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The vulnerability of an airborne early warning (AEW) system against stand-off noise jamming (SOJ)

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THE VULNERABILITY OF AN AIRBORNE EARLY WARNING (AEW) SYSTEM AGAINST STAND-OFF NOISE JAMMING (SOJ)

by

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Based on the lessons learned from the Falkland War, an airborne early warning (AEW) system's importance is fully appreciated, and many countries field the AEW system to be a force multiplier for their air defense system. In this thesis, the AEW system's vulnerability, the sensitivity of each factor dominating the AEW system's detection range under hostile jamming, and the effect of stand-off noise jamming (SOJ) impacting the AEW system's detection range are evaluated using a simulation model to explore the AEW system's susceptibility and detection range degradation in a realistic combat environment.

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ABSTRACT

Based on the lessons learned from the Falkland War, an airborne early warning (AEW) system's importance is fully appreciated, and many countries field the AEW system to be a force multiplier for their air defense system. In this thesis, the AEW system's vulnerability, the sensitivity of each factor dominating the AEW system's detection range under hostile jamming, and the effect of stand-off noise jamming (SOJ) impacting the AEW system's detection range are evaluated using a simulation model to explore the AEW system's susceptibility and detection range degradation in a realistic combat environment.

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I. INTRODUCTION

A. OBJECTIVES AND PROBLEM STATEMENT

Based on lessons learned from the Falkland War (1982), the Bekaa Valley Conflict (1982) and the Persian Gulf War (1990-1991), the importance of Airborne Early Warning (AEW) systems have been confirmed. On the other hand, this mobile airborne radar surveillance system is, like any other electronic system, also subject to electronic attack (EA), previously called electronic countermeasures (ECM), and this thesis investigates the vulnerability of such systems.

In this thesis, a simulation model is used to determine the vulnerability of an AEW system, the sensitivity of each factor dominating the AEW system's detection range under hostile jamming, and the effect of stand-off noise jamming (SOJ) impacting the AEW system's detection range.

Related electronic attack operation tactics, jamming techniques, AEW systems' features, and electronic protection (EP), previously called electronic counter-counter measures (ECCM), characteristics are described for synthesizing simulation scenarios. Different penetrating patterns are set to identify the degradation of the AEW's detection range performance in a realistic combat environment.

The term AEW, as used in this thesis, describes an airborne surveillance system with the function of locating air targets at long range. Some of the hypothetical parameters used in the simulation model were provided by Grumman Aircraft Company, the manufacturer of the E-2C *Hawkeye*. The simulation results provided in this thesis represent general AEW capabilities, and are not intended to represent those of the E2-C.

The purpose of this thesis is to examine the impact of SOJ on the performance of an AEW system. This is achieved through the use of a simulation. The simulation model reveals that SOJ is capable of impeding an AEW system's detection range significantly. If the AEW system is not equipped with enough sidelobe cancellers (SLC), the degradation problem will jeopardize the AEW system's ability to fulfill its mission. The number of sidelobe cancellers that can be installed in an AEW system is highly restricted by limited space (even large ground and fighting ship systems, such as the *Patriot* deploy only five SLC arrays; and *Aegis* class cruiser carries only six SLC arrays) (Schleher, 1986). The SOJ system is supposed to jam the victim radar from the sidelobes. Mainlobe jamming can occur, however, if the SOJ is aligned with the victim radar's mainlobe. A well-planned SOJ operation will address issues of placement and availability (quantity) of equipment, so that a corridor can be created in the AEW system for the ingress of a strike force.

B. AEW SYSTEM BACKGROUND

In 1945, the US Navy first placed an AN/APS-20 radar in the TBM-3W *Avenger* (a torpedo bomber designed by Grumman) in order to compliment ground-based air search radars' capabilities in detecting distant fast moving, low-altitude airborne targets. The AEW system provides additional capabilities by detecting targets shielded by earth surface curvature masking.

Ground-based radar systems can detect and track airborne targets in medium and high altitudes. Distant low-altitude aircraft, however, are masked by the terrain, preventing them from being detected. On the other hand, an AEW is primarily designed to detect airborne targets at all altitudes. As a secondary mission, it is also capable of detecting maritime ships and ground targets through strong surface clutter.

During the Persian Gulf War, AEW systems were proven to be an indispensable force multiplier. The United States Air Force (USAF) E-3 *Sentry* flew more than 400 missions and logged over 5,000 hours of on-station time conducting surveillance and command and control missions for nearly 120,000 coalition sorties. In addition, the E-3 controllers assisted in 38 of 40 air-to-air kills recorded during the air campaign. (US Air Force, 1992)

The US Navy's E-2C directed both combat air patrol (CAP) and land attack missions over the Kuwaiti and Iraqi theaters. The E-2C also provided real-time information to air operations commanders, helping them to gain and maintain control of the air. The E-2C guided fighters to intercept Iraqi combat aircraft and resulted in the downing of two Iraqi MiG-21 fighters in the Kuwaiti theater of operations (KTO). (US Navy, 1992)

By contrast, the Falkland Islands War demonstrated how a military situation can deteriorate in the absence of AEW support. The United Kingdom's (UK) naval task force, led by the aircraft carrier HMS *Invincible*, was unable to obtain badly needed battlefield surveillance information, resulting in heavy losses from joint air attacks by the Argentine Air Force (using the A-4 *Skyhawk*) and Navy (using the *Super Etendard*). Both the A-4 and the *Super Etendard* flew at low altitude (a "sea-skimming" approach) to avoid being detected by surface-based early warning radar. These tactics were effective in retarding the British air defense response, leading to the sinking of the *Sheffield*, *Atlantic Conveyor*, *Ardent*, and several other ships.

In recent years, more and more countries are using AEW systems to enhance their early warning and surveillance capabilities. Countering the AEW system has become a practical issue that must be resolved before formulating any air penetration strike plan. Basically the AEW system is a mobile radar system loitering in the sky, so any EA technique, whether ground or airborne, affects the AEW system.

A commonly used EA tactic is to employ stand-off noise jamming (SOJ) to saturate or deceive the AEW system. SOJ generally operates through the AEW system's sidelobes in order to mask the attack echelons penetrating into target areas, but is also effective in the main beam of an AEW system.

For the purpose of increasing the operational survivability and effectiveness, in addition to minimizing susceptibility, the AEW system uses various EP techniques, such as ultra-low/low sidelobe antenna, sidelobe blanker, sidelobe canceller, adaptive phased array antenna, frequency/PRF agility, and burnthrough mode, to prevent SOJ from degrading its detection ability.

In the following chapters, different EA and EP techniques are discussed and analyzed to explore the vulnerability of the AEW system from the SOJ system.

II. AEW SYSTEM VERSUS STAND-OFF JAMMING (SOJ) SYSTEM

A. FEATURES OF STAND-OFF JAMMING (SOJ)

1. Electronic Attack (EA) Operational Tactics Selection

The four basic options for EA operational tactics are:

- Stand-forward jamming
- Escort jamming
- Self-screening jamming (SSJ)
- Stand-off jamming (SOJ)

a) Stand-forward Jamming

In stand-forward jamming, the jammer is deployed in front of the attack echelon to jam the enemy's search and tracking radar for the purpose of covering a follow-on attack. Unfortunately, the jammer has to fly fast enough to keep a leading position ahead of the attack echelon. This results in a reduced payload (lesser and smaller jammers in most cases)so that the jammer is forced to jam the victim radar from the mainlobe (needs lower effective radiated energy (ERP)), and also must carry a deceptive EA jammer (lighter weight) for self-protection.

Under the above mentioned limitations, the jammer is detected by the enemy's radar (jamming an enemy radar from the mainlobe generates a strobe which reveals the jammer's azimuth position), causing the jammer to fall into the surface-to-air missile's (SAM) lethal coverage area. In the event that the jammer is destroyed, the whole strike force would be exposed to the enemy's air defense systems.

b) Escort Jamming

In escort jamming, the jammer accompanies the attack echelon into the target area through the entire mission. Accordingly, the escort jammer has the same limitations and vulnerability as stand-forward jamming, but is more effective, due to the proximity of the jammer to the attack echelon.

Usually, the escort jammer focuses its attention on the enemy's acquisition radar to screen the strike aircraft from SAM systems by denying acquisition. Basically, the jammer goes with the strike force in close formation and attempts to jam enemy radar with mainlobe and sidelobe jamming.

From an operational survivability point of view, both the jammer and the attack element are highly vulnerable. In addition, the jammer's capabilities may be curtailed due to payload limitation, which will jeopardize the whole task force in a high density threat environment (multi-layer-deployed air defense networks).

c) Self-screening Jamming (SSJ)

A self-screening jammer is carried by the strike aircraft while conducting penetration strike, interdiction, close air support (CAS) and suppression of enemy air defense (SEAD) missions. The function of SSJ is to protect the strike aircraft from being acquired and tracked by enemy terminal defense systems.

SSJ system must be able to handle multiple threats simultaneously against most lethal point defense systems like surface-to-air missile (SAM) and radar guided anti-aircraft artillery (AAA) in a widely spread electromagnetic (EM) spectrum (probably from 70 MHz to 20 GHz). (Schleher, 1986)

It is impractical for a tactical fighter-bomber to carry enough transmitters to jam all potential threats or to carry jamming power with enough frequency range to cover the potential threats' EM spectrum. The only solution is to use deceptive jamming directed at the victim radar's mainlobe, easing the required jamming power needs, and to concentrate on the enemy's tracking radar. SSJ also suffers from a penalty in payload capacity, electric power, cooling, increased aerodynamic drags (both induced and parasitic drag) and degraded maneuverability.

d) Stand-off Jamming (SOJ)

Stand-off jamming is accomplished using large aircraft with a dedicated EA mission. The SOJ aircraft can accommodate many heavy jammers and does not go with the strike force into the combat zone. Instead, the SOJ aircraft loiters in a racetrack pattern out of the enemy weapon systems' lethal range, injecting noise jamming signals into the victim radars' sidelobes for saturating, obscuring, deceiving, and degrading enemy radars' detection capabilities.

The objective for jamming a search radar from the sidelobes is to make a large sector of the indicator (the PPI display) unusable by masking targets in azimuths or generating false targets to mislead the enemy's air interception operation.

Usually, the SOJ aircraft is also equipped with adequate electronic support (ES) receivers to locate the potential victims and measure their EM parameters. In addition, the on-board computer will assess the related targets, allocate the jamming resources and manage the jamming (such as power management, time sharing, look-through jamming) in order to effectively neutralize enemy radars.

2. Advantage of Stand-off Jamming

Unlike other EA tactics (stand-forward, self-screening and escort jamming), the SOJ platform remains completely out of the enemy's air defense weapon system and anti-radiation missile (ARM) lethal range. It primarily radiates jamming signals into the enemy radars' sidelobes to protect friendly penetrating strike echelon which are at different ranges and azimuths than the SOJ aircraft.

The intended victims of the SOJ are the acquisition radars (air search radars), rather than those tracking radars used by terminal point defense systems, since the basic function of the SOJ is to open a safe corridor within the enemy's air search radar networks by curtailing their detection range allowing an opening for strike penetrations.

The SOJ needs large amounts of jamming power to achieve the same jamming effects as escort jamming due to the much longer operating range (typically, 30-100 nmi away from the victim radars) as compared with other jamming operations. Maneuverability is not a critical requirement for the SOJ jammer carrier, enabling the use of heavier aircraft.

