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A test methodology for the validation of Doppler video instrumentation for fighter aircraft radar in development of electronic protection

William Donald Bailey

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To the Graduate Council:

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Fred Stellar, Major Professor

We have read this thesis and recommend its acceptance:

Ralph D. Kimberlin, Frank S. Collins

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Test Methodology for the Validation of Doppler Video Instrumentation for Fighter Aircraft Radar in Development of Electronic Protection

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

William Donald Bailey
August 2001

ABSTRACT

There is a need to measure the effects of radar jamming on modern military radar systems. An advanced Doppler video system designed to measure the effects of jammers on radar systems was developed by the United States Air Force Electronic Warfare Division. This thesis develops a methodology that can be used to effectively validate such an instrumentation system. The Doppler video instrumentation system was an advanced system geared specifically towards developing counter-jamming techniques by capturing the raw RF data entering the radar. The methodology developed was a process of sequenced tests designed to evaluate the Doppler video instrumentation system. Applications into the development of electronic counter-countermeasures are described to illustrate the processes required by this methodology.

The typical radar instrumentation connects only to the radar processor, recording the various operating modes or calculated range and closing rates of targets, and does not capture the RF spectrum. That type of system is easily validated through the comparison of radar processor data to target tracking data from a surveyed ground radar or other truth source. The challenge of validating the Doppler video instrumentation was in selecting specific tests to determine the accuracy of the frequency and intensity measurements of the RF spectrum.

The methodology used a building block approach, starting with ground tests and advancing to flight tests. Ground testing involved direct injection of a signal into the radar, exercising the full range of bandwidth and intensity. Flight testing assessed radar baseline performance to determine the impact of the instrumentation system's insertion loss on detection and lock-on range. Flight testing included examining the effects of Doppler shifts and frequency roll-off at radar gimbal. Flight tests against a target equipped with a programmable radar jammer were designed to evaluate performance against techniques such as noise, range gate pull-off and velocity gate pull-off.

The methodology demonstrated that the Doppler video instrumentation system met the accuracy requirements for monitoring the frequency and intensity data from the radar under test in both ground and flight phases. Flight testing also successfully assessed the capability of the instrumentation system to capture jamming techniques. The radar under test was observed in jamming runs to apply an attenuating filter to manage the power levels for the receiver and in the process lose the faint skin return. Additional testing in an anechoic chamber or with a calibrated airborne signal collector was recommended to enhance the measurement of intensity error.

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LIST OF ABBREVIATIONS

A/D	analog-to-digital
CRV	combined range and velocity gate pull-off
dB	decibel
DSP	digital signal processor
EMI/EMC	Electro-Magnetic Interference/Electro-Magnetic Compatibility
EP	electronic protection
FFT	Fast Fourier Transform
GPS	global positioning system
Hz	hertz
IF	intermediate frequency
KHz	kilohertz
KIAS	knots indicated airspeed
MHz	megahertz
MSL	mean sea level
nmi	nautical mile
RF	radio frequency
RGPO	range gate pull-off
TSPI	time space position information
V_C	closing velocity
VGPO	velocity gate pull-off

Chapter 1 - Introduction

Background

In the history of electronic warfare, the ability to deny and deceive an opponent's use of electronic sensors is almost as old as the radar itself. Operational use of barrage noise jamming and chaff countermeasures date back to World War II (1). While most radar specifications emphasize detection range and tracking accuracy, protection from jamming, or electronic counter measures, is an equally valued characteristic. Designers program the radar with logic to detect and protect itself from jamming. Flight tests of these counter-countermeasures are extremely exacting. To this end, more sophisticated instrumentation has been developed to measure the effects of countermeasures on the radio frequency (RF) spectrum captured by the antenna. This thesis describes a methodology to validate the performance of such an instrumentation system.

Before an instrumentation system to measure the effects of radar countermeasures can be fielded for flight test, the end-to-end performance must be verified. Once the precision and accuracy of the system is demonstrated, radar developers can then use that data to evaluate the performance of their radars in the dynamic environment of flight test against various radar countermeasures.

This validation program was carried out using a Doppler video system developed by the Air Force Electronic Warfare Directorate. The system was designed to have a standard interface to adapt to a large number of aircraft radar systems. The validation methodology for this thesis was developed in parallel with the hardware to deliver a fully capable system to radar software developers.

The validation of this instrumentation is divided into two parts: ground test and flight test. Ground testing consists of Electro-Magnetic Interference / Electro-Magnetic Compatibility (EMI/EMC) testing and direct injection of radio waves. The objective of EMI/EMC tests is to examine the effects of the aircraft installation and operating environment on the data quality and operation of the instrumentation system. Direct injection allows careful control of the inputs (frequency and intensity) to evaluate against the design criteria. Flight testing encompasses modification checkout, dry target and wet target testing. Modification checkout ensures basic functionality of the design and re-baselining of the radar sensitivity. Dry target testing focuses on the precision and accuracy of the Doppler video system against a non-jamming aircraft. Wet target testing determines the system's ability to accurately capture representative countermeasures techniques transmitted by another aircraft.

The Doppler video system is unique in that the input comes from the radar's IF data, unlike most radar instrumentation which captures data coming out of the radar computer/receiver. The difficulty with countermeasures testing is that it requires data from what the radar sensed and what the radar processed. Evaluating only what the radar processed might be able to demonstrate when the radar was deceived, but not what caused it to be deceived. By capturing what the radar sensed, like jammer-to-signal ratios, tracking gates and local oscillator settings, the context in which a radar processed information can be examined.

Test Execution

Testing is divided into two phases: a ground phase and a flight phase. The flight phase is further divided into a non-jamming or “dry” portion and a jamming or “wet” portion. The emphasis on the ground phase is designed to characterize the response of the system to precisely controlled inputs over the full dynamic range of the system. The “dry” portion of the flight phase examines the impact of insertion loss on radar sensitivity. The “wet” portion of the flight phase introduces jamming to demonstrate the capability of the system to accurately capture several common jamming techniques. A total of six ground test hours and three sorties were completed over a period of two weeks to validate the Doppler video system.

Test Objectives

The general objective of this thesis was to develop a test methodology that validated the output of a Doppler video instrumentation system. The goal of the system was to support development of electronic protection algorithms. To support these goals, the radar frequency and amplitude data over time was required. To support these requirements, the following specific objectives were addressed:

1) Determine the accuracy of the Doppler video frequency and power measurements in a ground test.
2) Verify that the Doppler video modification did not affect the performance of the radar.

3) Determine the accuracy of the frequency displayed by the Doppler video in a non-jamming environment against a non-maneuvering target.

4) Assess the ability of the Doppler video system to capture the jamming techniques listed in Table 1.0 below.

The most complex tests of radar are evaluating electronic protection (EP). The nature of EP testing demands knowledge of the RF environment in close physical proximity to the radar. Capturing the frequency spectrum's content and intensity during the test provides insight into the radar computer's processing of the jamming target. An insidious failure mode in EP testing can be a malfunctioning jammer. The radar would closely track the target, indicating the counter-countermeasures were successful, however the truth was that the radar was never jammed in the first place. By looking at processed radar computer data alone, an assessment of radar functional performance cannot be accomplished.

Table 1.0 Selected Jamming Techniques

Technique	Abbreviation	Description
Noise	N	5 MHz Bandwidth
Velocity Gate Pull Off 1	VGPO1	12 KHz pull to zero in 5 seconds
Velocity Gate Pull Off 2	VGPO2	12 KHz pull to zero in 3 seconds
Velocity Gate Pull Off 3	VGPO3	12 KHz pull to zero in 1 second
Combined Range and Velocity Gate Pull Off 1	CRV1	12 KHz pull to zero in 5 seconds
Combined Range and Velocity Gate Pull Off 2	CRV2	12 KHz pull to zero in 3 seconds
Combined Range and Velocity Gate Pull Off 3	CRV3	12 KHz pull to zero in 1 second

To address this problem, additional instrumentation was introduced. The proposed solution required recording the RF data sensed at the antenna prior to the radar receiver processing function. At the microwave level, the information is analyzed for its frequency content and intensity. By analyzing the signal during the test, the radar engineer can monitor the jammer's attack on the radar.

Test Item Description

Radar Instrumentation

Most existing radar instrumentation uses processed information from the receiver/processor. Radar mode information typically covers the pilot inputs (e.g. designate track, break lock) and status (e.g. track-while-scan selected, searching for targets, tracking a target). Other data provided to the rest of the system include variables such as closing velocity, V_c, and range, R. All of these data assist in radar specification compliance testing but are inadequate for development of EP.

Hardware Description

The Doppler video unit developed by the Air Force Electronic Warfare Directorate only requires four signals: the Intermediate Frequency (IF) input, the reference frequency input, the receiver cutoff gate and +28V aircraft power (2). The unit then sends data, to include time, on separate RS-422 formatted lines.

The connections have negligible impact on the operation of the radar. The tap-off had an insertion loss of 0.5dB maximum and 0.2dB typical value. Since the excess noise from the microwave receiver is greater than 25dB and the noise figure of the radar receiver is much lower than that, an insertion loss of less than 0.5 dB is not significant (3).

The receiver cutoff gate comes from a test connector on the radar receiver and is lightly loaded. Both of these signals are buffered on the Doppler video unit to minimize coupling of any signals in the reverse direction.

The output data from the Doppler video unit are the magnitudes of the frequency spectra of the IF input waveforms. The unit performs the Fast Fourier Transform (FFT) internally, extracts the magnitude in dB for each of the frequency bins and formats the magnitude as eight bit values for the Pulse Coded Modulation (PCM) stream. This has the benefit of providing a much lower data rate for the telemetry link than would be needed to transmit the time samples directly. Another benefit is that the computer displaying the data does not require the computational power to perform the FFT, which can be time consuming.

Block Diagram

A functional breakdown of the Doppler video unit is included in Figure 1.0 below.

