CHAPTER 9
ELECTRONIC COUNTER-COUNTERMEASURES

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9.1 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 systems for surveillance, weapon control, communication, and navigation. Electronic countermeasures (ECM) are likely to be taken by hostile forces to degrade the effectiveness of electromagnetic systems. As a direct consequence, electromagnetic systems are more and more frequently equipped with so-called electronic counter-countermeasures (ECCM) to ensure effective use of the electromagnetic 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 9.2 starts with a recall of the definitions pertaining to EW and ECCM. The topic of radar signals interception by EW devices is introduced in Sec. 9.3; the first strategy to be adopted by radar designers is to try to avoid interception by the opponent electronic devices. Section 9.4 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 (Secs. 9.6 through 9.10), a classification is attempted in Sec. 9.5. 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 which cannot be classified as electronic, such as human factors, methods of radar operation, and radar deployment tactics (Sec. 9.10).

The ensuing Sec. 9.11 shows the application of the aforementioned techniques to the two most common radar families, namely, surveillance and tracking radars. The main design principles (e.g., selection of transmitter power, frequency, and antenna gain) as dictated by the ECM threat are also discussed in some detail.

The chapter ends with an approach to the problem of evaluating the efficacy of ECCM and ECM techniques (Sec. 9.12). 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 also be taken into account by calculating the radar range recovery.

9.2 TERMINOLOGY

Electronic warfare is defined as a military action involving the use of electromagnetic energy to determine, exploit, reduce, or prevent radar use of the electromagnetic spectrum.[3–6] EW is organized into two major categories: electronic warfare support measures (ESM) and electronic countermeasures (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.[3,6,7]

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

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.[3,6,8]

9.3 ELECTRONIC WARFARE SUPPORT MEASURES

ESM is based on the use of intercept or warning receivers and relies heavily on a previously compiled directory of both tactical and strategic electronic intelligence (ELINT).[4,9,10] ESM is entirely passive, being confined to identification and location of radiated signals. Radar interception, which is of particular interest in this section, is based on the information gleaned from analysis of the signals transmitted by radar systems. The scenario in which ESM should operate is generally crowded with pulsed radar signals: figures of 500,000 to 1 million pulses per second (pps) are frequently quoted in the literature.[4] The train of interleaved pulses is processed in the ESM receiver to identify for each pulse the center frequency, amplitude, pulse width, time of arrival (TOA), and bearing. This information is then input to a pulse-sort processor which deinterleaves the pulses into the pulse repetition interval (PRI) appropriate to each emitter. Further comparison against a store of known radar types permits the generation of an emitter list classified with its tactical value. 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 probably the most important sorting parameter available to the deinterleaving process since the target bearing does not vary from pulse to pulse. A rotating directional antenna could be used for direction finding (DF); however, an interferometric system with more than one antenna is preferred because the probability of interception is higher than with the system having only one antenna.

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 and good frequency resolution.[4] 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). One method of overcoming this problem would be to use banks of contiguous receiver channels. This approach is today feasible owing to the availability of accurate surface acoustic-wave (SAW) filters and the integrated optic spectrum analyzer which utilizes the Bragg refraction of an optical guided beam by an SAW to perform spectral analysis.[4] 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 very 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.[4]

Radar intercept receivers are implemented at varying levels of complexity. The simplest is the radar warning receiver (RWR), which in an airborne installation advises of the presence of threats such as a missile radar, supplying the relative bearing on a cockpit-based display. It is an unsophisticated low-sensitivity equipment which is preset to cover the bandwidth of expected threats, and it exploits the range advantage to indicate the threat before it comes into firing range. Receivers then increase in complexity through tactical ESM to the full ELINT (intelligence-gathering) capability. The specification of an ideal ELINT receiver for today's applications demands an instantaneous frequency coverage of 0.01 to 40 GHz, a sensitivity of better than −60 dBm, an instantaneous dynamic range greater than 60 dB, and a frequency resolution of 1 to 5 MHz. A diversity of signals, such as pulsed, CW, frequency-agile, PRI-agile, and intrapulse-modulated (chirp, multiphase-shift-keyed, etc.), must all be accommodated with a high probability of intercept (POI) and a low false-alarm rate (FAR).[4]

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 at the RWR:

$$\left(\frac{S}{N}\right)_{\text{at RWR}} = \left(\frac{P}{4\pi R^2}\right) G_t \left(\frac{G_r \lambda^2}{4\pi}\right)\left(\frac{1}{kT_S B}\right)\frac{1}{L} \tag{9.1}$$

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 (9.1) 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 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.[10]

9.4 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.

