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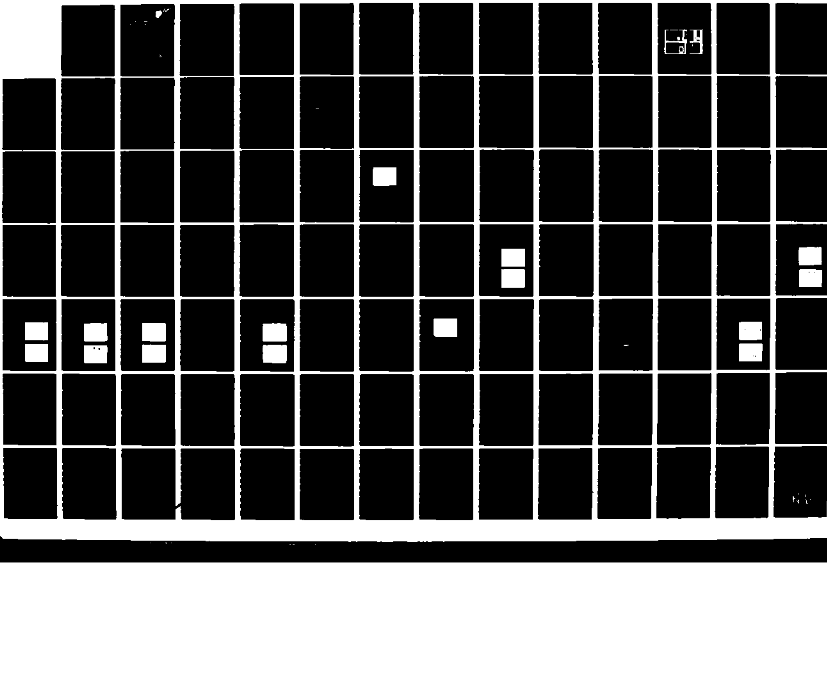

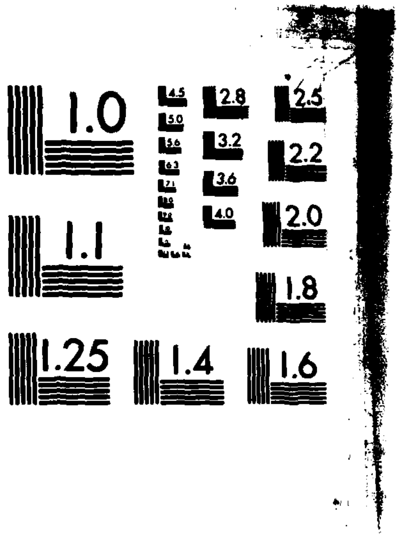

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Final Technical Report
April 1983

ECM SIGNAL DISCRIMINATION AND IDENTIFICATION TECHNIQUES

PAR Technology Corporation

Robert E. Bozek, Dr. Robert J. Dick and John P. Yermas

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This effort involved the design, development, and test of a stand-alone Electronic Counter Measure (ECM) Signal Monitor (ESIM) for the terrestrial Line-of-Sight (LOS) Defense Communication System (DCS). The sysem developed monitors the IF and Baseband outputs of up to four digital radios while they are in service, to assess link quality. If ECM signals are detected, the level of interference and type of interference are reported to an operator. Key components of the system are a PDP-11/23 minicomputer, an HP 8581A automatic spectrum analyzer, and a high-speed (60 MHz) analog-to-digital converter. This report

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provides a history of the project and a functional overview of the system.

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TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

This document represents the final technical report submitted by PAR Technology Corporation to the Rome Air Development Center (RADC) under contract F30602-80-C-0285, entitled "ECM Discrimination and Identification Techniques".

1.1 PROGRAM OBJECTIVE

The objective of this program was to define, design, develop and test a stand-alone Electronic Counter Measure (ECM) signal monitoring system to (1) identify that the terrestrial line-of-sight (LOS) Defense Communication System (DCS) is being jammed and (2) characterize the nature and magnitude of that jamming.

1.2 BACKGROUND

The requirement for such a capability stems from the current trend toward use of digital Time Division Multiplex (TDM) equipment over analog Frequency Division Multiplex (FDM) systems and the need for continued communication in an environment which may be subject to Electronic Warfare (EW) threats.

Evolution of the DCS from an analog system through a hybrid (analog/digital) configuration to an all digital system is a transitional process which will span the next several years. Production work to provide digital multiplexers and radios for the DCS began with the ARMY Digital Radio and Multiplexor Acquisition (DRAMA) procurement.

The Defense Agencies and Departments have been tasked by the Joint Chiefs of Staff to acquire the EW capabilities necessary to support combat operations. In response to this, the Defense Communication Agency (DCA) has sponsored programs to assess the ECM threat to the DCS as well as identify techniques that could be employed to increase DCS resistance to ECM threats. Examples of some of these supporting programs include:

- DCS Europe Vulnerability to Jamming
- DCS Communication Vulnerability Assessment (CVA)
- CVA Techniques Development
- ECCM Aspects of System Control for DCS
- DCS AJ Antenna Study
- DCS ECCM TROPO MODEM
- DCS ECCM RADIO

In order to properly design future computer controlled, adaptive, digital communication systems, with associated system control capabilities, additional technique development is required in the areas of ECM signal monitoring and ECCM system control. The stand-alone ECM signal monitoring capability developed under the ECM Discrimination and Identification Techniques program is a major step in this direction.

1.3 PROGRAM OVERVIEW

The development effort, which began in October of 1980, was broken up into four major phases, a data collection phase, a data analysis phase, a system engineering phase and a test phase.

The purpose of the data collection and analysis phase was to develop a data base of digital communication signals contaminated by known types and levels of interference and media effects. As the signal bandwidth of interest (up to 25 MHz) precluded recording of raw data, only selective signal measurements and scope photographs could be saved. The data base includes photographs of the IF spectrum and baseband eye pattern, and various measurements made on the baseband waveform.

Interference included CW, AM (tone and noise), FM (tone and noise) and pulsed versions of these as well. Media effects included multipath distortion and white noise. Data were analyzed to assess the effects of jamming on three different waveform types, namely 3-PR-FM representative of the Digital European Backbone (DEB I) hybrid equipment, and QPSK/QPR waveforms representative of the DRAMA radio. Extensive use was made of an HP 8581A automatic spectrum analyzer system and associated hardware interfaced by way of an HPIB (IEEE-488) bus to automate the collection and data reduction process wherever possible.

Following the data collection/analysis phase of the effort, the system engineering phase was entered. Using the knowledge developed during the data collection/analysis phase, a top level design of an ECM signal monitor was formulated and presented in a Functional Description which served as a starting point in the design and development effort which followed.

The ECM Signal Monitor (ESIM) consists of both hardware and software to perform its functions. The system consists of a Digital Equipment Corporation (DEC) PDP 11/23 minicomputer, an HP8581A automatic spectrum analyzer, a baseband signal processor, a CRT, radio IF and baseband couplers and disk storage in two standard size equipment cabinets. A photograph of the ESIM system is shown in Figure 1-1.

ESIM accepts as input an Intermediate Frequency (IF) of 70 MHz, baseband and radio status indicators from up to four radios. The IF is routed to the spectrum analyzer where frequency characteristics are determined. The baseband signal is processed with a Baseband Signal Processor developed by PAR to produce histogram and other signal measurements. The baseband processor

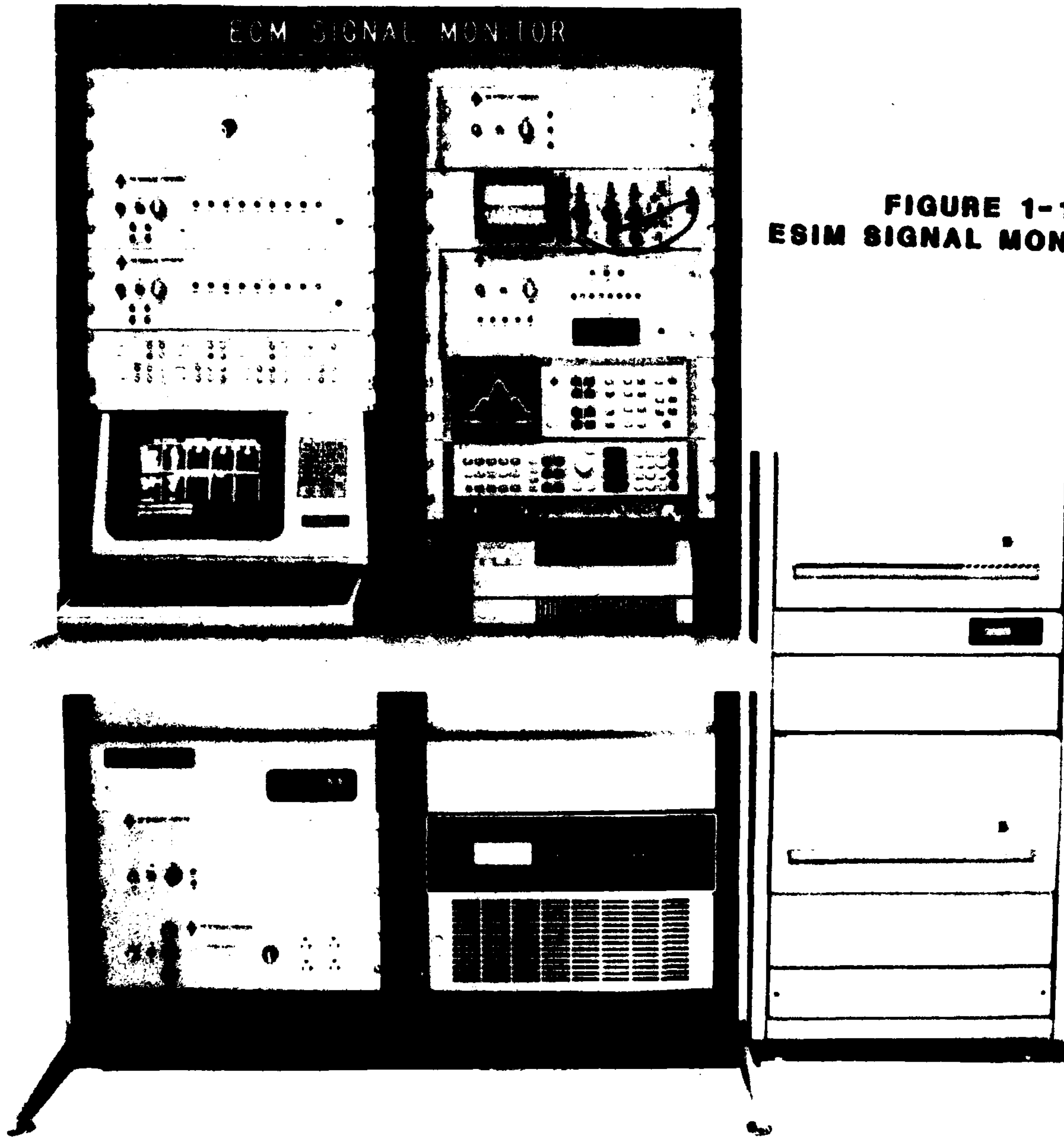


FIGURE 1-1
ESIM SIGNAL MONITOR

consists of a 60 MHz analog-to-digital converter and 1024 words of high speed memory which operates in a burst sampling mode. Histograms of the baseband data allow estimation of the statistics of the interference. Another measurement determines the spectral characteristics of the interference in the baseband signal by way of a technique termed decision feedback spectrum estimation. Decision feedback is used to cancel the data signal so that only interference is left. This technique is most useful when the interference is at a low level such that it is not apparent in the IF spectrum. Radio alarm and status indicators are routed to the computer and a LED indicator panel.