Typical SOJ aircraft, like the EA-6B *Prowler* and EF-111 *Raven* can carry a large amount of pod mounted jammer transmitters, which cover several different frequency bands so that they can cover almost all hostile radar systems. Such systems use frequencies that are widely spread in different EM bands. The multi-target jamming capability of the SOJ is an important advantage, which allows operations in a high threat density battlefield.

SOJ provides high duty-cycle CW noise jamming for masking purposes and smart deception low duty-cycle pulsed noise jamming to mislead enemy interception in both wrong directions and areas. It is a necessary compliment to self-protection jamming and anti-radiation missiles in the suppression of enemy air defense systems.

3. Noise Injection into Sidelobes

Antenna sidelobes are one of the most serious weaknesses in the radar system in terms of electronic protection (EP). They provide a path for jamming and electromagnetic interference (EMI) to enter the radar system aggravating system performance significantly.

Since the antenna represents the transducer between the radar and the environment, it is the first line of defense against hostile jamming. The space discrimination capability of a radar system is determined by antenna coverage, scan control, mainbeam width, and sidelobe controls (low sidelobes).

As to directivity of the radar antenna, antenna designers do their best to concentrate all outgoing radiated energy through the mainbeam surrounding the boresight to get the best target discrimination and detection capabilities. In the real world, however, these goals cannot be completely met, due to sidelobes located on either side of the mainlobe and even in the backside of the mainlobe (backlobe).

The desired radiation pattern focuses all of the transmitted energy into a narrow beam (mainlobe only), whereby the power is uniformly distributed just like a flashlight on an imaginary screen in the sky which would illuminate a single round spot with uniform intensity. An antenna's sidelobes are not limited to the forward hemisphere and, in fact, they extend in all directions, even to the rear.

For a uniformly illuminated rectangular aperture, such as that used in AEW radars, the gain of the strongest (first) sidelobe is about 13.5 dB less than that of the mainlobe (Skolnik, 1990), while the second sidelobe is about 20 dB less than that of the mainlobe. Typically, 25 percent of the total power is radiated by the sidelobes due to inefficiencies in the antenna (Edde, 1993). The sidelobes not only waste transmitted power in undesired directions but also increase the susceptibility of the radar to jamming. Interference from a powerful jammer into the sidelobes can be stronger than the echoes of small or distant targets in the mainlobe, resulting in the loss of desired targets.

The radar system will present these strong jamming signals coming from the sidelobes in the mainlobe direction on the display (angular deception), which obscures targets on the radar screen, thereby preventing track of the intended targets.

Without adequate EP techniques, the AEW system radar detection capability will be significantly affected by sidelobe jamming. Sidelobe handling is a critical concern in an AEW system's operational effectiveness (detectivity) and survivability (and anti-radiation missile (ARM) can home in on sidelobe radiation toward the AEW platform). In addition, sidelobe return (sidelobe clutter) degrades airborne radar system performance substantially.

Owing to the above mentioned reasons, sidelobes represent a major area of vulnerability to the AEW system.

B. AEW SYSTEM CHARACTERISTICS

1. Function of AEW System

Sir Winston Churchill said that "three things played decisive roles in winning the Battle of Britain: the RAF pilots, the *Spitfire* Fighter, and Radar." (Stimson, 1983). The importance of the radar system in air defense was obviously expressed. Based on lessons learned from the Falkland Islands War, the British Navy modified the Searchwater marine radar (installing a larger antenna and revised target processing algorithms) and integrated it into the S-3 *Sea King* Helicopter to fill the Airborne Early Warning and Control gap. In the Bekaa Valley, the Israeli Air Force fully utilized an AEW system (E2-C) and EA operation, creating a brilliant air-to-air kill ratio (87:0). From the above it can be seen that the importance of the AEW system is fully confirmed and battle proven.

AEW systems have been used as a command, control, communication, and intelligence (C^3I) force multiplier in air-to-air and air-to-surface (ground and sea) operations. The role of the AEW system in a typical modern war is addressed in the following paragraphs.

a) Air Defense Functions

As an air defense tool, the AEW system detects, identifies, classifies, and tracks all friendly and hostile air targets. As noted previously, the ability of radar systems to fulfill the air defense role is enhanced when mounted in airborne platforms, as opposed to the ground.

b) Command Functions

AEW systems also serve as a logical command center in the direction of CAP, offensive counter air (OCA), and defensive counter air (DCA) operations, as well as management of support task force elements (refueling tanker, EA aircraft, ES aircraft and combat search and rescue (SAR) efforts. A more direct combat role is played by the AEW system when it is the source of clearance for firing beyond visual range (BVR) missiles in long to medium range air-to-air engagements and serving as a forward deployed air command post.

c) Control Functions

The modern AEW system provides control functions to air operations in a variety of ways. Strike aircraft receive clearance to enter and exit battle zones, and penetration and maritime strike missions are monitored from, AEW systems in the relevant operational theater. AEW systems play a more direct combat role in guiding battlefield air interdiction (BAI), close air support (CAS), and suppression of enemy air defense (SEAD) missions. Additionally, strategic and tactical airlift and reconnaissance flights are accomplished using AEW systems on station to provide checkpoint information. Friendly aircraft are alerted to threats by the AEW system, which is also used to coordinate aerial refueling and for air traffic control.

d) Communication Functions

In air operations taking place over a wide geographic area, the AEW system serves as a communications relay between distant air task forces and their commands and support elements. When friendly forces from different commands rendezvous for joint operations, AEW systems in the area provide communications and coordination as elements enter the area of operations.

e) Intelligence Functions

The presence of an AEW system makes it possible to survey all air, sea, and ground vehicle traffic in a given area. This allows the provision of real-time information to theater commanders and decision-makers. Early warning of enemy activity provides key intelligence to battlefield commanders. The AEW system also fulfills an electronic support (ES/ESM) function.

2. AEW System Electronic Protection (EP) Implementation

The AEW system is designed to perform its surveillance mission in a highly hostile environment against possible adversaries that will utilize EA to enhance their penetration capability. The major EA threats against an AEW system are (1) noise jamming, (2) deception jamming, (3) chaff, (4) decoys and expendables, and (5) anti-radiation missiles (ARM). The possible EA counter-measures against the AEW system initiated by the adversary are focused on the following aspects of AEW operations (Farina, 1992):

- Denial of detection
- Operator confusion or deception
- Delay in detection or tracking initiation
- Tracking of an invalid target
- Overloading the computer (excessive number of false targets)
- Denial of measurement of target position and range rate
- Target tracking loss
- Errors in values of target position and range rate
- Target tracking loss
- Errors in values of target position and range rate

On the other hand, the AEW system will also utilize all available on-board EP equipment to secure their detection and tracking mission even under a severe EA situation against both single or a combination of denial and deceptive EA techniques.

The AEW system EP actions are as follows (Chrzanowski, 1990):

- Prevention of receiver saturation
- Constant false alarm rate (CFAR)
- Enhancement of S/J ratio
- Directional interference discrimination
- Rejection of false targets
- Maintenance of track

EP techniques utilized in AEW systems are discussed in the following paragraphs.

a) Transmitter Electronic Protection (EP) Techniques

(1) Frequency Agility (FA). Frequency agility complicates radar signal interception and identification by hostile ES/ESM systems and dilutes hostile jamming effectiveness. If the AEW system uses frequency agility transmitting, it will cause the enemy jammer to spread its jamming power over a much wider bandwidth (switching from spot jamming to barrage jamming), thus lowering jamming power density and effectiveness at any given time and frequency.

Frequency agility can be implemented on the basis of pulse-to-pulse, scan-to-scan, or burst-to-burst, depending on the system's capabilities and limitations. However, as a result of long coherent integration periods needed to facilitate the airborne moving target indicator (AMTI) and coherent integration functions used in the E-2C system, it does not use the frequency agility technique. From the EP standpoint, pulse-to-pulse frequency agility is the most effective way to counter jamming. The needed coherent integration time and the requirement for suppression of surface clutter make fully random pulse-to-pulse frequency agility impractical for use in AEW systems (Neri, 1991).

A possible compromise can be made by setting a predetermined fixed frequencies bank over a certain frequency range in which the transmitting frequency is chosen randomly; and then using a special memory to store each return in the appropriate Doppler bin for subsequent Doppler processing. This technique, however, is generally too complicated for application to practical systems.

(2) PRF Agility. The AEW radar's PRF should be able to change (PRF jittering/switching/staggering) in response to the EA situation and targets' maneuvering status. Switching the PRF not only deals with the target's Doppler frequency in different aspects (blind speeds) and velocities (high and low, opening and closing), but also enhances the effectiveness of radar frequency agility against EA.

The combination of exerting both PRF and frequency agility enhances the AEW systems survivability in a severe hostile jamming environment. The use of PRF agility, however, is still governed by some limitations (if the system is subject to long coherent processing intervals it will not be able to effectively apply PRF agility) (Winnefeld, 1994).

(3) Waveform. The AEW radar waveform can provide a very powerful EP capability. For example, spread spectrum (a wide bandwidth random waveform) can greatly complicate hostile electronic support (ES) system operation and also reduce the effectiveness of hostile jamming by forcing the jammer to spread its power over a wider bandwidth (Thomas, 1987).

Spread spectrum countermeasures make the AEW system more complicated, but the results are fruitful – especially in preventing an ARM from hitting the AEW platform and also by degrading the enemy's jamming capability.

(4) Pulse Compression. Pulse compression is a technique whereby long coded pulses (expanded pulse) are transmitted, allowing a higher average power output that improves signal-to-noise ratio while processing the received echo into a narrow pulse (compressed wave). This provides high range resolution consistent with the bandwidth of the transmitted pulse.

Pulse compression was applied by Germany in World War II as an electronic counter-measure against chaff. Owing to its good range resolution, the pulse compression technique permits discrimination of target echoes from chaff in some situations (chaff has long been used to provide corridor masking real targets and in generating false targets). In addition, pulse compression can allow targets in close formation to be discriminated from each other.

Significant advances in digital and surface-acoustic-wave delay (SAW) structure techniques allow the implementation of more exotic signal waveforms such as nonlinear FM. However, the most commonly used pulse compression waveforms are still linear-FM and phase-coded signals. AEW systems use pulse compression to improve the detection capability in noise jamming (higher S/J ratio), discriminate targets within close formation, and counter chaff operation. Pulse compression is fully compatible with Doppler processing techniques used to discriminate against clutter.

b) Antenna EP.

(1) Beamwidth. In a chaff environment, the AEW radar antenna beamwidth should be as small as possible in both azimuth and elevation to reduce the chaff illumination volume. Monopulse reception techniques provide some additional EP capabilities through the resulting beam sharpening.

If a jammer injects jamming power into the radar's mainlobe, any attack echelon within the main antenna's lobe will probably be masked. However, if the jammer is located on the target to be shielded, then it becomes susceptible to home-on-jam counter jamming techniques. This inhibits the use of noise jamming in deceptive self-protection jammers and increases the vulnerability of Escort and stand-forward jamming tactics. In SOJ, the main beam response is generally blended, creating a corridor of protection. This favors high frequency radar operation with associated narrow mainbeam radar beamwidths.

(2) Polarization Agility. Polarization agility may reduce the effectiveness of certain EA techniques. Many jammers employ circular polarization for handling different types of polarization (horizontal or vertical) used by the victim radars.