ECM tactics and techniques may be classified in a number of ways, i.e., by main purpose, whether active or passive, by deployment-employment, by platform, by victim radar, or by a combination of them.[8,11] An encyclopedia of ECM tactics and techniques can be found in the literature.[8,12] Here it is intended to limit description 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 noiselike 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.[8] 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.[8]

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 which impedes the detection and recognition of useful signals and determination of their parameters. The most common forms of active noise jamming are spot 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 wide band 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 which require no prime power. The chaff is made of elemental passive reflectors or absorbers which 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.[8] 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.[4,12–14] Chaff consists of dipoles cut to approximately a half wavelength of the radar frequency. It is usually packaged in cartridges which contain a broad range of dipole lengths designed to be effective over a wide frequency band. From a radar viewpoint, the properties of chaff are very similar to those of weather clutter, except that its broadband frequency capability extends 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.[12]

Decoys, which are another type of passive ECM, are a class of physically small radar targets whose radar cross sections 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.

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 continuous-wave (CW) signals for the purpose of misleading in the interpretation or use of information by electronic systems.[8] The categories of deception are manipulative and imitative. *Manipulative* implies the alteration of friendly electromagnetic signals to accomplish deception, while *imitative* consists of introducing radiation into radar channels which imitates a hostile emission. DECM is also divided into *transponders* and *repeaters*.[12] Transponders generate noncoherent signals which emulate the temporal characteristics of the actual radar return. Repeaters generate coherent returns which 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).[12]

The most common type of deception jammer is the range-gate stealer, whose function is to pull 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 jammer signal, being stronger than the radar's return signal, captures the range-tracking circuits. The deception signal is then progressively delayed in the jammer by using an RF memory, thereby "walking" the range gate off the actual target (range-gate pull-off, or 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.[12]

Another DECM technique is called *inverse-gain jamming*; it is used to capture the angle-tracking circuits of a conical-scan tracking radar.[8] This technique repeats a replica of the received signal with an induced amplitude modulation which 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.[12]

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.

In the deployment-employment of ECM, five classes can be singled out.[12] In the standoff 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. Standoff ECM systems employ high-power noise jamming which 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 which 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 which might be directed against the jammer radiations.[12]

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.

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 (RPVs) might be practical. RPVs 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.

According to the platform, the jammer can be classified as space-borne, airborne, missile-borne, based on the ground, or based on the sea surface.

A special class of missile-borne threat is the antiradiation 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; afterwards 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, 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, and accuracy in locating the victim radar is affected by the limited dimension of the ARM antenna.

9.5 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: (1) electronic techniques (Secs. 9.6–9.9) and (2) operational doctrines (Sec. 9.10). Specific electronic techniques take place in the main radar subsystems, namely, the antenna, transmitter, receiver, and signal processor. Suitable blending of these ECCM techniques can be implemented in the surveillance and tracking radars, as discussed in Sec. 9.11.

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.[3,15] Many other references describe the ECCM problem, among which Refs. 13, 16, and 17 are worth noting.

9.6 ANTENNA-RELATED ECCM

Since 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, while 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. Increased angular resolution of jammers in the main beam can be reached by resorting to spectral analysis algorithms, commonly referred to as *superresolution* techniques. 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.[18] 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 percent 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.[19] In order to keep the beamwidth small with low sidelobes, a larger and more costly antenna is needed. Other design principles involved in low antenna sidelobes are the use of radar-absorbent material (RAM) 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 which 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 extremely difficult in arrays which 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 which 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. Future antenna development will yield −45 dB sidelobe antennas which do scan electronically.[12]

Two additional techniques to prevent jamming from entering through the radar's sidelobes are the so-called sidelobe blanking (SLB) and sidelobe cancelers (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.[17]

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.[15]

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.[20] However, limited benefits (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 entering the radar receiver via the antenna sidelobes.[21–24] 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. 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 9.1*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 Fig. 9.1*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 Fig. 9.1*b*). 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: (1) 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 hypoth-