The PDP 11/23 accepts measurements from the spectrum analyzer and baseband processor and performs the detection and identification functions. Reports of radio status, whether or not jamming is present, type and level of jammer, and effect on the communication signal are made available to the technical controller by way of a CRT and LED light panel. Capability is also provided so that status reports can be sent to a remote location through a serial output port. This remote location could for example be the system control element which might put into effect some sort of ECCM or alternate routing scheme.

System software has been provided to allow efficient control over the various measurement devices. This makes the system particularly useful as a testbed for the development and analysis of new radio systems, and in the test and evaluation of new algorithms. This software has been written primarily in FORTRAN IV, although the HP spectrum analyzer control is handled with the HP Basic Language (HPL). The RT-11 operating system has been utilized in the PDP 11/23.

Completion of the system development effort was followed by a detailed test and evaluation phase which resulted in minor adjustments to the software and hardware. This was followed by installation at RADC's Digital Communication Experimental Facility (DICEF) and final acceptance testing.

1.4 APPLICATIONS

In addition to its stated purpose of an ECM signal monitor for LOS microwave links, the hardware capability and supporting software make it an excellent test bed for further research in related areas such as:

- analysis and evaluation of performance assessment algorithms
- automated data collection and display of wideband data (13 Mbps max)
- link vulnerability assessments
- further development of ECM identification algorithms
- extension of technology to TROPO and Satellite communications
- analysis and development of ECCM system control algorithms

1.5 SUPPORTING DOCUMENTATION

In addition to this final technical report, the following documentation has been prepared and submitted to RADC in support of this effort:

PAR Technical Proposal	27 May 1980
System Safety Hazard Analysis Report	28 June 1981
Test Report - Preliminary Testing	28 January 1983
Test Report - Final Testing	28 January 1983
C-E Facility Installation Specification	17 December 1982
Test Plan/Procedures	17 December 1982
Operating and Maintenance Manual	28 January 1982
Programmers Reference Manual	28 January 1982
Data Collection and Analysis Program Plan	14 November 1980

1.6 REPORT ORGANIZATION

The remainder of this report is divided into three section and two appendices as follows:

Section 2 describes the ESIM hardware configuration.

Section 3 describes the ESIM software, ESIM algorithm and how these evolved during the course of the effort. Results of the date collection phase are also included.

Section 4, presents recommendations for further research

Appendix A, provides a list of system specifications.

Appendix B, describes an intermediate ECM identification logic developed in the effort but not included in the final system.

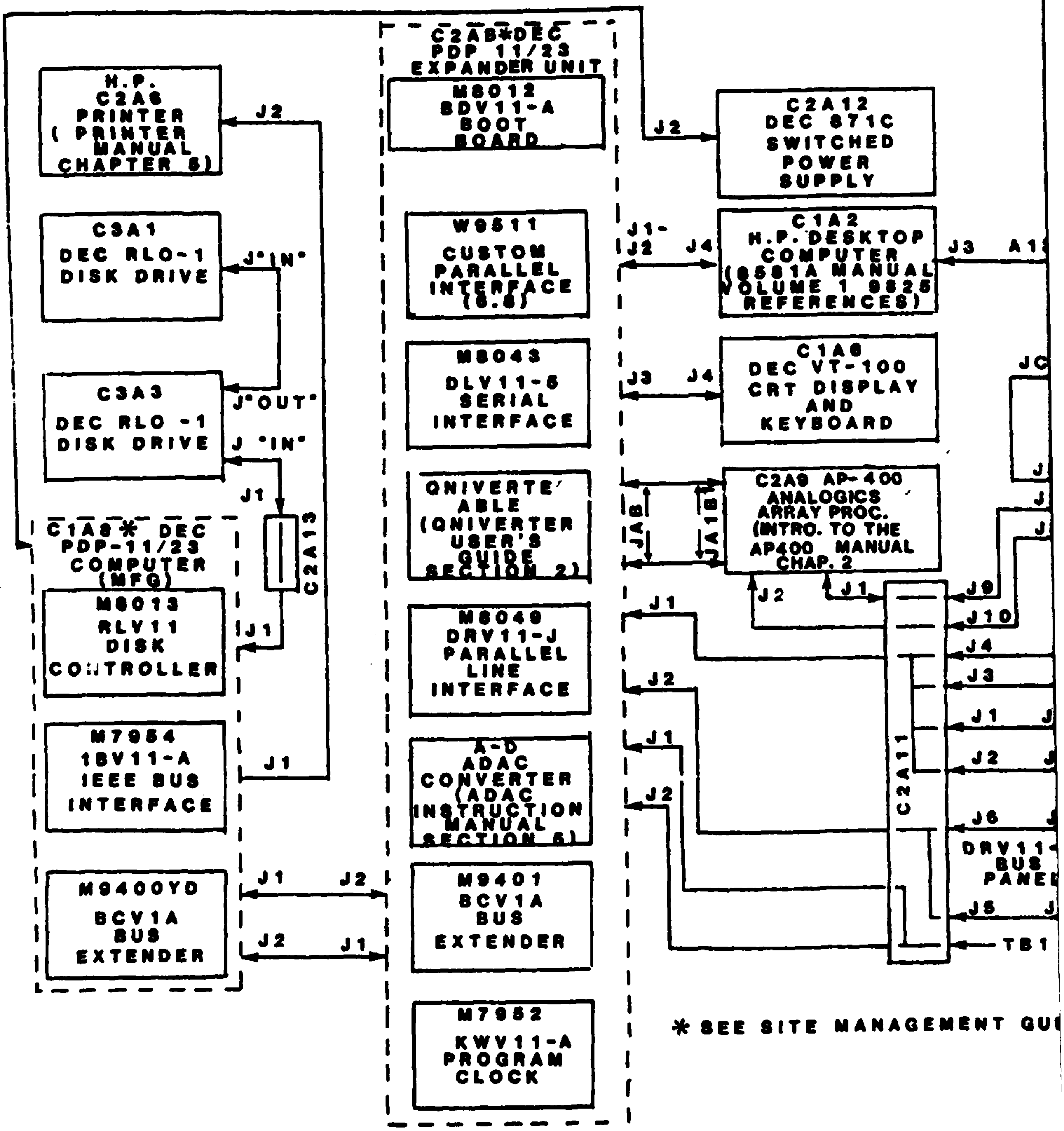
2. ESIM FUNCTIONAL DESCRIPTION

The ESIM system is composed of commercially-available and PAR-fabricated special purpose hardware. These are merged together forming a system which performs radio interference assessment. Appendix A provides specifications on the system.

Figure 2-1 is a block diagram showing individual subassemblies and interfaces. Included are the subassembly designation (C1A3) and name of equipment (Baseband Couplers). Figure 2-2 is a pictorial representation of ESIM showing the location of each subassembly in the cabinets. C refers to the cabinet number, C1 through C3, while A refers to the subassembly designator.

ESIM makes use of IF, Baseband, and selected alarm outputs from Line-of-Sight (LOS) communications radios. Considering Figure 2-1, the 70 MHz IF from the radio connects to couplers IF1 through IF8 of C1A3. These IF couplers are located at the rear of C1. Each coupler is used to isolate the ESIM system from the radio. The couplers may be connected to a 70 MHz test output from the radio or "in-line", where the coupler is placed in series with the 70 MHz communication radio line. Power must be applied to the ESIM coupler assembly for normal radio operation, or, the coupler must be removed and the radio reconnected.

Power and control for the couplers and switch is provided by the C1A4 rack mounted controller shown at the lower portion of the dashed C1A4 box in Figure 2-1. This chassis receives an address from the PDP 11/23 via the DRV11J interface M8049 to switch in the desired coupler. The address is decoded and the coupler is switched. A front panel LED display informs the operator which radio is selected.


C2A5*DEC PDP 11/23 EXPANDER UNIT
M8012 BDV11-A BOOT BOARD
W9511 CUSTOM PARALLEL INTERFACE (5.5)
M8043 DLV11-5 SERIAL INTERFACE
QNIVERTE' ABLE (QNIVERTER USER'S GUIDE SECTION 2)
M8049 DRV11-J PARALLEL LINE INTERFACE
A-D ADAC CONVERTER (ADAC INSTRUCTION MANUAL SECTION 5)
M9401 BCV1A BUS EXTENDER
M7952 KWV11-A PROGRAM CLOCK
H.P. C2A6 PRINTER (PRINTER MANUAL CHAPTER 5)
C3A1 DEC RLO-1 DISK DRIVE
C3A3 DEC RLO -1 DISK DRIVE
C1A8* DEC PDP-11/23 COMPUTER (MFG)
M8013 RLV11 DISK CONTROLLER
M7954 IBV11-A IEEE BUS INTERFACE
M9400YD BCV1A BUS EXTENDER
C2A13
C2A12 DEC 871C SWITCHED POWER SUPPLY
C1A2 H.P. DESKTOP COMPUTER (9881A MANUAL VOLUME 1 9825 REFERENCES)
C1A6 DEC VT-100 CRT DISPLAY AND KEYBOARD
C2A9 AP-400 ANALOGICS ARRAY PROC. (INTRO. TO THE AP400 MANUAL CHAP. 2
C2A11
DRV11- BUS PANE
J2
J"IN"
J"OUT"
J "IN"
J1
J1-J2
J4
J3
JA8
JA18
J9
J10
J6
J5
TB1
* SEE SITE MANAGEMENT GU