If possible, variable polarization should be provided in the AEW radar for altering its polarization, which might reduce the received jamming signal. If the radar transmits circular polarization and the receiver can receive several polarizations, one particular polarization may be found to provide an improvement in J/S ratio. In general, both target and clutter polarization characteristics may affect the results. Owing to the system and operational limitations, most AEW systems probably lack the flexibility of polarization agility. If the radar's received polarization can be adjusted to be orthogonal to the jammers polarization, substantial jamming energy is rejected.

(3) Low/Ultra-low Sidelobe Antenna (ULSA). Low sidelobe antennas and ultra-low sidelobe antennas are achieved through controlled antenna illumination functions, avoiding aperture blockage as well as careful manufacturing and handling.

The choice of the antenna illumination function is critical. With reflector antennas, the designer can only control the illumination function in the design of the feed. With arrays, newer modeling techniques allow good control of aperture illumination, so most low sidelobe antennas are arrays, but their bandwidths are limited. Recent work on reflector antennas has provided wide bandwidth, low sidelobe antennas.

Aperture blockage is another major concern in antenna sidelobe suppression techniques, and should be taken into account in antenna design. Near-field blockages external to the antenna, such as masts, poles, and guard railings have the same effect on sidelobes as blockages attached to the antenna (such as feeds and struts). As far as aperture blockage is concerned, array antennas are better than those using reflector type antennas. Surface smoothness in the case of reflectors, and phase control in arrays, significantly affect sidelobe levels. In phase-steered antennas, phase control granularity plays a major role in determining sidelobes. For this reason, newer phase-steered arrays tend toward finer control of phase-shifters (i.e., higher number of bits in distant phase control).

An ULSA antenna can eliminate some impacts caused by sidelobes. However, this sidelobe suppression method results in some penalties, such as a lowered gain and wider beam (reducing some range resolution and EP capabilities). Roughly speaking, the standard antenna's peak sidelobe could be -13 to -30 dB less than the mainlobe gain; in a low sidelobe antenna, the peak sidelobe is about -30 to -40 dB less (Schleher, 1986), while an ultra-low sidelobe antenna's first sidelobe would be -40 to -70 dB less. In addition, a traditional method to reduce sidelobes is to increase the size of the antenna aperture. However, the AEW system is subject to space limitations. The decision to employ such methods should consider the expected mission capabilities, available technology, and limitations of the platform.

(4) Sidelobe Blanker (SLB). The sidelobe blanker was originally used by radar for screening out electromagnetic interference (EMI) from nearby friendly radar, which entered through antenna sidelobes. Designers utilize the SLB to cope with low duty-cycle deceptive jammers (like the false target generator, or spoofer). Basically, the SLB can blank pulsed noise signal, but is ineffective against high-duty cycle continuous wave (CW) noise jamming.

The SLB system is useful in preventing acquisition of strong targets in the antenna sidelobes, and also for rejecting pulsed interference (jamming signal) in the sidelobes.

From the EP point of view, returns detected in the mainlobe are the only desired signal, which is then further processed and displayed on the radar scope. Besides, any signal received from the sidelobes should be rejected in order to avoid being deceived by the intended hostile jamming signals or interfered with by strong sidelobe clutter.

To achieve this screening function, the SLB system is composed of a guard (auxiliary) antenna, a sidelobe blanking receiver and a comparator. The gain of the guard antenna is less than that of the mainlobe of the radar primary antenna but bigger than the radar antenna's sidelobes. By suitable comparison of signals in the main and guard channels, the system can distinguish whether signals come from the mainlobe or the sidelobes. The output of two independent receivers (main and sidelobe blanking) are sent to the comparator to decide whether to initiate the blanking logic unit. The comparison is made at each range bin for each pulse received and processed by the two parallel channels.

If the detected targets are within the mainlobe, a large signal in the main receiving channel and a small signal in the auxiliary receiving channel results. The blanking logic unit will allow this signal to pass for further signal processing. On the other hand, if the jammers are situated in the sidelobes, the guard antenna signal will be bigger than the mainlobe signal, and the logic unit will block this signal from passing to the next level of the signal analysis circuit.

(5) Sidelobe Canceller (SLC). The SLC is utilized to suppress high duty cycle jamming signals received through the antenna's sidelobes. At least one SLC cancellation loop and an omni-directional auxiliary antenna (it could also be shared with SLB) are required to deal with each jammer by creating an antenna null at the azimuth position where the jammer is located. The objective of the SLC is to eliminate high duty cycle noise jamming signals received through the sidelobes of the radar.

In many cases, the SLC system is used in conjunction with a SLB or a low sidelobe antenna to suppress the jamming signal from the radar scope. The

SLC's basic operational function is to equip the radar with an array of auxiliary antennas used to adaptively estimate the direction of arrival (DOA) and the jamming power of each jammer. The resulting step is to adjust the receiving pattern of the radar antenna, putting nulls in the jammer's direction to prevent the jamming signal from entering the signal processing unit. Some of the current SLC systems are built with digital technology, but the use of existing analog adaptive coherent sidelobe canceller (CSLC) is more practical.

The auxiliary antenna gains are designed to approximate the average sidelobe level of the main antenna gain pattern. The target signal received by the auxiliary antenna is weak compared to the signals received by the main channel. The target signal time duration is also much smaller than the SLC's adaptation time. Thus, the target signals will pass through the SLC, while the jamming signal, which is continuous in time, will be reduced through the adaptive process generated in the canceller.

The SLC can be implemented with a reflector type of antenna where the auxiliary antennas are dipoles on the periphery of the reflector. The auxiliary antennas can also be integrated into a phased-array antenna (using sub-arrays), but the electromagnetic coupling between antennas should be minimized to maintain low quiescent sidelobe level.

C. RECEIVER AND SIGNAL PROCESSING EP

The AEW system can be deployed in hostile areas (potential flash points), so the receiver and signal processing unit should be able to work well under the strong signal EA situation and in a strong clutter environment. Receivers must be designed to function in a very high signal level environment, on the order of 20 to 40 dB J/S (Morchin, 1990), to avoid being saturated or to prevent the formation of intermodulation products. The receiving system must recognize, identify and counter the incident interference (jamming) as well as to discriminate targets masked by terrain or ground/sea clutter.

Pre-detection filters should be installed ahead of the RF amplifier and mixer to screen out-of-band signals, thereby alleviating the signal processing load and easing desensitization problems. For accommodating transmitter's frequency agility, the receiver should be able to work in a wide bandwidth to follow each possible frequency change by the transmitter. An image rejection filter with a high dynamic range IF mixer is very important to prevent spurious signals from being generated in the receiver. Adding the capability of examining the jammer signals to find gaps in their transmitted spectrum and select the frequency with the least level of jamming enables the AEW system to gain a favorable situation against EA.

To prevent the receiver from being saturated by CW noise jamming, the receiver's dynamic range should be appropriately wide (linear receivers are suggested). In addition, to process clutter and chaff effectively, digital coherent signal processing (fixed or adaptive MTI) must be integrated into the system.

In adaptive MTI, a notch in the receiver response is adaptively placed at the center of the AEW ground/sea clutter or chaff Doppler frequency spectrum to separate the real targets from the clutter and chaff cloud.

A scenario using both chaff corridors and active jamming (false target and CW noise jamming) to obscure the attack force is highly possible in a modern deep strike air operation.

A dilemma is presented when the AEW system needs to handle both active and passive (chaff) jamming simultaneously. Pulse-to-pulse frequency agility is effective against active (deception and camouflage) jamming. However, Doppler-based MTI techniques, which are the key to eliminate chaff masking effects, need constant frequency and stable PRF.

Constant false alarm rate (CFAR) is required to avoid the receiver's video and system computer from being overloaded by noise pulses. Different types of CFAR are available, such as log, cell averaging, distribution-free, and Dicke fix CFAR.

Countermeasures and counter-countermeasures continually respond to each other. The AEW system's receiver and signal processing unit require continuous evaluation, with focus on new EA techniques for adding threshold circuits and logic elements to fend off jamming signals and ensure the detection function.

III. EVALUATION OF SOJ EFFECTIVENESS AGAINST THE AEW SYSTEM

A. SCENARIO AND PARAMETER SELECTION

1. Scenario Selection

For the purpose of enhancing jamming effectiveness, penetrators will generally be covered using several SOJ jammers that inject large amounts of noise jamming signals into the AEW system's sidelobes and mainlobes from different azimuths (the implementation scheme is shown in Figure 1). The AEW system is equipped with eight sidelobe cancellers (ideally, one cancellation loop can deal with each jammer). Due to the moving platform factor, wideband jamming, and multi-path effects, the required number of sidelobe cancellers (sidelobe cancellation loop) is about three times larger than the number of jammers to be suppressed (Schleher, 1986). If the number of jammers is less than four, the AEW system radar can theoretically put spatial nulls in the jammers' direction, thereby filtering out the jamming signal to minimize the effectiveness of the SOJ. If the jammers number more than three, the AEW system detection capabilities are degraded by the increased J/S ratio. The sidelobe cancellation system is not effective against jamming signals which enter the radar through its main antenna beam.

As to how much degradation can be achieved by the SOJ, one must examine how many jammers have been deployed by the SOJ operation, their ERP, how many sidelobe cancellers are being deployed, and the sidelobes' gain of the AEW system.

Simulation will be used to evaluate the effectiveness of SOJ against a hypothetical AEW system in the following scenarios:

- Situations using no SOJ jamming; to determine the AEW system's full detection range
- Situations using one to three SOJ jammers
- Situations using more than three SOJ jammers
- Situations using combined EA techniques
- Situations using self-screening jamming alone (only one SSJ jammer)
- Situations using SOJ to open a screening corridor

The simulation model calculates the AEW system's detection range in response to pre-planned scenarios. Since this thesis relies on unclassified information, all parameters used in this simulation are hypothetical values that provide a rough estimation of SOJ impacts on the AEW system's detection capabilities.

As noted previously, the purpose of this thesis is not to generate precise results in simulating the response of a particular AEW system against SOJ noise jamming, but rather to identify the vulnerabilities of the AEW system that could be exploited by a well-planned and fully-equipped adversary.

Highly accurate prediction values are not available from this conceptual model (due to the hypothetical nature of system parameters). The model will still provide a groundwork for realistic evaluations of real systems when real EA and EP tactics and techniques are fed into this model.

2. Parameter Selection

Parameters for simulation modeling are based on hypothetical values obtained from open sources and related unclassified data from manufacturers. These parameters are not intended to represent any fielded system, as the primary goal of the simulation is to present a picture of current technology and model the response of an AEW system subjected to SOJ. The chosen parameters for the AEW system are presented in Table 1, while Tables 2 and 3 present the parameters for the SOJ system and the boundary conditions for the simulation model, respectively. Figure 1 illustrates the relative positions of the AEW system, SOJ elements, and attack echelons.

Table 1. Hypothetical AEW System Parameter Values.

