as a number of multipath components with different DoAs, both in elevation (due to the different heights of reflection points) and in azimuth (due to layer-dependent ionospheric tilts or gradients). In addition to multipath, each interference component is subjected to temporal and spatial distortions caused by the dynamic behavior of electron density irregularities present in the individual reflecting layers.[178] This physical phenomenon is known not only to deform the interference wavefronts relative to the anticipated plane wavefront, but also to induce a significant level of spatial nonstationarity on the various interference components over time intervals commensurate with the coherent processing interval of OTH radars (in the order of a few to tens of seconds).[179,180]

Relevance to Interfering Signals. Sources of interference within the radar coverage (e.g., on an airborne platform) can potentially screen the platform in range and impair the detection of other targets with similar azimuth but possibly at different ranges.

Such sources can expect good propagation to the radar receiver because the choice of operating frequency is usually optimized for the coverage area. In the case of standoff interference sources, which are located arbitrarily with respect to the surveillance region (e.g., a ground-based emitter), propagation conditions will generally be suboptimum. However, such sources may have greater power and antenna gain at their disposal, allowing the signals to reach the radar receiver with appreciable strength, sometimes after propagation via highly disturbed and nonstationary ionospheric paths (as commonly occurs in the equatorial and polar regions). Under normal circumstances, OTH radars seek to find relatively clear frequency channels in the user-congested HF spectrum, so the presence of interference from other manmade sources is effectively diminished by suitable frequency selection. When jamming is present, the radar may need to operate with much higher than usual levels of interference that can degrade performance. For this reason, protection in the form of ECCM techniques becomes necessary.

ECCM Techniques. Electronic protection for OTH radar antenna arrays can be provided in the form of adaptive signal processing in space and time. The stochastic constraints adaptive beamforming and STAP methods[181–184] were developed specifically for the HF environment to address the rejection of nonstationary interference while protecting the clutter doppler spectrum properties. A method for time-varying spatial adaptive processing (TV-SAP)[185] that addresses the same problem was found to be more attractive for practical implementation due to the much lower computational cost in real-time applications, as well as greater robustness in protecting sub-clutter visibility after doppler processing. The problem of reducing false alarms caused by strong sidelobe targets and spatially structured (non-gaussian distributed) RFI was treated in Fabrizio et al.,[186] where the advantages of adaptive subspace detectors relative to conventional approaches were shown. STAP techniques with temporal degrees of freedom spaced at the PRI (i.e., slow-time) have been proposed in Farina et al.[187] to jointly cancel RFI and clutter when both are of similar strength but neither can be isolated for estimation, whereas an alternative low-dimension STAP formulation with temporal taps spaced at the range cell interval (i.e., fast-time) has been proposed in Fabrizio et al.,[188] to jointly cancel sidelobe and main-beam RFI that exhibits correlation in the range dimension. The STAP methods used in OTH radar are very similar conceptually to those adopted for airborne radar, especially the former tap architecture.[187] The chief difference is that in benign conditions (free of significant co-channel interference[‡]), STAP is not indicated for OTH radar because the sidelobe clutter does not typically mask doppler shifted targets any more than the main-beam clutter.[§] A possible exception to this is shipborne HF surface-wave radar,* although such systems have been proposed, they have not yet demonstrated their practical utility.

‡ Co-channel interference for OTH radar refers mainly to other transmissions in the HF spectrum that either fully or partially overlap the radar bandwidth.

§ The main beam and sidelobe clutter received by airborne radars can have quite different doppler shifts due to the movement of the platform with respect to the ground resulting in the angle-doppler coupling of the clutter. However in OTH radar, main beam and sidelobe clutter from a single ionospheric mode typically have similar doppler spectrum characteristics because the radar is stationary. This means that sidelobe clutter appears at roughly the same doppler shift as main beam clutter and doppler filtering can be used effectively for detecting targets usually without special need to reject the sidelobe clutter spatially.