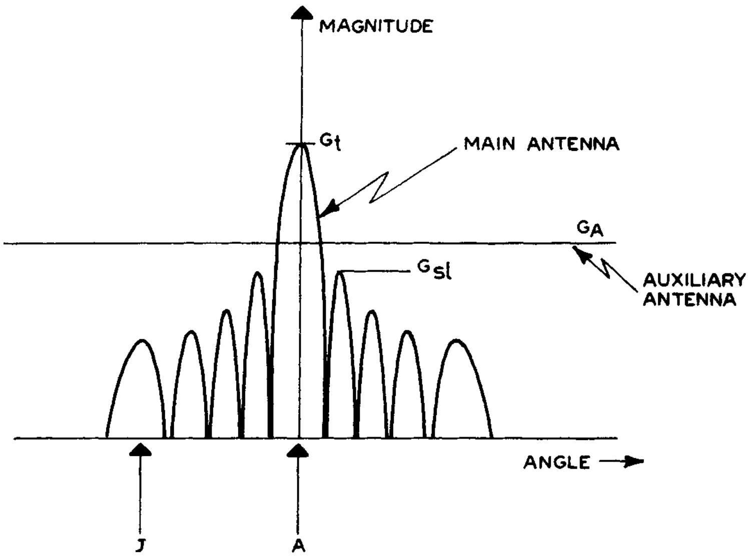

FIG. 9.1a Main and auxiliary antenna patterns for the SLB. (*From Ref. 21.*)

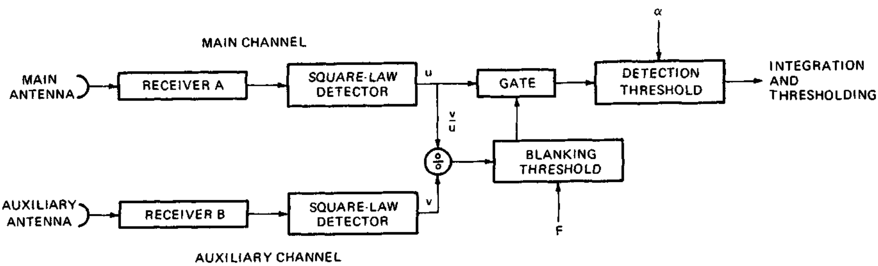

FIG. 9.1b Scheme of sidelobe-blanking system. (*From Ref. 21.*)

esis is true; P_B is a function of the jammer-to-noise ratio (JNR) value, the blanking threshold F, and the gain margin $\beta = G_A/G_{sl}$ of the auxiliary antenna with respect to the radar antenna sidelobes. (2) 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. (3) 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. (4) 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. (5) 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 some of these performance parameters can be found in the literature.[21,24]

The SLB design requires the selection of suitable values for the following parameters: (1) the gain margin β and then the gain w of the auxiliary antenna, (2) the blanking threshold F, and the normalized detection threshold α. The a priori known parameters are 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.

Sidelobe Canceler (SLC) System. The objective of the SLC is to suppress high duty cycle and noiselike interferences (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 direction of arrival 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.[25,26]

The conceptual scheme of an SLC system is shown in Fig. 9.2. 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 which 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 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 $\mathbf{W} = (W_1, W_2, \ldots, W_N)$. Jamming 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 the hypothesized linear combination of signals, it is advisable to resort to the techniques of linear prediction theory for stochastic processes.[27] 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 $\mathbf{M} = E(\mathbf{V}^*\mathbf{V}^T)$, where $E(.)$ denotes the statistical expectation, the asterisk * 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-