Nomenclature	Parameter Value	Remark
Transmitter Power (P_t)	Peak power: 2.5 MW	Average Power: 18.75 KW
Antenna Gain ($G_{R/t}$)	22.5 dB	177.8 Power Ratio
Antenna Scan Rate	6 rpm	Scan Rate=36°/sec
Pulse Repetition Frequency	300 HZ	PRF
Carrier Frequency (f_c)	425 MHZ ± 25 MHZ	UHF Band
Noise Figure (F_n)	3 dB	
System Loss (L_R)	6.0 dB	
Receiver Bandwidth	7.5 MHZ	B_r
3 dB Beamwidth (HPBW)	6.5°	
Sidelobe Gain ($G_{SL,\ 1st}$)	-5.5 dBi	First Sidelobe Gain
Averaged Sidelobe Gain	-15.5 dBi	G_{SL}, in free space
Frequency Agility (FA)	No frequency agility	
Receiving System Noise Temperature (T_S)	440° K	Includes Galactic Noise-150° Kelvin
Sidelobe Suppression	8 channel SLC and SLB	SLC: Sidelobe Canceller

Table 2. SOJ Parameter Values.

Nomenclature	Parameter Value	Remark
Transmitter Power (P_J)	1,500 Watts 200 Watts	for SOJ for SSJ
Jammer Antenna Gain (G_J)	3 dB	
Jammer System Loss (L_J)	7 dB	Including polarization loss, etc.
Jammer Bandwidth (B_J)	Spot: 5-20 MHZ Barrage: 50 MHZ	

Table 3. Boundary Conditions.

Nomenclature	Parameter Value	Remark
Target's Length	17.32 m	MiG-29 Fighter
Probability of Dectection (P_D)	90%	
False Alarm Rate (P_{fa})	10^{-6}	approximately one false alarm occurs each hour of operation
AEW Flying Altitude	25,000 ft	
Target's RCS	10 m^2	Typical Fighter-bomber

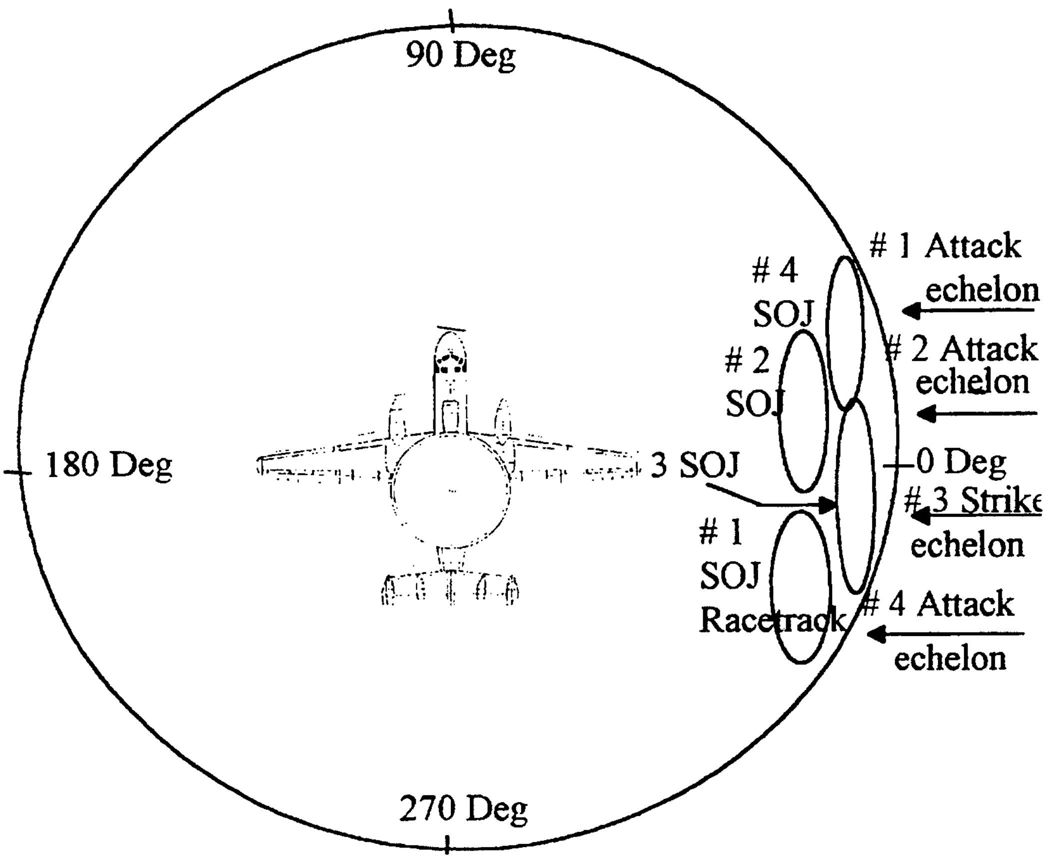

Figure 1. Penetration of AEW System using SOJ.

B. SIMULATION MODEL AND DATA GENERATION

The simulation code (RGJMAT) used was written by Professor D. Curtis Schleher of the Naval Postgraduate School using Quick Basic Code, based upon formulas in his book *Introduction to Electronic Warfare*. The code used Barton's and Alberhseim's methods for calculating visibility factors, S/N ratio, Swerling cases, and atmospheric and weather attenuation. Blake's method is applied to calculate the radar range equation, which then uses Newton's method to determine the range in atmospheric and weather attenuation. Jamming effects for a self-screening noise jammer and up to 10 stand-off jammers are included by combining the jammer power density with the system noise power density. The program allows radar detection range to be calculated for conventional, pulse compression, frequency agility, and pulsed Doppler radars.

Lt. Tim Rohrer, USN, converted Professor Schleher's Quick Basic Code to MATLAB Code and also completed a user's manual. A further reconfiguration and modification in input, output interfaces, display, and additional plotting function were made in the course of this work.

The simulation can handle steady and Swerling targets, atmospheric and weather attenuation, and SSJ and SOJ jamming techniques for conventional, frequency agility, and pulsed Doppler radar (PD).

The structure of the model is shown in Figure 2, and a flow chart of operations is presented in Figure 3. The building blocks of the model can be divided into eight parts, which include parameter input, subroutines, the main computation program, and the plotting program. Each of these components of the model is described in further detail below.

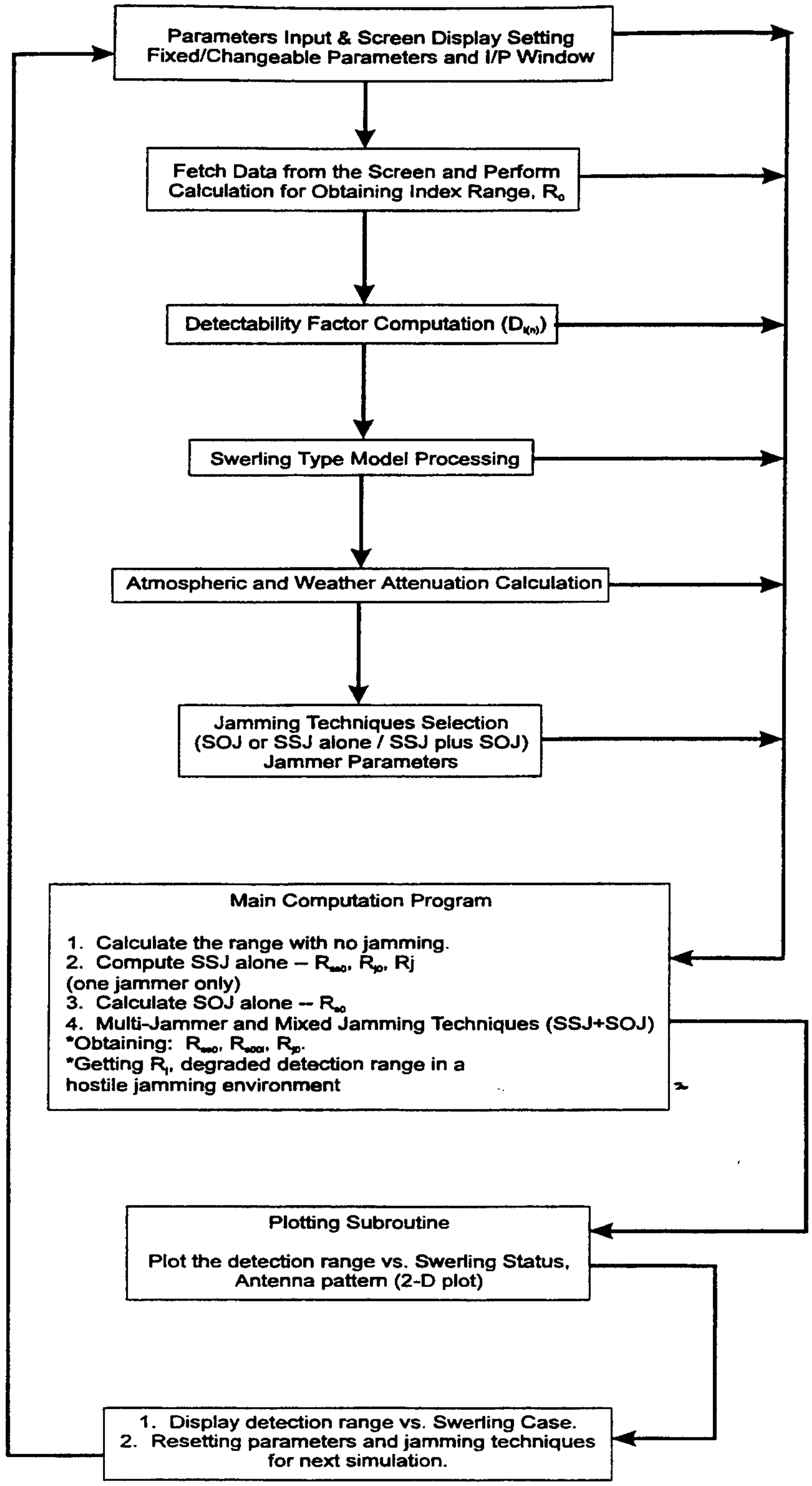

Figure 2. Simulation Structure Block Diagram.