* Obviously the situation may change in shipborne HF surface wave radar because the platform is moving with respect to the sea surface and hence a conceptually similar situation arises for the clutter as encountered in airborne radar.

24.12 ECCM AND ECM EFFICACY

There is a need for a quantitative measurement of the efficacy of one or more ECCM electronic techniques when a radar equipped with these devices is subject to an ECM threat. One performance measure generally used for an unjammed search radar is the detection range of a certain target against a system noise background; this situation is referred to as *detection in clear environment*. When the radar is jammed, it is of interest to calculate the degradation of the detection range with respect to self-screening, standoff, and escort jammers. These calculations apply to both search and tracking radars. For tracking radars, it is also worthwhile to consider the degradation of measurement accuracy and resolution. The benefits of using ECCM techniques such as frequency agility, coherent doppler processing, very low sidelobe antennas, and SLC can be easily assessed at a first approximation by properly modifying the parameters involved in the radar equation. If, for instance, an SLC is adopted against an SOJ, its net effect is to reduce jamming power by the amount of jammer cancellation ratio that the SLC can offer.

The prediction of radar range is difficult because of the many factors that are hard to represent with models of the required accuracy. The factors involve the target to be detected (target returns of an unknown statistical nature), the natural environment in which the target is embedded (e.g., clutter returns, unintentional interference, uncontrollable environmental refraction, and absorption), the random nature of the interference, and the radar itself (system noise temperature, signal distortions, etc.). Nevertheless, radar range prediction made under average conditions provides a preliminary and useful indication of performance under ECM threat and ECCM design effectiveness that produces baseline values prior to simulation and operational tests. A classical book presents accurate detection range equations in a variety of practical situations.[189] In the second part of this section, a review of software tools available for the prediction of range equation in jamming and chaff conditions is given.

Of course, the radar equation is a simplification in assessing ECM-ECCM interactions; a measure of ECCM effectiveness should involve the whole weapon system in which the radar operates. The measure of effectiveness should be expressed in terms of the number of attackers destroyed or the probability of radar survival. References in the literature attempt to assess the ECCM efficacy.[190–194]

Simulation is another means to assess the ECCM benefits in radar and weapon systems.[193] An advantage of this approach resides in the capability to artificially generate different types of threats and to look at the radar[160,161] and weapon system reactions. However, the simulation of such a complex system is a difficult, time-consuming task that sometimes involves the use of ad-hoc programming languages suitable for simulation.

Simulation of a complex system on a digital computer is a technique used for the analysis, design, and testing of a system whose behavior cannot be easily evaluated by means of analysis or computation. The procedure essentially consists of reproducing the algorithms of a suitable model of the examined system by means of computer programs. Proper inputs to the model, corresponding to the most relevant operational conditions for the real system, can be generated by the same computer programs. The outputs obtained are compared with some reference values (expected or theoretical) to assess system performance. When random inputs are provided, a number of statistically independent trials are performed to achieve a significant sample of the output values from which reliable statistics can be estimated.

The accuracy and detail of the model may vary from a coarse functional description of the system to a very accurate one, according to the purpose of the simulation and the required accuracy of the results. However, it is desirable to limit the complexity of the simulation tools in order to have manageable programs, giving results that are easily interpreted. The accuracy in representing each system function depends upon its relevance with respect to system performance. When a very complex system is to be simulated, it is generally preferred to resort to several programs of limited complexity in lieu of a single bulky simulation. This approach corresponds to partitioning the whole system into subsystems separately modeled in detail. From each partial simulation, a limited number of relevant features are extracted and employed to build a simplified model of the overall system.