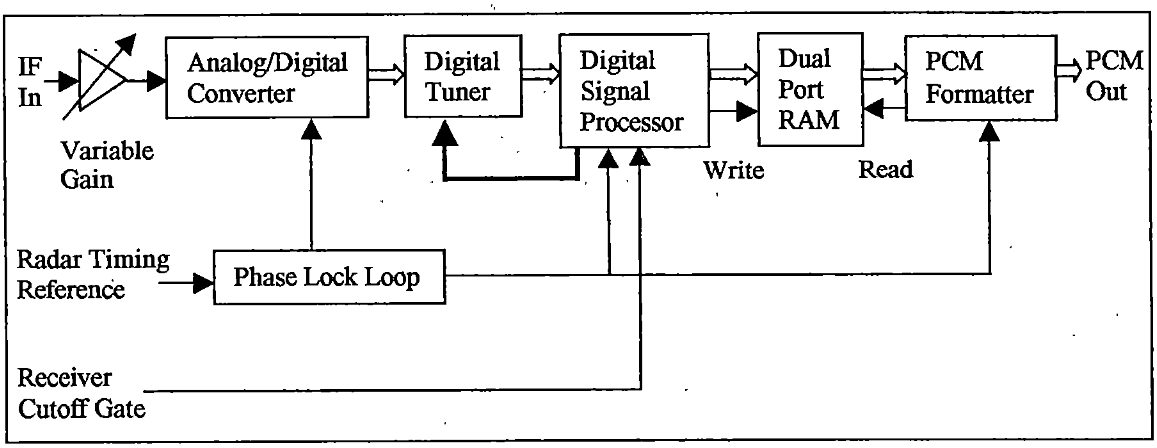

Figure 1.0 Doppler Video Unit

The front end amplifier has variable gain to manually compensate for gain and noise figure variations in microwave receivers. Typical variations can be as large as 30dB (3).

The Analog to Digital (A/D) converter digitizes the IF input to 12 bits at a rate of 64 MHz. The sample rate is near the maximum rate of 65 MHz for the A/D and Digital Tuner.

The Digital Tuner receives the samples from the A/D converter and performs a digital downconversion to baseband with in-phase (I) and quadrature (Q) channels. It also decimates and filters the data to reduce its overall bandwidth. The net effect is that the samples input the tuner as 12 bits parallel at 64 MHz and output the tuner as two channels, I and Q, of 23 bits each at 125 KHz. The serial output data is sent continuosly to the Digital Signal Processor (DSP) chip.

The DSP is a specialized microprocessor that performs floating-point multiplications very efficiently. The DSP is used to set up the tuner and receive its serial data, perform the FFT, convert the resultant magnitudes to dB and send those magnitudes to the dual port memory.

The PCM formatter simply reads the PCM frame data from the dual port memory and shifts it out serially. The output bit rate is 1 MHz and is phase locked to the radar reference frequency.

The receiver cutoff gate controls the sampling process. The output of the tuner is continuous, but the receiver is only functioning during the receiver gate time. To make sure the FFT is based on only the signals received, the sampling process is triggered by the receiver cutoff gate.

The phase lock loop ensures tuning accuracy, so that zero Doppler is represented by the first frequency bin even as the radar reference drifts.

Radar/EW Theory

As the Doppler video system is a radar instrumentation system, several key radar components are included in Figure 1.1 and described below.

Antenna

Perhaps the most basic of radar components, the antenna carries a dual role. In the transmit role, it shapes and concentrates the radiated energy into a coherent beam along a desired line. As a receiver, the antenna acts as a collector, focusing the energy of the radar reflections to be passed along to the receiver. It is generally a parabolic dish or a flat plate series of radiators mounted on a gimballing joint. The antenna is swept in azimuth and elevation to cover the entire search volume.

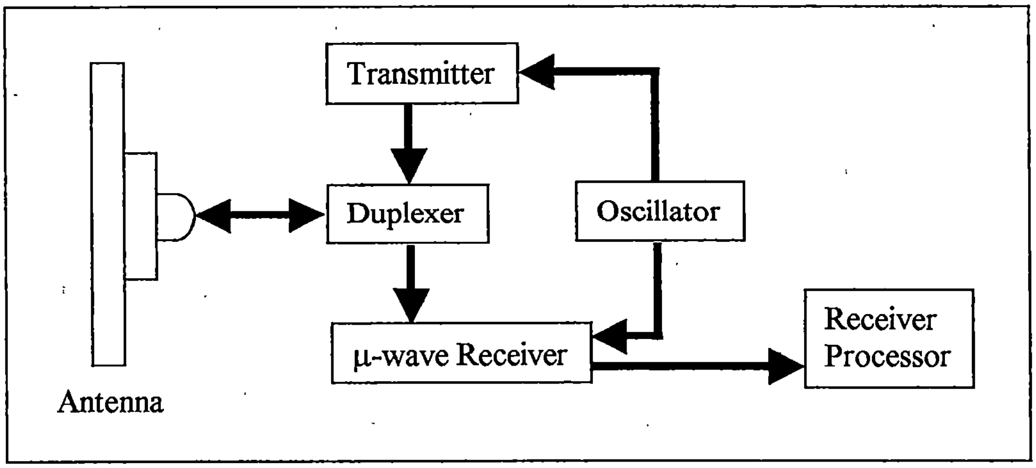

Figure 1.1 Generic Pulse Doppler Radar

μ-wave Receiver

The μ-wave Receiver is a generic term to describe the down-conversion of the RF signal to an IF for digital conversion and processing. The number of filters, amplifiers and detectors are unique to the design of the host radar. The Doppler video system adapts to the radar architecture, requiring only tapping into the signal after down-conversion. The RF signal at that point is at a low enough frequency to be sampled adequately for display and recording.

Oscillator

The oscillator is responsible for generating a highly stable, low power signal at a design frequency. The output of the oscillator is used to ‘tune’ the output of the transmitter as well as the input to the receiver. It serves as a metronome for all of the radar components, putting them on a common reference frame.

Receiver Processor

The receiver processor, like the μ-wave Receiver, is a generic term. It represents the filtering, signal processing and data manipulation center for the radar. Data from the receiver processor are provided to the pilot’s display in the form of coherent radar returns or search ‘hits’. Some radar architectures are federated, with these functions taking place in individual units, while others have a combined architecture, consolidating all functions into one box. These configurations are transparent to the Doppler video system as it captures the RF signal prior to it arriving at the receiver processor.

Jammer to Signal Ratio (J/S)

Jammer to signal ratio compares the intensity of the incoming jammer energy with the intensity of the radar echo from the target. Typical of most radar values, J/S is measured in decibels (dB). The radar echo's intensity is inversely proportional to the range raised to the fourth power, while the jammer signal is inversely proportional to the range squared. The mathematical relationships are described in Equations 1.0 and 1.1 (4). The jammer signal has the advantage of not having to make a round-trip. The geometries of the two scenarios are described in Figure 1.2.

Radar Power equation:

$$Pr := \frac{PtGtGr\lambda^2\,\sigma}{(4\,\pi)^3\,R^4} \qquad \text{EQN 1.0}$$

Jammer Power equation:

$$Pr := \frac{PjGjGr\lambda^2}{(4\,\pi)^2\,R^2} \qquad \text{EQN 1.1}$$

Where:
Pt = Intensity of the target return
Pj = Intensity of the jammer signal
Gt = Gain of receiving antenna
Gj = Gain of jammer antenna
σ = Radar cross section of target
λ = Wavelength
R = Range

At some point during an intercept, the intensity of the target return will exceed the transmit capability of the jammer. Shortly after that, the radar will be able to track the

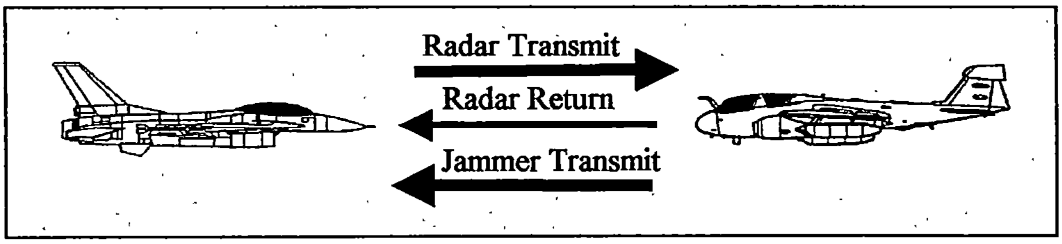

Figure 1.2 Signal Loss as a Function of Transmission Path

true return of the target. The range at which that happens is termed the burn-through range, as it describes when the target is no longer masked by any electronic countermeasure. Burn-through range can be calculated using Equation 1.2 (4).

$$Rjs := \sqrt{\frac{PtGt\sigma}{PjGj4\pi}} \quad \text{EQN 1.2}$$

Electronic Counter Measures (ECM)

The two basic forms of electronic counter-measures are noise jamming and deceptive jamming. Noise jamming attempts to mask the true skin return with a wide, high-power covering pulse. As the radar attempts to adjust to the higher noise level, it cannot detect the weaker target return. Noise jamming is illustrated in Figure 1.3. Deceptive jamming captures the radar tracking gates, either in velocity or range. A larger jamming strobe covers the aircraft return to 'capture' the gates. The strobe is then walked off in frequency for a velocity gate pull off (VGPO) or walked off in time for a range gate pull off (RGPO). For either pull off, the goal is to move the gates away from the real target return and then remove the jamming. The gates are then empty and the radar breaks lock. A velocity gate pull off is illustrated in Figure 1.4.