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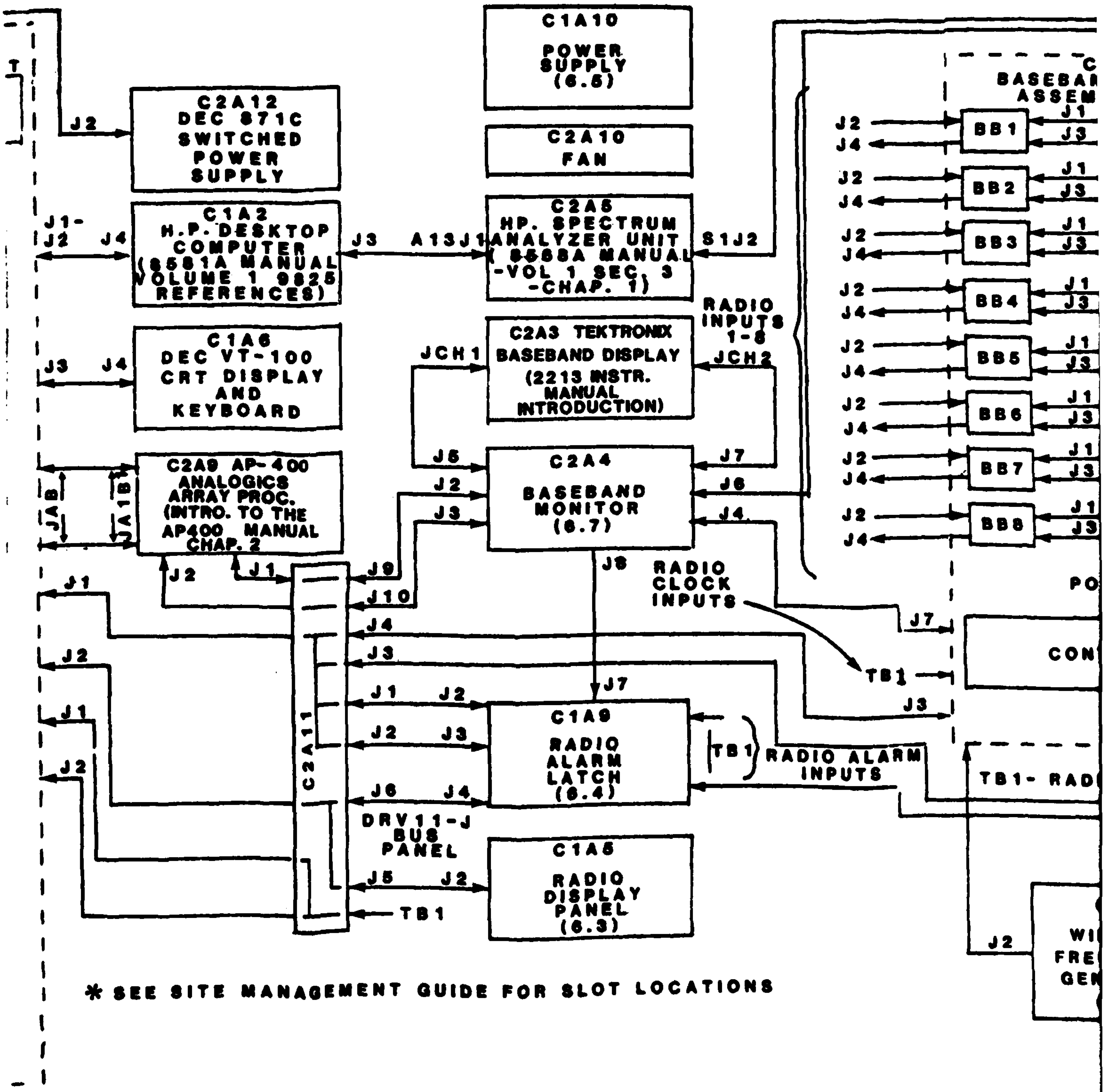

ESIM SYSTEM BLOCK DIAGRAM

FIGURE 2-1

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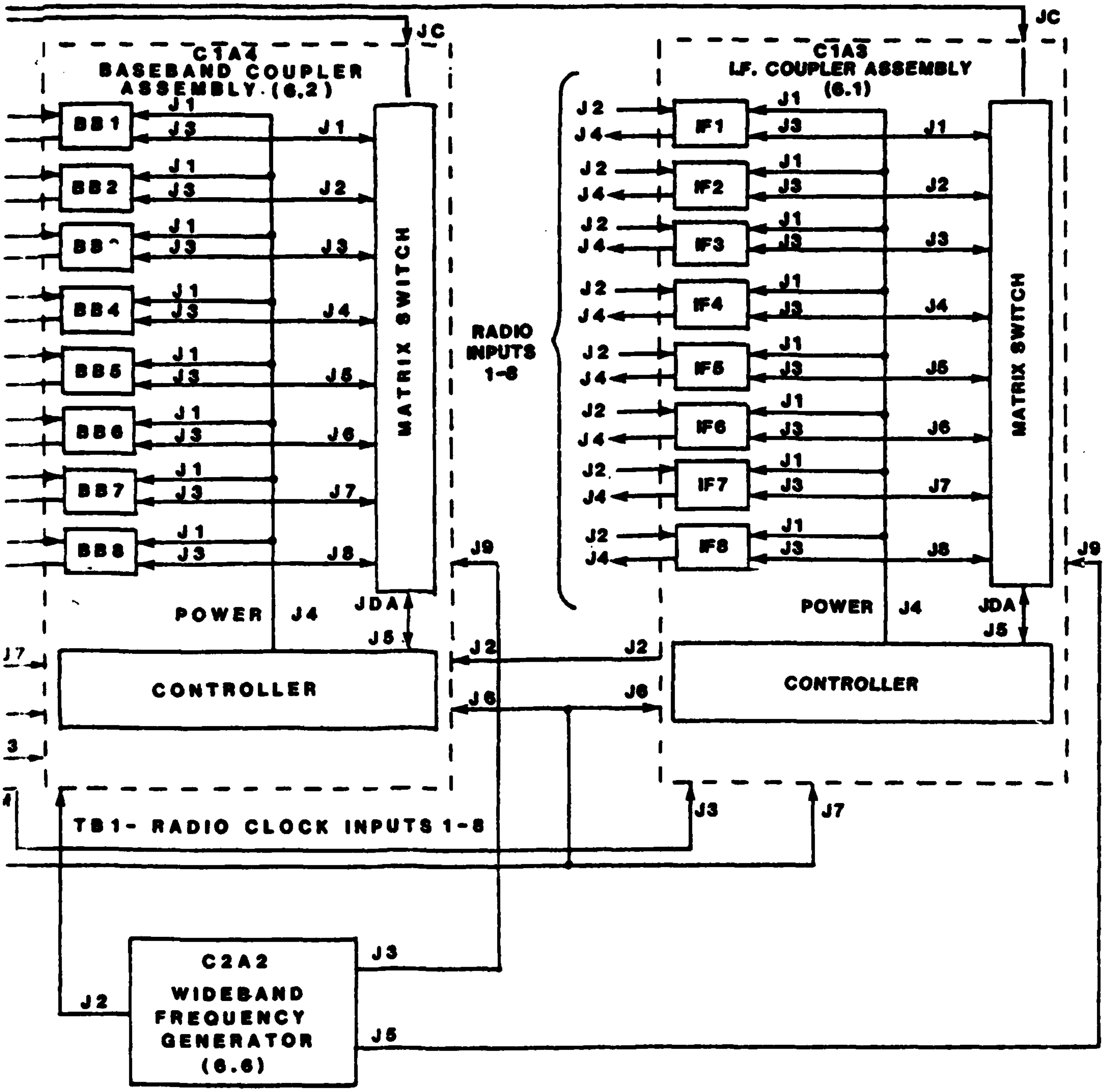

JC
C1A4
BASEBAND COUPLER ASSEMBLY (6.2)
BB1
BB2
BB3
BB4
BB5
BB6
BB7
BB8
J1
J3
J2
J4
J5
J6
J7
J8
MATRIX SWITCH
POWER
JDA
CONTROLLER
RADIO INPUTS 1-8
C1A3
I.F. COUPLER ASSEMBLY (6.1)
IF1
IF2
IF3
IF4
IF5
IF6
IF7
IF8
J9
TB1- RADIO CLOCK INPUTS 1-8
C2A2
WIDEBAND FREQUENCY GENERATOR (6.6)

:AM

3

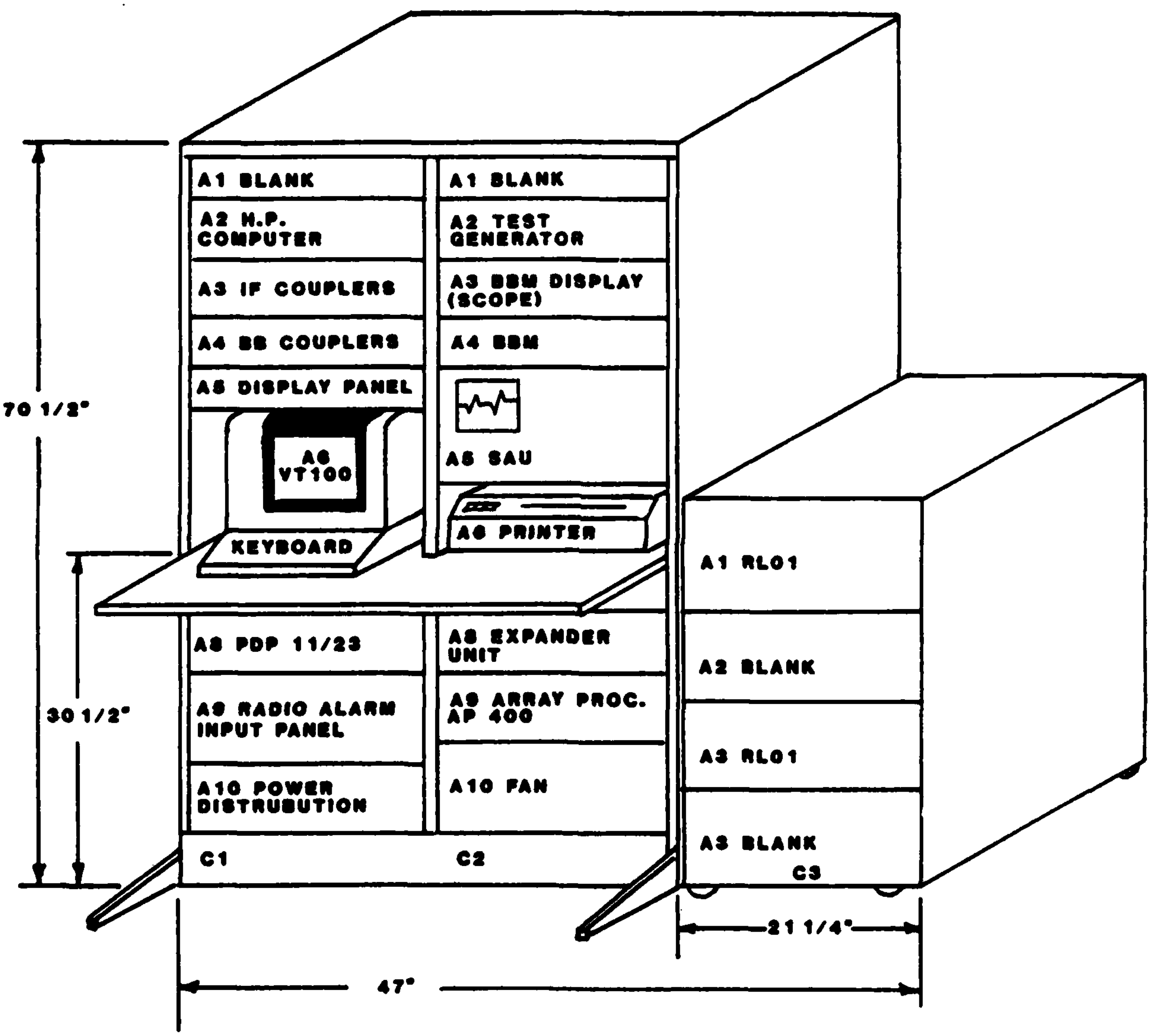


FIGURE 2-2
ESIM EQUIPMENT CONFIGURATION

Returning to the IF, the common matrix switch output is connected to the Hewlett Packard (HP) spectrum analyzer unit C2A5. The analyzer is part of an HP 8581 system. Command and control of the spectrum analyzer functions is provided by the Digital Equipment Corp. (DEC) PDP 11/23, C1A8, via the HP desktop computer, C1A2. The analyzer connects to the HP computer through the HPIB (IEEE-488) bus.

