Chapter 3 – T&E OF EA SYSTEMS

3.1 INTRODUCTION

This chapter addresses the T&E of the following types of EA systems:

- RF Self-Protection Jammers, RF Support Jammers and RF Towed Decoys;
- Active Infrared Countermeasures Systems and Countermeasures Dispensing Systems;
- Low Observable Systems; and
- Directed Energy Systems.

Figure 3-1 shows a sampling of EA systems.

Figure 3-1: Electronic Attack System Examples – (US DoD Photos, except the ALE-55 Towed Decoy, which is Courtesy of BAE Systems).

Each section addresses the general function, concepts of operation, and components of the subject EA system. The T&E of each type of system is also addressed at the component, sub-system, and integrated system levels. System level testing is approached from two aspects: uninstalled and installed. Uninstalled testing refers to all system and sub-system testing that is not conducted on the intended host platform. Installed system testing is that accomplished with the system installed on the intended host air vehicle.

3.2 RF SELF-PROTECTION JAMMER

SPJ are defensive EA systems that protect their host platform from hostile radar directed weapons systems. These systems can either be installed internally within the airframe or carried externally in a pod.

3.2.1 Radar Operation and Jamming Types

Understanding how radar systems work in light of the countermeasures that will be employed against them is important. The two categories of radar systems that will be discussed are TT radars supporting weapon direction and search or surveillance radars. Semi-active missile seekers are special cases of TT radars. Radar systems supporting weapon direction require very accurate target state information (azimuth angle, elevation angle, and range and/or radial velocity).

Radars can be classified as one of three types: Low Pulse Repletion Frequency (LPRF), Medium PRF (MPRF), and High PRF (HPRF) radars – including CW radars for the purpose of this discussion. LPRF radars track targets in angle (azimuth and elevation) and range. MPRF radars track targets in angle, range, and radial velocity. HPRF and CW radars track targets in angle and radial velocity. Some HPRF and CW radars also employ sophisticated techniques to measure target range. Table 3-1 summarises the characteristics of each radar type.

Table 3-1: Radar Types and Performance Characteristics.

Radar Type	Range Performance	Doppler Performance	Comments
LPRF	Unambiguous	Ambiguous	Generally cannot achieve good unambiguous Doppler performance
MPRF	Ambiguous	Ambiguous	Can achieve good unambiguous range and Doppler performance but requires the use of sophisticated waveforms and processing
HPRF, including CW	Ambiguous	Unambiguous	Can achieve good unambiguous range performance but requires the use of sophisticated waveforms and processing

The following discussions focus on LPRF and HPRF radars. Countermeasures directed at tracking radars aim to disrupt their TT capabilities by corrupting their target state information, thereby degrading or denying weapon employment.

A conventional low PRF radar system transmits a pulse of energy and measures the time that the pulse takes to make the round trip from the radar to the target and back. Since the radar pulse is travelling at the speed of light, the range to the target can be determined, but it is important to remember that the fundamental measurement is time-based. Similarly, pulse Doppler and CW radars measure the Doppler-shifted frequency of the signal returning from the target relative the transmitted frequency. This shifted frequency can be calibrated to the radial velocity of the target, but it is crucial to remember that the radar isn't measuring radial velocity, it is actually measuring frequency. Consequently, countermeasures directed at conventional pulsed radars create range errors by corrupting the time-based measurements of the radar. Similarly, countermeasures directed at pulse Doppler radars create radial velocity errors by corrupting the frequency measurements of the radar.

Radars can also be classified as coherent or non-coherent types. The coherent ones can measure Doppler with good accuracy but they need a constant fingerprint (RF and PRF) during the integration interval (a few milli-seconds) and can, due to that, be more sensitive to jamming.

Angle tracking is the most important of the tracking domains for TT radars associated with weapons systems. Many types of weapons systems can prosecute a successful target engagement in the presence of large range or velocity errors. Essentially, this is because the radar is still providing a line of sight to the target to the fire control system. Even relatively small angle tracking errors can sufficiently degrade the weapon system's performance to prevent a successful engagement. The most effective jamming result against a TT radar is to create an angle tracking error sufficiently large that the system breaks lock on the target. A break lock requires the threat system to re-acquire the target and re-initiate the weapon employment process.

TT radars employ two basic types of angle tracking mechanisms: Amplitude Modulation (AM) and monopulse. The AM techniques, such as sequential lobing, Track While Scan (TWS), and Conical Scan (CONSCAN) are mostly used by older radar systems. These techniques employ a scanning radar beam or series of beams to sequentially sample the target amplitude returns. When the boresight of a beam is pointed at the target the radar will receive the largest amplitude return, and when the boresight moves away from the target the amplitude will drop off. These amplitude variations can be used to produce an error signal and drive an automatic angle tracker. Monopulse angle-tracking radars instantaneously produce amplitude (or phase) errors in the azimuth and elevation channels, as opposed to the AM trackers which do it sequentially. Nearly all modern radars employ monopulse angle trackers and they have a high degree of immunity to AM angle jamming.

Radio frequency defensive EA systems employ active RF jamming transmissions to disrupt the operation of hostile radar systems. These transmissions can be broadly classified as either:

- **Noise Jamming** – Noise jamming attempts to increase the noise power level in the victim radar's receiver thereby decreasing the signal-to-noise ratio and correspondingly its maximum detection range. Figure 3-2 shows several types of noise jamming. Barrage noise spreads the jamming energy over a relatively wide frequency range. This technique has the advantage of covering a large frequency range and does not require any knowledge about the victim radars but at the cost of diluting the jamming power. Spot noise transmits the jamming energy over narrow frequency ranges and can achieve high power levels but requires knowledge of the victim radar's operating frequency. Swept spot noise sweeps a relatively high power signal through a frequency band of interest. This allows high jamming power levels and does not require knowledge of the victim radar, but at the cost of leaving the victim radar un-jammed some portion of the time.
- **Deceptive (or Deception) Jamming** – Deceptive jamming, also known as false target jamming, presents the radar with target-like waveforms with the intent of deceiving either an operator or the automatic detection and tracking features of the radar.

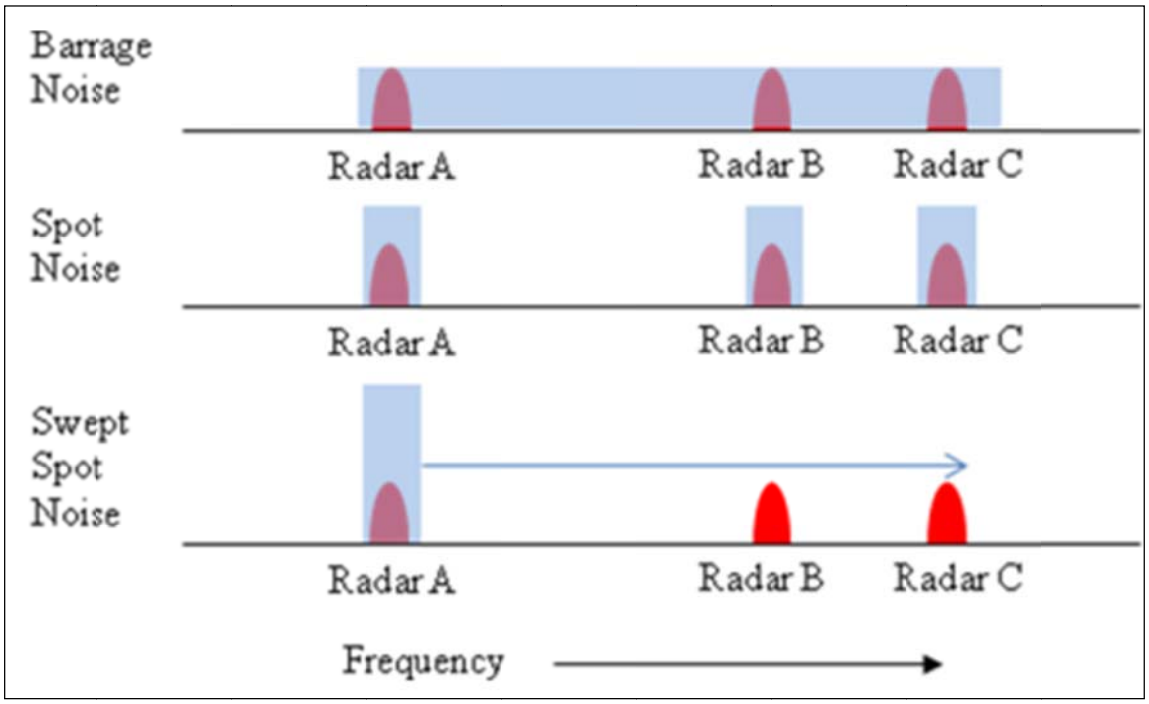


Figure 3-2: Types of Noise Jamming.

3.2.2 RFCM System Concepts and Operation

An RFCM system has several basic components. The front end of the system is similar to an RWR and consists of an antenna or an array of antennas, RF transmission lines, and a receiver/processor. In addition to the front end of the system, the RFCM system has a technique generator, a modulator/transmitter module used to modulate and amplify the jamming waveform and the transmit RF transmission lines and antennas. Figure 3-3 is a simplified block diagram of a RFCM system.

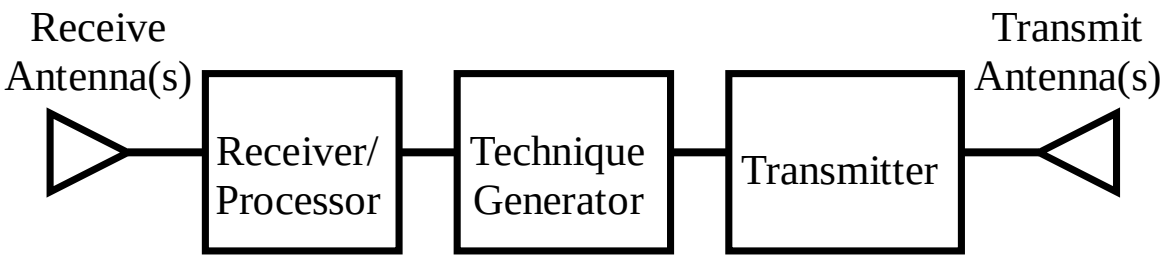


Figure 3-3: Simplified Jammer Block Diagram.

Figure 3-4 shows the individual components of the Advanced Integrated Defensive EW Suite (AIDEWS). AIDEWS is an example of a typical modern self protection jammer; this particular system also performs as an RWR and a controller for other onboard EW systems.

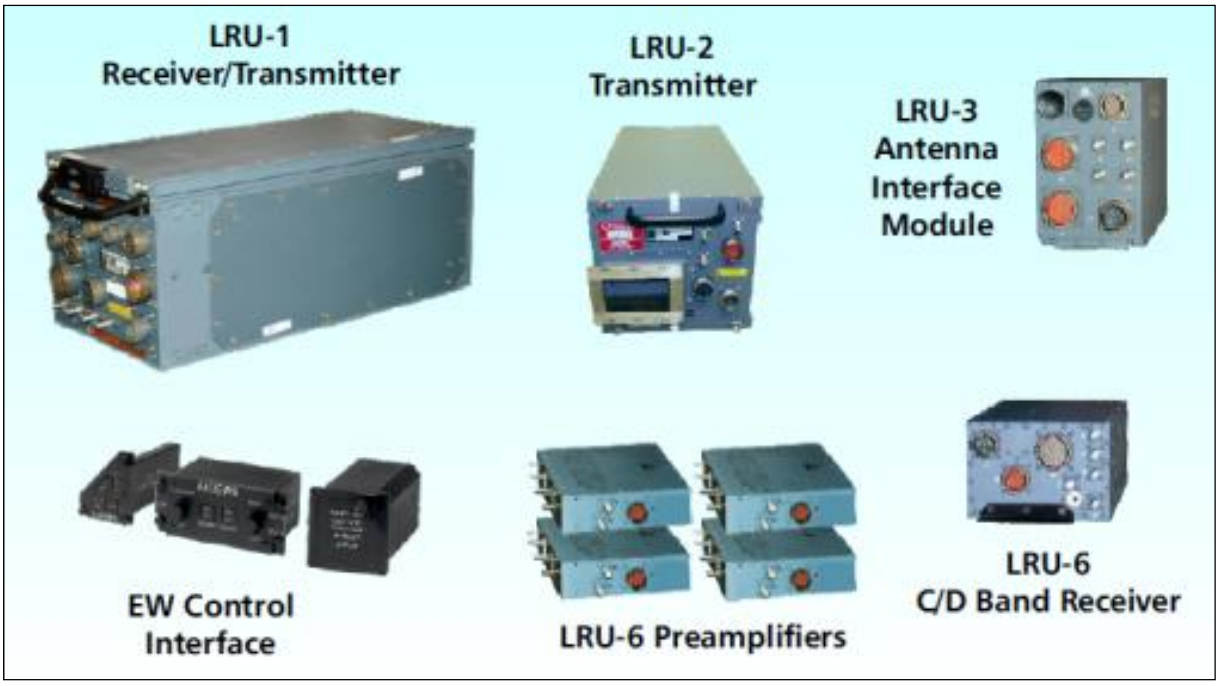


Figure 3-4: Typical Self-Protection Jammer Components – (Courtesy of ITT Corporation).

3.2.2.1 RF Front End and Receiver/Processor

The front end of an RFCM system is very similar to an RWR. It must survey the RF environment and, based on its mission data programming, identify, determine the angle of arrival, and prioritise incoming threat signals. All of the discussion in Section 2.2 about receivers applies to RFCM receivers as well.