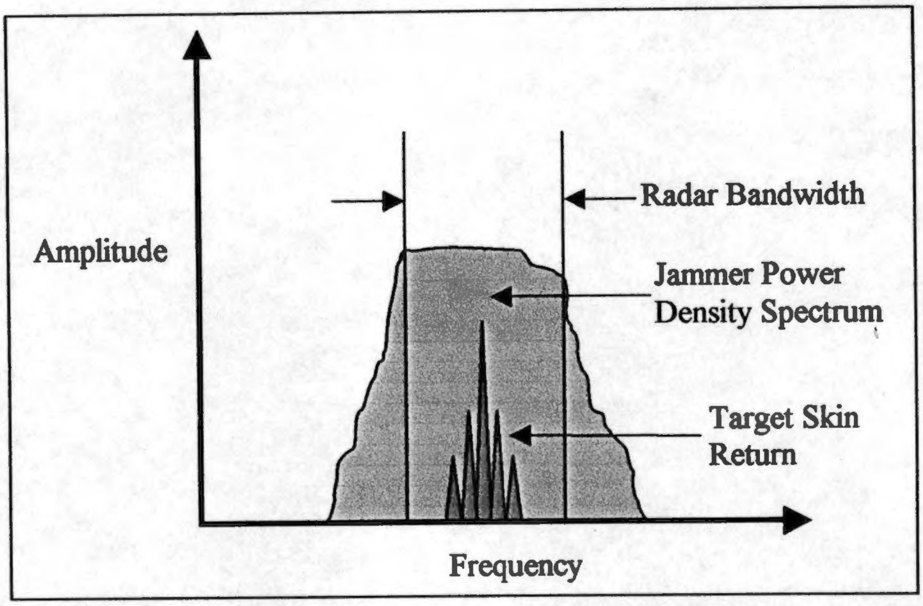

Figure 1.3. Noise Jamming

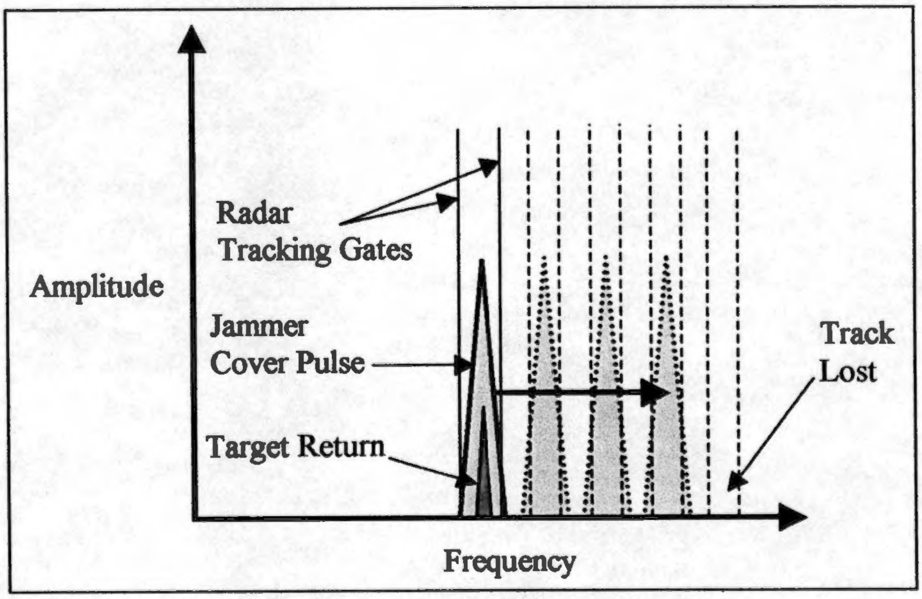

Figure 1.4 Velocity Gate Pull Off

Chapter 2 - Test Methodology

Radar Testing

Flight testing of airborne radars is influenced by a number of factors. Atmospheric attenuation can vary daily based on water vapor content in the air (5). Clutter or ground return can provide additional energy into the radar from sidelobes. The radar cross section of the target varies as the aspect changes only a slight amount (5). Multipath returns from different reflecting surfaces of the target spread out the return over time. To combat these effects, the following procedures are followed. To minimize the impact of a change in atmosphere, all runs took place on the same day, in Visual Meteorological Conditions. To negate the effects of clutter, all passes were completed at higher altitudes with no look-down in the geometry.

Electro-Magnetic Interference/Electro-Magnetic Compatibility Testing

Before flight-testing any avionics modification to the aircraft, the interaction between the new hardware and existing hardware was assessed by means of an Electro-Magnetic Interference/Electro-Magnetic Compatibility (EMI/EMC) test.

EMI/EMC testing demonstrated the prevention of unwanted interaction between the aircraft existing avionics and the modification hardware. Given the ability of the Doppler video system to monitor all energy coming into the antenna, all other emitters, such as the tracking radar and aircraft data links, were included to assess the impact on data quality.

Time-Space-Position Information (TSPI)

Precise location of the test aircraft and target were key pieces of data for radar testing. Generically, this data is referred to as Time Space Position Information (TSPI). Many difference sources can be used to provide TSPI data, most notably ground based radar trackers and Global Positioning System (GPS) based pods carried on each aircraft. Ground based radar trackers operate in the C (4-8 GHz) or X (8-12 GHz) band from surveyed locations, providing an accuracy of 0.1 milliradian root mean squared (rms) error in azimuth/elevation and less than five yards rms in range (6).

The airborne GPS pods, ARQ-52(V), combine a four channel GPS receiver with an inertial package of gyroscopes and accelerometers. The published accuracy of the ARQ-52(V) is six feet horizontally and 10 feet vertically for a 1 sigma rms error (7). The GPS pods transmit their TSPI data via a downlink operating at L band frequencies.

Data Display

To display frequency spectrum data from radar testing, custom displays were required. The challenge was to capture frequency, intensity and time on a single plot. Based on discussion with the Joint AIM-120 Advanced Medium Range Air-to-Air Missile (AMRAAM) office at Point Mugu Naval Air Station (8), the plots in Figures 2.0 and 2.1 were developed.

Figure 2.0 displays frequency, on the X axis versus intensity, on the Y axis. These data reflect a single instant in time and allow for detailed Jammer-to-Signal ratio analysis. Figure 2.1 is a three dimensional plot of frequency, intensity and time. The

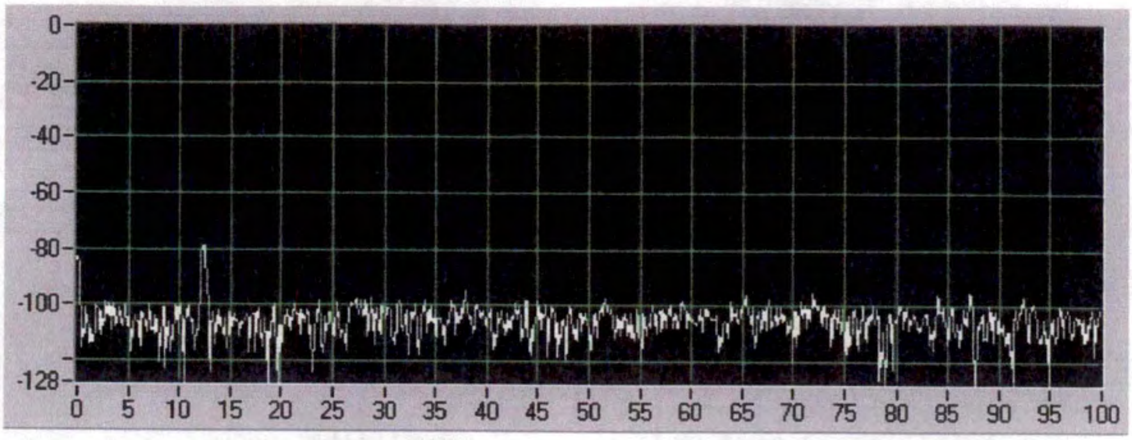

Figure 2.0 Frequency versus Intensity Plot

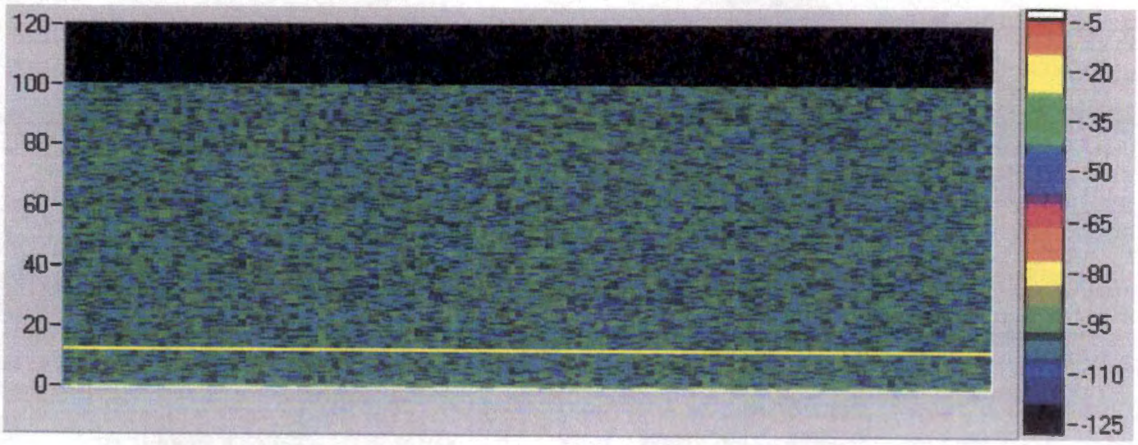

Figure 2.1 Frequency, Intensity, Time Plot

data waterfall from right to left in time, covering all frequency bins in the Y axis. Each column of cells reflects one radar frame with the intensity of the return in each cell indicated by a color. In these figures, the radar was receiving a self-test pattern consisting of a continuous 12 KHz signal with a strength of -80 dB, which translated into a bright yellow line in Figure 2.1.

Traditional X/Y plots of existing basic radar parameters, such as oscillator frequency, range and range rate, complimented the analysis of radar performance. Figure 2.2 is an example of a comparison between radar reported range and TSPI range.