Functionally the spectrum analyzer displays and collects a narrow, medium and wideband spectrum of the 70 MHz IF and transfers the information to the HP. desktop computer. This operation is performed on every measurement cycle for each radio, in the ESIM auto mode. The data is then inputted to the PDP 11/23 through the W9511 custom parallel interface.

Similarly, as in IF, the baseband information is brought into ESIM from the radio via coupler assemblies. Located at the rear of C1 are the baseband couplers BB1 through BB8. The controller chassis, C1A3, supplies power to the couplers and switches the Matrix switch to the proper radio when addressed from the PDP 11/23. Again, these couplers may be connected "in line" with the radio baseband, or to a radio testpoint.

In addition, each radio data clock is brought into C1A4 via terminal board TB-1 located at the rear of the chassis. This clock is buffered in C1A4 and inputted to the clock select circuitry which switches the clock to the baseband monitor. The same address from the PDP 11/23, controlling the baseband Matrix switch, is used for the clock select. Also contained in the clock circuitry is a means for changing the clock delay in relation to the baseband signal. This allows the BBM to sample at the proper place on the waveform through compensation of cable delays.

Wideband frequency generator, C2A2, performs a built-in-test function to ESIM. Internally, a pseudo random bit generator, 2^{15} bits in length, modulates a 70 MHz carrier. The 70 MHz modulated carrier is then brought out to the Matrix switch on C1A3.

The generated 70 MHz is also demodulated in C2A2. The demodulated or baseband is outputted to the Matrix switch located on C1A4. In addition, the data or bit clock is outputted, and is connected to TB1 of C1A4 where it is switched and inputted to the baseband monitor.

The baseband monitor (BBM), C2A4, contains a fast A-D converter and memory. Baseband data is sampled at the inputted data clock rate or through use of an internal 10 MHz clock. This clock is selectable via the PDP 11/23. Although the A-D runs continuously, data is stored in memory in 1024 word bursts. Maximum A-D clock rate is 13.25 MHz. Data is outputted at a much slower rate to the Analogics AP-400 array processor C2A9.

The BBM also contains a hit counter, made up of digital comparators. The hit counter uses a fixed window threshold setting on the baseband sample. Over a specified time period, as determined through the PDP 11/23 computer, the BBM counts the number of A-D samples within the window. This can be indicative of pulsed interference. Hit count is displayed on the BBM front panel. In addition, the front panel presents clock and A-D status information.

The Analogics array processor, C2A9, receives hit count and digitized baseband data from the BBM. Digitized data is used to derive a histogram and spectrum. The histogram provides a measure of interference, while the spectrum provides frequency information on the interferer.

This information, along with hit count, is passed to the PDP 11/23 through the Qniverter interface, ABLE, located in C2A8. The function of the Qniverter is to convert the array processor output bus, which is DEC Unibus compatible, to the PDP 11/23 input Q-bus structure.

At this time let us consider the PDP 11/23 computer, C1A8, and its associated expander unit, C2A8. Contained within these units are the interface boards, shown within the dashed portions of C1A8 and C2A8 of Figure

2-1. The PDP 11/23 computer provides all input and output functions for the operation of ESIM.

The DEC VT-100 CRT Display and Keyboard, C1A6, provides the operator with radio status and ESIM interference classification logic outputs. The keyboard allows the operator access to change ESIM parameters, radio selection, or measurement file updates. The VT-100 is interfaced to the PDP 11/23 through M8043, a DLV11-J serial interface. Note the DLV11-J is located in C2A8, the expander unit. Cables are connected to a connector panel C2A11, where the ports are paralleled to allow routing to various units. All ports are set up for unidirectional communication, either to the user device or into the expander unit (PDP 11/23).

To better understand the communications* of the DRV11J ports, we will briefly discuss and explain the functions of the sub assemblies to which they connect.

Inter connection to the PDP 11/23 is provided by Port C of the DRV11J interface, M8049, in the expander unit, C2A8.

C1A9, the Radio Alarm Latch assembly receives radio alarms or radio performance information in the form of TTL levels. These are generally taken from radio or modem test points and may include frame sync loss, bit error rate detector output, remote alarm or channel select status. Presence of one of these outputs responding with a high level causes an interrupt to the PDP 11/23.

Alarms are brought into C1A9 on TB1. These are buffered, latched, and outputted to DRV11J Port A. Port B signals are communicated from the PDP 11/23 to the user device. A latch is cleared by setting a bit (I/08 to I/O 11 on port B) and performing a write from Port B. Radio inputs are in groups of

* For more detailed information, consult the ESIM Operation and Maintenance Manual.

four alarms per radio, 4 radio groups, where all interrupts are cleared together within a group.

The channel select inputs, from the radio, respond slightly different in that the alarm latch circuitry latches a state change in the input: low to high or high to low. It should also be noted that the specific alarms can be other than those mentioned, as long as an alarm is represented by a normally low, positive going TTL signal lead.

Another function of the Alarm Latch circuitry is the determination of the error count. This error count may be based on format violations in a multiplexer. Each low to high TTL transition causes a binary counter within the alarm latch assembly to increment by one.

The time window for which the counter counts errors is determined by the baseband monitor. This error count window is synchronizing with the hit count. When reading the count into the computer, binary count is read from Port D of the DRV11-J and after the read is complete, the counter is reset.

Another function of the DRV11J is control of the display panel, C1A5. The panel consists of an LED display giving the operator visual indication of radio frame synchronization loss, active radio, interference type, (media, RFI or ECM) and potential danger of the interference disrupting the communication link (low, medium or high).

Radio selection is user inputted to the measurement file. The display panel is updated through the PDP 11/23. Frame sync. status is updated through use of the PDP 11/23 interrupt routine. Interferences type and danger level is presented as a result of an ESIM decision based on a processing result.

The address structure for enabling the lights, uses a radio select to select the radio, R1 to R4. Primary/backup and Frame synch Yes/No is set by a high level placed on the appropriate line of the DRV11J. Interference and danger are also updated by setting addresses.

The last function performed by the DRV11J is, as previously discussed, control of the baseband and IF couplers in selecting the radio to be processed. Again, the baseband or IF enable line is set high and the proper address set for the radio. Performing a write on Port B then sets up to that radio.

Interface M7954, the IBV11-a IEEE bus interface, located in C1A8, connects the HP printer, C2A6, to the system. The printer allows a permanent record of ESIM status information.

Interface M8013, the RV11 disk controller, interfaces the two RLO-1 disk drives C3A1 and C3A3, to the PDP 11/23. These disks each supply 5 megabyte storage capacity for programs and data manipulations.

M9400YD in C1A8 and M9401 in C2A8 are DEC BCV1A-06 bus extender modules which connect the DEC 11/23 Q bus to the backplanes of each unit.

M7952, the KWV11-A programmable clock allows accurate event timing within the PDP 11/23, while M8012, the BDV11-A boot board enables automatic booting of the RT-11 operating system.

The last interface board on C2A8 is designated as ADAC, the A-D converter. This unit has 16 channel single ended input capability and can sample at a 100 KHz rate. Input selection and gain setting is programmable through the PDP 11/23. ESIM uses 8 channels of this unit for inputting received signal level (RSL) for each radio. RSL, derived from the radio AGC loop provides indication of changing input signal levels which is indicative of fading.

The remaining subassemblies C1A10, C2A10, and C2A12 provide power and air circulation to the system. The power supply, C1A10, provides distribution of primary 117 VAC, 60 Hz power throughout the system. It also provides a main power cutoff switch and safety grounding. Switched power supply, C2A12, located at the rear of C2, provides control of AC power to selected subassemblies by way of the PDP 11/23 power switch. C2A10, the fan, contains two squirrel cage fans used for air circulation within the cabinets. Louvered top and back panels in cabinets C1 and C2 vent heat to the room.

3. ESIM ALGORITHM DEVELOPMENT

3.1 SUMMARY OF THE ESIM ALGORITHM DEVELOPMENT

The ESIM algorithm development process started with a data collection using hardware existing at the start of the project. This hardware included an off-the-shelf spectrum analyzer and desktop computer manufactured by Hewlett-Packard. It also included a special purpose device developed by Honeywell and known as a Baseband Eye Monitor, or BEM. PAR made some modifications to this BEM and used it and the spectrum analyzer to perform a data collection. Signal formats included three level partial response frequency modulation (3PR-FM), quadriphase shift keying (QPSK), and two rails of 3PR in phase quadrature (QPR). How the SAU and BEM were used is discussed in Section 3.2.

The principal result of the data collection was the finding that the BEM was inadequate as a device for helping to characterize the type of interference when wide ranges of interference types and parameters were allowed. The results of the data collection are discussed in Section 3.3.

The next step in the algorithm development process was the conceptual design of a baseband signal processor to improve upon the BEM. The replacement device became known as the Baseband Monitor, or BBM. Because of the advance of technology since the BEM was built, a much more computationally powerful device could be designed. For one thing, a high speed digitizer is available which allows the direct conversion of the received signal to digital form with samples being taken at the baud rate. High speed digital memory is also available so that a burst of such digitized samples can be preserved for further analysis by slower speed circuits. The central computational unit for the BBM was chosen to be an AP400 array processor manufactured by the Analogic Corporation. The design of the BBM is discussed in Section 3.4.

Once the BBM was designed, a software system was developed, designed to be flexible in order to allow automated data collection and automated logic testing. The software system was also designed to be modular, with a chain of modules, each module transmitting information to the next via a data file. This allowed overlaying successive modules, a feature essential to making optimum use of the PDP 11/23 computer with its limited (32k words) memory. Programming was done in Fortran whenever possible in order to maximize programmer effectiveness and software maintainability. An important feature of the software system was its ability to generate a data base of measurements which was both machine and human readable. The system could also be used to classify either data just collected or data collected earlier and stored in data files. The design of the software system is discussed in Section 3.5.

A set of measurements to be collected by the SAU and BBM was designed. These measurements were refined somewhat as data was collected. There were three distinct SAU settings, each designed to react differently so as to use more fully the capabilities of the SAU to characterize interference. The bandwidths of the SAU settings were chosen to fit the bandwidths of the data signals. The BBM settings were designed to exercise the BBM capabilities. The design of these measurements is discussed in Section 3.6.

The next step in algorithm development was the collection of a machine and human readable measurements data base. This was done once the ESIM hardware was substantially completed. Data was collected for QPSK, simulated QPR, and for 3PR-FM. The spectrum analyzer was used to display simultaneously 3 traces representing 3 distinct spectrum analyzer (SAU) settings. This display was photographed. It also was used to display the baseband monitor (BBM) histogram, decision feedback spectrum, and hit count simultaneously. This display also was photographed. Together these photographs represented to human observation a concise summary of the measurements taken by the BBM and SAU. The data collection is discussed in Section 3.7.