3.2.2.2 Technique Generator and Transmitter

When the processor has identified and prioritised the threat systems in the environment the system will then determine a countermeasures response. The MDF identifies the optimum technique or series of techniques that will be transmitted against the threat system. Most RFCM techniques attack the victim radar's tracking domains: range, Doppler, and angle and the MDF contain the parametric definitions of these techniques.

The technique generator may use oscillators, or a part of the incoming signal, and time, frequency, and/or amplitude to modulate the signal to achieve the desired technique. The transmitter then amplifies and transmits the jamming waveform.

Modern radars employ a variety of EP techniques to improve their signal processing gain and mitigate the effects of hostile EA. Many of the EP features employed by modern radars address the ability to discriminate between the radars' transmitted waveforms and jamming waveforms. Therefore, it is becoming more critical in deceptive (false target) jamming that the jamming waveforms resemble the radar waveforms such that they are not rejected by the victim radar's EP logic. Digital RF Memory (DRFM) technology is increasingly being employed in RF countermeasures systems. DRFM-based techniques allow a jammer to produce very high quality false targets. They do this by sampling the incoming pulses and storing them. The stored pulses retain the nuances of the received pulses, such as phase coherency or intrapulse modulation. These stored pulses can them be modulated and re-transmitted back toward the victim radar.

3.2.2.3 Transmit Antennas

The RFCM system designers employ a wide variety of transmit antenna configurations. Regardless of the transmit antenna configuration it is designed to direct as much jamming energy as possible back toward the threat system. The system may have dedicated transmit antennas or it may timeshare an RF transmission line with the receive system. Dedicated transmit antennas can be as simple as just forward and aft antennas or may be as complicated as multiple electronically steered phased array antennas.

3.2.2.4 Displays and Controls

The aircrew interface usually consists of a control panel for selection of system operating modes and indicator lights identifying the threat environment. Typical operational modes for the jammer consist of standby, receive only, and transmit. Some displays will show which threat systems are being countered.

3.2.2.5 RF Management Systems

SPJ systems transmit high power RF energy that can adversely affect SPJ operation as well as that of other onboard systems. Antenna isolation is an important consideration for EMC. Ideally, the receive antennas on an aircraft would be electrically isolated from the transmit antennas and the receiver would not detect any onboard-generated RF transmissions. However, if there is insufficient isolation to prevent onboard receivers from detecting and processing the transmitted signals, their performance can be affected.

Potential inference examples include the SPJ system detecting, processing, and jamming the fire control radar; the RWR seeing the SPJ system transmissions, misinterpreting them and erroneously displaying threat symbols; the SPJ receiver seeing the SPJ system transmissions and processing them as threats (a condition known as ring around). System designers attempt to optimise antenna placement to meet the system's field of view requirements and to maximise isolation.

An RF management system, such as a blanker, must be employed where insufficient antenna isolation exists to prevent the receiver from seeing the transmitted signals. Installed system testing allows testers to determine if the chosen RF management scheme has been properly implemented. Temporal blankers merely 'turn off' the target receiver when the related transmitter transmits and verifying the correct timing of the blanking pulses is critical. More sophisticated schemes pass operating information from the transmitting system such as frequency and PRF, so that the receiver can identify the transmitted signal and then ignore it.

3.2.3 SPJ System Testing

The discussion from Section 2.2 on RWR testing applies to the receiver aspects of SPJ systems. In addition to the receiver components, the SPJ system has additional components and considerations related to the transmitter portion. There is a significant difference between testing an RWR and testing an SPJ system. The RWR is an open-loop system. It merely monitors the environment and communicates information to the aircrew or countermeasures systems. The SPJ is a closed-loop system, as is the radar system it is attacking. While it surveys the environment in the same manner as an RWR, its purpose is to actively disrupt the behaviour of the threat system.

If the SPJ system is effective, it will cause the threat system and/or its operators to adapt to the jamming and likewise the SPJ system will respond to changes in the threat-system behaviour. This dynamic environment greatly complicates the T&E of SPJ systems. It is imperative that the test team, including the test planners and the analysts, have a thorough understanding of not only how the SPJ system operates, but also how each of the victim radars works and how they are employed operationally.

Two measures that are central to SPJ system T&E are miss distance and Jamming-to-Signal ratio (J/S). These measures are important indicators of overall system performance. Unfortunately, both are difficult

to measure directly and can be difficult to interpret. These measures must be considered throughout the development programme and should be re-evaluated as higher fidelity measurement data becomes available.

SPJ effectiveness is evaluated by its ability to improve the survivability of the host aircraft. This ultimately involves determining the success or failure of an engagement by a hostile weapons system. The success or failure of an engagement is determined by the miss distance of the missile or the bullets in the case of a ballistic system. The degree of survivability improvement afforded by the SPJ can be inferred by statistically comparing the miss distance data collected under the same conditions with the SPJ off versus the miss distance data with the SPJ operating, conditions known as ‘dry’ and ‘wet’, respectively.

Since the evaluation involves a weapon miss distance, it can only be performed through M&S or live-fire testing with unmanned aircraft. Live-fire testing provides very useful anecdotal information about the SPJ system effectiveness and performance but, due to the cost, rarely produces enough data to make statistically relevant performance estimates about the population. Operationally, the SPJ system is only one contributor to aircraft survivability. Other contributors include chaff, manoeuvres, and tactics. Since all of these are interrelated it is extremely difficult to cost effectively isolate the specific contribution of the jammer to aircraft survivability.

The relationship between the SPJ system output and its effectiveness is complicated and somewhat counter-intuitive. The J/S ratio is the SPJ system jamming power entering the radar’s receiver divided by the target skin return signal power entering the radar’s receiver. The J/S ratio is an important measure and it is vital to understand its implications.

The jammer power entering the victim radar’s receiver increases as the jammer gets closer to the victim radar. Although it would seem to, this does not result in increased jammer effectiveness, because while the jammer power is increasing, the target skin return signal power is also increasing, but at a much faster rate. Annex C discusses this in more detail. Thus, with all else being equal, the jammer will become less effective as the range to the victim radar decreases. At some point the jamming will become ineffective. The range at which this occurs is called the burn-through range.

An SPJ system can be functionally decomposed and the performance of each component can be determined and evaluated. Key performance measures are good indicators of SPJ system performance. As the performance of each component is better understood, the assumptions underlying the M&S can be refined and the fidelity of the M&S improved. In-depth analysis can take the overall effectiveness requirements and determine how the various components of a given design must perform in order to achieve them. The decomposed requirements identify important performance specifications for system components such as installed system sensitivity and Effective Radiated Power (ERP). The EMC of all RF transmitters and receivers in their installed configurations must be characterised. The EMC test results allow designers to eliminate or mitigate EMI effects.

As with RWRs, SPJ system specifications, testing, and performance assessments can be broken down into three main categories: T&E done on the SPJ system and its constituent components, T&E done on the SPJ system as installed on the host aircraft, and OT&E to determine if the overall system is effective and suitable to perform its intended mission. The SPJ system testing has additional requirements related to the transmitter and related components. The system also requires evaluations that focus on the behaviour of the operators of the victim systems.

3.2.3.1 Uninstalled SPJ Component Testing and Performance Assessments

Uninstalled SPJ testing can be either open or closed loop. Open loop testing is conducted by injecting the SPJ’s receiver with simulated RF threat signal(s), to stimulate the processor and transmitters,

and monitoring the output jamming waveform. The SPJ output does not affect the input signal and the effectiveness of the jamming waveforms cannot be evaluated. Closed loop testing includes a representation of TT radar receiver, TT loop, and radar operator, and allows effectiveness to be evaluated.

3.2.3.1.1 Open Loop Component and System Level Testing

Testing performed at the manufacturer's laboratory facilities is almost always open loop and focuses on individual components' performance and, at the system level, ensuring that SPJ output is consistent with expectations based on the RF input. Receiver and processor component testing is addressed in Section 2.2.

The technique generator should, based on the processor's identification and the received RF threat signal, select and generate the countermeasures technique defined in the MDF. The specific RF output of the technique should be measured to ensure that the frequency, timing, amplitude, and pulse characteristics are consistent with the intended technique. The timing relationship between the input RF signal input and the jamming output signal is critical, especially for false target generators. Additionally, when more than one radar-directed threat system engages the host platform, it is necessary to verify that the system properly prioritises the associated threat signals and correctly assigns the transmitter resources. It is important to ensure that the most lethal threats receive jamming resource priority.

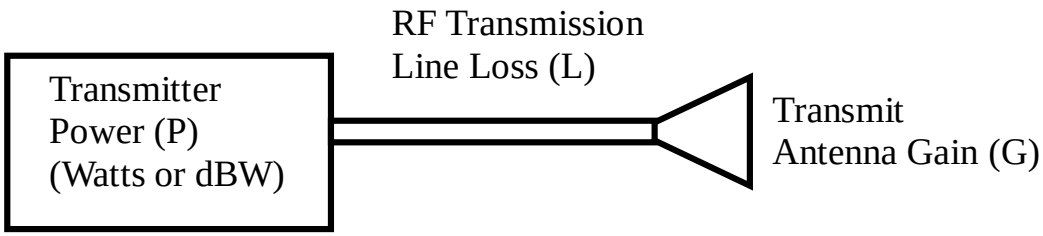
The SPJ J/S ratio spatial coverage should be evaluated on a threat-by-threat and technique-by-technique basis. This allows analysts to determine where the jammer will and will not be effective. While J/S cannot be directly measured in a laboratory, a complete analysis can be performed based on laboratory measurements, modelling results, and other measured characteristics. The J/S is a function of range to the target and these other factors:

- Threat radar system ERP;
- RCS of the SPJ host aircraft; and
- SPJ system ERP.

The threat system ERP is the power directed by the threat radar toward the aircraft carrying the SPJ. It is a function of the radar transmitter power, transmission line loses, and transmit antenna gain. Threat system ERP is commonly obtained from intelligence estimates.

The RCS of the aircraft carrying the SPJ system can be obtained either from software-based predictions or measured at an RCS measurement facility.

The SPJ power directed toward the victim radar is the product of the transmitter output power, the RF transmission line loss, and the transmit antenna gain. Figure 3-5 shows the components of an SPJ transmit path and how ERP is calculated. The transmitter power output can be measured in the laboratory. Transmission line losses can be estimated from waveguide and RF switch characteristics of the system design or measured on the aircraft, if available. Installed antenna gain patterns can either be obtained from either software-based predictions or measured at an antenna pattern measurement facility.



$$\text{Effective Radiated Power (ERP in Watts)} = \frac{P\,G}{L}$$

Or in decibel form:

$$\text{ERP (dBW)} = \text{P (dBW)} - \text{L (dB)} + \text{G (dB)}$$

Figure 3-5: RF Transmit Path Components and Effective Radiated Power.

The RF spectrum of the transmitter should be characterised in the laboratory. An ideal transmitter only amplifies and outputs the specific signal injected into it. However, real transmitters often produce 'extra' or **spurious signals**. Spurious signals are most likely to occur at harmonics of the injected signal but they may appear anywhere in the spectrum due to limitations and/or errors in system design, manufacture, or installation. These spurious signals waste valuable jammer power and in some cases can be exploited by a threat system's EP features.

3.2.3.1.2 Closed Loop System Level Testing

HITL test facilities generally present the first opportunity to examine the closed-loop SPJ system performance and effectiveness. HITL simulations typically employ high-fidelity threat simulations and sometimes generate realistic simulated displays to support a threat operator in the loop. The simulation also generally employs a scripted aircraft flight path and a dynamic engagement geometry that accounts for the changing RCS and transmit and receive antenna gains, and can be used to generate a realistic J/S ratio throughout the simulated engagement. The operator in the loop is a critical element of the threat system's EP design. The HITL testing can be used to optimise the SPJ technique design to deceive the man in the loop.

Since HITL simulations incorporate high fidelity threat simulations they can support detailed SPJ performance and effectiveness evaluations. The measures associated with the tracking loops of the radar such as range and/or radial velocity error and azimuth and elevation angle errors can be generated from dry and wet cases and compared to evaluate performance. Simulated missile and projectile fly-out data can also be generated and the dry and wet cases can be compared to evaluate the system effectiveness.

There are a variety of threat system models with varying degrees of fidelity that address threat system behaviour, especially the radar, fire control system, and missile or projectile aerodynamics. Analysts need to understand what the various threat models do and how they work, particularly with respect to how the operator is addressed.

The HITL testing is a cost effective way to generate significant amounts of data. Limitations include a scripted flight path (i.e., the aircraft doesn't normally react to the engagement, it just flies a predetermined path and the SPJ system is normally operating in a standalone configuration without the effects of other onboard systems). The HITL also provides the best chance to evaluate system performance when a simulated or actual radar system is not available on an OAR.

Another case of system-level closed-loop testing occurs when an SPJ system is rack-mounted, normally in a trailer, and taken to an OAR. The system can then be tested against OAR radar threat simulators to evaluate closed-loop performance. This type of testing is often called pole testing because the receive antenna is mounted on a pole and elevated some distance above the ground to mitigate the effects of multi-path and reflections. This type of testing has the advantage of working against a simulated or actual tracking threat radar systems. Limitations include the static configuration and the lack of actual RCS or antenna pattern effects.

3.2.3.2 Installed SPJ Testing and Performance Assessments

Installed-system ground testing is primarily open loop and focuses on aircraft system integration and EMC testing. Integration testing can either occur at the PSI's SILs or on the aircraft. Increasingly, ISTFs are capable of generating high fidelity threat simulations and limited closed loop capabilities.