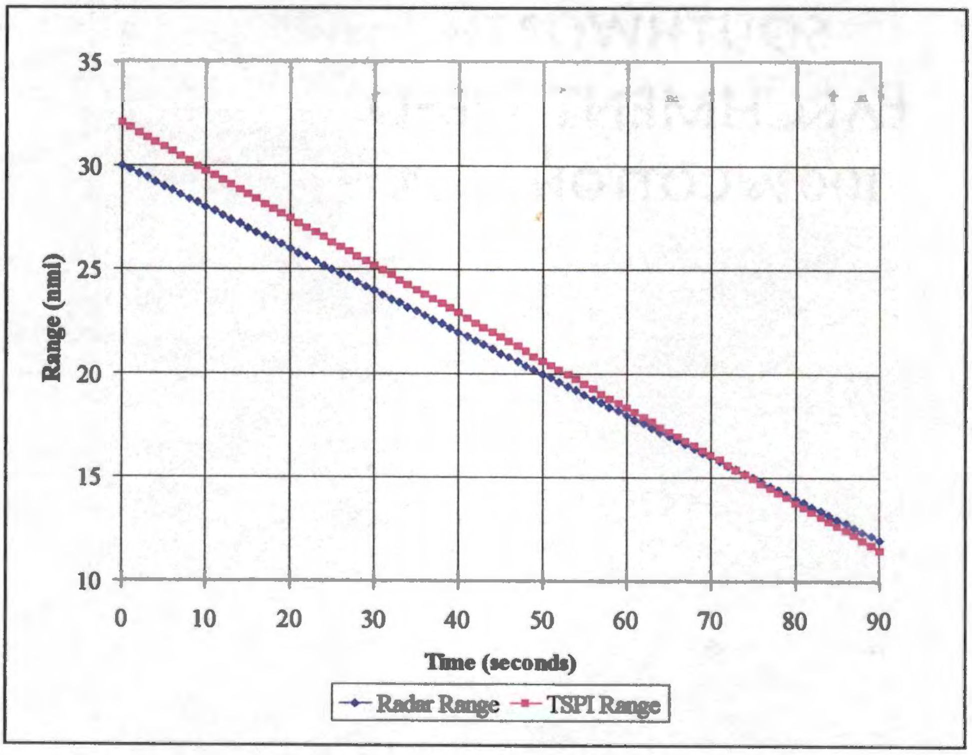

Figure 2.2 Basic Radar Plots

Flight Test Methodology

Two distinct phases made up the test methodology, each building on the previous one in terms of scope and complexity. The most basic of these was the ground phase, where, in a controlled environment, a full range of synthetic inputs were used to exercise the system. After satisfying the functionality of the system, the flight phase incorporated a "dry" portion examining the impact of insertion loss on the baseline radar and the functionality of the hardware in the open-air environment. With a full understanding of the radar-Doppler video system interaction, jamming was introduced during the "wet" portion to characterize the system's ability to accurately capture generic jamming techniques.

Ground Phase

The structure of the ground phase targeted the accuracy of the Doppler video system's frequency and intensity data. Given the controlled environment (i.e. inside a hanger, using a signal generator connected directly into the receiver), uncertainties seen in open-air testing would be eliminated. The ground testing established the absolute accuracy of the system's measurement of frequency and intensity. Figure 2.3 describes the ground phase hardware setup.

The measures of performance in the ground phase were the average error in frequency measurement and power measurement. The signal generator input a continuous wave at a specific frequency and controlled intensity. The base frequency was then shifted over a range of discrete steps covering 80 KHz. This process was repeated for all conditions listed in Table 2.0.

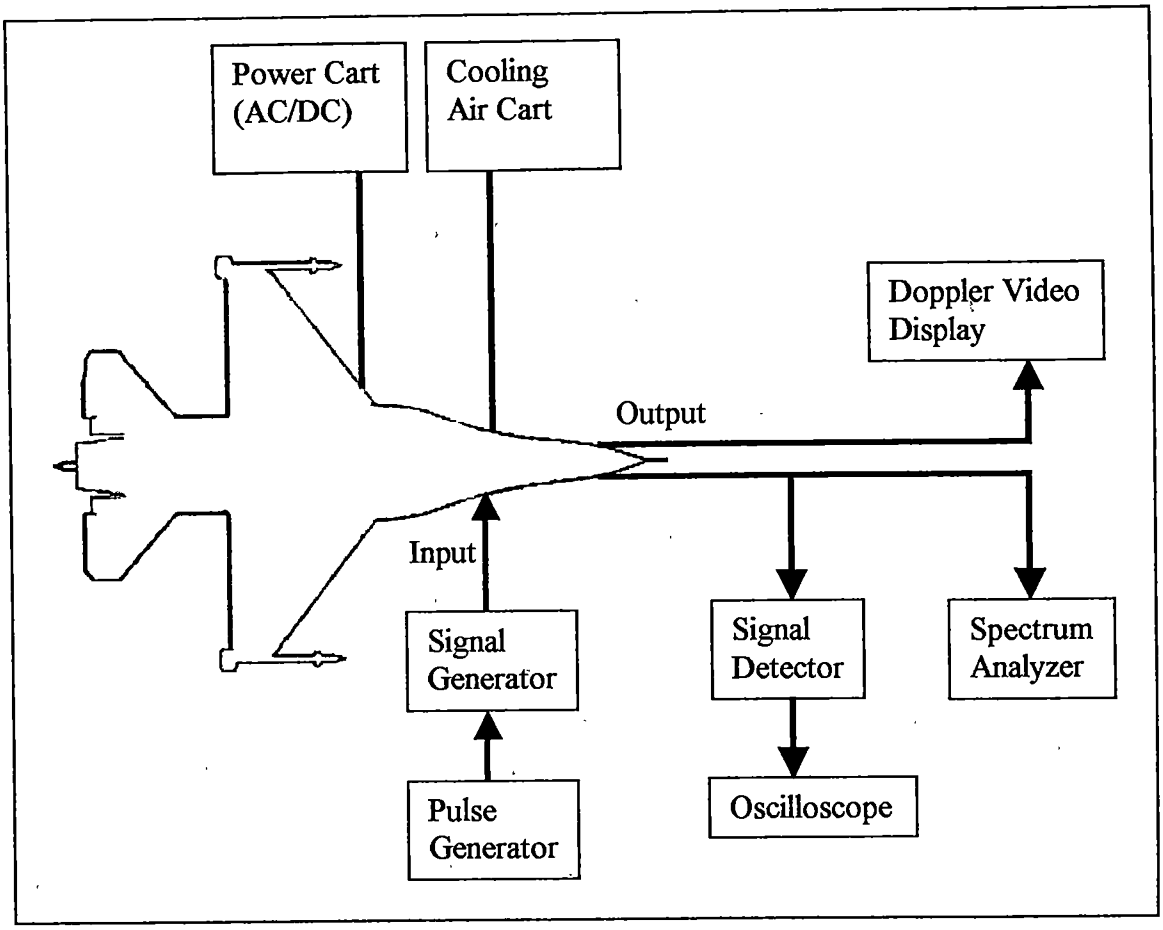

Figure 2.3 Ground Phase Hardware Configuration

Table 2.0 Ground Test Frequency and Intensity Matrix

Base Frequency (MHz)	Intensity (dB)	Frequency Shift (KHz)
A	-20	0,2,4,10,20,30,50,80
B	-40	0,2,4,10,20,30,50,80
C	-60	0,2,4,10,20,30,50,80
D	-80	0,2,4,10,20,30,50,80
E	-100	0,2,4,10,20,30,50,80

The output of the Doppler video display was compared to the signal generator inputs to assess the average error and standard deviation. The performance was evaluated against a standard of an average of 1000 Hz error in closure and 2 dB error in intensity.

Flight Phase

Dry Portion

Based on a thorough understanding of the response of the system across the full range of inputs, the flight-test portion of testing began. The objectives of the dry portion were two-fold. Most importantly, testing had to establish that the modification did not effect the performance of the radar. Also, the dry portion demonstrated the accuracy of the frequency data collected against a stable, non-jamming target.

To assess the impact on the radar sensitivity, maximum detection and lock-on tests were compared to pre-modification data. The test and target aircraft performed the procedure described in Figure 2.4.

The airspeeds, altitudes and separations were selected to match the baseline test data for maximum detection and lock-on ranges of the radar. The target aircraft radar was stowed to prevent spiking in the intensity of the return caused by 'flat-plating' of the target's radar antenna.

A total of eight samples were collected in each scenario to achieve basic statistical significance. The measures of performance for this objective were the average maximum detection range and average maximum lock-on range.

Ranges were determined by comparing range from TSPI with the radar state (target detect, lock) as captured by telemetry and radar display video. The performance

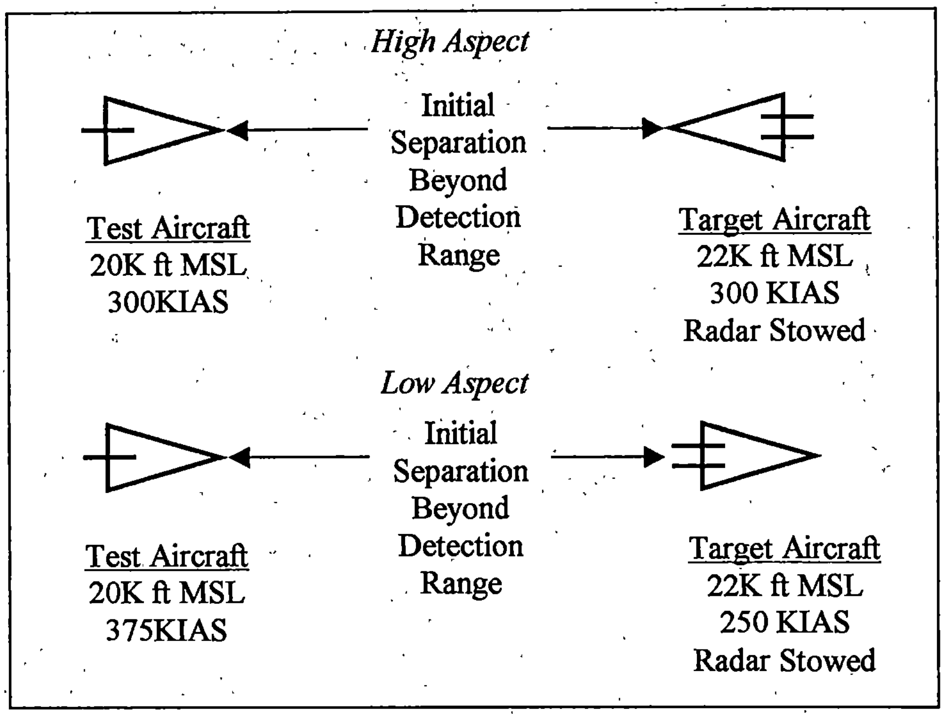

Figure 2.4 Maximum Detection and Lock-on Test Set-Up

of this portion was evaluated against a standard of zero decrease in average detection and lock-on range.