Next a variety of candidate features were devised and applied to the stored measurements data base. A feature is a many-to-one mapping which represents a multidimensional data measurement in terms of a simpler measurement, usually a single number. For example, the average value of the elements of a 256 element vector would be a feature because it reduces a 256 dimensional measurement down to one dimension. The features found through testing to be most successful were then incorporated into a features extraction software module. Feature extraction is discussed in Section 3.8.

Next the patterns of features resulting from various classes of interference were tabulated. Based on this table a preliminary pattern classification logic was designed. This logic gave very good results on the recorded data base upon which it was designed. It was therefore coded into a pattern classification software module. However, when this logic was tried out on a variety of additional interference cases not in the data base, it was found that the logic often failed to classify the type of interference. The preliminary logic is discussed in Appendix B.

The preliminary logic was found to be quite sensitive to the particular characteristics of the particular data samples upon which it was designed. The basic principles of the logic were therefore revised. In the development of the revised classification logic (the logic delivered with the system) less ambitious performance criteria were set. Further, the classification output formats were revised so that several stages of successively finer decisions were made. The result was a simpler more robust logic. The revised logic is discussed in Section 3.9.

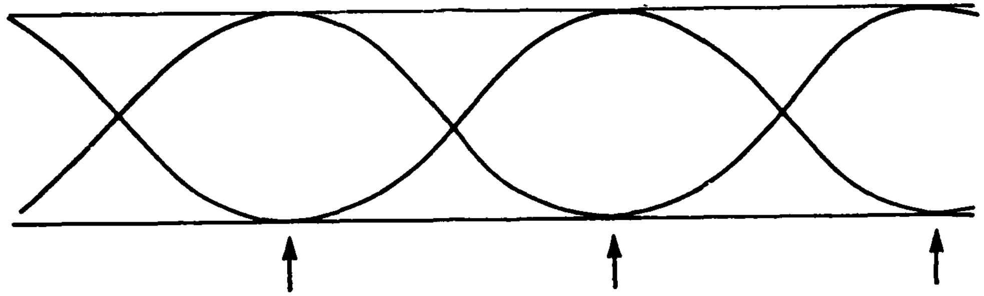
One result has become evident as the ESIM algorithm development proceeded. This is that there is as yet untapped potential in the ESIM hardware and in the measurement software. In particular, it is possible for a trained human observer scanning the ESIM measurements to characterize the interference being experienced. Such human characterization is considerably superior to the automated pattern classification developed to date. This indicates that further developments in the areas of pattern classification and artificial intelligence are in order. Such development can result in machine implementable algorithms which are robust, specific, and accurate. Recommendations for further development are discussed in Section 3.10.

3.2 USE OF THE SAU AND BEM

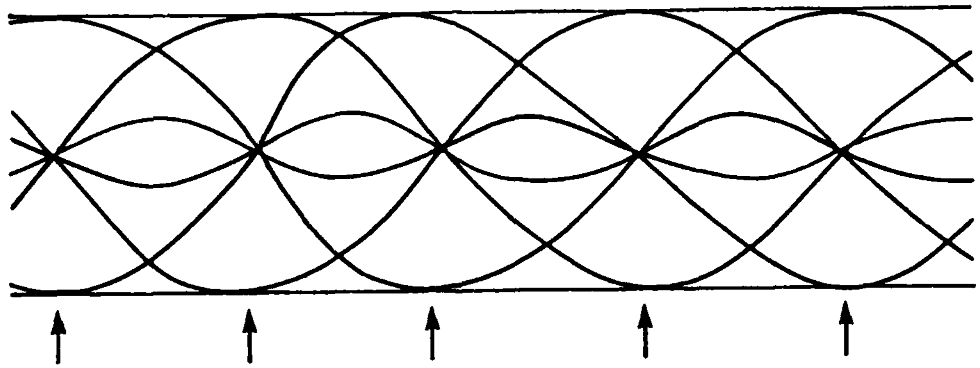
The two best ways to characterize signals are characterization in the time and frequency domains. These ways are complementary, each allowing easier recognition of some aspects of the signal. Characterization in the time domain of a digital signal and its interference is best performed using the signal as it appears in the digital demodulation just prior to the slicing converting the signal from analog to digital form. The signal is best characterized because it is here that the signal is resolved into what is known as the received eye pattern.

Figure 3-1 illustrates the ideal eye patterns for a two level eye and a three level eye. The two level eye results from binary phase shift keying (BPSK), or one of the rails of quadriphase shift keying (QPSK). The three level eye results from three level partial response (3PR) or one rail of quadrature partial response (QPR). 3PR is also known as duo-binary. The eye pattern results when the received baseband signal is displayed on an oscilloscope with the traces synchronized to the baud timing clock. In the figure the arrows indicate the baud timing. Samples taken at the times indicated by the arrows would be two valued for the two level eye and three valued for the three level eye.

In practice the ideal eye pattern is dispersed by noise and interference. Then the samples obtained vary about their ideal values. The more severe the variation the more the eye is said to be closed. Different kinds of noise and interference can result in different patterns of sample variation.



a) TWO LEVEL EYE PATTERN



b) THREE LEVEL EYE PATTERN

FIGURE 3-1
IDEAL RECEIVED EYE PATTERNS

The Baseband Eye Monitor (BEM) is a device developed by the Honeywell Corporation to monitor the dispersion of the eye pattern from the ideal (Reference 1). It was specifically designed to work with the Vicom T1-4000 3PR modem and to monitor the level of white noise imposed upon the signal. In a later study, Honeywell attempted to extend its use to deal with a variety of interference types. The BEM can also be adapted to work with a two level eye.

The BEM contains its own automatic gain control (AGC) circuits and baud timing adjustment. It samples the received baseband signal at the appropriate times. It performs two measurements upon this stream of time sampled data. These measurements are known as the dispersion and the hit count. The dispersion is obtained by adjusting a voltage threshold so that a fixed fraction of the lowest level samples exceed the threshold. This is done by feeding back the count in an up/down counter to control the threshold. The variation of this threshold from the nominal lowest level voltage (as controlled by the AGC) indicates how dispersed are the baseband samples. Strapping options in the BEM control the fraction which controls the threshold.

The hit count is obtained by counting how many samples fall between two voltage thresholds over a fixed period of time. The time interval to be used is controlled by strapping options. In the original BEM the hit count is given by indicating the power of 2 closest to the hit count without exceeding it. The voltage thresholds are set so that the region between the thresholds (the hit region) adjoins one of the two decision levels of the three level eye. Thus a hit represents a received voltage value which is likely to be an error in reception. It is for this reason that a hit may also be termed a pseudo-error.

For use as part of the ESIM system it was clear that multiple dispersion measurements would need to be made in order to estimate the shape of the baseband dispersion. Previously when it was known that Gaussian noise was the interference only one dispersion measurement needed to be made. That one measurement would give the spread of the bell-shaped curve produced by the Gaussian noise. Then an extrapolation could be made to estimate what fraction of received samples would be dispersed beyond the decision thresholds, thereby giving the error rate. However, when the shape of the dispersion distribution is unknown then this extrapolation method does not apply. Initially therefore it was planned to have three dispersion readings for each interference case. The fractions used were one per 128, one per 512, and one per 2048. Test results showed that use of these three dispersions alone were not very informative, and five more dispersion ratios were included, ranging from one per 32 to one per 4096.

The SAU used was a Hewlett Packard 8568A spectrum analyzer, controlled by a Hewlett Packard 9825T desktop computer. This spectrum analyzer is of the swept frequency type. The incoming signal is heterodyned with a linearly frequency modulated tone. The result is lowpass filtered and then squared. There follows an optional logarithmic amplifier and then another lowpass filter. The bandwidth of the first lowpass filter is called the resolution bandwidth, while the bandwidth of the second lowpass filter is termed the video bandwidth. The spectrum analyzer has a digital display memory in which up to three distinct traces are stored, each in a 1001 element vector of values ranging from 0 to 1023. The display of the traces on the unit's cathode ray tube (CRT) is independent of the unit's frequency sweep rate. Besides controls for sweep rate, start and stop frequencies, resolution bandwidth, gain, video bandwidth, there are several additional useful features of the SAU. One feature is maximum holding, or max hold for short. In this mode the trace on the CRT records the maximum values of all previous frequency sweeps. Another feature is termed video averaging. In this mode the average of a set number of sweeps is displayed. This video averaging mode is especially useful for averaging out random variations in a linear scale spectrum so as to produce a smoothed power spectrum.

3.3 DATA COLLECTION USING THE SAU AND BEM

Data was collected over the period of January to April of 1981 for the three signal types of 3PR-FM, QPR, and QPSK. A variety of interference types were introduced, in addition to white Gaussian noise from a line of sight (LOS) media simulator.

The SAU was generally used with a single fixed setting. For display and analysis purposes a reference spectrum due to an unperturbed signal was displayed, as well as the difference between the observed spectrum and the reference spectrum. This made it clear what were the perturbations on the observed spectrum. It also indicated what an automated feature extraction system would have to work with if it subtracted a reference spectrum from the received spectrum. Figure 3-2 shows a typical photograph of an SAU display from the initial data collection. The top trace is the observed spectrum on a logarithmic scale. The middle trace is the reference, while the bottom trace is the difference.

The BEM was used as described in the previous section. The BEM results were evaluated by plotting them on what might be called Q paper. This is a graph calibrated vertically on a linear scale of volts. The horizontal scale is calibrated linearly in multiples of the standard deviation of a Gaussian distribution. However, instead of the scale showing multiples of standard deviations it showed values of the Q function. For example, a threshold removed from the mean by 2.886 times the standard deviation of a Gaussian distribution is exceeded in one out of 512 trials. Thus a horizontal distance of 2.886 units would be marked with the value of 1/512. This Q paper then has the property that any Gaussian distribution of the BEM samples, regardless of the mean and variance, would plot as a straight line when the various values of the BEM dispersions were plotted.

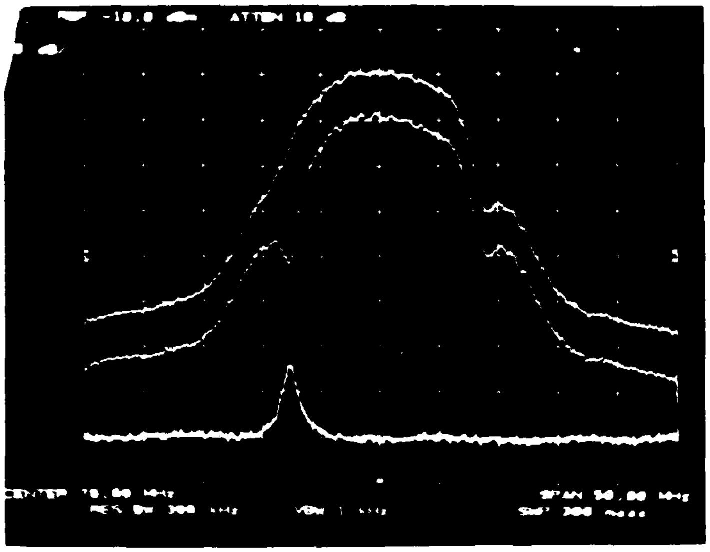


FIGURE 3-2

SAU Display from Initial Data Collection

The performance of the BEM was disappointing. In general it did not distinguish between Gaussian and non-Gaussian distributions. It was somewhat useful to indicate the presence of pulsing in the interference. The SAU results indicated that using a single SAU setting was not likely to be sufficient. Many types of interference that seriously degraded the error rate were not visible in the spectrum plot.