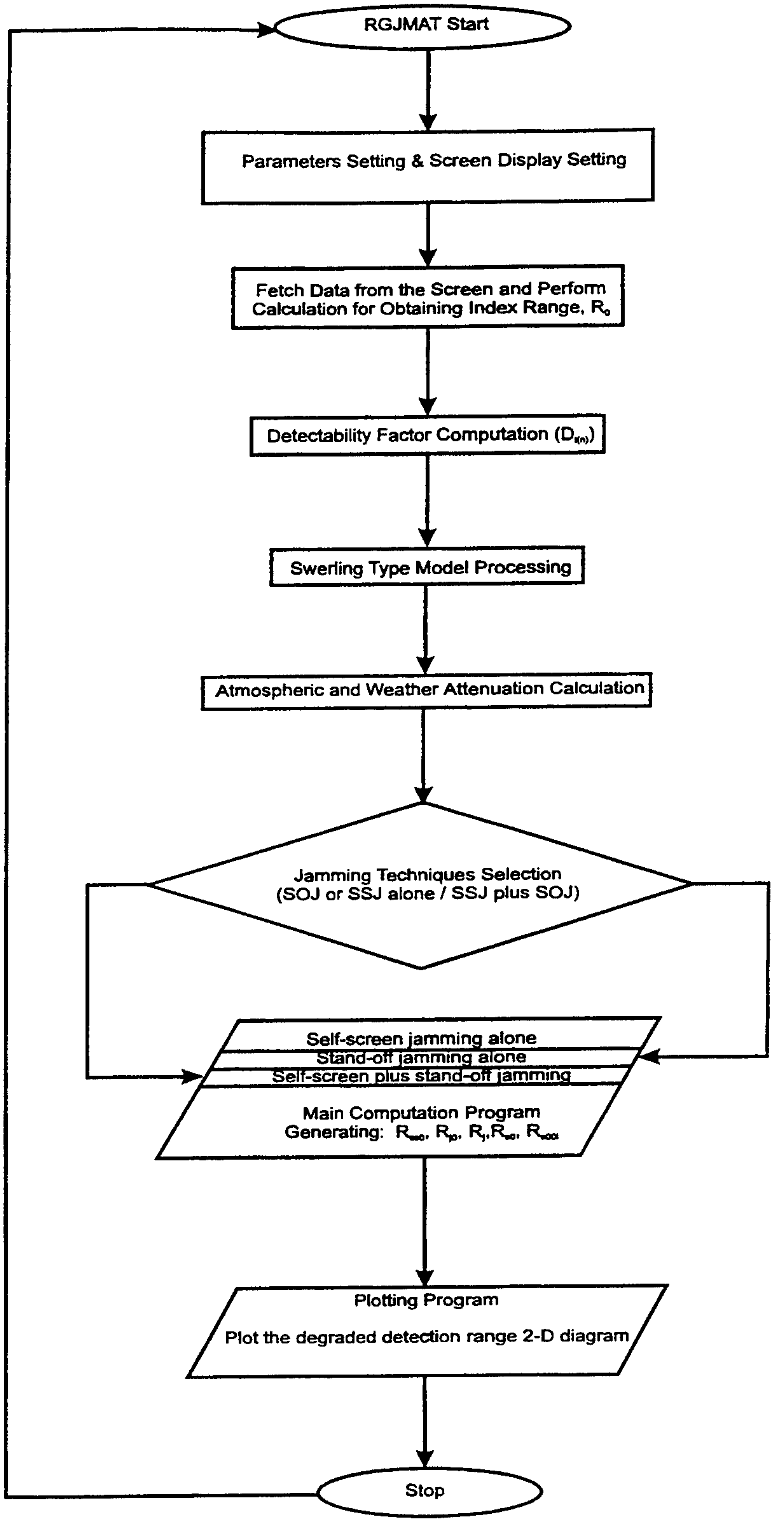

Figure 3. Simulation Flow Chart.

Parameter input requirements include both fixed and variable parameters. Fixed values are used for propagation constants, ambient temperature, rain and atmospheric attenuation tables, and system constants. Variable parameters for the AEW system include center frequency, pulse repetition frequency, pulse width, transmitter power, transmitter antenna gain, receiver antenna gain, antenna sidelobe gain, radar system loss, Doppler bandwidth, frequency agility bandwidth, antenna scan rate, half-power beamwidth, probability of detection, probability of false alarm, and noise figure. Variable parameters for the SOJ and SSJ systems include jammer power, antenna gain, system loss, elevation angle, height, selected technique, bandwidth (spot or barrage), the number of jammers, the target's radar cross-section (RCS) and length, and the rainfall rate.

The second part of the program is responsible for fetching parameters keyed in on the screen and for calculating the index range (free space clear detection range when S/N=1, R_0) for the follow-on manipulations.

The third part of the program calculates the detectability factor (S/N ratio), which is used to calculate the detection range based on the selected probabilities of detection and false alarms. The fourth part of the program is the Swerling model, which covers all type of target RCS fluctuations, including the effects of frequency agility.

The fifth part of the program is the atmospheric and weather attenuation subroutine, which calculates the attenuation caused by atmospheric and weather absorption. Attenuation is heavily dominated by the frequency chosen by the AEW system.

Jamming mode selection (SSJ/SOJ alone or SSJ+SOJ) is the sixth part of the program, and includes parameter selection for the various jamming options. The seventh element is the main part of the simulation model – the main computation program, which obtains the index range R_0, self-screening range R_{SS0} (S/J=1), R_{j0} (under SSJ and S/J=1), jammed detection range R_j (the degraded detection range caused by jamming in different Swerling cases), stand-off jamming detection range R_{S0} and degraded detection range due to the combined SSJ and SOJ jamming.

The last component is the plotting program. This includes 2-D schemes, which show the normalized theoretical AEW antenna pattern and degraded detection range in different Swerling cases. The results of this simulation model are shown on the screen as both a figure (2-D plot) and numerical data set (atmospheric attenuation, weather attenuation, and degraded detection range forms). In addition a new run could be started by resetting the parameters through the keyboard.

1. Simulation Model Description and Parameters

a) Determining the Index Range

The index range is the range at which S/N=1. At this range, there is no hostile jamming, or atmospheric or weather attenuation. The free space index range R_0 is given by

$$R_0 = 129.2 \times \left[\frac{P_{t(KW)} G_t G_r \tau_{(us)} \sigma}{f^2_{(MHz)} T_s L_R} \right]^{\frac{1}{4}}$$

Table 4 presents the baseline parameters used for the sensitivity analysis of the model. Substituting the parameters given in the table in the above equation results in a range of 363.51nmi.

The index range R_0 (S/N=1) is utilized for calculating R_{j0} and the jammer degraded detection range R_j and their relations where

$$R_{j0} = \frac{R_0}{\left[1+\left(\frac{R_0}{R_{SS0}}\right)^4 + \sum_{i=1}^{n}\left(\frac{R_0}{R_{S00i}}\right)^4\right]^{\frac{1}{4}}}$$

and

$$R_j = R_{j0} \cdot 10^{-D_i(n)/40}$$

b) Determining Key Drivers and Special Considerations

For the purpose of finding crucial factors in dominating the degradation, the simulation model was repeatedly run, and only one or two parameters were changed for each run in order to determine the interaction among the variables. The baseline is based upon the parameter values listed in Table 4, and the evaluating procedures are described in the following paragraphs.

(1) Baseline Comparison. A fixed baseline value set allows the examination of individual parameters' role in evaluating the AEW system detection performance. In order to get a better picture of this process, different increments and decrements were used for specified purposes (such as a G_{SL} value of -30 dB for an ultra-low sidelobe antenna, but 30% deviation is the typical case). In terms of deciding the baseline value and their deviations, both technical limitations and operational considerations have been taken into account in order to get this simulation as close as possible to real world situations.

Table 4. Baseline Parameters for Sensitivity Analysis.

P_t	2,500 KW
f_c	425 ±25 MHZ
Pulse Width	25 uSec
RCS	10 m^2
G_T	22.5 dB
G_R	22.5 dB
G_{SL}	-15.5 dB
F_n	3 dB
L_R	6 dB
PRF	300 PPS
HPBW	6.5°
P_D	0.9
P_{fa}	10^{-6}
BW_{DOPP}	18.75 HZ
BW_{FA}	0 (without frequency agility)
Antenna Rotation Speed	36°/sec
Elevation Angle	0°
Target Length	17.32 m (MiG-29)
SSJ (Boolean)	0
SOJ (Boolean)	1
P_J(SSJ)	200 W
G_J(SSJ)	0 dB
BW_{SSJ}	20 MHZ
L_J(SSJ)	7 dB
P_J(SOJ)	1,500 W
G_J(SOJ)	3 dB
BW_{SOJ}	7.5 MHZ (spot jamming) 50 MHZ (barrage jamming)
L_J(SOJ)	7 dB
H_J (Height)	25,000 ft
R_J (Jamming Range)	30 nmi
Number of jammers	3 (SOJ)
Rainfall	4 mm/hr
T_S	440° K

(2) Sensitivity Analysis. Table 5 contains results of modeling using different parameter values. The purpose of this comparison is to determine how sensitive the model results are to changes in specific parameter values. Changes in value for radar effective radiated power (P_TG_T, ERP), jammer ERP (P_JG_J), jammer bandwidth (spot or barrage jamming), jammer stand-off range (R_J), and radar transmitter-to-sidelobe gain ratio yield a greater impact on detection range than changes in other input parameters. The decision to use higher frequencies, which result in narrower beamwidth and lower sidelobes, and lower frequencies, which yield wider beamwidth and higher sidelobe levels, is a function of mission requirements.

(3) Key Drivers. Comparison of the values in Table 5 allows the determination of key variables in the model, that is, parameters for which changes in value represent significant changes in AEW systems detection range. The results of this tabular sensitivity analysis are in agreement with the equation for jamming range

$$R = R_j^{1/2}\left(\left(\frac{P_T G_T}{4\pi S_A}\right)\left(\frac{L_J}{L_R}\right)\left(\frac{\sigma}{P_J G_J}\right)\left(\frac{B_J}{B_R}\right)\left(\frac{G_T}{G_{SL}}\right)\right)^{1/4}$$

(4) Special Considerations. The hypothetical AEW system is equipped with 8 sidelobes cancellers (SLC) which can typically deal with 3 jammers while providing a G_{SL} of -15.5 dBi, thereby reducing jamming signals. The -15.5 dBi value for G_{SL} is derived as follows. It is assumed that the average sidelobe level (see Table 1) is degraded through installation in the aircraft by 10dB (ap Rhys, 1974). Further, a typical ground-based radar SLC processing gain of 20-30 dB (Schleher, 1986) is estimated to only provide 10 dB in this airborne installation due to multi-path factors,

platform motion, and polarization effects. If there are more than three jammers, the resulting G_{SL} will be -5.5 dB, as no additional cancellers are present and no more SLC processing advantage is available to suppress the jamming signals. According to the simulation model, as soon as the number 4 jammer is actuated, the detection range will drop from 62.21 nmi (three jammer case) to 32.56 nmi (four jammer case), thereby reducing the AEW system detection performance significantly.

Table 5. Sensitivity Analysis.

	P_T (KW)			G_T & G_R (dB)			G_{SL} (dB)		
Value	-30%	Baseline	+30%	-100%	Baseline	+100%	Test Value	Baseline	Test Value
	1,750	2,500	3,250	19.5	22.5	25.5	-5.5	-15.5	-30
R_J	56.91	62.21	66.43	44.04	62.21	87.88	34.99	62.21	139.89
	P_J			G_J (dB)			B_J (MHZ)		
Value	-30%	Baseline	+30%	-100%	Baseline	+100%	Spot Jam	Baseline	Barrage Jam
	1,050	1,500	1,950	0	3	6	7.5	20	50
R_J	68.02	62.21	58.26	73.94	62.21	52.35	40.96	62.21	78.61
	HP PW (Deg.)			R_J (nmi)			RCS (m^2)		
Value	-30%	Baseline	+30%	-50%	Baseline	+67%	-30%	Baseline	+30%
	4.55	6.5	8.45	20	30	50	7	10	13
R_J	57.95	62.21	65.43	50.61	62.21	80.84	56.91	62.21	66.43
	# of Jammers			H_J (ft)			Antenna Scan Rate (deg./sec.)		
Value	-66.7%	Baseline	+30%	-30%	Baseline	+30%	-30%	Baseline	+30%
	1	3	4	17,500	25,000	32,500	25	36	47
R_J	81.79	62.21	32.56	62.5	62.21	62.06	66.69	62.21	59.01

2. Simulation Results

a) Detection Ranges

The computer program, using the parameters for the hypothetical AEW system given in Table 1 provides a detection range of 242.17 nmi on a 10 m^2 Swerling 1 target. The Swerling 1 target is used since it represents the target fluctuations exhibited by a typical tactical fighter-bomber.

b) Situations using One to Three SOJ Jammers

In the presence of only one SOJ, the detection range is reduced from 242.17 nmi to 81.79 nmi. The SOJ influence in reducing the AEW system's detection performance is quite clear. The detection range performance for one to three SOJs is given in Figure 4 for cases 0-4.