3.2.3.2.1 Installed-System SPJ Ground Testing

The PSI will conduct integration testing in their SILs to ensure that the SPJ system properly communicates with other onboard systems. The SPJ manufacturer, as is the case with the RWR manufacturer, normally will emulate data bus traffic. The PSI's SIL will often be the first time that the SPJ will interface with other actual aircraft hardware.

The EMC testing discussed in Section 2.2.2.2.2 also applies to SPJ systems. Additionally, an ISTF can cost-effectively expose the SPJ to high fidelity threat representations such that the end-to-end performance of the installed SPJ can be evaluated in a secure environment. Occasionally, EA technique deficiencies are discovered and can be corrected before moving on to flight testing.

Some ISTFs have developed limited closed loop test capabilities. The test team needs to ensure that the test objectives are tailored to be compatible with the limitations of these capabilities.

3.2.3.2.2 Installed-System SPJ Flight Testing

Flight testing presents the ultimate 1-versus-1 (1-v-1) closed-loop environment to evaluate the SPJ system performance. The SPJ is normally in a production-representative configuration and all of the testing takes place in the far field (testing will sometimes be conducted in various non-production configurations to support specific development test objectives). The system operates against a high-fidelity simulated threat radar or actual radar system with operators in the loop. The operator is a key EP feature of many threat systems. A well-trained operator can recognise jamming techniques and manually intervene to counter the effects of the jamming and maintain radar track. Operator skill is an important consideration in any SPJ system testing.

Rules Of Engagement (ROE) define operator behaviour during the test, particularly with respect to the EP features the operator is allowed to use. Two of the most common ROE address optical systems and reacquisition procedures. Operators are frequently precluded from using optical systems to aid tracking (a good optical angle track can be used to provide angle information to the tracker in lieu of radar angle track information). This is often done to simulate night conditions. When the jammer is effective and causes the victim radar to break lock, the operator needs to know how he will go about reengaging the target aircraft. This brings up a case where the test team needs to balance test efficiency with realism. The fastest way to reacquire the target is to allow the operator to use the OAR's real-time instrumentation truth data to locate the aircraft. This approach maximises the amount of data collected during limited-range times. The most realistic method is requiring the operator to use the onboard acquisition radar system. The test team must weigh the value of additional data versus the more realistic conditions. The ROE for a given threat system and SPJ system will vary with the specific test objectives. The importance of clearly defined ROE cannot be overstated and the entire test team should be involved in their development.

The performance of an SPJ system can be degraded by the operation of other onboard transmitters, e.g., the blanker may inhibit jammer transmissions when the terrain-following radar is transmitting (the TF radar will generally have priority). Comparing the 1-v-1 performance under similar conditions of the jammer when it is operating alone to its performance in an operationally representative condition (with other onboard systems operating) allows analysts to determine if the RF management system is degrading the SPJ system performance. Multiple-ship operations also need to be considered. For example, the interactions of jammers and fire-control radars within a tactical fighter formation need to be examined to determine potential limitations.

In-flight J/S measurement can be a valuable tool but generally requires specialised, non-operationally representative EA techniques to be loaded in the SPJ systems MDF. One technique, shown in Figure 3-6 delays the EA response from the incident radar pulse by a fixed time period. The separate returns are collected in discrete range gates. Since there are an infinite number of points around the aircraft the test team needs to carefully select the flight test profiles to ensure that data are collected at the required frequencies, aspects, and ranges.

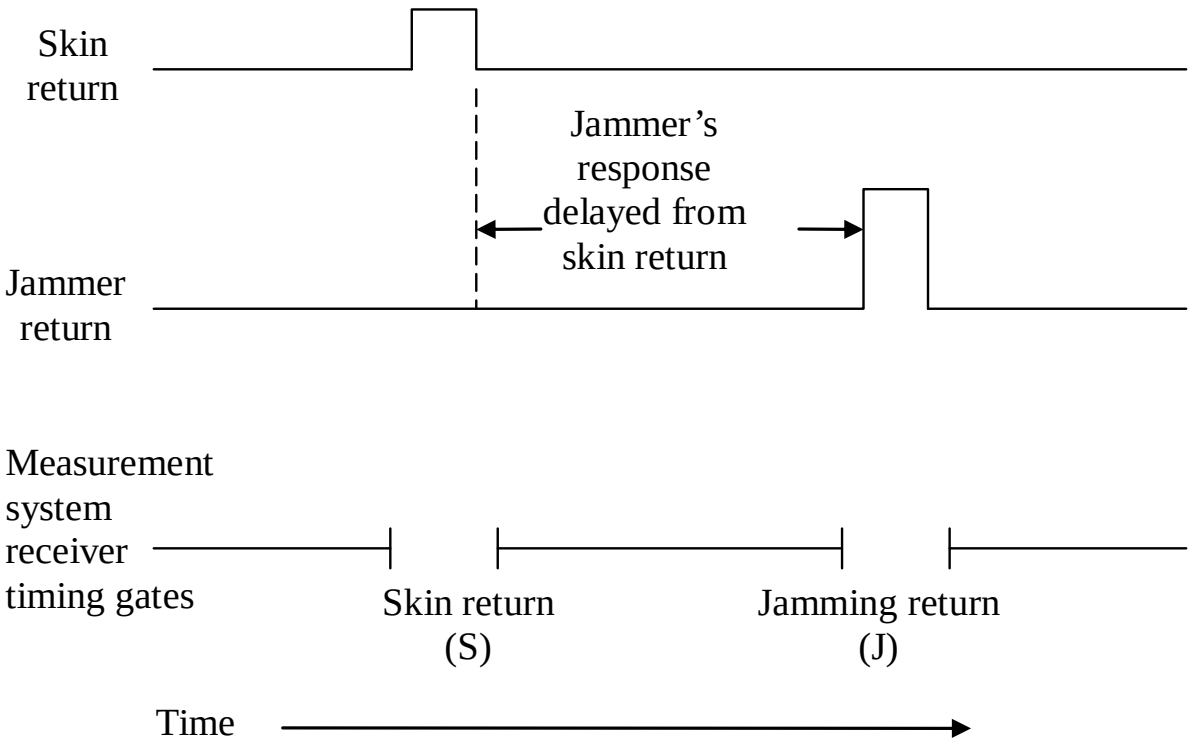


Figure 3-6: Example J/S Measurement Technique.

There are a number of limitations associated with flight testing on an OAR. As is the case with RWRs, only a small number of threat simulator systems exist on an OAR. If a required threat system isn't available on an OAR, the best level of fidelity that can be achieved is using a HITL facility. The background environment is limited and thus restricts the pulse densities that can be achieved to evaluate the SPJ performance at required high-pulse densities.

EMC testing on some airborne SPJ systems can only be accomplished in flight. This type of testing may or may not require OAR ground-based radar participation. If the test aircraft has sufficient onboard ability to stimulate and control the SPJ system to achieve the desired test conditions, OAR support may not be necessary.

3.2.3.3 Additional SPJ T&E Considerations

Many decision makers want to quantify the contribution that an SPJ makes to aircraft survivability and ultimately mission accomplishment. It is difficult to isolate the jammer's contribution because there are a number of interrelated complementary factors that affect survivability and the jammer's effect is only one of these.

Another consideration working against the direct applicability of DT&E flight test results to operational effectiveness assessments is that operational aircrews do everything possible to minimise their exposure to hostile air defences. An aircraft when detected and engaged by a hostile air defence system will, to the extent possible, practice threat avoidance, e.g., terrain masking, employ other countermeasures such as chaff, and employ tactical manoeuvres in concert with the active jamming. If DT&E were conducted according to this philosophy, the test team might not get much data and the data collected would confound the jammer effects with other factors.

A developmental tester wants to collect as much relevant data as possible about the SUT. Due to the cost of OAR time and scheduling difficulties, this often drives the use of non-operationally representative test profiles (ones that maximise the exposure to the threat systems to make the best use of valuable range time) that isolate jammer performance so that it can be segregated from other factors. It is important to remember that even though this type of testing isolates the jammer performance, it does not necessarily translate into quantifying the jammer performance for operational effectiveness assessments.

In most cases the DT&E test conditions are conducted using straight and level flight conditions. This is done to focus the analysis on whether or not the jammer is performing properly. This is obviously not an operationally representative condition and the results are difficult if not impossible to extrapolate to draw quantifiable tactically relevant conclusions about the jammer's contribution to survivability. While operationally representative test conditions are generally not central to DT&E evaluations, they should be kept in mind.

No single MOP encapsulates the worth of a RFCM system. Even taken in aggregate it is difficult to make value judgments. Some MOPs such as those addressing track errors (azimuth, elevation, range and/or velocity), are quantifiable. However, while they provide good measures for evaluating radar performance, they don't directly relate to the ability of the weapons system to successfully engage a target. Other measures that focus on the success of the weapons engagement, such as miss distance, rely on fly-out simulations and their associated assumptions. Additionally, miss distance by itself doesn't directly address the success or failure of the weapon engagement; most RF missile warheads are proximity fused and the engagement geometry, fusing, and warhead characteristics significantly affect the engagement outcome. While missile miss distance produces a quantifiable result, a number of measures require the analyst to make a hit/miss determination and this involves a number of subjective judgments.

Analysts need to have a thorough understanding of how threat-radar systems work and operate in order to evaluate test results. As previously stated it is difficult to quantify a jammer's contribution to overall platform survivability. However, by evaluating a number of MOPs in aggregate, the analysts need to determine if the RFCM system is having the intended effect on each victim radar and whether or not the effect will be significant (even if it can't be quantified in terms of overall survivability).

3.3 SUPPORT JAMMERS

Support jammers perform offensive EA. They share many similarities in design and functionality with SPJ, but unlike the SPJ, a support jammer is primarily designed to protect other aircraft from the surveillance radars of hostile air defence systems while they conduct their missions. [1]

3.3.1 Support Jammer System Concepts and Operation

Support jammers perform three basic roles:

- **Stand-Off Jamming (SOJ)** – Normally performed by a manned aircraft operating outside the engagement range of hostile air defence systems;
- **Escort** – Normally performed by a manned aircraft accompanying a strike package; and
- **Stand-In Jamming** – Normally performed by unmanned expendable air vehicles operating within the engagement range of hostile air defence systems.

Figure 3-7 illustrates these roles.

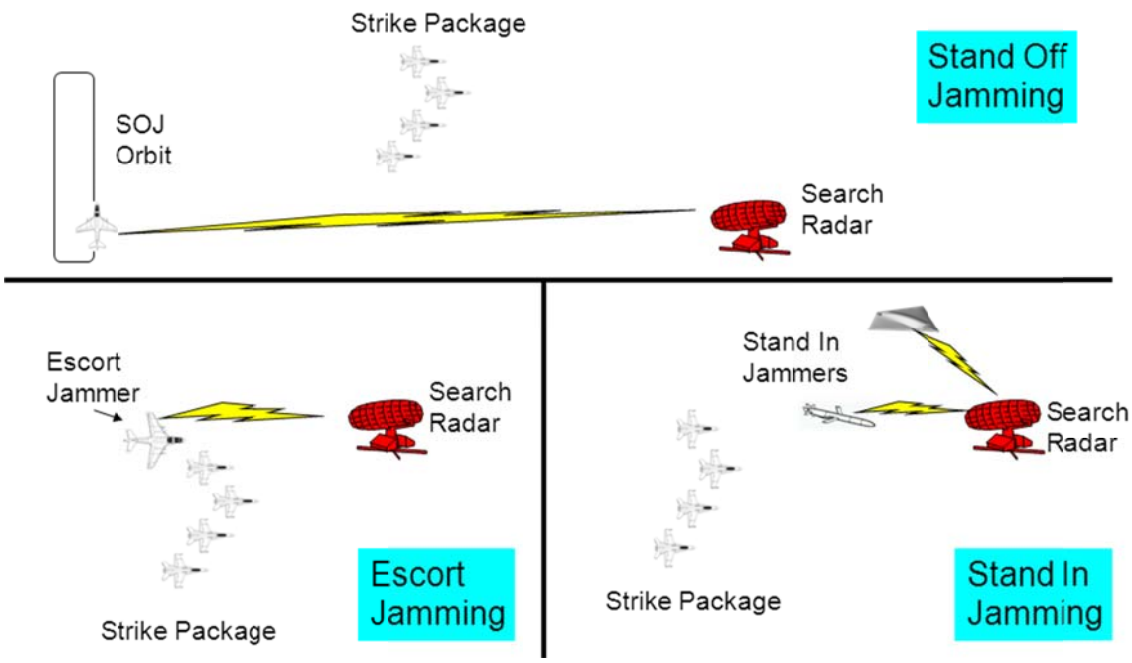


Figure 3-7: Different Types of Support Jamming.

Support jammers have the same functional elements as described in Section 3.2.2 and shown in Figure 3-3. These systems can be carried internally or externally on a manned aircraft. Commonly the receiver systems are internally mounted and the transmitters are carried in external pods as shown in Figure 3-8. Stand-in jammers are normally expendable and launched from a host platform. Figure 3-8 shows a Miniature Air-Launched Decoy (MALD). A special MALD variant, the MALD-J, performs stand-in jamming.

Figure 3-8: a) EA-6B Aircraft with External Jamming Pods; b) Miniature Air Launched Decoy Carried by F-16 – (U.S. DoD Photos).

Support jammers conduct EA operations primarily to deny, degrade, or delay the detection of friendly aircraft by the surveillance radars of an IADS. As with SPJ systems, it is important to understand the basic operation of the radar systems that the jammer attacks. Surveillance radars commonly scan a volume of airspace covering 360 degrees in azimuth, although some cover more limited sectors.