Simulation is particularly important to account for the adaptive nature (e.g., CFAR, adaptive beamforming, automatic radar management, adaptive tracking, adaptive clutter cancellation) of modern radar systems.[195] In this case, traditional static measures such as detection range against a given target will no longer adequately define the capabilities of radar systems. Measures of radar dynamic characteristics, such as the susceptibility to processor overload or the time to adapt in changing conditions, are more important. Modeling and simulations to evaluate the radar response to standardized changing scenarios represent an attractive technical solution.[195]

Simulation is always of value; however, the effectiveness of ECM and ECCM is ultimately done, when possible, with tests of real EW capabilities against real radar systems under real-world conditions. This is especially important for radar equipped with adaptive techniques since they might not be always fully modeled in a simulation as they are in the real-world environment in which they must operate.

The Radar Equation in Jamming and Chaff Conditions. An example of radar range performance under noise jamming is reported on pp. 14–19 of Farina,[34] where the important role played by a radar with low sidelobe antennas is also noted. Today the use of computer programs for predicting radar performance under jamming, clutter, and chaff, and in the presence of various refined propagation models is well established: there are programs developed in house by individual radar companies[196] or available on the market.[197]

The Radar Work Station (RWS) is an example of a developed in-house program[196]; RWS originates from the modeling and simulation activities carried out for prediction of radar performance in several scenarios. One main objective of RWS is to provide the radar analyst or system designer with a friendly but comprehensive toolkit for prediction of radar performance based on well recognized, flexible, and documented mathematical models. A broad range of radar types (bi-dimensional, multi-beam three-dimensional, phased-array), composite clutter, ECM and propagation scenarios, and a target's kinematics and RCS features are covered. Input and output data can be saved, loaded, and exported to other similar applications or for general use (i.e., MS Office tools for data analysis). A second purpose is to provide a handy and reliable tool for technicians and engineers performing system setup at the site or acceptance tests by means of field trials, by providing not only the software tools and models but also, where required, a database of prediction results, and allowing simple parametric excursions thereof, without the need to consult a bulky reference documentation. In brief, the most valuable outcomes that can be obtained with the RWS are radar range calculation, radar elevation coverage diagrams in clear, ECM and multi-propagation both for coherent and noncoherent radars; range and velocity responses in complex scenarios (multiple clutter sources, user defined trajectory) in terms of signal-to-disturbance power ratio and detection probability; and radar range and height accuracy calculation, radar resolution evaluations employing suitable data extracting logics. The RWS suite consists of the following main modules: C\C++ and Fortran (to calculate special functions like Gamma and Bessel K) coded libraries; a standard library of Windows APIs (Application Programming Interfaces) to draw the coverage diagrams; a template library to implement the matrix algebra; an application based on MS Office Excel to code the Blake Chart†; a set of Visual Basic tools to evaluate some aspects of radar performance (e.g., ADC jitter, atmospheric loss, tapering loss, etc.); and an unformatted archive of radar data, as simple ASCII files, pertinent to performance, environment, trajectories, terrain height, and waveform. User-friendly interfaces run on low-cost platforms (PC) and popular environments (Win98, WinNT, Win2000, Windows XP, Vista) for users and developers.

In the RWS, the chaff volume clutter model is characterized in terms of volume extent, EM reflectivity, and doppler spectrum. The signal-to-noise plus chaff ratio is determined on the basis of the chaff location in the space, the antenna receiving pattern, and the radiated radar waveform. The radar equation can be applied, and the signal processing scheme can be emulated to determine the amount of chaff mitigation. A barrage noise jammer is modeled in terms of effective radiated power (ERP) and frequency band of operation. The signal-to-noise plus jammer ratio is determined on the basis of the JDoA and the antenna receiving patterns; the radar equation is then applied; and suitable ECCM signal processing schemes can be emulated to determine to which extent the jammer is attenuated.

Computer Aided Radar Performance Evaluation Tool (CARPET) is an example of available software on the market. In the CARPET 1.0 manual,[197] the equations for calculating the contributions from chaff (volume clutter) in the signal-to-interference ratio are described on pp. 59 and 60, and the equations for calculating the contribution from noise jamming (barrage or responsive) are described on p. 61. CARPET is programmed in C++ and has a Windows XP-compatible user-friendly graphical interface.