To determine the accuracy of the system against a dynamic or maneuvering target, the aircraft performed the maneuvers as described in Figure 2.5. The airspeeds, altitudes and separations were selected to insure sufficient performance for the target to complete a full 180-degree turn at 5Gs at a representative airspeed (9). As before, the target aircraft radar was stowed to prevent spiking in the intensity of the return caused by 'flat-plating' of the target's radar antenna.

A total of eight samples were collected in each scenario to achieve basic statistical significance. In this scenario, the measures of performance were the Doppler frequency

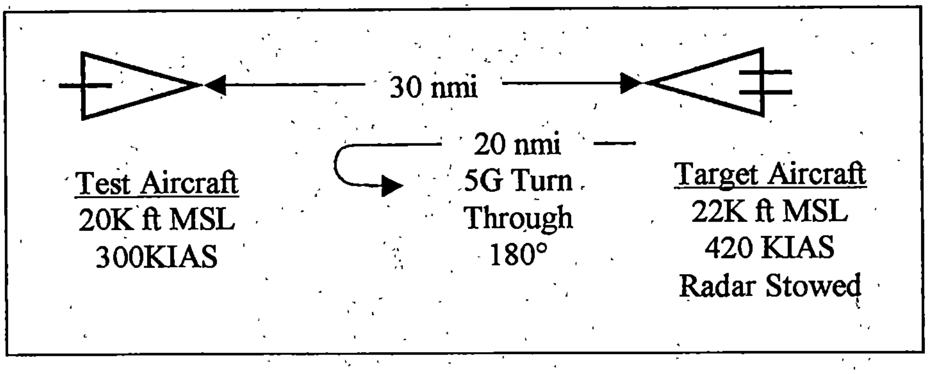

Figure 2.5 Maneuvering Target Set-Up

reported by the Doppler video system and the closing velocity of the test aircraft and target based on TSPI data.

The closing velocity was converted to a Doppler frequency (10) as

$$f_D = 2V_c (f/c) \tag{EQN 2.0}$$

where f_D is the Doppler frequency, V_c is the closing velocity, f is the operating frequency of the radar and c is the speed of light. Once converted to frequency, comparisons between the instrumentation system frequency and the TSPI measured frequency were made. A 2 KHz standard was applied for accuracy between the Doppler video data and TSPI. At X-band frequencies, a 2 KHz error translated into approximately 50 knots which was sufficient for analysis of jamming techniques.

Wet Portion

With the build-up phases complete, the only remaining task was to evaluate the system in the jamming environment. Specifically, the objective of the wet portion was to determine the accuracy of the frequency displayed by the Doppler video system compared to the jamming techniques in Table 1.0. The techniques were chosen as a representative cross-section of electronic counter-measures.

To evaluate the performance of the Doppler video system in a jamming environment, the procedure in Figure 2.6 was accomplished.

The altitudes and airspeeds were selected to be similar to the other set-ups in the testing. The target aircraft radar was stowed to prevent interference with its radar signature or the reception of the jamming techniques.

The measure of the performance of the system in the wet portion was the complete Doppler video display, including the frequency, time and intensity data. A total of two runs containing eight samples (i.e. eight range/velocity pulls) of each deceptive technique and 120 seconds of noise jamming were collected. The information from the display was compared to the programmed technique in the jammer.

Unlike the previous test points, the evaluation criterion in the wet portion was a qualitative evaluation of the system's ability to capture a particular jamming technique.

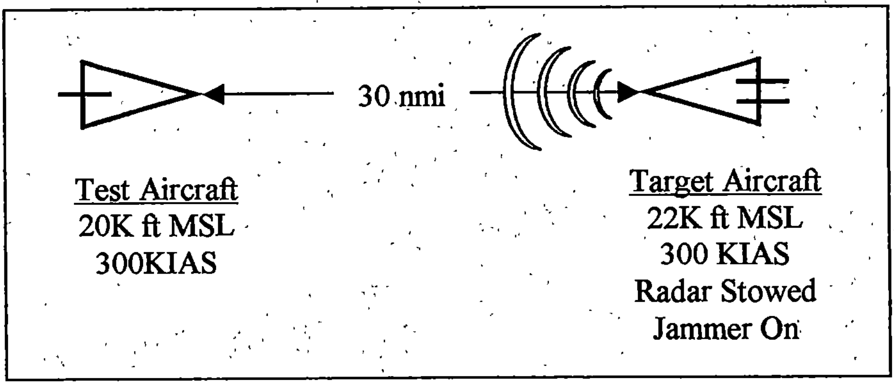

Figure 2.6 Jamming Target Set-Up

Given the time and cost constraints of the project, it was not possible to operate an airborne truth source to measure the transmitted jammer signal to compare to the Doppler video system recorded signal. Since only data available from the jammer was the commanded technique, the most appropriate evaluation possible was an analyst's assessment of the utility of the information for the purposes of develop electronic protection algorithms.

Chapter 3 - Flight Test Program

Ground Phase

Test Execution

The EMI/EMC portion of testing required 2 hours to complete. All aircraft systems were powered up with engines running. X and C band tracking radars irradiated the aircraft and the GPS TSPI pod was turned on. The Doppler video system telemetry was monitored from a test control room.

The direct injection portion of testing required six hours to complete. All test points listed in Table 2.0, Ground Test Frequency and Intensity Matrix, were completed. A sample of the data is included as Figure 3.0.

The test point depicted was the injection of an 80 KHz signal at a strength of –60 dB. There was some minor interference from the facility power supply that affected the signal generator, adding spurious returns in the data. This interference did not inhibit the measurement of the intended signal and would not be seen in flight.

Analysis of Results

The EMI/EMC portion of testing ruled out the use of X and C band tracking radars for TSPI data. The RF energy from the tracking radars would corrupt the RF energy from the aircraft radar. The tracking radars would also inadvertently trigger the jammer during the wet portion of testing, causing the jammer to put out a spurious waveform. The GPS Pod L-band downlink did not interfere with Doppler video operation, mainly due to the large transmitting frequency separation.

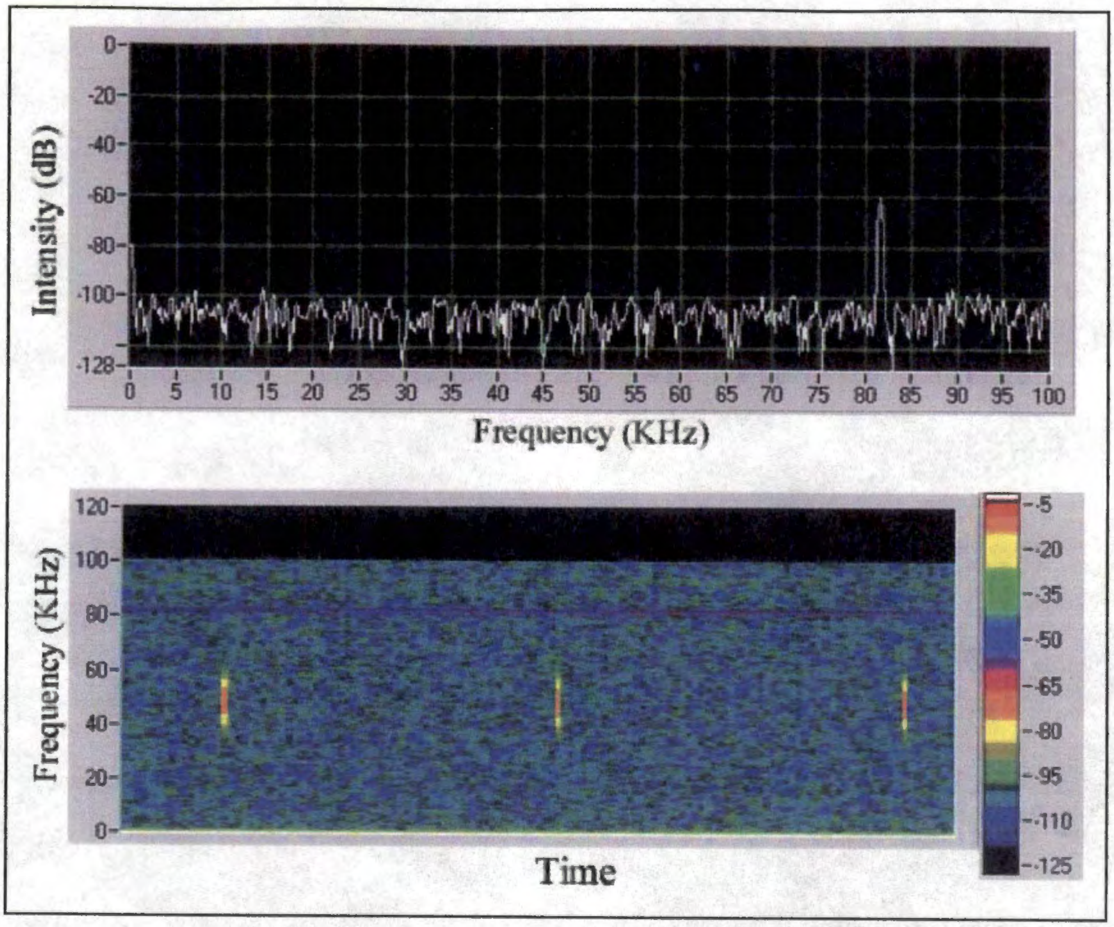

Figure 3.0 80KHz Direct Injection

The measures of performance for the direct injection portion of testing were the average error in both frequency and power measurement. A total of 40 points were collected, with the results displayed in Figures 3.1 and 3.2.