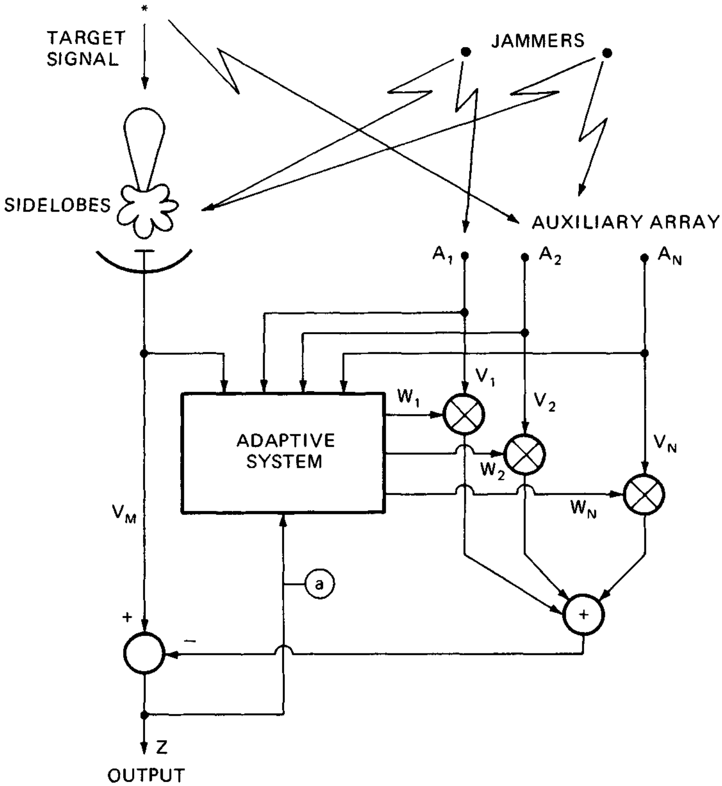

FIG. 9.2 Principle of SLC operation (connection *a* only in the closed-loop implementation techniques).

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:

$$P_Z = E\{\,|Z|^2\} = E\{|V_M - \hat{\mathbf{W}}^T\mathbf{V}|^2\} \tag{9.2}$$

where Z is the system output. It is found that the following fundamental equation applies:[27]

$$\hat{\mathbf{W}} = \mu\mathbf{M}^{-1}\mathbf{R} \tag{9.3}$$

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:

$$JCR = \frac{E\{|V_M|^2\}}{E\{|V_M - \hat{\mathbf{W}}^T\mathbf{V}|^2\}} = \frac{E\{|V_M|^2\}}{E\{|V_M|^2\} - \mathbf{R}^T\mathbf{M}^{-1}\mathbf{R}^*} \tag{9.4}$$

By applying Eqs. (9.3) and (9.4) to the simple case of one auxiliary antenna and one jammer, the following results are easily found:

$$\hat{W} = \frac{E\{V_M V_A^*\}}{E\{|V_A|^2\}} \triangleq \rho \qquad JCR = \frac{1}{1 - |\rho|^2} \tag{9.5}$$

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. (9.3)] is essentially related to the real-time estimation of **M** and **R** and to the inversion of **M**. Several processing schemes have been conceived which may be classified in two main categories: (1) closed-loop techniques, in which the output residue (connection *a* of Fig. 9.2) 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 **V**. Broadly speaking, closed-loop methods are cheaper and simpler to implement than direct-solution methods.[27,28] By virtue of their self-correcting nature, they do not require components which have a wide dynamic range or a high degree of linearity, and so they are well suited to analog 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.[27,29] 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.

Practical considerations often limit the SLC nulling capabilities to JCR of about 20 to 30 dB, but their theoretical performance is potentially much higher.[30,31] Examples of possible limitations are listed below:[27]

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.[32,33]

2. The limited number of auxiliary channels adopted in a practical system as compared with the number of jamming signals.[32]

3. The limited bandwidth of the majority of the schemes implementing Eq. (9.3) as compared with the wide band of a barrage jammer which can be regarded as a cluster, spread in angle, of narrowband jammers.[28,30,34]

4. The pulse width which limits the reaction time of the adaptive system, in order to avoid the cancellation of target signal.[33]

5. The target signal in the auxiliary array which may result in nonnegligible steering of the auxiliaries toward the main-beam direction.[33]

6. The presence of clutter which, if not properly removed, may capture the adaptive system, giving rise to nulls along directions different from those of the jammers.

7. The tradeoff which has to be sought between the accuracy of weights estimation and the reaction time of the adaptive system.

8. The quantization and processing accuracy in the digital implementation.

Adaptive Arrays. An adaptive array (Fig. 9.3) is a collection of N antennas, feeding a weighting and summing network, with automatic signal-dependent weight adjustment to reduce the effect of unwanted signals and/or 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.[28,34–40] The adaptive array is a generalization of the SLC system concept described in the preceding subsection. The basic theory of jammer cancellation and target enhancement is considered first, and attention is then focused on the use of adaptive arrays to obtain superresolution capabilities which can be of help for ECCM. The implementation of the adaptive array concept is more and more related to digital beamforming technology.[41–43]

Jammer Cancellation and Target Signal Enhancement. Adaptive array principles have found a thorough mathematical treatment since the early 1970s.[40] The basic result is given by the expression of the optimum set of weights:

$$\mathbf{W} = \mu \mathbf{M}^{-1}\mathbf{S}^* \tag{9.6}$$

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. (9.6) to Eq. (9.3) 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 (i.e., the set of received