3.4 DESIGN OF THE BASEBAND MONITOR (BBM)

Once the existing BEM was found to be inadequate it was clear that a device with much more signal characterizing power could be constructed using current technology. In particular, a new device could use a high speed digitizer to form 8 bit digital samples at the baud rate of the LOS transmission system. Then instead of having one or a few dispersion estimating measurements as the old BEM had, the new device, called the BBM, could form a 256 bin histogram of the baseband eye dispersions. Samples could be taken by the digitizer in 1024 sample bursts and stored in fast memory. Then the samples could be read out at a slower rate and entered into a computer. The computer could then update a histogram. The computer could also form a decision feedback power spectrum.

In decision feedback the most probable value of the data signal is subtracted from each received sample. Provided the interference power is not too high the result is a good estimate of the interference alone. This interference sequence could then be transformed by means of the Fast Fourier Transform (FFT) and the square of the magnitude could be taken. The result would be a noisy version of the interference power spectrum. Then averaging many such noisy versions would result in a smooth version. It was determined experimentally during the BBM data collection that averaging 100 power spectra taken over one burst each resulted in a smooth power spectrum.

In order to be sure of catching the effects of pulsed interference the BBM needed some kind of measurement that resulted from continuous monitoring of the incoming signal. This was provided for in a hit counter. The principle of the BBM hit counter was the same as the principle of the BEM hit counter, but the BBM implementation was different. In the BBM the hit counter came after the digitizer. This allowed the two thresholds of the hit counter to be variable over the entire 256 values of the digitized samples. Also, the BBM was designed so that the duration over which hits were counted was variable from 2 to 30 seconds in increments of 2 seconds.

3.5 DESIGN OF THE ESIM SOFTWARE SYSTEM

A software system was developed for data collection, signal processing, and pattern classification. The system was designed to be modular, with a number of options for use of combinations of some modules without others. Separation into modules, besides allowing use of subsets of the entire system, was essential in order to get the most performance out of the LSI 11/23 computer with its limited memory space.

Figure 3-3 shows a data flow diagram (also known as a bubble chart) for the ESIM signal processing system. Circles represent processes, while underlined expressions represent data repositories, in this case files on the RL01 disks. As the figure shows, the signal analysis process is divided into three successive stages, namely measurement, feature extraction, and classification. Each of these stages is represented in the software by a module.

There are six main modules in the software. These are the configuration and setup program, the root executive, the measurements compiler, the features extractor, the decision logic, and the output/hardcopy producer. The root executive swaps the other modules, except the setup program, in and out of memory. There are four major types of disk data files. These are setup files, measurement files, features files, and logic decision files.

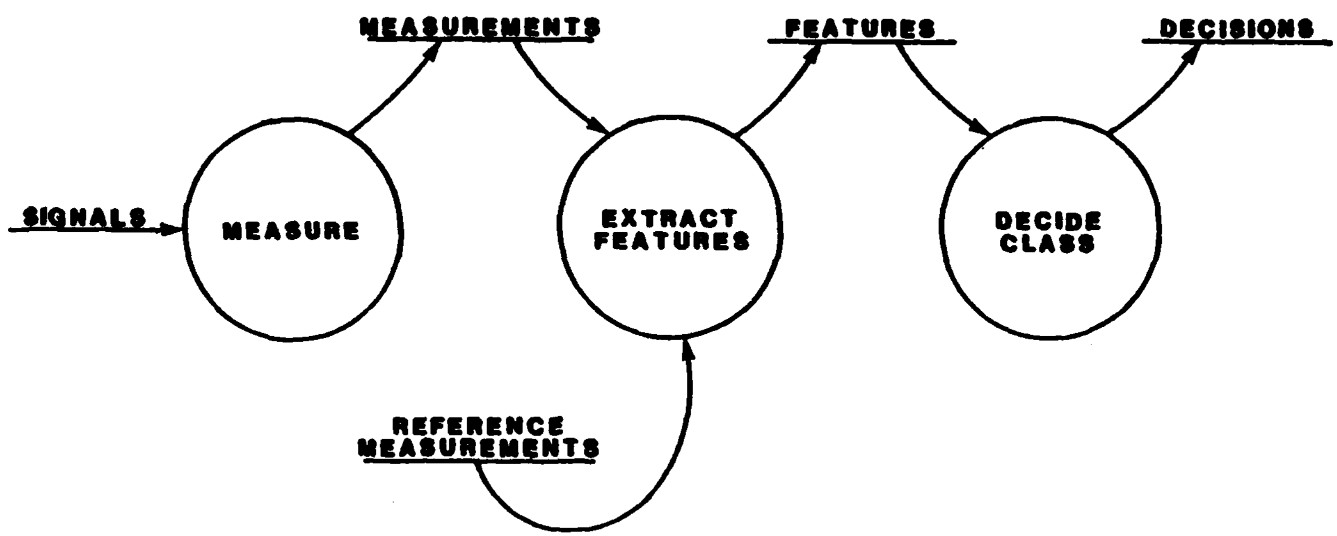


FIGURE 3-3
DESIGN OF THE ESIM SOFTWARE SYSTEM

In the preliminary design of the software it was proposed that unintentional interference (also known as radio frequency interference, or RFI) be distinguished from intentional interference (also known as jamming, also as electronic countermeasures, or ECM) by operator designation. That is, the system initially would classify all interference as ECM. However, the operator could save various features files in a library defining what types of interference are to be classified as RFI. Then whenever the ESIM system proposed to classify some interference as ECM it would first check its library of RFI features files to see if the classification should be changed to RFI.

The RFI features library remains a sound concept in principle, however the concept was not implemented in the present project due to technical difficulties in the areas of artificial intelligence and pattern classification. The RFI library concept requires that interference characterization be both specific and robust. It requires that features be developed that sort out the universe of all possible interferences into a large number of specific interference conditions. At the same time, robustness is required, that is, certain changes in an interference condition should be treated as minor and should not alter the classification. For example, some changes in the signal to interference ratio (SIR) should not change the classification, because multipath fading is to be expected. Further work in this area is indicated. In section 3.10 we give recommendations for future work in algorithm development.

Figure 3-4 shows the ESIM signal monitor filing system. Parts of this system can be used without the other parts. In particular this was very useful for algorithm development. For the data collection the Measurement Supervisor was used alone, along with a measurement file saving module that allowed the operator to specify a name under which to save each measurement file. Later, after a data base of measurement files was completed, a variety of candidate features were developed and tested on the measurements data base. A feature is a function which operates on a multi-element measurement such as a power spectrum and produces one or a few numbers which characterize the

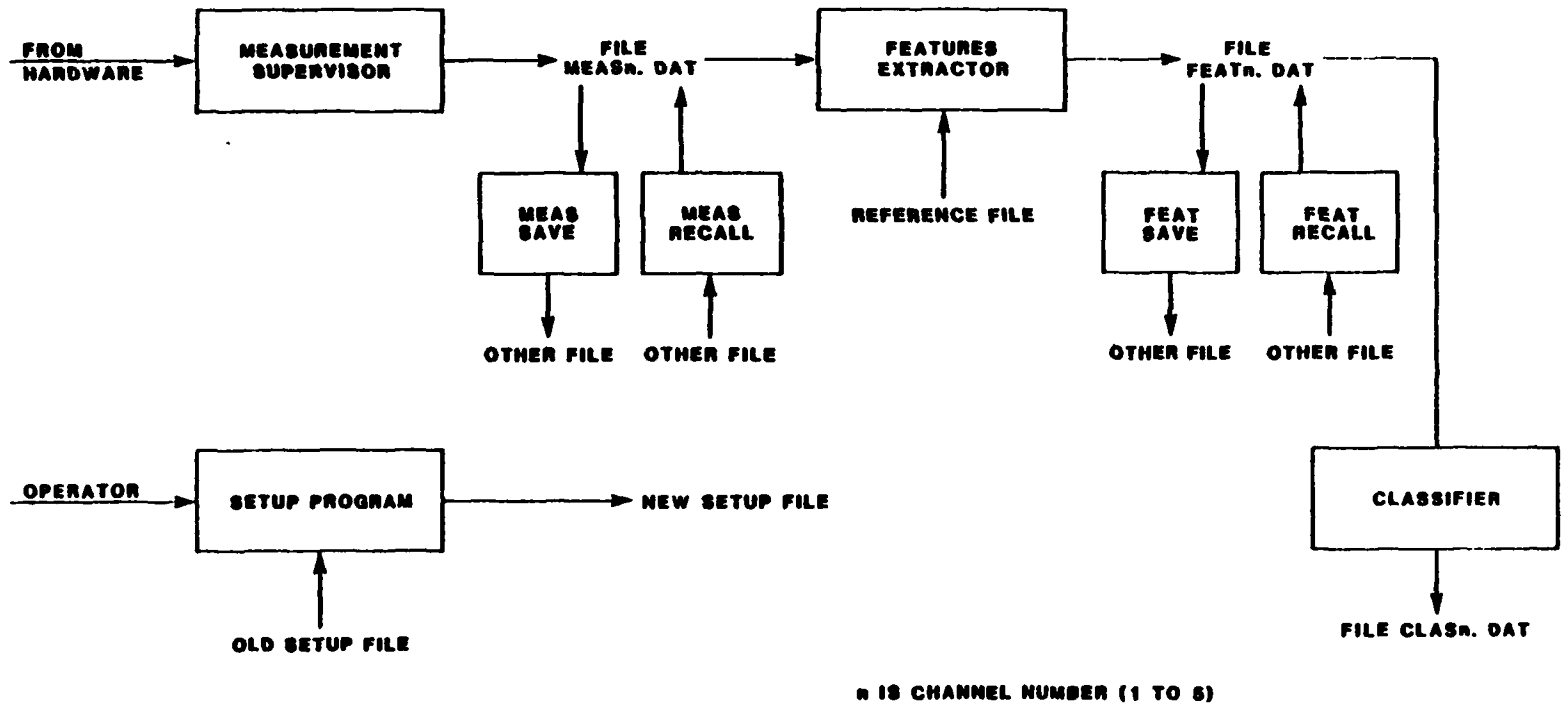


FIGURE 3-4
SIGNAL MONITOR FILING SYSTEM

measurement. Still later, candidate classifier modules were developed and tested against the data base.

3.6 DESIGN OF THE SAU AND BBM MEASUREMENTS

After the initial data collection it became clear that no one spectrum analyzer (SAU) setting would be sufficient to characterize all the various interferences that are possible. It was found, for instance, that when a logarithmic scale was used interference power could be concentrated in the main lobe of the signal spectrum in such a way as to cause a severe error condition yet not be visible in the spectrum. Also, for example, swept CW (also known as linear FM) did not show up in the spectrum. The remedy was to have several spectrum analyzer settings available.