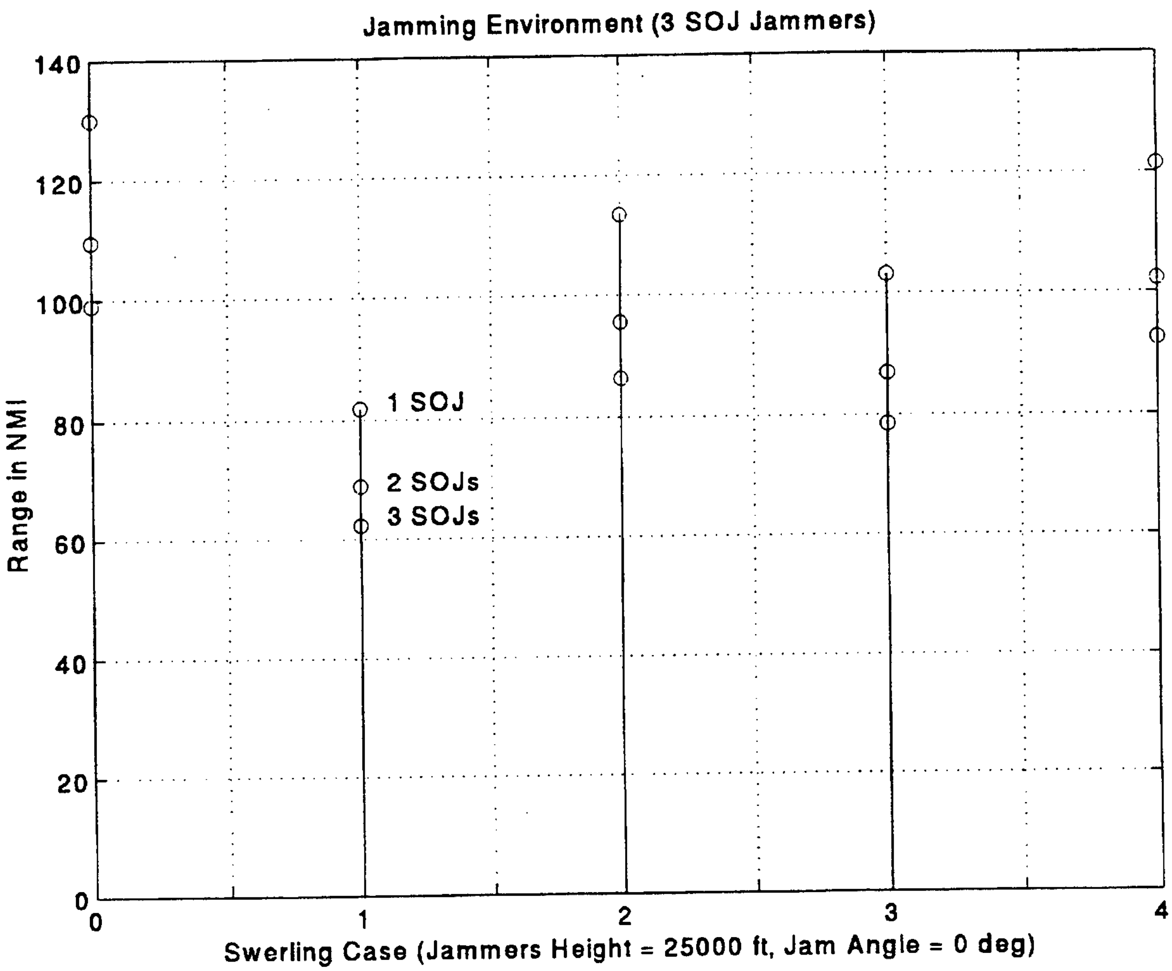

Figure 4. Detection Performance of AEW System in the Presence of One to Three Stand-off Jammers.

c) *Situations using Four SOJ Jammers*

The detection performance of the hypothetical AEW system with one to four SOJs is depicted in Figure 5. The fourth jammer is assumed to have no SLC processing, since all eight SLCs are occupied with processing the first three jammers. The detection range for this case is reduced to 32.56 nautical miles.

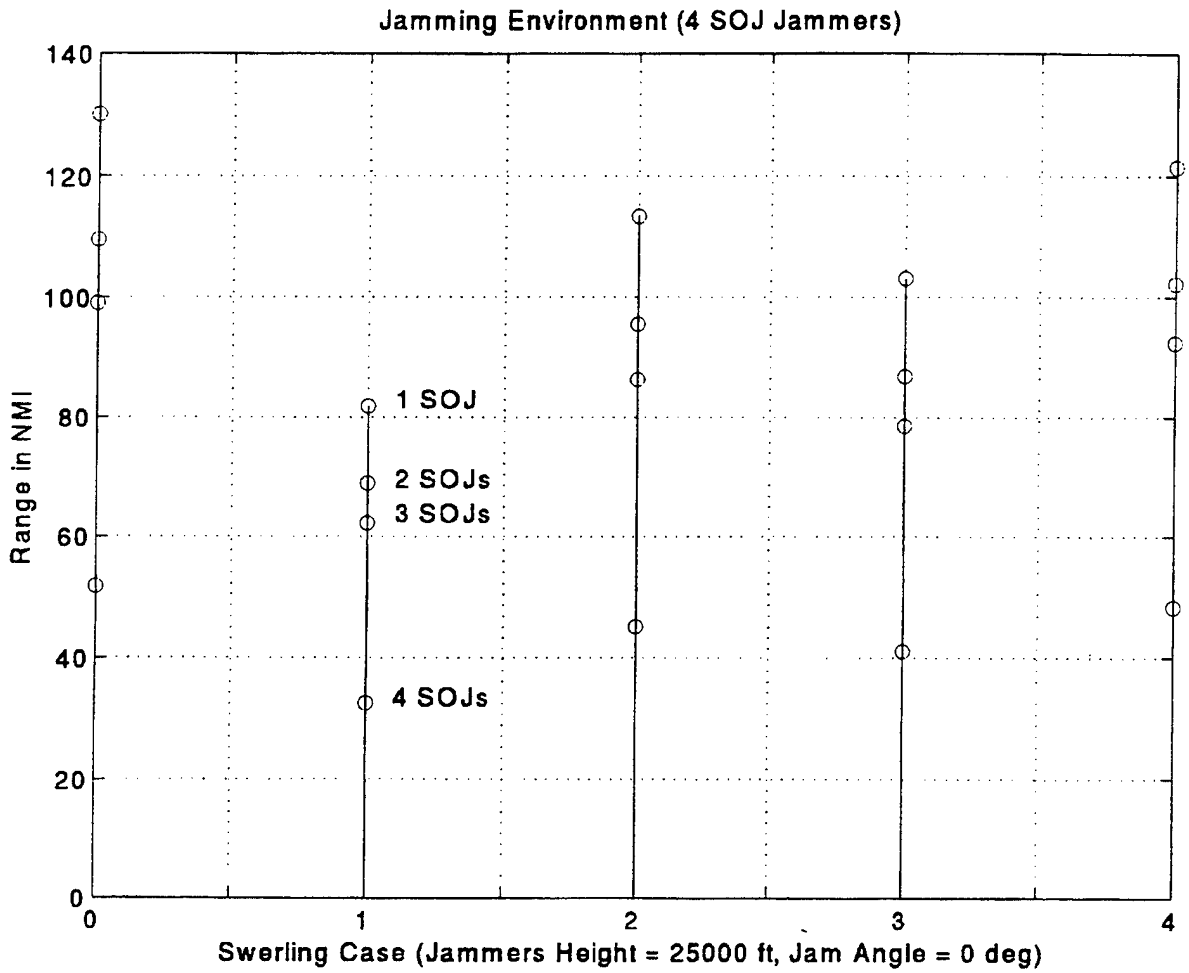

Figure 5. Detection Performance of AEW System in the Presence of One to Four Stand-off Jammers.

d) Self-Screening Jamming (One SSJ Jammer Only)

SSJ is applied through the victim radar's mainbeam at close-in range; therefore less ERP is required, as compared with SOJ jamming. A single SSJ jammer can degrade the AEW system's detection range to about 13.84 nmi. However, SSJ at these ranges is susceptible to home-on-jam attack, and is generally not tactically utilized.

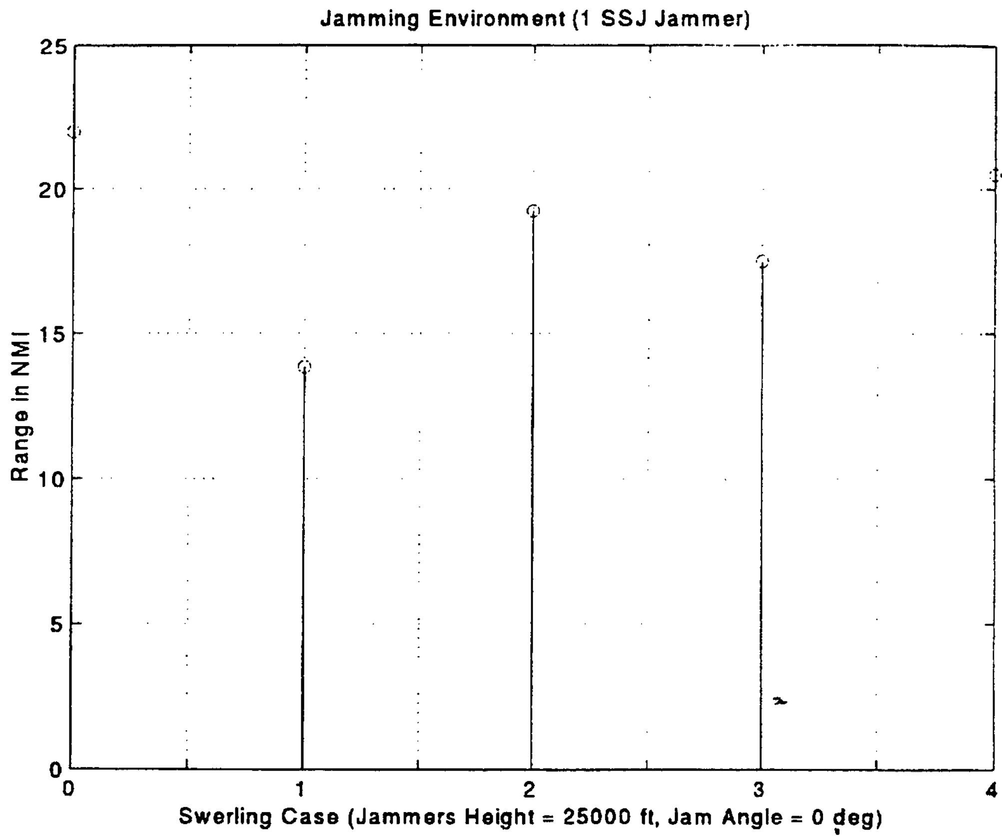

Figure 6. Detection Performance of AEW System in the Presence of Self-Screening Jamming (One SSJ Jammer Only).

e) Combined EA (Three SOJ and One SSJ)

As a result of joint EA, the AEW's detection range is further compressed, to 13.84 nmi, when a SSJ is used in conjunction with three SOJs. SSJ at these ranges, however, is not generally operationally practical, since the SSJ is subject to home-on-jam missile attack.