Surveillance radars report detected targets up echelon to the command and control elements of an IADS to aid in forming the air picture in one of two ways: an operator watching a radar scope manually identifies targets or a computer called a target extractor automatically identifies targets. Noise jamming is designed to raise the noise level in the victim radar's receiver thereby reducing the signal-to-noise ratio and decreasing the probability of target detection. False target jamming is designed to present the operator or the target extractor with a large number of false targets that cannot be discriminated from the real targets. Figure 3-9 shows the effects of noise and false target jamming on a Plan Position Indicator (PPI) displays.

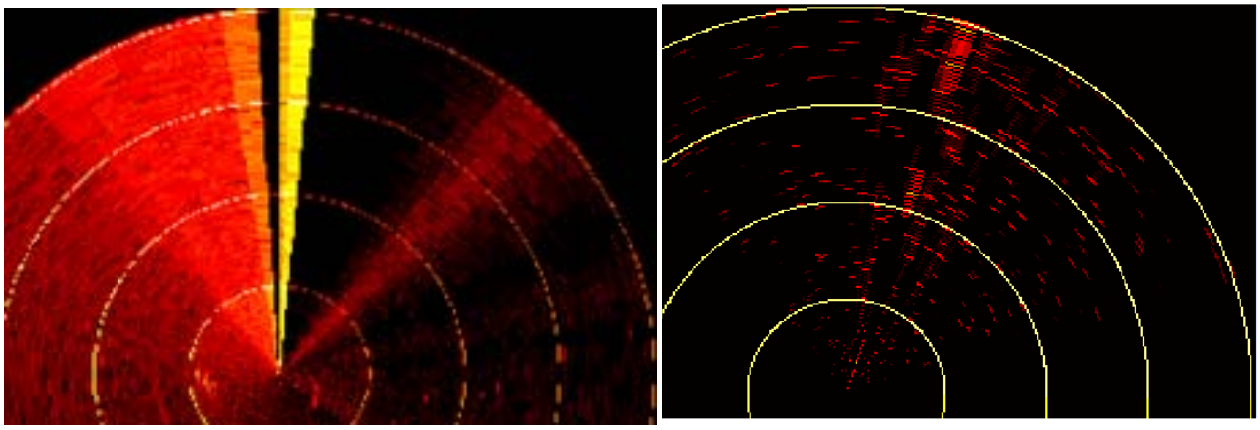


Figure 3-9: Effects of Noise and False Target Jamming on PPI Displays.

3.3.2 Support Jammer System Testing

Support jammer testing is in many ways similar to SPJ testing and most of the discussion in Section 3.2.3 applies. The following paragraphs address the areas that are unique to support jammer testing.

J/S ratio is also a critical measure for support jammers, but it is manifested differently. In the SPJ case, the main beam of the threat system TR radar is centred on the target it is tracking, allowing the SPJ to continuously direct most of its jamming energy into the victim radar's antenna main lobe. This maximises

the jamming energy transfer by virtue of the geometry. In contrast, the support jammer normally operates against scanning radars antenna side lobes and can only jam into the victim radar antenna's main lobe when it is aligned with the jamming platform. Annex C develops the J/S expression for the support jamming case.

Jamming performance assessments against search radars are different for noise and deceptive techniques. This is because they are fundamentally attacking two different things. Ideally, a noise jammer raises the noise level in the victim receiver to the point that targets cannot be detected. In the ideal deceptive jamming case the victim receiver is presented with an overwhelming number of realistic false targets where the true targets cannot be discriminated.

Flight testing against high fidelity simulators or actual threat radar systems provides the highest level of fidelity when evaluating the jamming effects on an individual surveillance radar system. This environment provides actual radar clutter, multi-path effects, and operator displays.

Support jamming effectiveness against manned systems can vary significantly with operator skill level. One operator may be able to see targets in a high-level noise jamming environment while another may not. Similarly, some operators may be able to tell the difference between real and false targets while others may not.

ROE defining what EP features the radar operators will be able to use need to be clearly defined. The ROE relate to the specific objective that the test address.

3.4 RF TOWED DECOY SYSTEMS

Radio frequency towed decoys are defensive EA systems performing self-protection jamming. They differ from onboard SPJ in that they are countermeasures systems dispensed from the host aircraft either pre-emptively or automatically in response to a hostile radar threat engagement. They are towed behind the aircraft and designed to present a more seductive target to the hostile radar or missile seeker. Most towed decoys are expendable, although retractable models exist.

3.4.1 Towed Decoy System Concepts and Operation

A towed decoy has one significant advantage over onboard SPJ system. It is difficult for onboard SPJ systems to create angle tracking errors against monopulse radars. In the towed decoy case, if the radar or missile seeker is tracking the towed decoy, it is not tracking the targeted aircraft and there is an inherent angle tracking error.

There are two basic types of towed decoys. The first is a simple repeater that retransmits the targeting radar waveform at a higher signal level in order to seduce the track away from the target aircraft; it is essentially a beacon. Figure 3-10 shows a block diagram of a simple repeater. Once deployed the system only requires power and control from the host platform. When the system receives an RF signal via the towed decoy onboard receiver that meets the threat criteria, it amplifies and retransmits the signal in hopes of seducing the threat track.

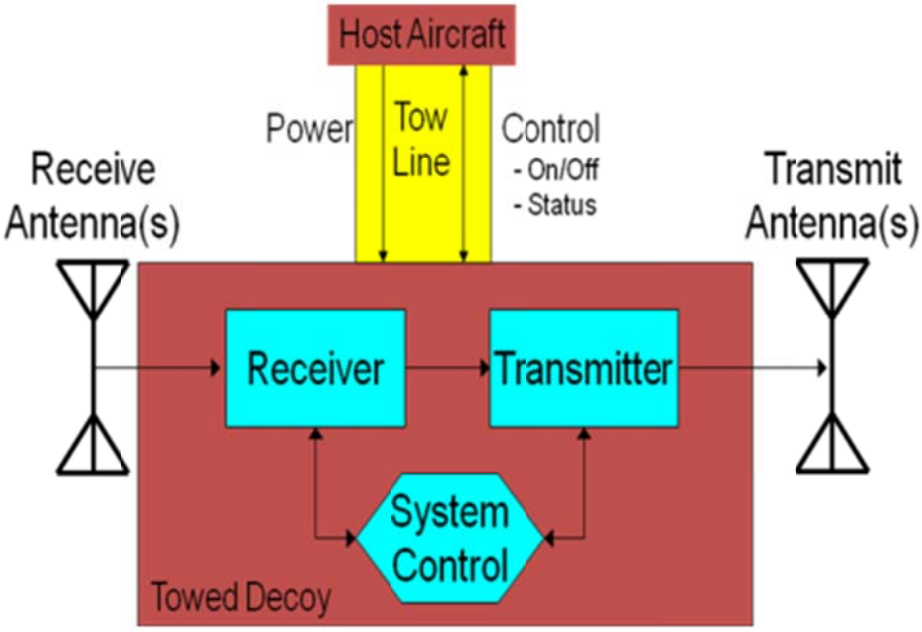


Figure 3-10: Simple Repeater Towed Decoy Block Diagram.

The second type are Fibre-Optic Towed Decoys (FOTDs). FOTDs employ sophisticated receivers and technique generators onboard the host aircraft. Figure 3-11 shows a block diagram of an FOTD system. The receiver systems associated with FOTDs are very similar to EW receivers discussed in Chapter 2. The onboard receiver passes threat information to the technique generator in a manner similar to the SPJ operation. It differs from the SPJ case in that it converts the RF technique to optical wavelengths and transmits it via fibre-optic cable to the FOTD where it is converted back to RF, amplified, and retransmitted.

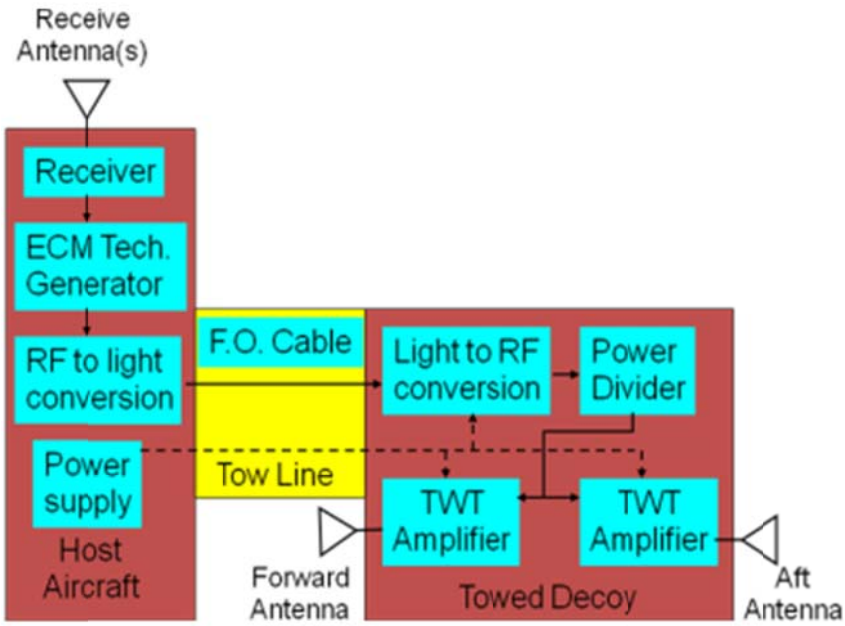


Figure 3-11: Fibre Optic Towed Decoy Block Diagram.

Both decoy types typically use Travelling Wave Tube Amplifiers (TWTAs), although Microwave Power Module (MPM) technology is now also used. Figure 3-12 shows a typical towed decoy.

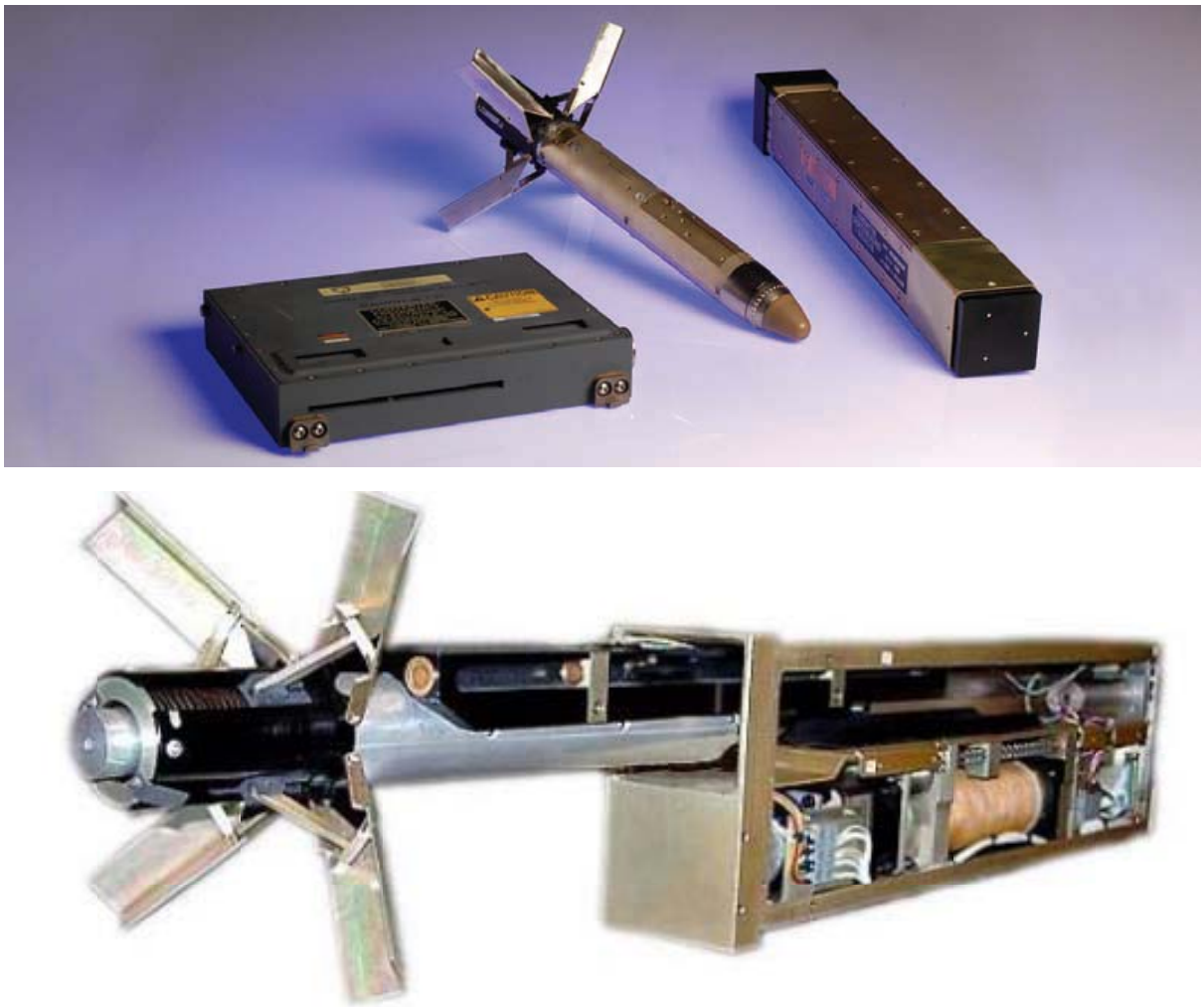


Figure 3-12: Typical Fibre Optic Towed RF Decoy – AN/ALE-55 – (BAE SYSTEMS Photo).

3.4.2 RF Towed Decoy Testing

All of the discussions in the EW RF receivers test section apply to towed decoys and the technique generation testing is similar to the SPJ testing. The major difference is that the decoy must properly deploy in a timely manner. Decoy deployment is a complicated process, as is retraction, for those systems with that capability.