The standard of evaluation for the direct injection was an average error of 1000 Hz in closure and 2 dB in intensity. The averages for the Doppler video system error were 585 Hz in frequency and 1.53 dB in intensity. This performance was adequate for use in developing electronic protection.

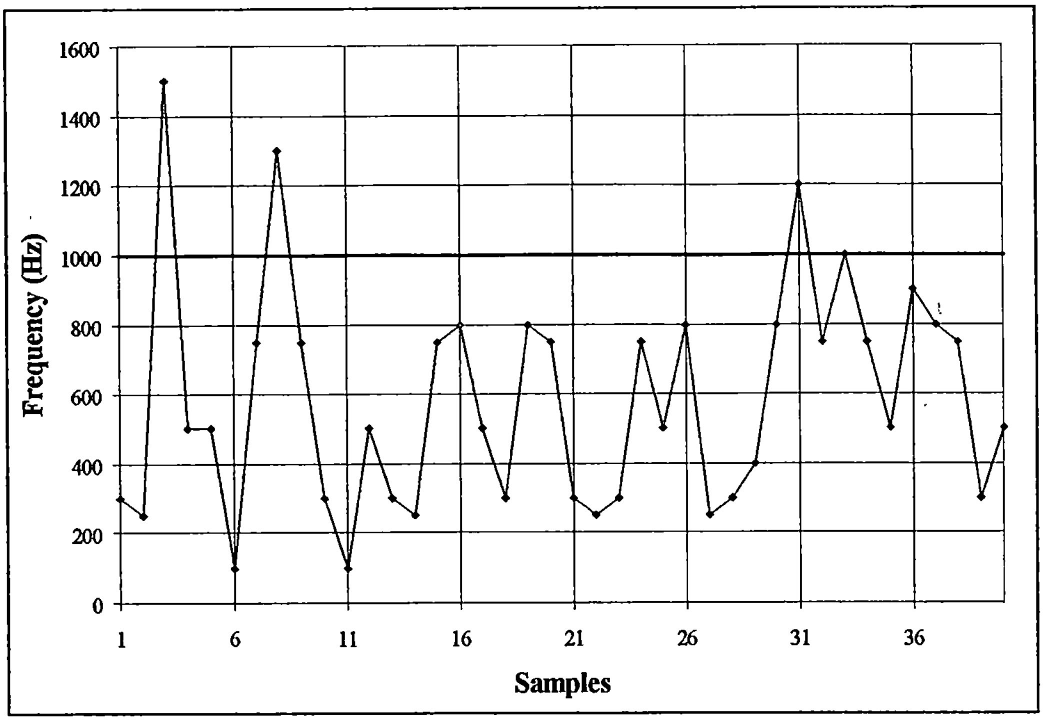

Figure 3.1 Average Frequency Measurement Error

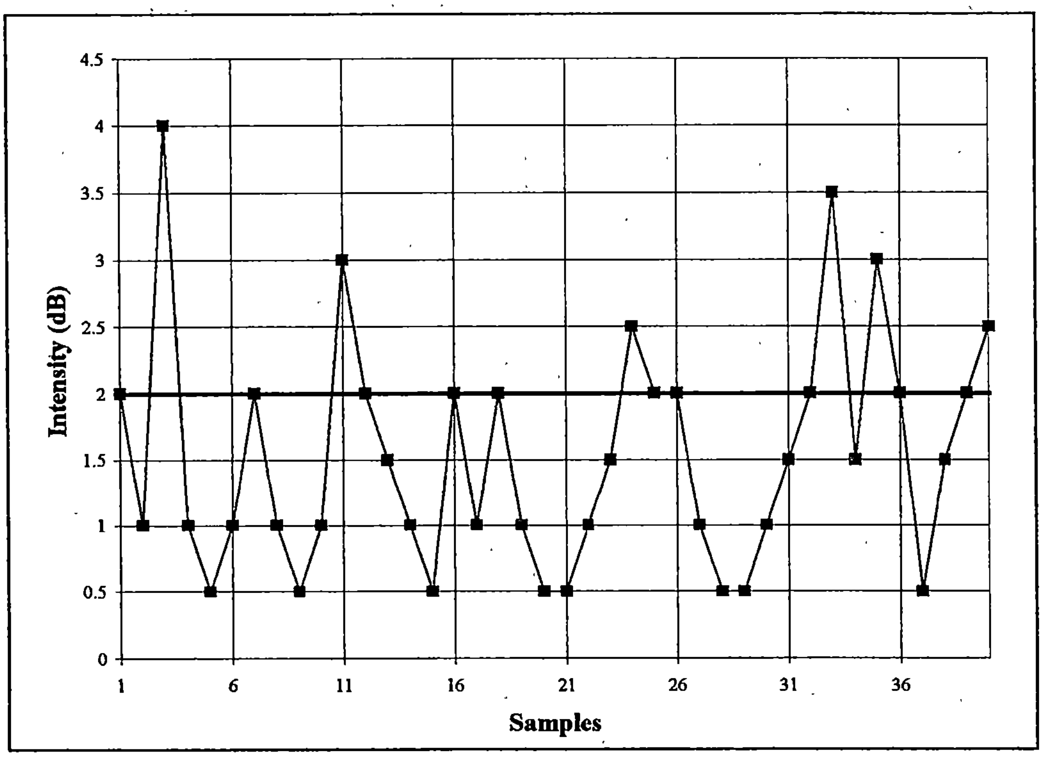

Figure 3.2 Average Power Measurement Error

Flight Phase

Dry Portion

Test Execution

The objectives of the dry portion were completed over the course of two sorties. The objectives were twofold: first, to determine the impact of the modification on receiver sensitivity and then, to assess the accuracy of the measured Doppler frequency compared to a Doppler frequency calculated based on closing velocity.

All test scenarios listed in Figure 2.4, Maximum Detection and Lock-on Test Set-Up, and Figure 2.5, Maneuvering Target Test Set-Up, were completed. A sample of the data is included as Figure 3.4. The figure depicts the radar return from a tracked target performing a beaming maneuver. A beaming maneuver is a flying tactic where an aircraft abruptly turns perpendicular to an opponent. The goal of a beaming maneuver is to lower the closing velocity of the two aircraft to a point where the Doppler frequency matches the ground return of the opponent's radar, often causing the attacker to lose the track.

Analysis of Results

A total of eight samples of maximum detection and lock-on range were collected in each scenario described in Figure 2.4. Data were compared to a pre-modification detection and lock-on range database against a standard target using identical setup geometries. All detection and lock-on ranges were within the band of the pre-modification data. Thus, no loss in radar sensitivity was experienced.

The assessment of the measured Doppler frequency accuracy was achieved by executing the test scenario described in Figure 2.5. A sample of typical data is included in Figure 3.4. The closing velocity was provided by TSPI data off the GPS pods carried on each aircraft. A total of eight samples were collected over three runs, with the standard for accuracy being an average error of 2000 Hz. The average error in measured Doppler frequency versus the calculated Doppler frequency was 795 Hz. This performance was excellent considering dynamic flight conditions.

Review of the Figure 3.5 provides insight into the RF data coming into the radar. The radar locked the target approximately 105 seconds into the run. The target Doppler frequency was 29 KHz with a signal strength of –76dB. As the aircraft closed, the target return increased to –58 dB and it began a beaming maneuver 130 seconds into the run.