Table 6. Detection Range Degradation Under Various Jamming Conditions.

	Detection Range (R_J)	Remark
One SOJ alone	81.79	G_{SL}=-15.5 dBi
Three SOJs	62.21	G_{SL}=-15.5 dBi
Four SOJs	32.56	G_{SL}=-5.5 dBi for #4 SOJ
One SSJ plus three SOJs	13.84	SSJ jamming from mainlobe SOJ jamming from sidelobe SSJ dominates the combined EA operation due to mainlobe jamming
One SSJ alone	13.84	
• All values are for 10 m^2, Swerling 1 targets • P_J for SOJ's are 1,500 watts and 200 watts for SSJ		

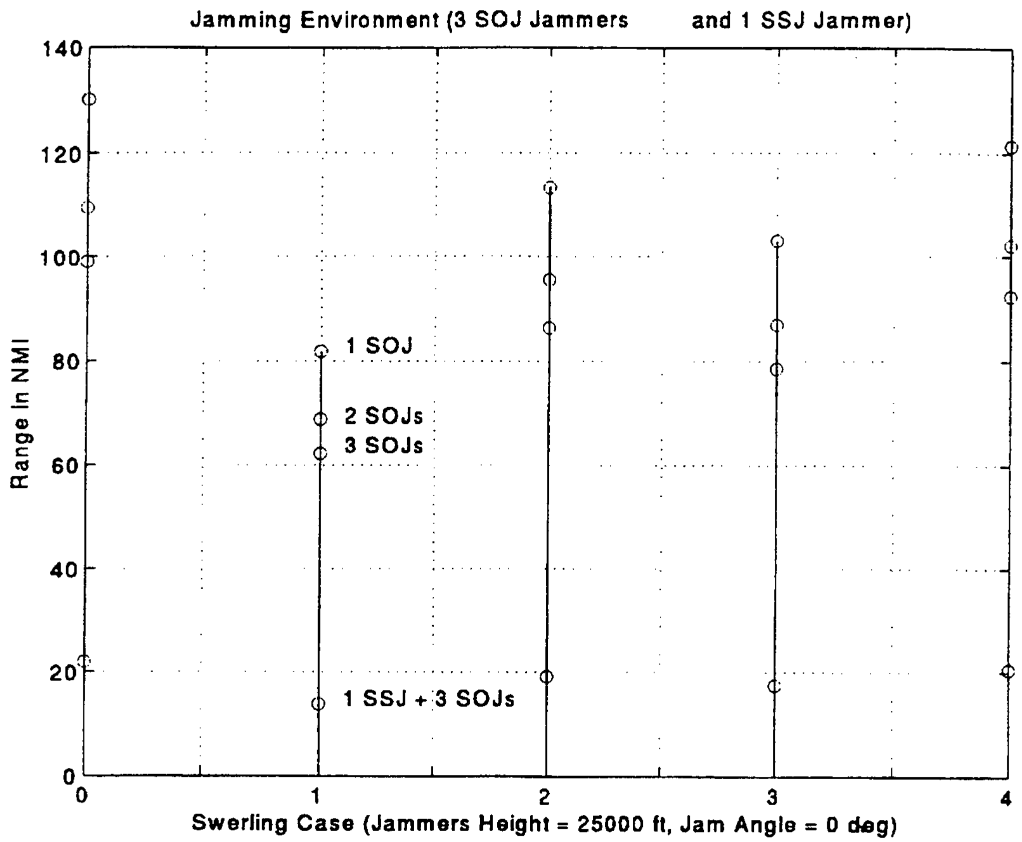

Figure 7. Detection Performance of AEW System in the Presence of Three SOJs and One SSJ.

f) Opening a Screening Corridor

One of the primary missions of SOJ operation is to create a corridor through the enemy's radar networks in order to conceal attack echelons from detection and in facilitating deep strike mission implementation. Figure 8 shows the hypothetical AEW system antenna pattern in free space.

By assuming a Gaussian shaped antenna beam pattern, as shown in Figure 9, it can be determined that the mainbeam beamwidth at the 28 dB point is about 20 degrees. This is the angular width through which mainbeam jamming severely degrades the AEW system's detection performance. This occurs whenever the main radar antenna beam points at the SOJ. A common jamming tactic is to cascade several SOJs to collectively create a jamming corridor.

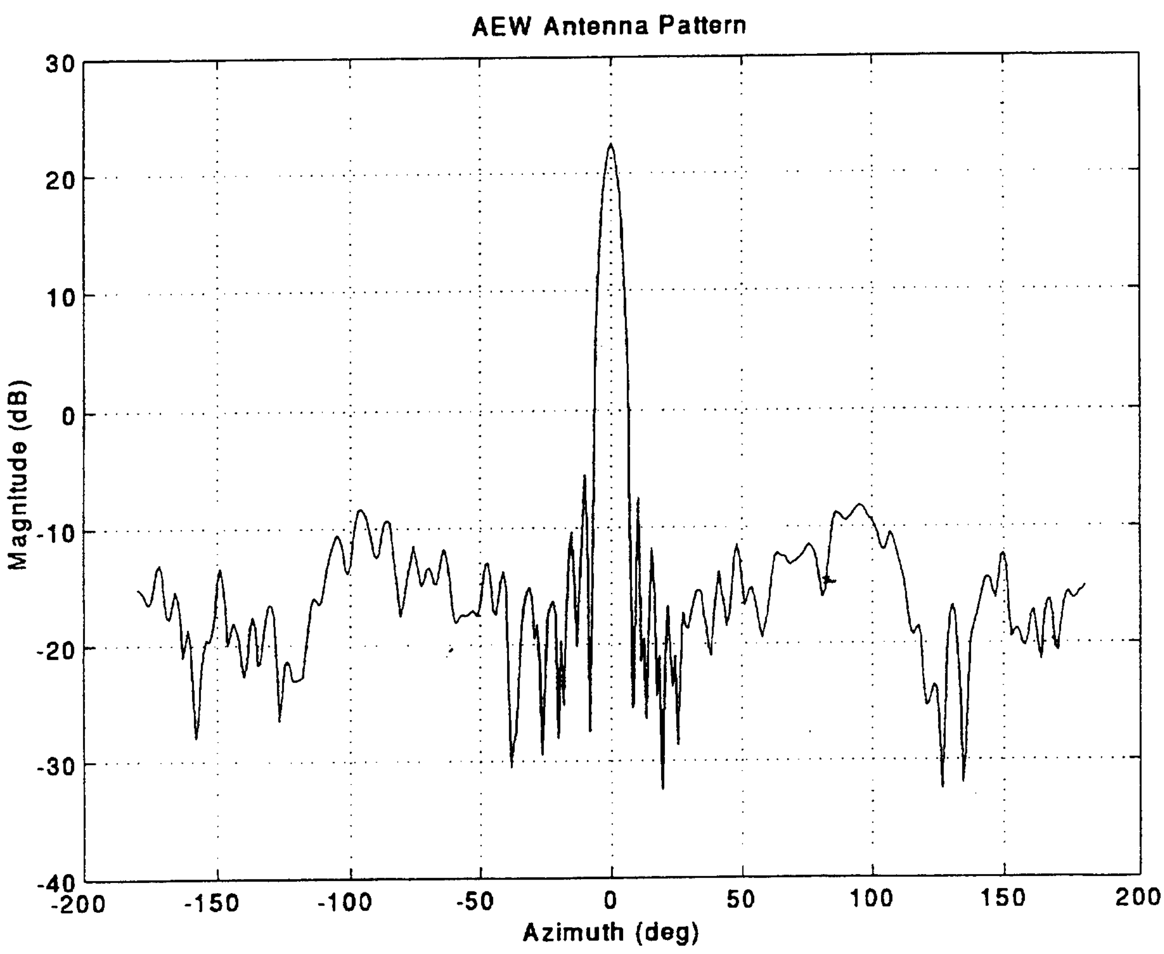

Figure 8. AEW System Antenna Pattern in Free Space.

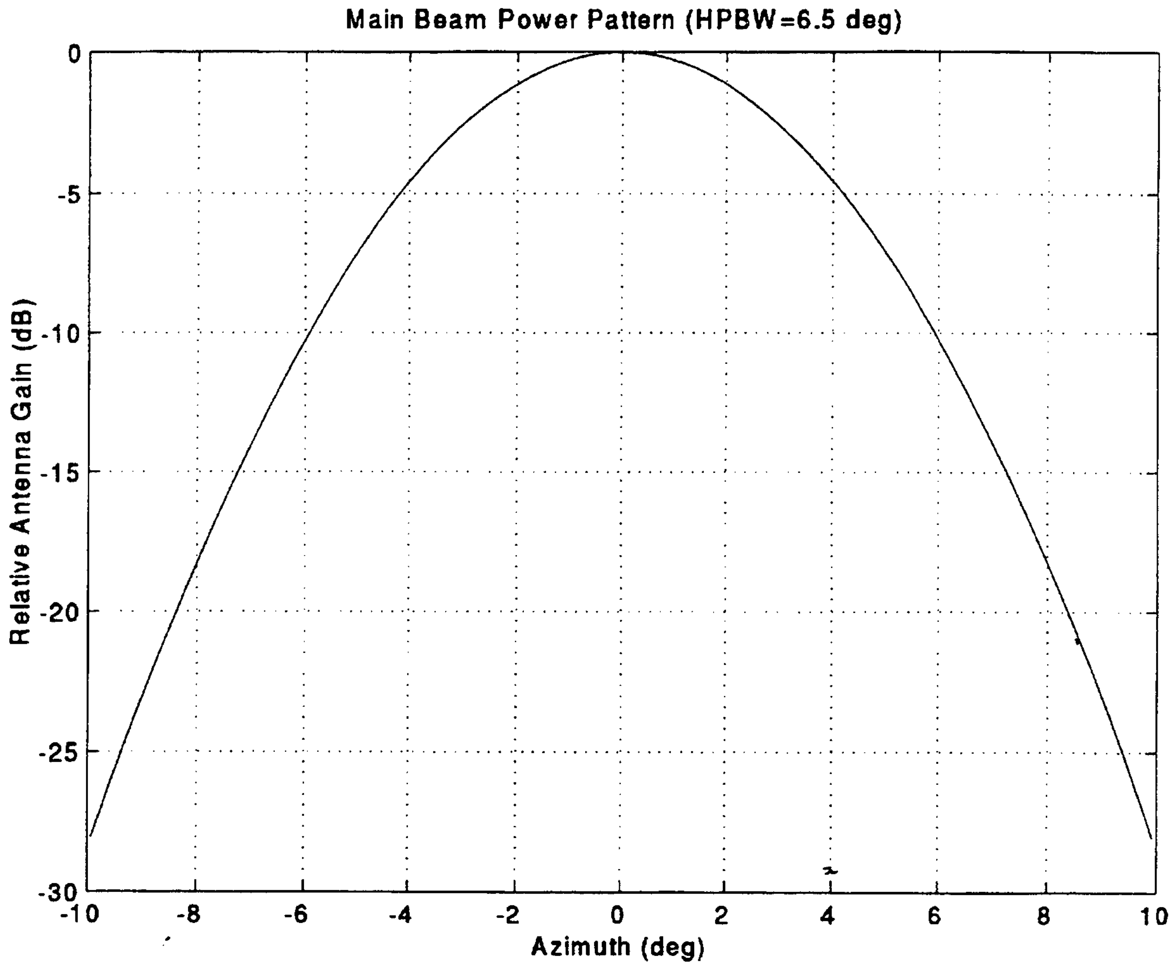

Figure 9. Main Beam Power Pattern.