3.4.2.1 Uninstalled Towed Decoy Component Testing

All of the concepts associated with testing RF receivers, signal processing, and technique generation also apply to towed decoy development and testing. M&S can be used to evaluate the aerodynamic separation characteristics as well as the performance and effectiveness of the towed decoy system.

One of the most challenging aspects of towed decoy development is the mechanical deployment (and possibly retraction) of the device. Flying test beds provide the system developers an opportunity to collect data under a variety of flight conditions.

3.4.2.2 Installed Towed Decoy Testing and Performance Assessments

Towed decoy deployment from a flying test bed provides an excellent opportunity to develop the system and reduce risk. However, the flying test bed is likely to have a significantly different aerodynamic and vibro-acoustic environment and towed decoy separation characteristics than the production airframe. The decoy needs to cleanly separate or it may damage the host aircraft and/or the decoy. Decoy deployment testing should be conducted throughout its required operating envelope to determine any deployment or towing limitations.

Fully functional towed decoy rounds are expensive and are generally not required to evaluate separation and deployment characteristics. Towed decoy mass models have the same weight and balance and aerodynamic characteristics as an actual round without any of the expensive electrical components.

Towed decoy deployments happen rapidly and high speed cameras installed at one or more locations on the host aircraft can document the towed decoy separation from the aircraft. Safety and photo chase are also very useful in case there is a deployment mishap.

Reactive towed decoy systems need to deploy the decoy to its full deployment length in a very short time and operate properly when it gets there. The mechanical braking system and associated algorithms must be evaluated to ensure they work properly. If too much breaking force is applied, the decoy will take too long to deploy. If too little braking force is applied near the end of the deployment, the sudden stop may subject the towline to a load that will cause the towline to fail and the decoy to break away. A properly instrumented decoy system will greatly aid in deficiency investigations.

Towed decoy systems present several test safety considerations. The towed decoy rounds typically use pyrotechnic charges to initiate the decoy deployment and to sever the round when it is no longer needed or if it has malfunctioned. An armed towed decoy round is a munition and need to be treated with all the appropriate safety precautions.

Towed decoys can inadvertently separate from the host aircraft and present a risk to personnel on the ground. Developmental towed decoy operations should take place over controlled ground ranges to ensure personnel and high-value material will not be put at risk if a decoy malfunction causes an unplanned separation.

3.5 ACTIVE INFRARED COUNTERMEASURES SYSTEMS

Conventional active IRCM systems are electrically powered defensive EA systems designed to protect aircraft from IR-guided missiles. There are several types of IRCM systems. The simplest is a ‘turn on and forget’ system that uses a modulated IR jamming waveform that transmits continuously over its field of view. Figure 3-13 shows a typical undirected IRCM system installation.

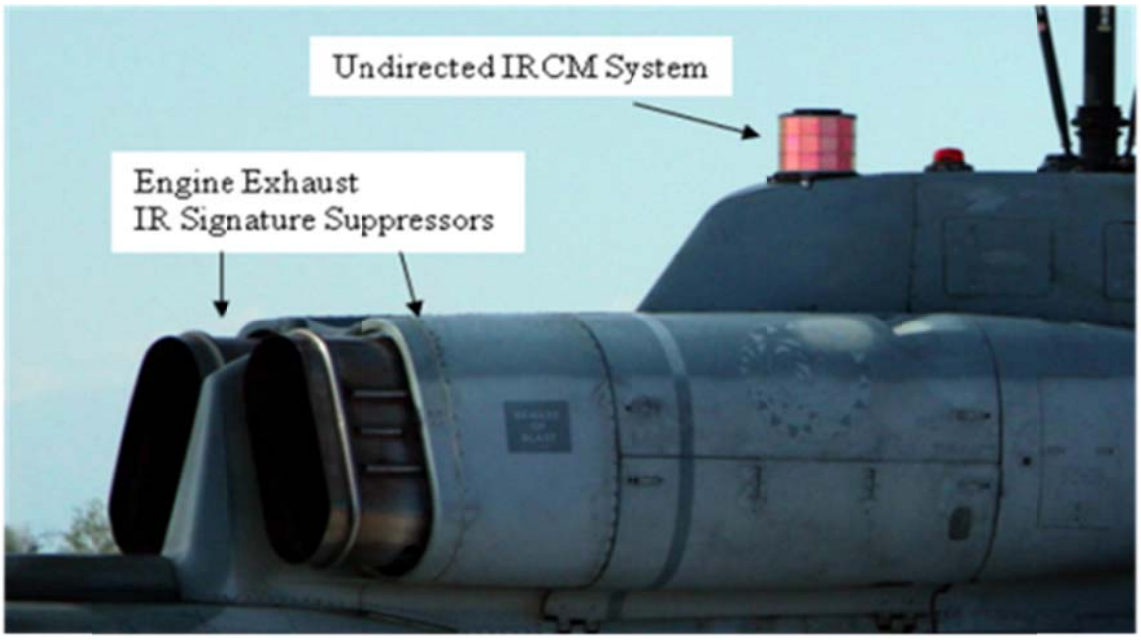


Figure 3-13: AH-1 IRCM Installation and IR Signature Suppressors – (U.S. DoD Photo).

More sophisticated IRCM systems, often called Directed IRCM (DIRCM) systems, are turret mounted and receive cuing information from MWS. These systems typically use either arc-lamp or laser-generated AM jamming waveforms. Laser-based systems have the advantage of directing significantly more energy into the victim missile seeker. Figure 3-14 shows a typical DIRCM installation.

Figure 3-14: Department of the Navy Large Aircraft Infrared Countermeasures Installation on a CH-53E Helicopter – (U.S. Naval Air System Command Photo).

DIRCM systems typically receive cuing from an MWS and slew a turret assembly (an aircraft may employ several turrets to achieve the required spatial coverage) toward the threat missile. Each turret has a fine-track sensor that will then take over tracking (as with the MWS, the fine-track sensor also tracks the missile plume) the inbound missile and direct the countermeasure transmitter or laser toward the missile seeker. The DIRCM transmitter or laser is boresighted to the fine-track sensor, such that the jamming energy is directed along the line of sight of the fine-track sensor toward the missile seeker. Figure 3-15 shows a typical DIRCM engagement sequence.

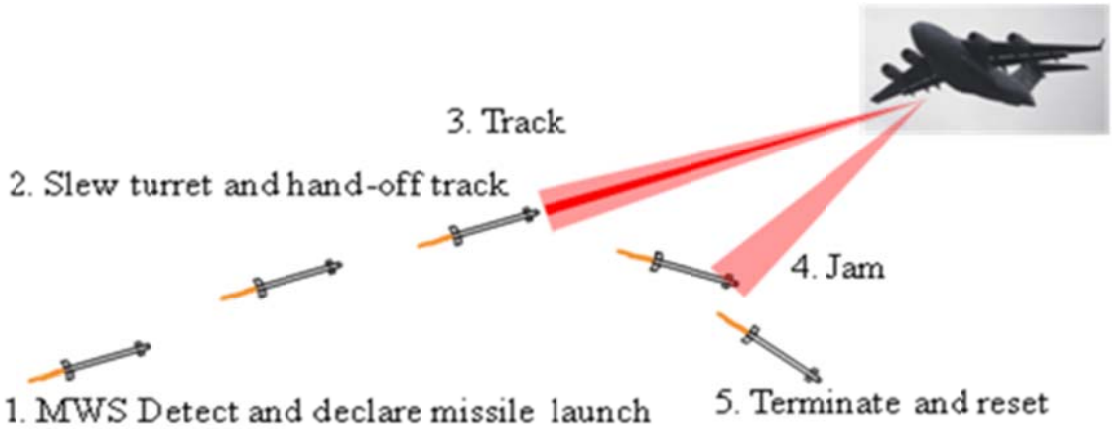


Figure 3-15: DIRCM Event Sequence.

IRCM performance can be enhanced by reducing the IR signature of the target aircraft. This can be accomplished by a variety of means, including installing engine exhaust suppressers as shown in Figure 3-13 or by using low-IR-signature paint on the aircraft fuselage. To further enhance IRCM performance, flare expendables are often used with IR jammers.

3.5.1 Active IRCM System Components and Operation

The following sections address the components of a typical active IRCM system. The MWS portion of DIRCM systems is addressed in Section 2.3.

3.5.1.1 Countermeasures Codes

The ‘processor’ of an IRCM system is a modulated power supply that drives the transmitter. Through threat analysis or exploitation, the scanning frequencies of the missile-tracking circuits are determined and these frequencies are programmed into circuitry used to modulate the power supply. The modulated power supply is either present as standalone hardware in the cargo bay area or integrated in the transmitter. In both cases, manual switches are present to allow selection of pre-programmed jam codes. Additional IRCM codes can be pre-programmed as new threats are defined.

3.5.1.2 Controls and Displays

The pilot interface is through a control indicator located in the cockpit. The pilot control indicator is either a standalone module for the IRCM system or it is shared with another EW system. The interface is usually quite simple, only providing a means of turning the system on or off and a way to alert the pilot that a malfunction has occurred.

3.5.1.3 Transmitter

There are several methods to generate the required IRCM pulses. One technology uses heated carbon-material rods and mechanical modulation techniques to generate the pulsed IR radiation to deceive the incoming missile seeker. Another technology uses an arc lamp in a vacuum tube, which is electronically modulated to provide the required pulsed IRCM radiation. Lasers are becoming the IRCM transmitter of choice due to their ability to inject high energy jamming into the missile seeker.

The basic undirected IR transmitters usually have a wide field of view (180 to 360 degrees in azimuth) and are typically located as close to the engine exhaust as possible since most of the IR threat missile seekers tend to initially acquire and lock onto this 'hot spot.'

DIRCM systems employing arc lamps and lasers focus their energy toward the homing missile seeker. The laser systems employing coherent energy have very small beam divergence and can direct significant energy into the victim seeker. The arc lamp will spread its energy over a wider field of view resulting in lower energy levels incident on the victim seeker detector.

3.5.2 IRCM System Testing

As with RFCM systems, the chief concern for IRCM systems is the degree to which they enhance the survivability of the host platform. Similarly, missile miss distance is a key consideration in evaluating the effectiveness of the IRCM system. There are several factors making the IR case somewhat easier to evaluate. First, once launched, IR missiles do not have an operator in the loop. Unlike the RFCM system, the IRCM system is an open-loop system; it does not get feedback from the system it is jamming (the missile seeker is a closed-loop tracker and the focus of the evaluation). Also, live-fire events are somewhat less costly and more practical.

A major figure of merit for IR jammer effectiveness is the J/S ratio that the system can achieve. Specifically, the higher the amount of modulated radiation output (provided by the jammer) over the host aircraft signature, the better the IRCM performance will be in countering the threat of the same IR spectral bandpass.

An end-to-end flight test of an integrated MWS and DIRCM system would require live-fire missile launches at a drone aircraft carrying these systems. While this is feasible and potentially desirable, there are other ways to evaluate the performance of these systems. Testing can be broken down into two parts: the missile launch detection and hand-off information accuracy (see Section 2.3.2), and the IRCM effectiveness. These two pieces can be tested and evaluated independently. The first evaluation addresses whether or not the MWS can quickly and accurately detect and hand off the engagement to the fine-track sensor. Once the fine-track sensor has acquired the missile, the IRCM will be directed in an open-loop fashion at the missile seeker.

3.5.2.1 Uninstalled IRCM System Component and System Level Testing

The jammer spectral and temporal signatures can be measured with great precision and accuracy in a laboratory and the host aircraft signature can be measured in flight. In-flight signature measurement with ground-based or airborne radiometers requires accurate range to the target and angle information and meteorological conditions (barometric pressure, ambient temperature, and relative humidity) to account for atmospheric transmissivity. The J/S of the host aircraft can be calculated when the jammer characteristics and the aircraft signature are known.

HITL facilities provide an excellent venue to develop and evaluate IRCM techniques. These facilities allow evaluation of the effects of the actual IRCM transmitter, such as a laser, on actual seeker hardware. A highly instrumented seeker installed on a full-motion flight table, such as shown in Figure 3-16,

supporting a high-fidelity missile fly-out model, tracks a dynamic simulated target in an IR scene. The laser countermeasures are injected into the scene through a series of folded optics. This presents a realistic target scene with both the simulated target IR signature and the IRCM energy concurrently being presented to the missile seeker. This allows a wide variety of conditions to be evaluated in a short time.

Figure 3-16: IR-Guided Missile Seeker Mounted on Full Motion Simulator – (U.S. DoD Photo).

An end-to-end system test can be accomplished using the cable car testing addressed in Chapter 2. In this case the instrumented MWS is integrated with the instrumented IRCM system and a live missile launch is directed at the cable car. The MWS can be evaluated on its ability to detect the launch and hand off the track and the IRCM system can be evaluated on its ability to acquire the missile and counter it.

One of the most complete and correspondingly expensive means of evaluating IRCM performance is live-fire testing. Live-fire evaluations can be conducted by installing an instrumented (preferably with telemetry capability) IRCM system, or IRCM and MWS system in the integrated case, on a drone aircraft and a true end-to-end engagement can be considered. The cost of certain IR-guided missiles is relatively low and this can be a cost-effective means of testing the IRCM system. However, the cost effectiveness of the test is directly related to how well the IRCM system performs. The cost planning needs to account for the possibility that the IRCM system is ineffective or malfunctions, resulting in the loss of drone and SUT.