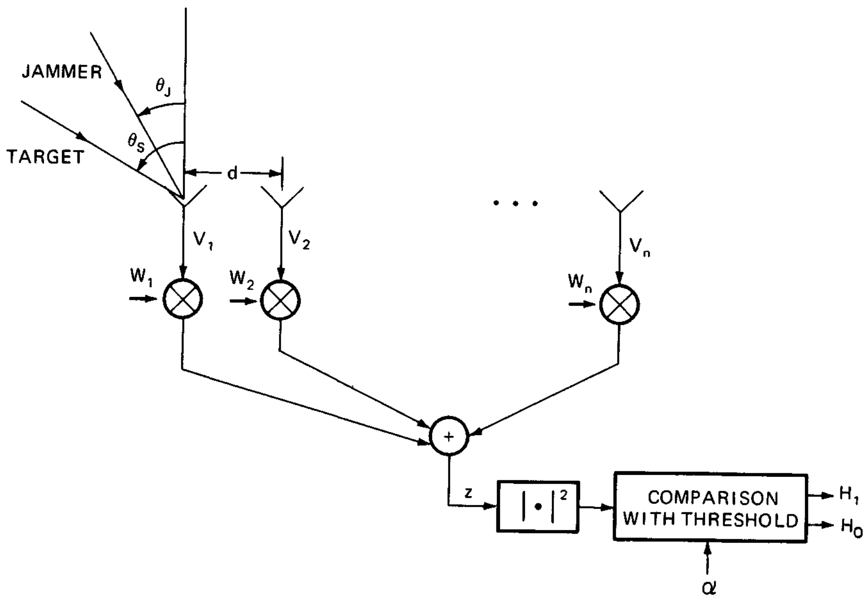

FIG. 9.3 The adaptive array scheme.

pulses from each antenna of the array) to the enhancement of the target signal and to the cancellation of clutter, chaff, and jammer.

Several generalizations of the basic theory have been considered, including: (1) the target model S is not known a priori, as it is assumed in deriving Eq. (9.6); (2) in addition to spatial filtering, doppler filtering is performed to cancel clutter and chaff; and (3) the radar platform is moving as in airborne and shipborne applications.

The detection probability P_D for the optimum filter of Eq. (9.6) is:[40]

$$P_D = Q\left(\sqrt{\mathbf{S}^T\mathbf{M}^{-1}\mathbf{S}^*}, \sqrt{2 \ln 1/P_{FA}}\right) \tag{9.7}$$

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. (9.6) provides the maximum value of the improvement factor I_f, which is defined as follows:

$$I_f = \frac{\text{signal-to-interference power ratio at the output}}{\text{signal-to-interference power ratio at the input}} \tag{9.8}$$

The signal-to-interference power ratio $(SNR)_I$ at the input is measured at the input of an antenna of the array and refers to one echo pulse. The I_f value corresponding to the optimum set of weights of Eq. (9.6) is[40]

$$I_f = \frac{\mathbf{S}^T\mathbf{M}^{-1}\mathbf{S}^*}{(\mathrm{SNR})_\mathrm{I}} \tag{9.9}$$

The I_f is better suited than the cancellation ratio, adopted in the SLC, to represent the performance of the adaptive array. In fact, in the latter case the useful signal is integrated while the interference is canceled.

The implementation of an adaptive array has been limited to experimental systems with a small number of antennas (say, 10), so that the matrix inversion can be handled by practical computing systems.[44,45] 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 which form the inputs of the adaptive processor. Careful selection of the subgroup elements is necessary to avoid grating lobes.[46,47]

Other simplifications of the fully adaptive array are deterministic spatial filtering and phase-only nulling techniques. In the first case, 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.[48] The idea of phase-only nulling in phased array antennas is appealing because the phase shifters are already available as part of the beam-steering system. Hence, if the same phase shifters can be employed for the dual purposes of beam steering and adaptive nulling of unwanted interferences, costly retrofitting could be unnecessary. However, phase-only null synthesis presents analytic and computational difficulties not present when both the amplitude and the phase of the element weights can be freely perturbed.[49,50] Nevertheless, experimental systems have been tested with success.[51–53]

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 signal-to-thermal noise ratio, an adaptive array antenna may achieve a narrower *adaptive beamwidth*, giving a sharper bearing estimation of the incident wave. This is important for ECCM purposes: very accurate strobes of the jammers can be obtained. It is also possible to measure the source strength and to obtain a spatial spectrum pattern without sidelobes. The estimated angles of the jammers can be used to form beams in the jammer directions, which are used as auxiliary channels for adaptive interference suppression.[54] The interference directions can also be used for deterministic nulling, which is of special interest for main-beam nulling.[55] 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 catalog the interference sources in order to properly react to them.