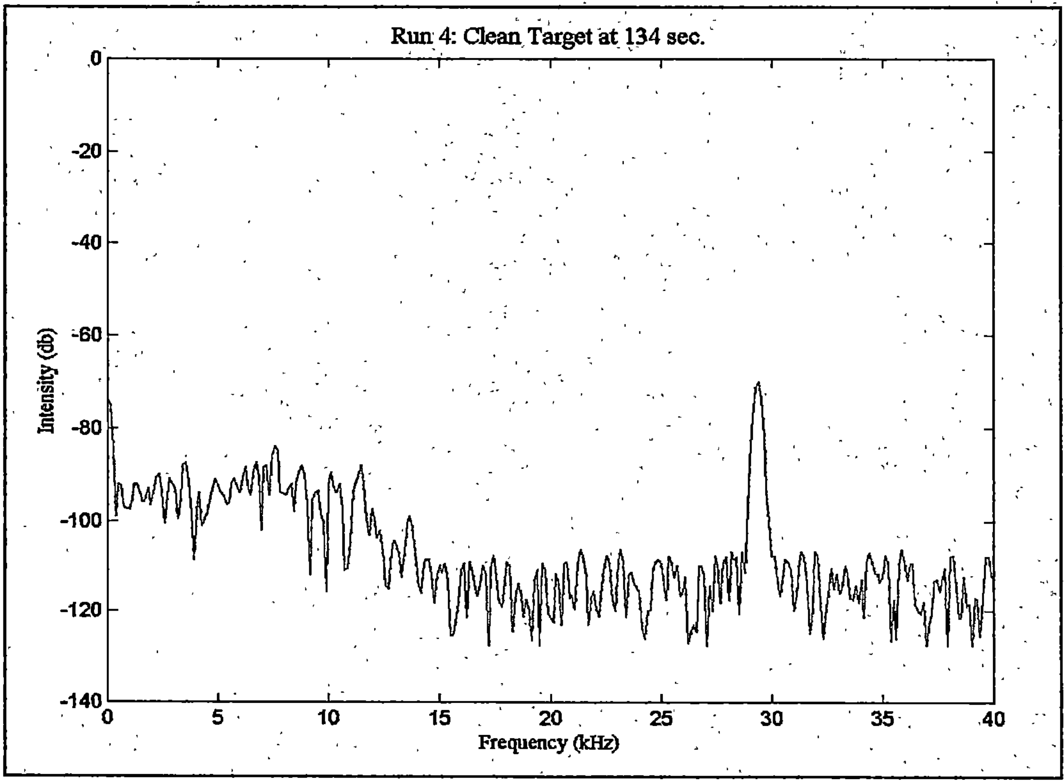

Figure 3.4 Doppler Frequency Comparison

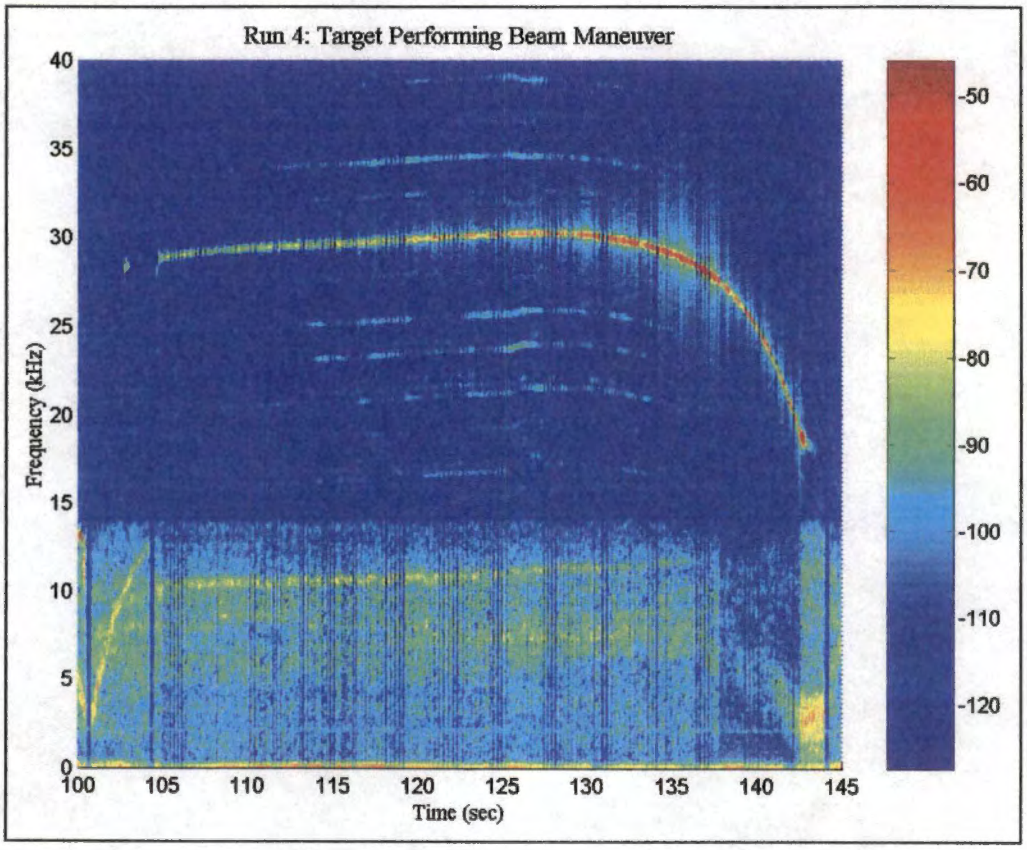

Figure 3.5 Maneuvering Target Doppler Video Plot

As the target turned, scintillation of the reflecting surface caused a blooming in the frequency of the return. The Doppler frequency rolled off as the closing velocity reduced and the radar eventually dropped the lock at 17KHz.

Wet Portion

Test Execution

The final phase of testing incorporated jamming into the signal return over the course of two sorties. The objective of the wet portion was to evaluate the capability of the system to capture a given jamming technique. A total of 14 test points were executed as described in Figure 2.6, Jamming Target Set-Up.

The Airborne Threat Simulation Team at Point Mugu Naval Air Station programmed an ALQ-167V(15A) jamming pod with the techniques listed in Table 1.0, Selected Jamming Techniques. A description of the pod is included in Appendix A. The pod was selected for its easy custom programming and flight envelope clearance on a number of fighter aircraft.

Analysis of Results

The objective of the wet portion , unlike the build-up, was a qualitative evaluation. The ability to reconstruct and monitor the electronic attack of a jammer on the radar was assessed.

Noise Jamming

A sample of noise jamming is included as Figure 3.6. The target is clearly visible at 25 seconds into the run. The initiation of noise jamming is also evident at about 60 seconds. The 10 MHz wide band noise completely masks any trace of a target radar return. As the two aircraft close on each other, the intensity of the jamming increases from approximately –80 dB to –60 dB compared to the background. At that point, the radar switches on attenuating filters, knocking the signal strength down –15 dB.

Velocity Gate Pull-Off

Figure 3.7 shows a time slice from a 5 second, 12 KHz VGPO data point. The target signal was visible initially at 45 seconds into the run. When the jammer began transmitting at 47 seconds, the incoming signal triggered the radar's attenuator. The –15 dB in attenuation was enough to erase the true target skin return, leaving only the jammer technique. The 12 KHz pull, as well as additional fainter 24 KHz and 48 KHz pulls, was

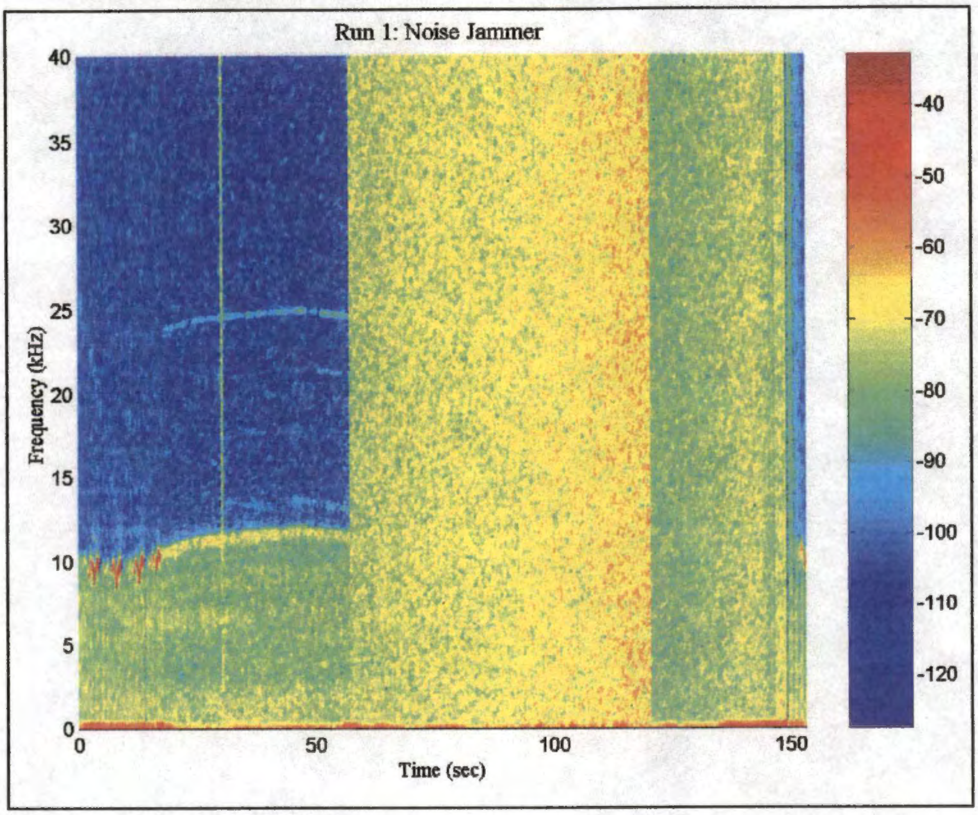

Figure 3.6 Noise Jamming

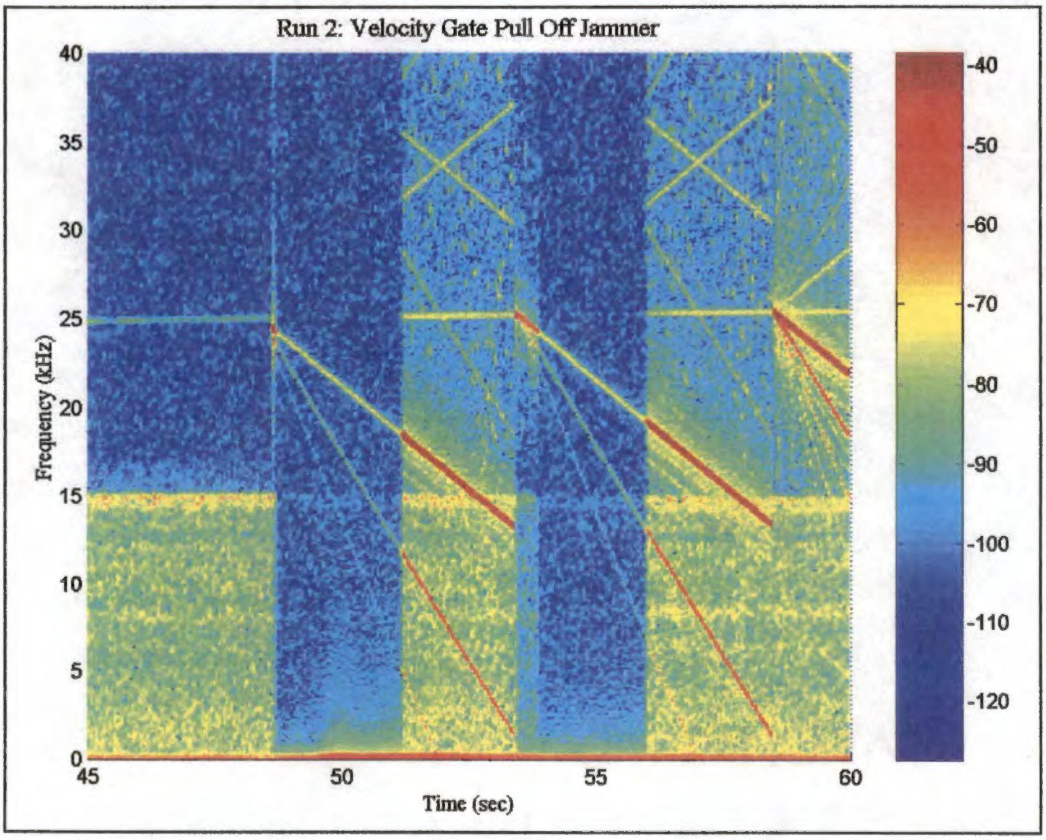

Figure 3.7 Velocity Gate Pull-Off

present at more than 20 dB over the background environment. The technique was repeated every 5 seconds as programmed in the pod.