If three SOJ jammers are deployed at 350°, 0°, and 10°, as shown in Figure 10, they will blank the AEW sytem over a sector about 40° wide in azimuth (for the purpose of ensuring a corridor, the jamming areas are overlapped so that three jamming elements create a 40 degree opening). The effective ranges for this condition are depicted in the figure. Note that when the SOJs are not pointing at the radar's beam, then the SOJ performance depicted in Figure 4 applies.

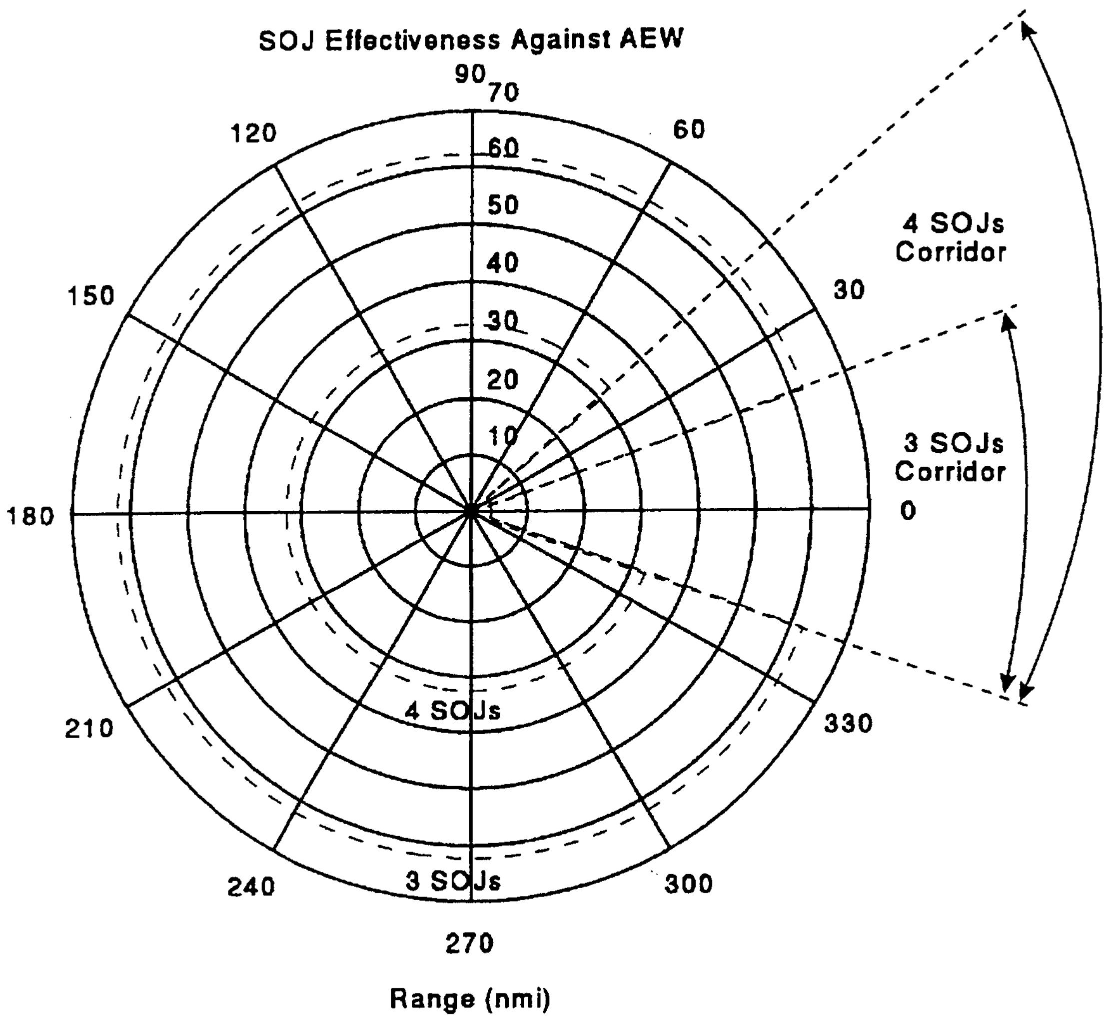

Figure 10. SOJ Corridor Creation Against the AEW System.

In Figure 10, the first scenario consists of three SOJ jammers opposed to the AEW system, where one of the jammers is located within the mainlobe, resulting in jamming of the mainlobe (SSJ) with 1,500 watts of power. This curtails the AEW system detection range, reducing it to 3.58 nmi. The SLC is not effective for mainlobe jamming. The outer ring represents the effect of three SOJ jammers directed into the AEW system's sidelobes. The degraded detection range is about 62.21 nmi in this region, as compared with the mainlobe jamming of 3.58 nmi.

A second scenario (the inner ring in the figure) is comprised of four SOJ jammers, where one jammer is within the AEW radar's mainlobe and the azimuthal opening width is about 60° (from 340° to 40°). In this case, the detection range of a four-jammer SOJ from sidelobes is 32.56 nmi. If one jammer falls into the AEW radar's mainlobe the response in detection range is 3.58 nmi. One factor that is very important is that the SLC is not effective when the SOJ jammer is in the AEW system's mainlobe response.

The primary goal of the SOJ is to open a penetration corridor in which the strike force can remain obscured. Reinforcement of EP must be undertaken by the AEW system to cope with this possible EA from potential threats.

As far as EP and carrier frequency are concerned, the E-3A (AWACS) and E-2C adopt different approaches. The E-3A utilizes S-band frequency (2-4 GHZ), resulting in a very narrow beamwidth (around 1-2°), so that it minimizes SOJ effectiveness within its main beam response. The E-2C uses a lower frequency (around 400 to 450 MHZ, within the UHF-band), resulting in a wider beamwidth (about 6.5°) and a larger impact from the SOJ than that experienced by the E-3A. The E-3A also uses a ULSA antenna to further minimize the impact of SOJ.

If the E-3A encounters hostile jamming, it will have about a 2° strobe on the PPI, due to mainlobe jamming, while the E-2C will probably have a 20° strobe on its

PPI. Narrower beamwidth is not only good for discriminating targets in close formation (higher azimuth resolution), but also minimizes the blanking effect (opening a corridor) from mainbeam jamming.

IV. CONCLUSION

A. AEW SYSTEM VULNERABILITY

According to the simulation results, an AEW system's detection range is highly subject to hostile jamming, especially in the presence of cooperative jamming. Table 7 shows how vulnerable the AEW system is in a minor, moderate, and severe jamming environment and the reductions in detection range experienced in such environments.

Table 7. Vulnerability of an AEW System to EA.

	Minor Jamming	Moderate Jamming	Severe Jamming
Number of Jammers	1	3	5 (SSJx1, SOJx4)
Jamming Mode	SOJ	SOJ	SSJ + SOJ
Jamming Mode	Barrage Jamming B_J=50 MHZ	Spot Jamming B_J=20 MHZ	Spot Jamming B_J=7.5 MHZ
Jamming Range	70 nmi	50 nmi	30 nmi
Jamming Power	1,500 W x 1	1,500 W x 3	1,500 W x 4 (SOJ) 200 W x 1 (SSJ)
Swerling Type	1	1	1
Detection Range (no jamming)	242.17 nmi	242.17 nmi	242.17 nmi
Degraded Detection Range (due to jamming)	153.79 nmi	80.84 nmi	13.61 nmi
Reduction in Detection Range	36.5%	66.62%	94.38%

In the worst jamming environment, the AEW system loses over 94% of the detection range to hostile noise jamming. This allows the AEW system to detect only targets that are within 13.61 nmi. In moderate jamming conditions a 66.62% reduction in detection range has occurred. This reduction could be exploited by the intruding strike force as they attempt to evade detection. The AEW system suffers a loss of around 36.5% (~88.38 nmi) in an environment that includes only minor jamming. If the SOJ jammer is within the AEW system's mainlobe, the detection range will be further reduced to 3.58 nmi in the jammer's direction.

The AEW system is supposed to provide early warning intelligence to the theater air operations commands, ground-controlled intercept (GCI) units and friendly forces (CAP and SAM sites). If the AEW system's detection capability is degraded substantially by hostile noise jamming, the follow-on operation would be jeopardized when the AEW system's performance is no longer as good as it should be and the system cannot perform its designated function in the manner expected.

From the susceptibility and vulnerability point of view (based on the sensitivity analysis in Table 5), the crucial factors related to the AEW systems detection range are the radar's ERP and effective sidelobe level and the jammer's ERP, stand-off range, bandwidth, and the number of jammers. The last two factors (B_J and the number of jammers) are determined by the invader so that the remaining factors are related to the AEW system, which is under the control of the defender. Special efforts must be made to improve the AEW system's sidelobe suppression effectiveness (lower sidelobe gain as much as possible). The E-3A radar uses an ultra-low sidelobe slotted waveguide array to achieve low sidelobe control.

As a result of the limited payload of airborne radars and other current technological restraints, increasing radar transmitted ERP has only limited potential for upgrading performance, so the best solution for maintaining AEW system detection capability against hostile jamming, EMI, and ground clutter is to utilize an ultra-low sidelobe antenna while providing a sufficient number of sidelobe cancellers.

Table 8 shows that sidelobe gain is a significant parameter in determining the AEW system's detection range in the presence of jamming. The E-3A takes advantage of an ultra-low sidelobe antenna that possesses very good immunity from EA.

Table 8. Sidelobe Gain -- Comparison of Effectiveness.

	G_{SL}=-5.5 dBi (Ordinary sidelobe antenna)	G_{SL}=-15.5 dBi (Low sidelobe antenna)	G_{SL}=-30 dBi (Ultra-low sidelobe antenna)
One SOJ Jammer	46.04 nmi	81.79 nmi	175.56 nmi
Three SOJ Jammers	34.99 nmi	62.21 nmi	139.89 nmi
Four SOJ Jammers	32.56 nmi	57.89 nmi	131.03 nmi

In this thesis, the conclusion is drawn that the hypothetical AEW system encountering hostile stand-off noise jamming results in curtailed detection range. The simulation model generates evidence that adequate EP should be available to ensure that the AEW system can survive in the presence of severe jamming and still provide acceptable detection range in fulfilling the early warning function.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

The simulation model utilized in this thesis suffered from the difficulty in obtaining all the necessary data to identify input parameters. More interesting conclusions might be possible in the areas of SOJ jamming against the AEW system through specified azimuthal angles, and mixed power situations at different altitudes and elevation angles if such data were more readily available.

Further study should focus on enhancing the simulation program so that it can deal with sophisticated jamming environments and the effects of sidelobe cancellers (SLC) and sidelobe blankers (SLB) to filter out false target generating (low duty-cycle noise jamming) and high duty-cycle CW noise jamming. Further research could help to determine how to integrate these two types of EP systems and more fully exploit ultra-low sidelobe antenna (ULSA).

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