3.5.2.2 Installed IRCM System Testing

There are several common methods of evaluating IRCM system performance in flight test. Each has advantages and disadvantages. Much of the DIRCM installed system testing is done in flight, providing an

end-to-end evaluation incorporating the actual target aircraft signature. End-to-end testing requires three things, the ability to:

- Simulate a valid missile launch and generate an MWS missile launch declaration;
- Determine if the IRCM has been properly directed; and
- Assess the effectiveness of the IRCM on actual missile seekers.

Ideally, the test aircraft will be instrumented to record the MWS missile detection and declaration data as well as the hand-off and IRCM turret pointing data. The JMITS shown in Figure 2-17 and Figure 3-17 incorporates all of the elements necessary to perform end to end testing. Figure 2-17 shows the high fidelity JMITS IR/UV missile plume simulators and Figure 3-17 shows the JMITS laser radiometers used to detect the IRCM response and the instrumented missile seekers. The capability to record the IR signature of the test aircraft with ground-based radiometers is also desirable.

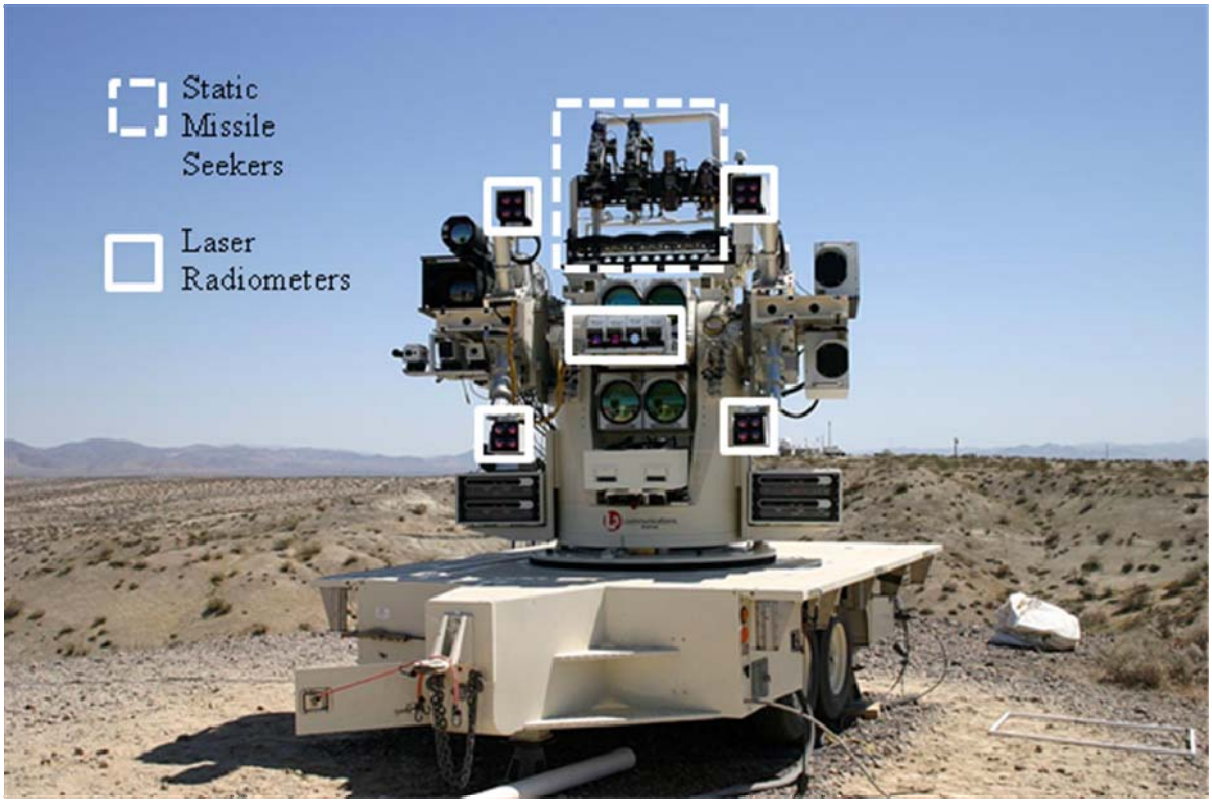


Figure 3-17: Joint Mobile IRCM Test System – (U.S. DoD Photo).

Static, ground-mounted, seeker-based test systems have the advantage of using actual instrumented seeker hardware tracking the host aircraft against which the IRCM performance can be evaluated. There are, however, several disadvantages that need to be considered during test design. First, the test aircraft flight profile must be designed to ensure that MWS doesn't reject the launch simulation based on engagement kinematics. Second, static missile seekers do not have realistic motion associated with an actual missile fly-out. Specifically, the missile isn't closing on the target at a realistic rate and doesn't have to react to the high angular rates of change associated with a real engagement, particularly at endgame.

3.6 COUNTERMEASURES DISPENSING SYSTEMS

CMDS are most commonly employed in a defensive electronic attack role. They dispense expendable payloads to deceive hostile air defence weapons systems. Conventional chaff and flares are the most common payloads and some CMDS are also capable of ejecting expendable (non-towed) RF decoys.

Chaff is one of the oldest forms of radar electronic countermeasures. It consists of a large number of micro-fibre reflective dipoles. When dispensed it disperses in the air stream forming a cloud and presenting the hostile radar with other competing large RCS targets. Figure 3-18 shows a typical round assembly and chaff fibres.

Figure 3-18: Typical Chaff Rounds and Chaff Dipoles – (U.S. Navy Photo).

Flares are pyrotechnic devices designed to deceive IR-guided missiles by presenting the missile seeker with a more attractive target than that the target aircraft. Conventional flares are made of various combinations of magnesium, phosphorus, and Teflon which is ignited when the flare is dispensed from the magazine and tries to mimic relevant spectral aircraft engine characteristics. Figure 3-19 shows F-16 and AC-130U aircraft dispensing conventional flares.

Figure 3-19: Flare Dispensing by F-16 and AC-130U Aircraft – (U.S. DoD Photos).

Flare technology continues to adapt to keep up with the advancing threat. Conventional flares are highly visible in the visual portion of the electromagnetic spectrum and can give away the position of an aircraft, particularly at night. To alleviate this problem, flares with minimal visual signature have been developed that still retain the required IR signature characteristics. Kinematic flares have also been developed to overcome the kinematic EP logic in some modern threat missile seekers. These essentially fly along with the aircraft as they separate and have a less abrupt angular separation from the host aircraft.

3.6.1 CMDS Components and Operation

CMDS are commonly installed in an integrated configuration and receive threat-related information from RWR and MWS to optimise dispense patterns and enable automatic operation. Most have three modes:

- **Manual** – Aircrew-initiated programmed response;
- **Semi-Automatic** – Automatically generated response requiring aircrew prior consent; and
- **Automatic** – Autonomous operation, i.e., without aircrew input.

A typical CMDS comprises a Cockpit Control Unit (CCU), a programmer, sequencers, the dispenser and magazine, and a safety switch. Figure 3-20 depicts these components and their functions.

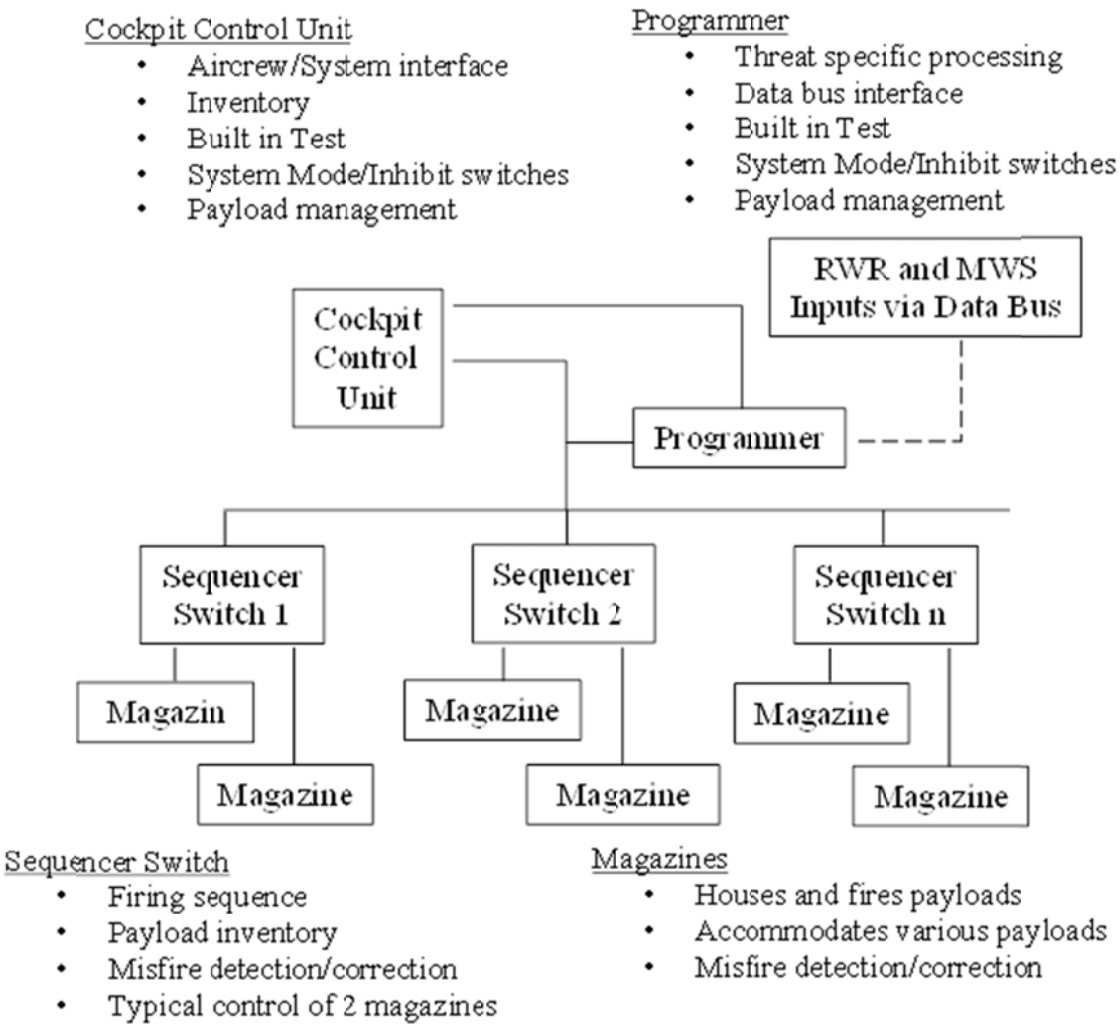


Figure 3-20: Block Diagram of Countermeasures Dispensing System.

Figure 3-21 indicates these components in a typical CMDS.

Figure 3-21: Typical CMDS – AN/ALE-47 – (Symetrics Industries Photo).

3.6.1.1 Control Unit

The CCU is the aircrew interface with the CMDS. It allows the operator to select the system mode, determine the remaining inventory, and programme the manual dispense parameters. The manual dispense parameters include the number of rounds in a burst and the time intervals between bursts. Other functions accessible through the CCU include the built-in-test and jettison. In many systems these features can be integrated with the avionics system and can be accessed via a glass cockpit.

3.6.1.2 Programmer

The programmer is the CMDS processor where both OFP and MDF reside. It typically receives threat data inputs via a data bus from the MWS and the RWR. The RWR typically provides threat specific data that along with aircraft airspeed and attitude data are used to optimise the response. The threat data consist of the parametric data that define the threat system. Pulse width, RF frequency range, amplitude or scan modulation, and pulse-repetition frequency are typical RF-threat parameters. Response data involve the specific dispensing technique against a known or identified threat. Responses consist of IR expendables, RF expendables (chaff), or a combination.

Dispense techniques are defined by the quantity and intervals at which the expendables are deployed. Payload data identify the types of expendables loaded into the dispenser and are available to be dispensed. During flight, the system monitors the magazine to keep track of how many and what type of expendables remain.

3.6.1.3 Sequencer

Sequencers distribute power and commands to dispensers. They manage payload inventories and determine if a misfire has occurred. Typically, one sequencer is used for every two dispensers.

3.6.1.4 Dispenser

The dispensers are housings for the magazines and are installed in the aircraft at the location where the expendables are to be released. The magazines are the modules that actually hold the expendables. Dependent upon expendable origin, preparation may be required prior to insertion into magazines:

- The US normally procures squibs (the pyrotechnic firing mechanisms) and flares separately, and these are not combined until shortly before use. They are inserted into the magazine, one squib for each expendable, prior to inserting each expendable.
- European manufacturers generally supply expendables with squibs ready fitted.

Squibs can only be used once and must be replaced like the expendables. Expendables are then loaded into the magazines in a safe area and then an entire magazine is inserted into a dispenser housing before each flight. Typical magazines on tactical aircraft hold approximately 30 expendables each. Figure 3-22 shows a typical CMDS dispenser with magazines installed.

Figure 3-22: CMDS with Magazines Installed on a C-130 – (U.S. DoD Photo).

The safety switch is an important part of the CMDS. When engaged, it does not allow any current to reach the dispenser, thus eliminating the chance of a squib accidentally firing.

3.6.1.5 Expendables

Expendables payloads are generally not produced by the CMDS manufacturer. All CMDS support conventional chaff and flare rounds. Many support other advanced payloads such as kinematic flares. Chaff,

flare, and other advanced expendable rounds, including RFCM, are continuing to evolve and the CMDS must be able to accommodate them. The expendable payload manufacturers design their products to be compatible with existing dispensers. CMDS OFP and MDF changes may be required to accommodate new expendable products. Figure 3-23 indicates typical flare and chaff cartridge used across NATO. [2]

Flare Cartridges: 36 mm, 2 x 2.5, 2 x 1, 1 x 1; and their associated impulse cartridges

Chaff Cartridges: 36 mm, 1 x 1 (dual), 1 x 1 (Standard) and their associated impulse cartridges

Figure 3-23: Examples of Expendable Configurations Within NATO (From [2]).