Combined Range and Velocity Gate Pull-Off

The Doppler portion of the data was very similar to the VGPO techniques. Figure 3.8 is an example of a 3-second, 12 KHz, 6.5 G, combined range and velocity pull data point. Similar to previous runs, the target is visible initially, but becomes masked with the introduction of the radar's signal attenuators. The jammer's pull-off signal remains visible, with a steeper 3-second cycle time. The jammer signal strength is more than 30 dB greater than the skin return, which peeks through sporadically.

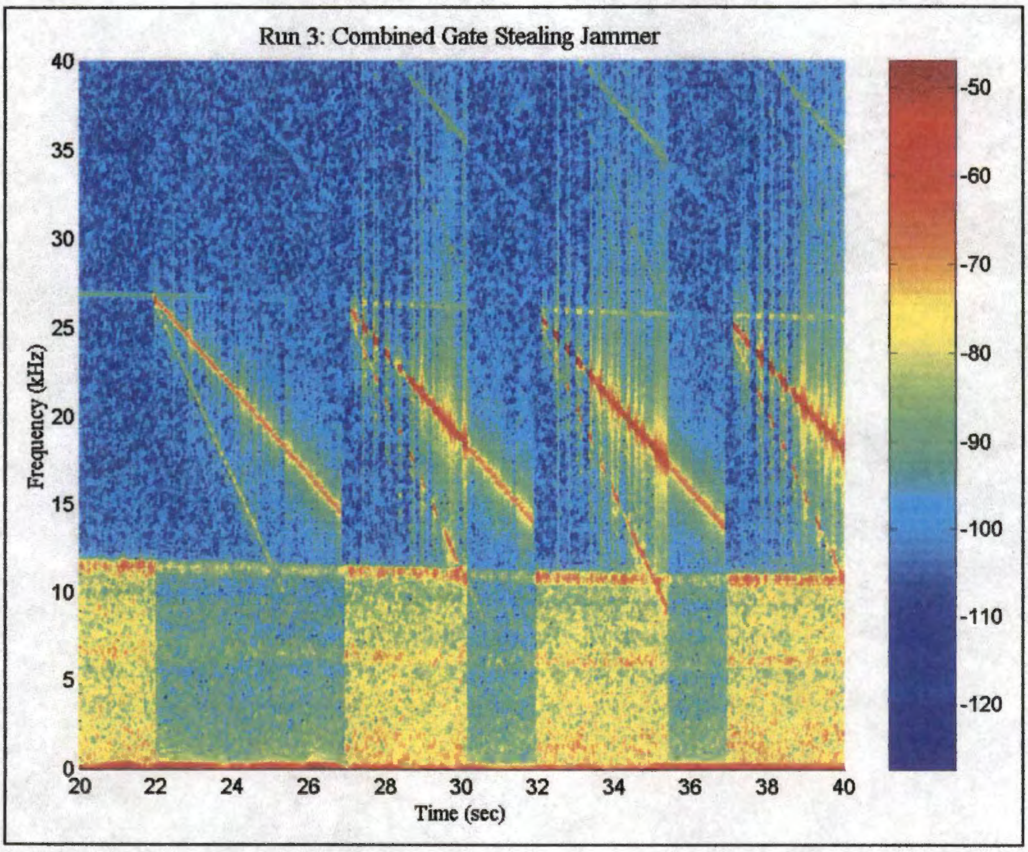

Figure 3.8 Combined Range and Velocity Gate Pull-Off

Chapter 4 – Conclusions and Recommendations

The methodology for validating radar instrumentation for testing the effects of radar countermeasures was successfully developed and tested. The methodology consisted of a series of tests that included direct injection of RF energy during ground tests, followed by flight testing in non-jamming and then jamming environments. This methodology was proven during validation of the Doppler video instrumentation system designed for measuring the effects of electronic countermeasures.

The combination of ground and flight phases of testing substantially characterized the frequency and intensity capabilities of the system. By following this methodology, technical problems were addressed in increasing complexity, but from a strong foundation proven during the previous phase of testing. The basic frequency and intensity capability of the hardware was measured in a tightly controlled ground test. If the basic capability was not sufficient, redesign could be completed prior to expensive flight test. The dry portion of testing successfully determined the impact on baseline radar performance and accuracy of frequency measurement using actual targets in a benign RF environment. Once the ground phase and dry portion of the flight test phase were complete, evaluation of system performance in a jamming environment was a straightforward test. The timing and frequency modulation of the jamming techniques were apparent and even uncovered a limitation in how the radar employed attenuators.

The validation of the intensity data could be improved, providing a given program had the requirement and sufficient resources. The methodology covered in the thesis was adequate to validate relative signal strengths (i.e. signal to noise ratio, jammer to signal ratio), but not absolute signal strength. The direct injection portion of testing did not include signal path losses due to the waveguide or radome. The intensity data at that point could only be referenced to other signals coming into the receiver, such as the ground return or another target. To improve on the direct injection of a signal into the radar, the radar could be operated in free space either in an anechoic chamber or with a calibrated signal measurement aircraft. Chamber testing is quite expensive, but would include transmission path loss of the waveguide and radome in the fidelity of intensity measurement (11). An airborne truth source, such as a calibrated COMBAT SENT RC-135U signals measurement aircraft, could be flown in formation with the test aircraft to precisely monitor the radar returns (12). Obviously, test operations would be more complex and expensive to address the additional and dissimilar heavy aircraft. While both anechoic chamber testing and a calibrated airborne collector should improve the accuracy of the error measurement, both have the potential to increase the cost of a validation program by an order of magnitude. Careful consideration based on a program's technical, schedule and cost requirements should dictate the appropriate methodology to employ.

While insight into the Doppler spectrum is critical for development of electronic protection, basic radar processor parameters are required to completely capture combined range and velocity gate stealing (CRV) techniques. The evaluation of the CRV test points was nearly identical to the velocity gate pull-off test points. The only reason to distinguish between the two types of counter-measures was to account for possible differences in electronic protection logic from radar to radar. In the radar under test, there was no difference. In more advanced radars, the detection of jamming could initiate more sophisticated attenuation and tracking algorithms. The performance of the radar against techniques that include range deception will require the radar processor's computed range to compare to TSPI range.

Finally, the Doppler video system was successfully validated as a radar instrumentation system. The system met the evaluation criteria of the ground phase, with an average error of 585 Hz in frequency and 1.53 dB in intensity. In the dry portion of the flight phase, the average frequency error grew only to 795 Hz, well below the 2000 Hz requirement. In the wet portion, the system accurately captured the programmed noise and deception jamming techniques for reconstruction.

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APPENDICES

Appendix A – ALQ-167 V15 Description

The following text is taken from the Naval Air Warfare Center, Airborne Threat Simulations Group Users Guide:

"The ALQ-167 Countermeasures (CM) set is a noise and deception jamming system that is used to provide an electronic attack (EA) environment for the development, test and evaluation of US weapon systems electronic protection capabilities and for training weapons systems operators in a realistic EA threat environment. The ALQ-167 provides EA threat simulation for all microwave oriented Navy weapon systems operating within the B-, C-, D-, E/F-, G/I- and J-bands.

The ALQ-167 is comprised of a pod with EA modules mounted internally on an equipment tray. Different configurations of these modules, called variants, are used for specific purposes. The EA modules used are primarily from one of two CM sets: the AN/DLQ-3C(V) (DLQ-3) or the AN/ULQ-21(V) (ULQ-21). Additionally, the ALQ-167 can be fitted with B-band and C-band transmitters in three pod variants. There are two types of pod antenna configurations: forward radiating and forward/aft radiating (FAR).

The ALQ-167 pods are approved for flight on subsonic and supersonic aircraft. They mount externally on many types of aircraft, including the A-6E, EA-6A, EA-6B, EP-3J, F-14A/B, F-18A-D, EC-24A, Lear Jet and NKC-135. Cable assemblies interface the ALQ-167 with the aircraft and the control indicator via aircraft wiring. Specific operating frequencies and parameters are preset prior to flight in accordance with mission objectives. The control indicator provides remote selection of the preset EA operating modes during flight."

The ALQ-167 variant used during testing was the V(15). The V(15) was a ULQ-21 heritage system that had forward and rear transmit capability in the I band. The V(15) also incorporates a Digital RF Memory (DRFM) Unit to enable coordinated range and velocity pull-off techniques.

Appendix B – ALQ-167 V15 Program

The ALQ-167 V15 used during the test was programmed as follows:

Hardware

Receiver/Transmitter: 7 dB low gain, Effective Radiated Power (ERP) 50 dBm

DRFM: ERP 30 dBm, Sensitivity –42 dB

Modes

1. Spot Noise, 9.0GHz, ±5 MHz.
2. VGPO, 0 dwell, 5 sec. walk, 12 KHz deviation, linear-down.
3. VGPO, 0 dwell, 3 sec. walk, 12 KHz deviation, linear-down.
4. VGPO, 0 dwell, 1 sec. walk, 12 KHz deviation, linear-down.
5. DRFM coordinated 12 KHz, 0 dwell, 5 sec walk, 3.9g, time deviation 3 μs, 9-9.9 GHz.
6. DRFM coordinated 12 KHz, 0 dwell, 3 sec walk, 6.5g, time deviation 2 μs, 9-9.9 GHz.
7. DRFM coordinated 12 KHz, 0 dwell, 1 sec walk, 19.5g, time deviation 1 μs, 9-9.9 GHz.

VITA

William Bailey was born in Wilmington, Delaware on August 2, 1966. He graduated from Archmere Academy in Claymont, Delaware in 1984. William then attended the University of Notre Dame in South Bend, Indiana, graduating with a Bachelors Degree in Electrical Engineering in 1988. Upon graduation, he was commissioned in the United States Air Force and was assigned to Space Division, Air Force Systems Command, Los Angeles Air Force Base. In 1995, William attended United States Air Force Test Pilot School at Edwards Air Force Base. He presently serves as a Flight Test Engineer in the United States Air Force.