At first the idea was considered of taking one SAU measurement, doing some analysis, and then deciding what more, if any, measurements could profitably be taken. However, this concept has serious drawbacks. For one thing, the concept would require considerable signal analysis during the measurement process, thus negating the concept of signal processing modularity. This would also make the signal processing design task much trickier. For another thing, the problem is that certain interference types do not show up at all for certain measurement settings. No amount of analysis on a normal-looking spectrum could indicate whether or not other spectrum settings were required. Therefore, the concept of feedback from signal processing to SAU measurements was rejected.

In setting up the SAU measurements it became clear that three settings would be a reasonable choice. One setting would cover a wide frequency span, with a logarithmic power scale. This would show obvious interference, especially whatever components of the interference were not hidden in the main lobe of the signal spectrum. This first setting was called the wide span mode (WSM), or Spectrum One. A second setting would detect steady state interference which tended to be covert versus the signal spectrum. This would be on a linear power scale and would employ multi-sweep averaging to reduce transients and random variations. This setting would be narrow span and with fine resolution so as to pull up any narrow bandwidth spikes in the interference power spectrum. This setting was called the narrow span mode (NSM), or Spectrum Two. A third setting would operate with a coarse resolution bandwidth. Thus it would be especially sensitive to interference transients. In order to capture and hold the transient effects this setting used the maximum holding (max hold for short) feature of the spectrum analyzer. This third setting was called Spectrum Three, or pulse mode (PM), because it was designed to catch pulsed interference. It also turned out to be good at catching swept CW.

In the experiments the spectrum settings varied between two cases. One case was for 3PR-FM and QPR using the Vicom T1-4000 modems with their 12.56 megabaud data rates. The SAU settings for this case are shown in Table 3-1.

Table 3-1 : 3PR-FM and QPR SAU Settings

Spectrum #: 1

Scale: LOG

db/division: 10.00

Sweep: CONTINUOUS

Video Averaging: OFF

Trace: A: WRITE

Trace: B: BLANK

Trace: C: BLANK

Display Line: OFF

Threshold: OFF

Center Frequency: 70.00 MHz

Frequency Span: 50.00 MHz

Reference Level: 0.00 dB

Resolution Bandwidth: 300.00 kHz

Video Bandwidth: 1.00 kHz

Sweep Time: 300.00 msec

Attenuation: 10.00 dB

Spectrum #: 2

Scale: LINEAR

Sweep: CONTINUOUS

Video Averaging: ON

Number of Averages: 10

Trace: A: WRITE

Trace: B: BLANK

Trace: C: BLANK

Display LIne: OFF

Threshold: OFF

Center Frequency: 70.00 MHz

Frequency Span: 20.00 MHz

Reference Level: -20.00 dB

Resolution Bandwidth: 100.00 kHz

Video Bandwidth: 1.00 kHz

Sweep Time: 500.00 msec

Attenuation: 10.00 dB

Spectrum #: 3

Scale: LOG

db/division: 5.00

Sweep: CONTINUOUS

Video Averaging: OFF

Trace: A: MAXHOLD

Trace: B: BLANK

Trace: C: BLANK

Display Line: OFF

Threshold: OFF

Center Frequency: 70.00 MHz

Frequency Span: 50.00 MHz

Reference Level: 0.00 dB

Resolution Bandwidth: 3000.00 kHz

Video Bandwidth: 30.00 kHz

Sweep Time: 20.00 msec

Attenuation: 10.00 dB

The other case was for QPSK with a Harris modem, operated at 4 megabaud, which was close to its maximum rate. The SAU settings for this case are shown in Table 3-2.

Table 3-2 : QPSK SAU Settings

Spectrum #: 1

Scale: LOG

db/division: 10.00

Sweep: CONTINUOUS

Video Averaging: OFF

Trace: A: WRITE

Trace: B: BLANK

Trace: C: BLANK

Display Line: OFF

Threshold: OFF

Center Frequency: 70.00 MHz

Frequency Span: 25.00 MHz

Reference Level: 0.00 dB

Resolution Bandwidth: 100.00 kHz

Video Bandwidth: 1.00 kHz

Sweep Time: 300.00 msec

Attenuation: 10.00 dB

Spectrum #: 2

Scale: LINEAR

Sweep: CONTINUOUS

Video Averaging: ON

Number of Averages: 10

Trace: A: WRITE

Trace: B: BLANK

Trace: C: BLANK

Display Line: OFF

Threshold: OFF

Center Frequency: 70.00 MHz

Frequency Span: 10.00 MHz

Reference Level: -20.00 dB

Resolution Bandwidth: 30.00 kHz

Video Bandwidth: 1.00 kHz

Sweep Time: 500.00 msec

Attenuation: 10.00 dB

Spectrum: #: 3

Scale: LOG

db/division: 5.00

Sweep: CONTINUOUS

Video Averaging: OFF

Trace: A: MAXHOLD

Trace: B: BLANK

Trace: C: BLANK

Display Line: OFF

Threshold: OFF

Center Frequency: 70.00 MHz

Frequency Span: 25.00 MHz

Reference Level: 0.00 dB

Resolution Bandwidth: 1000.00 kHz

Video Bandwidth: 300.00 kHz

Sweep Time: 20.00 msec

Attenuation: 10.00 dB

The spectrum variation between the two cases is mainly in the bandwidth.

Design of the baseband monitor (BBM) measurements was a fairly straightforward implementation of the BBM design concept. There are three measurements which the BBM produces, namely the baseband histogram, the decision feedback spectrum (DFS), and the hit count. Specification of the baseband histogram consists simply of determining how many data bursts of 1024 samples each would be used. In theory, one might expect that using a larger number of bursts might result in a smoother histogram. In particular, the count in each bin might be expected to be Poission distributed.

The Poisson distribution is the model of ideal randomness for count distributions. The Poission distribution with mean M is given by

$$p(k)_m = e^{-M} M^k / k! \qquad \text{for } k = 0, 1, 2, \ldots \ .$$

This distribution has variance M, so its standard deviation equals the square root of its mean. Then if histogram bin counts are Poisson distributed a normalized histogram for a large number of bursts, say 100, should look noticeably smoother than a normalized histogram for only 10 bursts. In particular, the deviation of the 100 burst histogram should be slightly less than one third of the deviations in the 10 burst histogram. However, in fact the histograms had similar deviations. There was no smoothing of the histograms visible indicating any improvement of a 100 burst histogram. However, there is still an advantage to using a fairly large number of bursts, namely that in case of pulsed interference a larger number bursts is more likely to catch the effects of the pulsing. Due to these considerations, 30 bursts were used in each case to calculate baseband histograms.

For the decision feedback spectrum (DFS) it was decided that the decision level(s) should be set dynamically. This allows for variation in signal level and deviations from the ideal in the received eye pattern. The method used to set the decision levels was as follows. First a histogram was compiled, then the decision level(s) and signal value levels were estimated from it. Next a number of bursts were taken. For each sample in each burst the appropriate signal value was subtracted. A 1024 point fast Fourier transform (FFT) was then taken for each burst. The magnitude squared of each FFT was taken and the resulting power spectra for all the bursts were averaged. The result was the decision feedback power spectrum.

The decision levels and nominal signal levels were determined from a histogram as follows. First the nominal signal levels were found by locating the appropriate percentiles of the experimental distribution. For a two level signal these were the 25th and 75th percentiles. For a three level signal these were the 12.5, 50th, and 87.5 percentiles. Next each decision level was taken to be halfway between its neighboring nominal signal levels.

The histogram used to set the decision levels was compiled separately from the histogram delivered by the BBM as output. This allowed separate settings of the number of bursts in a histogram. There were thus three settings used to control the DFS computation process. These were the number of data bursts in the histogram, how many data levels were expected (2 for QPSK, 3 for 3PR-FM and QPR), and how many data bursts were in the DFS. Values selected were 30 bursts for the histogram and 100 bursts for the DFS.

In contrast to the histograms, for the DFS the use of a large number of bursts was found to have a significant impact on the smoothing of the resulting measurements. This is as predicted by digital signal processing theory (ref. 2 chapter 11). For this reason a large number (100) of bursts were used to compute the DFS.

The thresholds for the hit count were set by specifications in the ESIM setup file. In retrospect it appears that consideration should be given to setting the bit count thresholds more dynamically. One possibility is setting them based on the histogram in the reference file used to indicate the baseline condition. Another possibility is to set them by a similar process to the way the DFS signal and decision levels are set, that is, compute them anew before each hit count collection session. One procedure to use the present way of specifying the hit thresholds is to have the ESIM operator determine the hit thresholds based on observation of a baseline signal. Further work with the hit count settings is indicated. See section 3.10. For QPSK the hit thresholds were set at 124 and 132, out of a range of 1 to 256 and the time interval for counting hits was set at four seconds. For 3PR-FM and QPR the hit thresholds were set at 96 and 100, and the time interval was also four seconds.

3.7 DATA COLLECTION USING THE SAU AND BBM

The final data collection was done using the ESIM hardware and software system, once that system was substantially completed. Data bases of spectrum analyzer unit (SAU) and baseband monitor (BBM) measurements were produced. These data bases were both human and machine readable.

Figure 3-5 shows a typical report page summarizing the data stored on magnetic disk in a measurements file. At the top of the page is the operator's name, the date and time of report creation, and the name of the setup file that controlled the measurements. In this case the disk file is the default scratch file MEAS1.DAT. This indicates that the measurements were not saved for later use. Next come the signal type and interference type. In this case the measurements represent the baseline (no interference) condition. Next come remarks. These show that the array processor (AP) in the BBM was used to compute the decision feedback spectrum (DFS). A preliminary set of controlling parameters were in use. The histogram reported as a measurement involved 20 buffers (instead of 30, the final value.) The histogram used to calculate the decision feedback involved 10 buffers instead of 30. However, the histogram and the DFS show nearly identical characteristics to those produced with the final settings.

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: B DICK　　　DATE|TIME: 07-SEP-82 | 11:51:48

SETUP FILE: SETH.DAT　　　DATA FILE: MEAS1.DAT

SIGNAL TYPE: QPSK　　　INTERFERENCE TYPE: NONE

REMARKS

DFS VIA AP, 100 BUFFERS, HIST 20 BUFFERS, DEC FEEDBACK 10 BUFFERS, BASELINE, NO INTERFERENCE.