3.6.2 CMDS Testing

CMDS and airframe designers and developers extensively employ M&S to explore the critical question of where the CMDS dispenser should be installed on the host airframe. This is a particularly important consideration for flare dispensers. High fidelity aircraft structure and signature models allow designers to evaluate a variety of potential installations and their associated payload trajectories against the models of the threats of interest under a variety of engagement geometries.

Much of the CMDS and payload development testing can be conducted independently and concurrently for new systems. However, the CMDS and payload combined performance and effectiveness can only be evaluated in flight with the CMDS installed on the intended host platform using the intended payloads. This allows the payload effects to be evaluated with actual aerodynamic and host aircraft signature characteristics.

3.6.2.1 Uninstalled CMDS Testing

3.6.2.1.1 CMDS Component Testing

Hardware laboratory testing includes verifying that each separate CMDS module functions properly and operates within design parameters. Power, continuity, voltage, and Built-In Tests (BITs) are performed. These tests help to isolate hardware configuration or interface problems.

Software laboratory tests are performed on each module containing software. These tests help isolate any programming or timing errors and verify that the system software has been correctly implemented. Such errors can impact not only system performance, but may affect safety and survivability. Manual and automatic dispense capabilities are also evaluated to verify performance.

3.6.2.1.2 CMDS Level Testing

When the performance of the individual components has been verified, the CMDS can be tested as a complete system. Unlike many other EA systems the CDMS system does not have associated sensors. However, it does communicate via data buses with sensor systems such as RWR and MWS. Emulated data bus messages are generally sufficient to evaluate system level performance and laboratory RF threat simulation is generally not required for initial system level testing.

System level CMDS testing also verifies the proper operation of all operator switch settings. All system modes of operation can be tested in conjunction with a wide range of emulated RWR and MWS data bus messages. The dispenser assemblies are monitored to ensure that the proper firing pulses are generated in response to the test conditions.

Integration testing is the next stage of testing. It is conducted with the complete CMDS installed in a laboratory environment connected to actual avionics and EW hardware with representative aircraft cabling. This type of testing allows end-to-end system integrated system evaluations where the RWR is injected with simulated RF threat signals and/or the MWS sensors are stimulated. The data bus message traffic and the CMDS responses are monitored and recorded to verify proper operation.

Cable car testing is an effective means to evaluate end-to-end system level flare performance against actual missiles. The MWS and CMDS are integrated and installed on a cable car, see Figure 3-24. The number of flares dispensed and the timing between them is critical. This type of testing allows analysts to optimise system performance by evaluating the effects of number of bursts and timing intervals.

Figure 3-24: Flare Testing Using a Cable Car – (U.S. DoD Photo).

3.6.2.1.3 Expendable Payload Testing

Expendables are tested to verify that they meet their design specifications and requirements. Key IR expendable parameters include time to ignite, total burn time, spectral signature content, and intensity. RF expendables are tested to measure RCS "bloom" rate, which is how fast the expendable can achieve the desired RCS, fall rate, and actual frequency range over which the RCS can be achieved.

A single type of expendable payload will likely be employed on a variety of host aircraft and each dispenser installation will have unique separation characteristics. Additionally, many platforms employ a variety of expendable payloads. Software modelling should be performed to predict the separation characteristics for each type of expendable round that will be employed.

3.6.2.2 Installed CMDS Testing

3.6.2.2.1 Ground Testing

During installed-system test facility testing, dispenser systems are installed on a production representative aircraft and all functional tests are repeated to verify the system operates properly. These tests are conducted to verify electrical, mechanical, software, and EMC/EMI functionality and performance.

When EMI/EMC testing is conducted in an anechoic chamber where munitions cannot be used CMDS maintenance test sets can often provide a suitable means of monitoring the CMDS dispenser firing commands. It is critical to verify that the system will not inadvertently dispense its payload when operating in the presence of onboard RF transmitter or anticipated external RF transmission sources.

3.6.2.2.2 Flight Testing

The first consideration in CMDS flight testing is evaluating the expendable separation characteristics throughout the required flight envelope. It is important to verify, for example, that flares do not strike the airframe. Separation testing should be performed using a build up approach. The build up begins with test points where the modelling predictions show the largest separation margins and progresses toward the test conditions with the smallest margins.

Cameras mounted externally on the host platform can document separation characteristics for post-flight analysis. Chase aircraft perform several important roles during separation testing. First, the chase aircraft aircrew can provide real-time observations regarding the expected separation margins to the test conductor.

If the margins are less than expected the test team may decide to terminate the test and re-evaluate the predictions. Second, if a round strikes the dispensing aircraft the chase aircrew can advise the test aircraft aircrew about the condition of their aircraft. Finally, the chase aircrew can provide additional photographic documentation about the separation events.

CMDS performance and payload effectiveness are evaluated by testing against ground-mounted missile seekers and radiometric measurement systems, airborne pod-mounted missile seekers and radiometric measurement systems, and live-fire testing as discussed in active IRCM section. Figure 3-25 shows the Airborne Turret IR Measurement System III (ATIMS III) carried by an F-15 conducting a test on an F-18 aircraft dispensing flares. The ATIMS III pod carries up to four fully instrumented missile seekers.

1. Seekers
2. Mid-IR Imager
3. Televisions
4. Laser

Figure 3-25: Airborne Turret IR Measurement System III – (NAVAIR Photo).

3.7 LOW OBSERVABLE SYSTEMS

LO technology is a passive form of EA and has become a significant contributor to aircraft survivability and mission effectiveness. RCS and IR signature are the two areas most relevant to EW T&E. Signature reduction reduces the detectability of the subject aircraft. It also benefits any aircraft employing or benefiting from RF or IRCM, as the lower signature results in higher J/S ratios at the victim sensor.

3.7.1 LO Concepts

The most important RCS consideration in aircraft design is vehicle shaping. The air vehicle is designed to minimise the incident energy that is backscattered toward the radar, that is, the energy is directed in

another direction. RAM is also applied to the surfaces of the vehicle to dissipate incident radar energy. There are RCS reduction techniques to address major scattering sources such as cockpits, engine inlets and exhaust, antennas, etc. Aircraft canopies can be coated with conductive material such that incident RF energy does not enter the cockpit. Engine turbo machinery is a major scattering source and inlet/ exhaust designs that minimise their visibility to threat radars have proven effective. There are specially designed LO antennas to minimise their contribution to the overall RCS.

There are also a number of ways that aircraft designers can reduce an aircraft's susceptibility to IR-guided missiles. Shortwave-IR missile seekers track hot metal parts such as engine exhaust nozzles. Engine installation designs that prevent an IR missile seeker from having a line of sight to hot metal parts can significantly reduce the susceptibility of an aircraft to IR-guided missiles. Longer-wave IR missiles track the aircraft engine exhaust plume, and mixing cooling air into the exhaust can reduce the signature of the aircraft in the longer wavelengths. The signature of existing airframes can also be reduced by adding signature suppressers that either block the line of sight to hot metal parts or provide mixed cooling air. Add-on IR signature suppressors can adversely affect aircraft weight and performance.

3.7.2 LO Systems T&E

3.7.2.1 M&S

3.7.2.1.1 RCS Prediction and Mission Effectiveness Assessment

M&S plays a key role throughout the design and development of an LO air vehicle. The two interrelated areas where M&S play important roles are signature prediction and mission effectiveness assessment. Early in development, sophisticated software design tools can be used to conduct trade studies and predict the signatures of candidate aircraft designs. The modelled signature and predicted aircraft performance characteristics can be inputs to mission-level modelling simulating relevant missions to evaluate the effectiveness of the system.

M&S is also used to estimate mission effectiveness. The ability of search radars and radar-directed air defence weapons to detect and engage the air vehicle are established through engagement level modelling. These modelling efforts produce detection contours for search radars where the detection ranges are established as a function of aircraft aspect angle. The engagement modelling against terminal threat systems produces probability of kill (P_k) grids, where the P_k is established for each threat system of interest as a function of range, aircraft aspect, and flight conditions.

An acquisition programme commonly establishes operationally representative mission scenarios against which the aircraft performance will be evaluated. The results of the engagement modelling are incorporated with modelled command and control elements of a hostile air defence system to evaluate aircraft survivability in the reference scenarios. M&S is repeatedly performed as the design evolves to estimate the effects of design changes on performance.

The accuracy of RCS data will improve throughout the programme. Initial modelling will be based solely on digital RCS predictions. As the design matures static RCS measurements are made on major component assemblies as well as sub-scale or full scale aircraft models at measurement facilities. Finally, when actual aircraft are available, in flight RCS measurements of the actual air vehicle can be performed.

3.7.2.1.2 IR Signature Prediction and Detection Assessment

M&S also plays a significant role in IR signature prediction. IR aircraft signature modelling must account for a number of factors, such as engine settings, aerodynamic heating, and solar glint. The resultant model provides a database of IR spectral radiant intensity as a function of wavelength and aircraft aspect angle

that can be used in engagement level modelling. Once the IR signature of the air vehicle has been modelled, further M&S is conducted to evaluate the ability of IR sensors and guided weapons systems to detect, track, and engage the air vehicle. Atmospheric conditions have a significant effect on IR transmissivity and the model must account for factors such as humidity and particulate matter.

3.7.2.2 Signature Measurement

3.7.2.2.1 RCS Measurement

Ground-based RCS measurement facilities support LO platform design and development by providing measured RCS data on either scale or full-sized models. These facilities allow designers to optimise platform signature during development and provide analysts with high fidelity data to support mission effectiveness M&S. RCS measurements are performed on pole-mounted models. The models can be positioned in azimuth and elevation such that the RCS can be measured at each aspect of interest. Precisely calibrated radars measure the RCS of the model at relevant frequencies and polarisations. Figure 3-26 shows an F-35 model undergoing RCS measurements. Figure 6-1 shows another type of ground test capability for the measurement of RCS of real aircraft.

Figure 3-26: F-35 Model Undergoing RCS Measurements – (Lockheed Martin Photos).

In-flight RCS measurement facilities, such as the Patuxent River Atlantic Test Range, are used to collect data on actual aircraft. Specialised flight profiles are flown against ground-based precision measurement radars. Flight profiles are designed to maintain the proper geometric alignment between the measurement radar and test aircraft such that the RCS measurements are collected at the required frequencies, polarisations, and azimuth and elevation angles.

3.7.2.2.2 IR Signature Measurement

The IR signature of an aircraft can be measured in flight either using ground-based or airborne measurement systems. Airborne systems have the advantage of being able to measure the signature at fixed points around the platform. Figure 3-27 shows the Threat IR Generic Emulation Radiometer (TIGER) Pod which can provide all aspect air-to-air signature measurement of fixed and rotary wing aircraft and IRCM flares.

Figure 3-27: Air-to-Air TIGER Pod Mounted on F-18 – (NAVAIR Photo).

Measurements should be made at all relevant aircraft conditions. The various engine throttle settings can affect the IR signature of the aircraft. Aerodynamic heating related to airspeed also affects the aircraft's IR signature. The IR signature of an aircraft can, with limitations, be measured using MFs similar to that shown in Figure 6-1.

3.8 DIRECTED ENERGY SYSTEMS

DE weapons are, by definition, EA systems because they use DE "to attack personnel, facilities, or equipment with the intent of degrading, neutralising, or destroying enemy combat capability." [1] Two major DE areas are HPM and HEL systems. The potential advantages of DE include:

- Speed-of-light delivery;
- Invisible propagation;
- Directionality;
- Agility for engaging multiple targets;
- Deep magazines; and
- Immunity to the effects of gravity.

Disadvantages include:

- Attenuation with distance;
- Absorption by the atmosphere and moisture;
- Blockage due to weather;

- Complexity and sophistication; and
- Line-of-sight path to the target generally required.

The path to the target includes propagation physics. Propagation is a key consideration for effective use of both HPM and HEL weapons. HPM weapons tend to provide a soft-kill, or a disruption or denial effect, whereas HELs tend to be hard-kill devices.

3.8.1 HPM Systems

HPM weapons are systems that emit RF energy at high peak power levels and are often categorised by the bandwidth-to-frequency ratio of their waveforms. These are typically very large ratios. They have been divided into narrowband, wideband, and ultra-wideband. Peak power levels may exceed a gigawatt, but average powers may be less than a kilowatt. Some of the lower-frequency HPM devices have been called synthetic or non-nuclear Electromagnetic Pulse (EMP) or High-altitude EMP (HEMP). HPM devices have a smaller effective range than the EMP effects of a nuclear weapon. Narrowband devices tend to operate on specific electronic vulnerabilities in the target and therefore require knowledge of enemy systems to be effective. Ultra-wideband devices tend to be simpler and cheaper, using powerful transient waveforms, and requiring less knowledge of the target. A few HPM weapons function by making use of psycho-sensory or neural phenomena, rather than just high power levels, to deter human actions or cause confusion among attacking troops.

3.8.1.1 HPM System Components and Operation

Figure 3-28 illustrates the basic elements of an HPM-type system. Controls may include on/off, output level and repetition rate selections. Displays may be limited to input power indications or may include some feedback from the output, providing output waveforms and power estimates. Prime power is often electrical or chemical, or both. Pulse power may be provided by an explosive, one-time burst to effect dielectric, magnetic, or ferromagnetic generation of high voltages and currents; by a discharge of capacitors through spark-gaps, or through the use of special, high-power modulation circuits coupled to large special-purpose vacuum tubes. The output waveform must be matched to an antenna for energy transfer efficiency. Voltages are very high, requiring attention to air and dielectric material breakdown.