The superresolution concept was mainly developed and analyzed by W. F. Gabriel.[56] Different methods for bearing estimation were described by Gabriel and, subsequently, by other authors.[39,57–59] One is the maximum-entropy method (MEM). It works well with a Howells-Applebaum adaptive beamformer, which has an omnidirectional receiving pattern except where signals are present. The presence of signals is indicated by nulls in the receiving pattern. Since nulls are always sharper than antenna lobes, signal 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 points 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 are identical mathematically, use the same algorithms, and have identical hardware. 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 (superresolution of jammers).

The achievable degree of superresolution depends heavily on the way in which the algorithms are implemented. The required accuracy of signal quantization and the matching of channels are comparable with those of adaptive nulling. The heavy computational task required by the algorithms can be handled by resorting to systolic array processors.[60] Experiments indicate that the resolution limit is determined rather more by implementation factors like channel mismatching errors than by the pure *SNR*. Two incoherent sources separated by a quarter beamwidth seem to be the lower limit for superresolution with the current technology for achieving equality between the channels, offset compensation, equality of *I* and *Q* channel amplification, etc. Resolution is worse for more than two sources.[58]

9.7 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 defeating 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 which 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.[61–64] *Frequency agility* usually refers to the radar's ability to change the transmitter frequency on a pulse-to-pulse or 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 on a pulse-to-pulse basis. The frequency of the next pulse cannot generally be predicted from the frequency of the current pulse.[65] *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) 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.[15] Signals with wide instantaneous bandwidth exhibit considerable variation of the frequency within each transmitted pulse. A spread of about 10 percent of the transmitter center frequency can be proper. Three of the more common coded-pulse waveforms are recalled: (1) the linear frequency-modulated signal, where the carrier frequency is varied linearly within the pulse; (2) the frequency-shift-coded signal, where the carrier frequency is changed in a stepwise fashion within the pulse; and (3) the phase-coded signal, in which the phase of the RF carrier is shifted at a rate equal to the bandwidth of the waveform.

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.[12,29] Waveform coding includes pulse-repetition-frequency (PRF) jitter, PRF stagger, and, perhaps, shaping of the transmitted radar pulse. All these techniques make 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, they give assurance of maximum range performance against 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).[64,66]

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 which is blanked by main-beam jamming and also provides a strobe in the direction of the jammer. Strobes from two or three spatially separated radars allow the jammer to be located.

9.8 RECEIVER-RELATED ECCM

Jamming signals that survive the antenna ECCM expedients can, if large enough, saturate the radar processing chain. Saturation results in the virtual elimination of information about targets. Wide dynamic range (i.e., log and lin-log) receivers are normally used to avoid saturation.

Other special processing circuits can be used in the radar to avoid saturation, i.e., fast-time-constant (FTC) devices, automatic gain control (AGC), and constant-false-alarm rate (CFAR).[3,15,17] 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 display. 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. CFAR is a technique made necessary because of the limitations of the computer in automatic systems. It prevents the computer from being overloaded by lowering the capability of the radar to detect desired targets. In conclusion, these devices have a place in the radar but not as means for fighting the ECM battle.

A log (logarithmic) 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 is useful in preventing receiver saturation in the presence of variable intensities of jamming noise, rain, clutter, and chaff. Log receivers have the ECCM advantage of permitting the radar receiver to detect target returns that are larger than jamming noise, chaff, or clutter levels. By comparison with a linear receiver of low dynamic range, moderate jamming noise levels will normally cause the display to saturate so that the target signal will not be detected. However, the disadvantage lies in the fact that low-level jamming signals will be amplified more than higher-level target signals, thereby reducing the signal-to-jamming ratio and allowing a low-level noise jammer to be more effective. Another 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 (moving-target indicator) or pulse doppler radar if the spectrum of clutter echoes were to spread into the spectral region in which target returns were expected.[13,15]

In a lin-log (linear-logarithmic) receiver the output signal amplitude is closely proportional to the logarithm of the envelope of the RF input signal amplitude for high input signal amplitudes, while the output signal amplitude is directly proportional to the envelope of the RF input signal amplitude for low input signal am-