ACRONYM LIST

ADC	Analogue-to-Digital Converter
ADT	Automatic Detection and Tracking
AF	Ambiguity Function
AFS	Automatic Frequency Selection
AGC	Automatic Gain Control
AMF	Adaptive Matched Filter
API	Application Programming Interface
A-RGPO	Anti Range Gate Pull Off
ARM	Anti Radiation Missile
A-SOJ	Anti-Stand Off Jammer

† Actually, it is a generalized Blake chart (that improves on the original Blake chart), which includes details such as antenna patterns, processing, system losses, etc., in a suitable electronic format.

BM	Ballistic Missile
CARPET	Computer Aided Radar Performance Evaluation Tool
CFAR	Constant False Alarm Rate
CORDIC	COordinate Rotation Digital Computer
COSRO	Conical Scan-on-Receiver Only
COTS	Commercial Off The Shelf
CRI	Coherent Repeater Interference
CRLB	Cramer-Rao Lower Bound
CUT	Cell Under Test
CW	Continuous Wave
DAC	Digital-to-Analogue Converter
DAR	Digital Array Radar
DECM	Deceptive ECM
DF	Direction Finding
DoA	Direction of Arrival
Dof	Degree of freedom
DRFM	Digital Radio Frequency Memory
DToA	Difference Time of Arrival
EM	Electromagnetic
EA	Electronic Attack
ECCM	Electronic Counter-Counter Measure
ECM	Electronic Counter Measure
ELINT	ELectronic INTelligence
EMCON	EMission CONtrol
EP	Electronic Protection
ERP	Effective Radiated Power
ES	Electronic Support
ESM	Electronic warfare Support Measure
EW	Electronic Warfare
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Arrays
FTC	Fast Time Constant
GA	Genetic Algorithm
GSLC	Generalized Side Lobe Canceler
HOJ	Home On Jam
HF	High Frequency
IF	Intermediate Frequency
IMM	Interacting Multiple Model
ISAR	Inverse Synthetic Aperture Radar
JCR	Jammer Cancellation Ratio
JDoA	Jammer Direction of Arrival
JNR	Jammer-to-Noise Ratio
LORO	Lobing-On-Receive Only
LPI	Low Probability of Intercept
MBC	Main Beam Canceler
MEM	Maximum Entropy Method
ML	Maximum Likelihood
MTD	Moving Target Detector
MTI	Moving Target Indicator

NLI	Noise Like Interference
OTH	Over The Horizon
PAR	Phased-Array Radar
PDR	Phase Difference Rate
PDW	Pulse Description Word
Penaids	Penetration Aid Decoy
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PSLR	Peak-to-Side Lobe Ratio
RCS	Radar Cross Section
RF	Radio Frequency
RFI	Radio Frequency Interference
RFM	Range Filter Map
RGPO	Range Gate Pull Off
RWR	Radar Warning Receiver
Rms	Root Mean Square
RWS	Radar Work Station
RX	Receiver
SAR	Synthetic Aperture Radar
SAW	Surface Acoustic Wave
SINR	Signal-to-Interference plus Noise Ratio
SLB	SideLobe Blanking
SLC	SideLobe Canceler
SNR	Signal-to-Noise Ratio
SOJ	Stand Off Jammer
SP	Self-Protection
SSJ	Self-Screening Jammer
STAP	Space-Time Adaptive Processing
STT	Single Target Tracker
ToA	Time of Arrival
TSI	Terrain Scattered Interference
TV-SAP	Time-Varying Spatial Adaptive Processing
TWS	Track While Scan
UHF	Ultra High Frequency
ULA	Uniform Linear Array
VGPO	Velocity Gate Pull Off
VHF	Very High Frequency
VLSI	Very Large Scale Integration

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