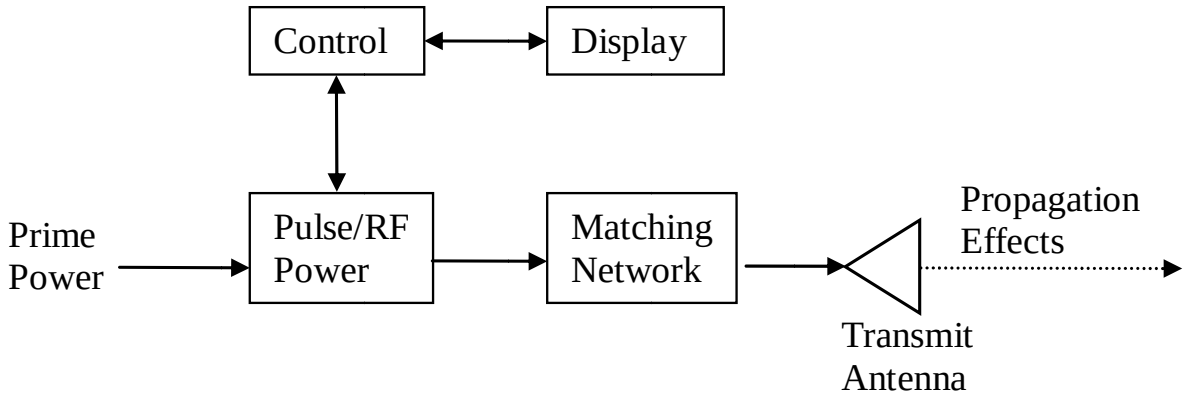


Figure 3-28: Simplified HPM Weapon/Source Block Diagram.

3.8.1.2 HPM System T&E

HPM weapon performance testing may include measuring performance metrics or confirming the lack of degradation of specific parameters, such as, the following:

- Power;
- Efficiencies of the pulse power conversion and RF conversion;
- Losses in the path to the antenna;
- Antenna gain or directivity; and
- Beam intensity.

Ultimately, performance comes down to an effect on enemy systems or forces. Operational performance can be summarised by the ability to create an effect, probability of effect (P_e). Those effects can be:

- Damage to a circuit;
- Upset of a system;
- Disturbance or denial of use of a system; and
- Interference while trying to employ a system.

The probability of an effect is often plotted as a family of curves against incident power levels. P_e is the most important parameter for weapons T&E. The other parameters are important for the engineering tasks of design and modelling.

Range is very important for mission planning, and can usually be derived from the parameters listed above for a particular desired effect, but may also include antenna gain as a function of angle from the source.

The often specialised nature and unique designs for DE weapons means that testing will differ between systems. Some of the common T&E approaches for DE systems are discussed in the following sections.

3.8.1.2.1 M&S

M&S is an important part of design, testing and usage of HPM weapons due to electromagnetic propagation phenomenology. Safe and effective testing cannot be performed without accurate estimates of electrical and magnetic field levels and energy densities. Power levels and field intensity levels derived from the models are required for test planning from the beginning, meaning that M&S is a continuing part of the test programme.

3.8.1.2.2 Laboratory Tests

Development of HPM systems and HPM test design may require iterations of analysis to quantify electromagnetic-field levels and repetitive effects testing. Multiple trials on specific electronics may result in an intensive investigation. For the ultra-wideband HPM weapon, multiple trials in the laboratory may be required to develop statistical estimates for the transient waveforms and repeatability of the output. These tests are best done at the laboratory level of development.

3.8.1.2.3 Ground Tests

In anechoic chambers or remote open-air ranges, HPM systems are measured and characterised. Effects data on targeted systems are collected and analysed. Adequate instrumentation is essential for performance measurements and also for safety. Instrumentation requirements must include measurements of transient fields from systems or sources by field sensors that often are made using B-dot or D-dot field sensors. Sometimes, these sensors may have to be placed inside equipment to properly characterise the effects at the physical level. Fast data acquisition equipment is required since some measurements may be required under the nanosecond timeframe.

3.8.1.2.4 Flight Tests

Flight tests will tend to be focused on system and mission compatibility. There is more emphasis on operational utility and target effects, although this may be difficult since the observable effect may be subtle. In addition to displayed information on the flight platform, instrumentation at, on, or in the target is required. Weather and other atmospheric parameters will be needed.

Unmanned HPM test platforms and target vehicles may require flight termination systems for safety. Those systems must be implemented such that they survive the HPM exposures and can still provide the safety functions required.

3.8.2 High Energy Laser Systems

HEL weapons direct light energy at targets using the properties of coherent electromagnetic radiation. The HEL systems are often categorised by the method of excitation, cooling, or the gain material. Some HELs are gas-dynamic lasers. These lasers are pumped by combustion or an energetic chemical reaction. Some lasers have a liquid gain medium or are liquid-cooled. Solid-State lasers (SSLs) have a crystalline or glass gain medium. SSLs have recently become viable contenders for HEL applications. Recent developments also include fibre-optic lasers and free-electron lasers. Fibre-optic laser development may result in easier handling and lower cost. HELs offer wavelength tunability. All lasers can be formed into a tight beam because of the property of coherence, meaning that the phase relationship is preserved to the point that interference of the waves can occur.

The best known HEL system is the YAL-1 Airborne Laser (ABL) shown in Figure 3-29. The ABL is a modified Boeing 747-400 designed to kill ballistic missiles in the boost phase. It autonomously detects, tracks, and engages ballistic missiles, and provides accurate missile launch location and impact points. [1]

Figure 3-29: The YAL-1 Airborne Laser System – (USAF Photo).

3.8.2.1 HEL System Components and Operation

Figure 3-30 illustrates the basic elements of an HEL-type system. Prime power can take different forms, such as chemical or electrical. The prime power provides energy to the pump mechanism. Lasers must have a pump to put energy into the gain medium such that a population-inversion of the laser energy states is created. Most lasers require an efficient cavity to support multiple passes of photons through the gain medium. Controls may be complex due to the requirement for beam steering and control, including precise pointing. Propagation includes not only attenuation effects, but optical effects from atmospheric turbulence, scattering, or a heterogeneous path. As a result, the beam control may include optics to compensate the beam for the atmospheric effects for longer-range systems.

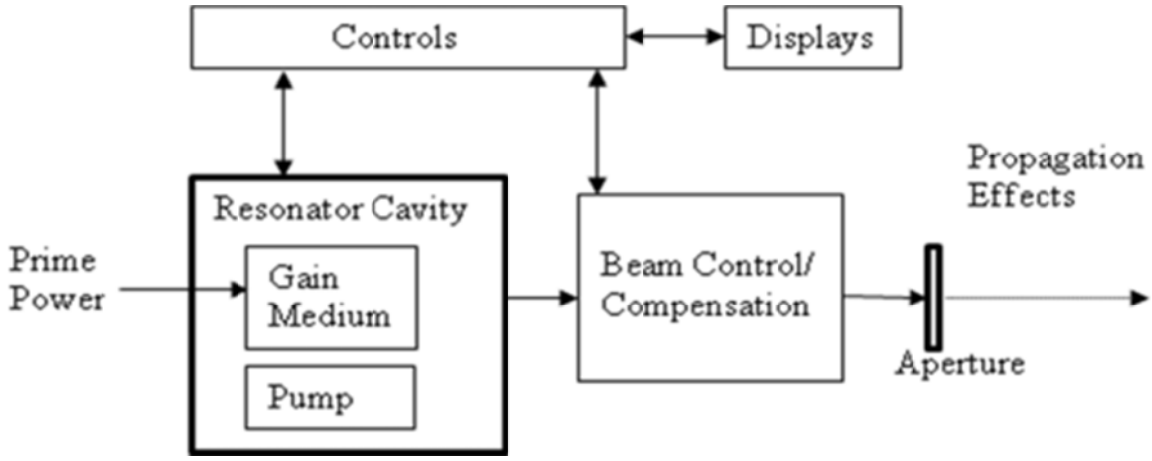


Figure 3-30: Simplified HEL Weapon/Source Block Diagram.

3.8.2.2 HEL Systems T&E

Testing of lasers will vary depending upon the physics phenomenon that produces coherent emission. These lasers have different test objectives based upon the unique properties of the medium and proposed effect. They will, however, have certain input and output characteristics and figures of merit that allow comparison and produce some commonality in weapons applications.

3.8.2.2.1 M&S

Because of the EM propagation phenomenon, M&S is an important part of design, testing and usage. Power levels and field intensity levels derived from the models are required for test planning from the beginning, meaning that M&S is a continuing part of the test programme. Because of the often specialised nature and unique designs for DE weapons, the testing will differ between systems. Some of the common T&E approaches for DE systems are discussed below.

3.8.2.2.2 Laboratory and Ground Tests

Laboratory testing of concepts and demonstrators is likely to be very technically complicated. Testing of sub-systems is likely to be extensive due to the complexity and the need for a build-up approach.

In the laboratory, key laser performance characteristics can be accurately measured and characterised. Output is usually measured by instrumentation that records multiple temperature measurements in a beam dump, converting it into a calorimeter.

Common laboratory and ground test performance measures include:

- Power;
- Brightness (in units of power per solid angle); and
- Delivered fluence (in joules per unit area).

The amount of fluence, or flow of energy, on a target is related to the beam quality. Beam quality is generally a ratio relationship between the total energy deposited to an ideal amount of energy, expected in a diffraction-limited system. There are several parameters used to describe beam quality, to include Strehl, M-squared, and power-in-the-bucket. Formulas and algorithms for predicting and calculating these from test data are found in textbooks and scientific publications.

Based on laboratory and ground test results, three operationally important measures can be determined:

- Probability of kill (P_k);
- Required dwell time in units of seconds; and
- Effective range, in miles or kilometres.

Some of the common data requirements involved in integrating a HEL into a flying platform are power consumption, charging timelines for the energy storage elements, heat dissipation, and the ability to focus the beam in the flight environment. For production versions of HEL systems on a flying platform, compatibility testing, EMI/EMC, EW, HPM susceptibility, and network-centric interoperability tests may be required. These tests are done more efficiently in the appropriate ground facilities, such as installed-equipment facilities and anechoic chambers than during flight tests. For the flight environment assessment, the beam focus estimates must account for the aerodynamic effects around any exit apertures.

3.8.2.2.3 Flight Tests

Early flight testing to reduce the risk of adding an HEL to an aircraft may be prudent. These tests may involve the aerodynamics changes for installing turrets, fairings, and windows. Early flights with sub-systems or surrogates may be used to verify heat removal and other form, fit, and functions of the interfaces to a laser pallet or system.

Final flight testing of HEL weapons will tend to be more operational-effect oriented. Targets may be used with various instrumentation schemes. A successful effect is likely to be a visible one that includes significant damage, as opposed to HPM where the effect is more subtle. Although the effect may be obvious from visual and infrared sensors and human observations, failures to achieve an effect may be much less clear. As a result, instrumentation on and around the target is required. Pointing and tracking may have to be assessed at lower power levels to avoid damage to sensitive detectors and data acquisition systems on the targets. To determine functions that predict P_k, target fluence levels will be required for each set of trials. Weather and other atmospheric parameters will be needed. Their effects on propagation must be modelled and verified.

Safety requirements for the test range may include monitoring the intended beam as well as inadvertent reflections or glint, to avoid inadvertent propagation to populated areas or other craft. Flight termination systems on targets must be implemented such that they either survive or avoid exposures and provide the safety functions required.

3.9 REFERENCES

[1] United States Air Force, “The Air Force Handbook 2007”, 2007.

[2] NATO Industrial Advisory Group SG-105: Study on NATO Aircraft and UAV Self Protection Systems – Flare/Chaff round Interchangeability: Final Report. NIAG-D(2007)0022-REV001, 31 October 2007.

3.10 FURTHER READING

Chrzanowski, E.J., "Active Radar Electronic Countermeasures", Norwood, MA, Artech House, Inc., 1990, (ISBN 0-89006-290-0).

Golden, A., "Radar Electronic Warfare", New York, New York, American Institute of Aeronautics and Astronautics, Inc., 1987, (ISBN 0-930403-22-3).

Hecht, J., "The Laser Guidebook", Blue Ridge Summit, PA, TAB Books, 1992, (ISBN 0-8306-4274-9).

Hecht, J., "Beam Weapons: The Next Arms Race", Lincoln, NE, iUniverse.com, Inc., 2000, (ISBN 0-595-09450-3).

Lynch, D., Jr., "Introduction to RF Stealth", Raleigh, NC, SciTech Publishing Inc., 2004, (ISBN 1-891121-21-9).

Schleher, D.C., "Electronic Warfare in the Information Age", Norwood, MA, Artech House, Inc., 1999, (ISBN 0-89006-526-8). Chapter 8: DEW and Stealth Technology.

Stimson, G.W., "Introduction to Airborne Radar", Raleigh, NC, SciTech Publishing Inc., 1998, (ISBN 1-891121-01-4).

Van Brunt, L.B., "Applied ECM", Dunn Loring, VA, EW Engineering, Inc., Vol.1 (1978, ISBN 0-931728-00-2); Vol.2 (1982, ISBN 0-931728-01-0); Vol.3 (1995, ISBN 0-931728-03-7), Ch.7 Test and Evaluation.

Weigand, R.J., "Radar Electronic Countermeasures System Design", Artech House, Norwood, MA, 1991, ISBN 0-89006-381-8.