INTERFERENCE MODULATION PARAMETERS: NONE

POWER LEVELS: dbm|mw

SIGNAL.
-7.7 DBM, .171 MW

INTERFERE[illegible]E:

INTERFERENCE
+SIGNAL:

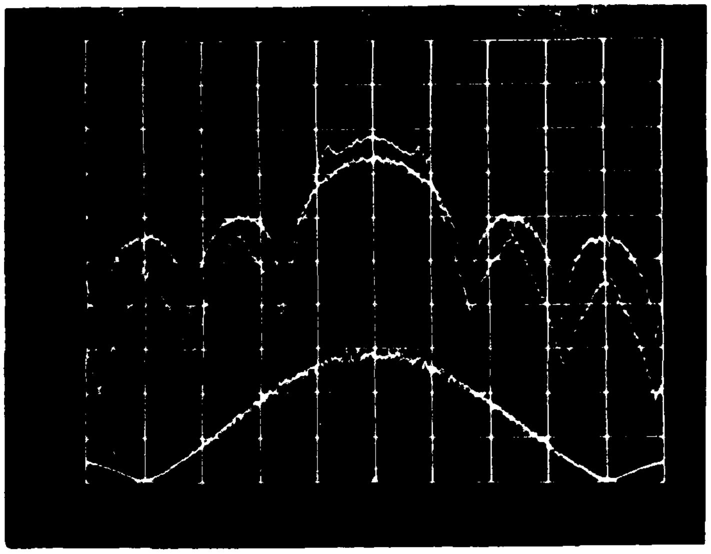
BIT ERROR RATE:
0.0 E-7

[illegible]ROR RATE:
[illegible]

DATA RATE:
8 MBPS

DATA COLLECTED ON

07-SEP-82 / 11:45:07



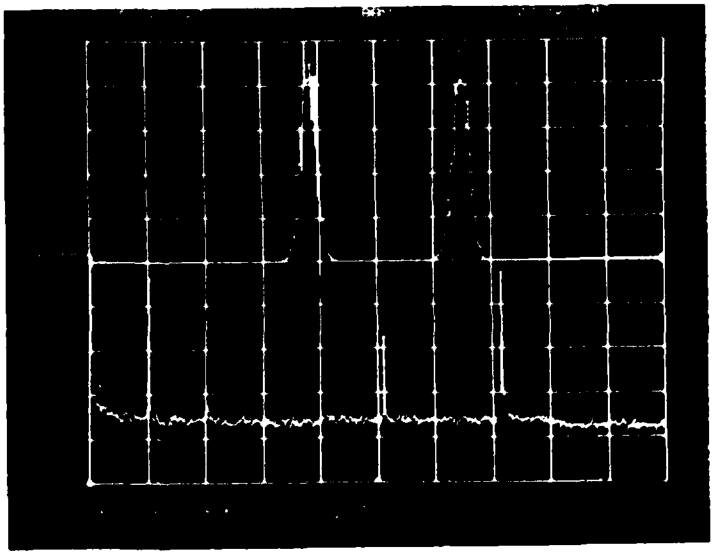


FIGURE 3-5

A Final Data Collection Report Page

Since there was no interference, the interference modulation parameters and power level are not given. The signal power level measured at the IF band centered on 70 MHz was -7.7 dBm, a reading which should be used on a relative scale to indicate signal to interference power ratio when the interference power level is measured. The bit error rate (BER) was measured by a Hewlett Packard data generator and tester to be less than the smallest error rate measurable with that device, namely less than 0.1 E-7, or 10^{-8}. In the experimental setup for 3PR-FM and QPR a counter was connected to the 4023 module in the Vicom T1-4000. This module produced a pulse every time there was a format violation in the 3PR signal. Such format violations occur with virtually every error of 3PR or QPR transmissions and therefore offer a very good non-intrusive error rate indicator for the signals to which it applies. Finally, the report text indicates that the QPSK data rate was 8 megabits per second, and it gives the date and time of the measurement collection.

At the lower right of the report are two photographs which summarize the SAU and BBM data. The upper photograph shows all three of the SAU spectrum traces superimposed on the same grid. Digits to the left of the grid identify the traces. The lower photograph displays the BBM measurements. The grid here should be viewed as divided into upper and lower halves. The upper half shows the BBM histogram. Here the 1001 point SAU trace memory has been filled with the 256 point histogram data as follows. The histogram data has been normalized so that its maximum value just reaches the top of the grid. The first 116 points of the 1001 point display are always zero. The next 768 points contain the histogram, with each histogram point expanded to occupy three SAU display points. Finally, the remaining 117 points are all zero. The histogram shows two narrow peaks separated by a large stretch of all zero values. This is how a baseline QPSK histogram should look.

The lower half of the BBM data photograph shows a baseline decision feedback spectrum (DFS). Here a 512 point DFS is plotted on the 1001 point display with each DFS point represented by two plotting points. The highest frequency eleven points of the DFS are not shown. This plot shows a typical behavior of the Harris QPSK modem being used, namely that it produced sinusoidal interference in addition to the white Gaussian noise to be expected in any circuit.

The DFS frequency scale may be interpreted as follows: The left end of the scale represents zero frequency offset from the center frequency of the transmission band. The right end represents approximately two megahertz offset from the center frequency. Due to the well-known phenomenon of aliasing, or frequency folding (see ref. 2.) multiple frequencies are represented by the same point on the measured spectrum. Figure 3-6 illustrates the folding function. For example, for a data rate of 4 million symbols per second (4 megabaud) shown in part a, the first point of the DFS can stand for zero frequency offset, also plus or minus 4 megahertz offset, also plus or minus 8 megahertz, and so on. Point 256 in the measured DFS (halfway along it) presents the sum of all interference occurring at plus or minus one megahertz from band center, plus or minus three megahertz, plus or minus five, and so on. For a different baud rate the folding function is different. The folding function that results is always proportional to the baud rate. Part b of the figure shows the folding function for the 12.6 megabaud rate of the Vicom T1-4000 3PR modem.

Referring back to the report figure, the DFS shows the presence of a white noise floor at about 1.2 divisions above zero. It also shows several spikes which are characteristic of the particular modem producing the data. There are spikes in the spectrum at approximately zero, one, 5.1, and 7.1 divisions across the grid. The spike at one division is quite large, but difficult to discern because it falls on a grid line. The spikes constitute fairly small components of the modem's self interference in terms of total power contributed. However, they introduce a complicating factor in the DFS, and especially into the problems of feature extraction and pattern classification.

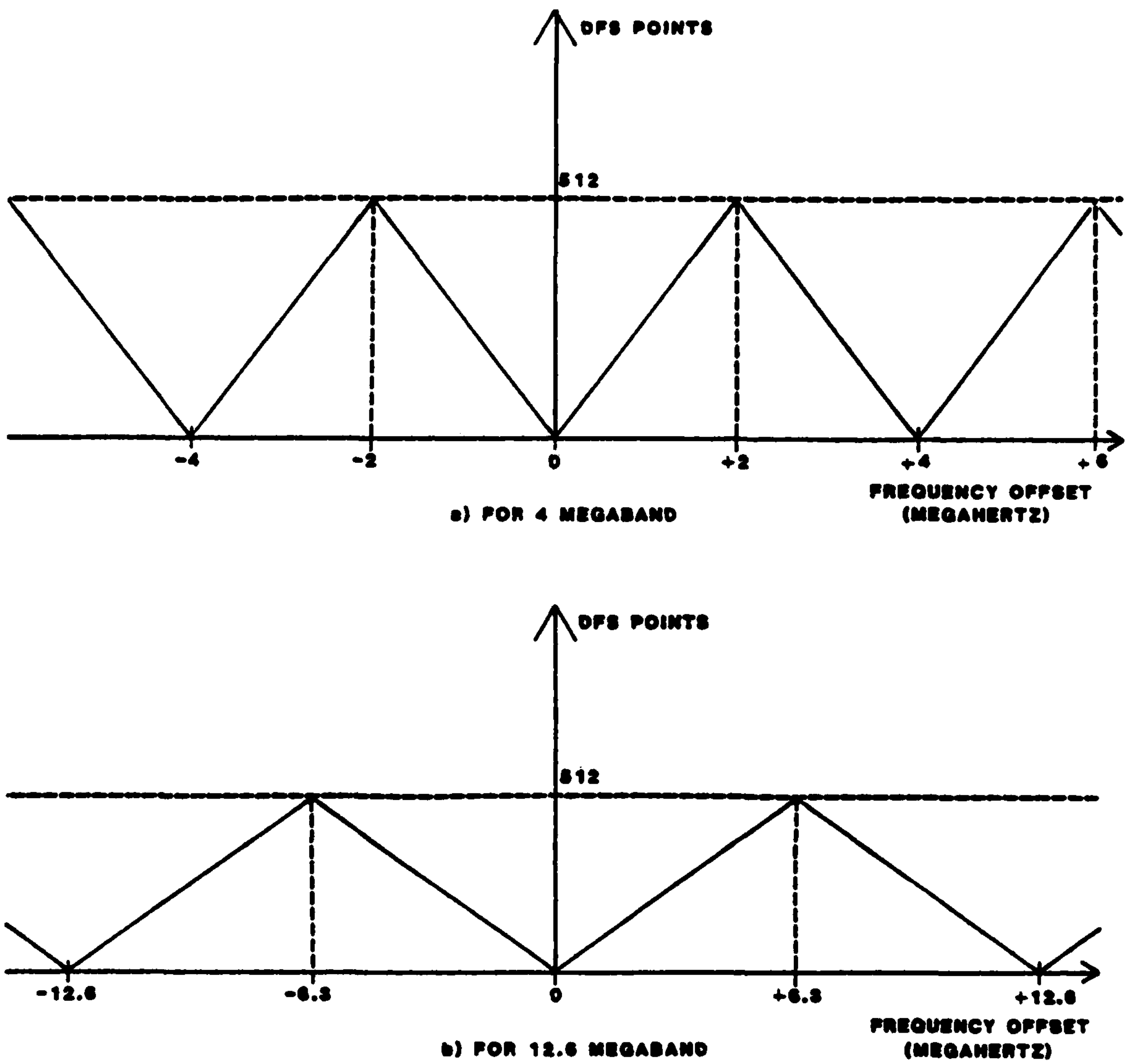


FIGURE 3-6
DFS FREQUENCY FOLDING

A variety of information is displayed around the edges of the grids on the photographs. These include the measurement file name, the controlling setup file name, and the date and time of the measurement. This data is common to both photographs. Also shown in the BBM photo, below the grid, is the hit count and the histogram scale. In the example the hit count is zero and the histogram scale is 0 to 701.

The results of the data collection were complex. However, a few data reports may give some of the flavor of it. Figure 3-7 shows a report on white noise added to a QPSK signal. The two log scale spectrum traces appear raised and compressed. The histogram shows the bell shaped curves characteristic of white noise. The decision feedback spectrum shows white noise added to the spikes characteristic of the modem.

Figure 3-8 shows the effect of wideband tone FM. The spectral spikes are barely visible in spectrum 1, but very pronounced in the linear scale spectrum 2. The histogram humps are clearly U-shaped, indicating constant envelope interference. The decision feedback spectrum shows the multiple spikes characteristic of wideband tone modulated FM.

Figure 3-9 shows the effect of a low level of binary phase shift keying (BPSK) interference. The level was so low that no errors occurred. The interference is visible as a small bump on the linear scale spectrum. In the histogram the interference has produced the U-shaped humps characteristic of constant envelopes interference. In the decision feedback spectrum (DFS), a large hump indicates that the interference has a nonwhite spectrum.

Figure 3-10 illustrates a baseline condition for a simulated QPR transmission. The spikes in spectrum 1 are artifacts of the simulation and do not represent interference. The format of the baseband monitor (BBM) plot has been changed, with the DFS appearing above the histogram. The bar graph at the bottom near the fifth grid line represents the hit count. The edges of the bar show the boundaries of the hit region, while its height represents the

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: B DICK

DATE|TIME: 07-SEP-82 | 12:04:58

SETUP FILE: SETH.DAT

DATA FILE: MEAS1.DAT

SIGNAL TYPE: QPSK

INTERFERENCE TYPE: WHITE NOISE

REMARKS

NOISE ATTEN 20 DB

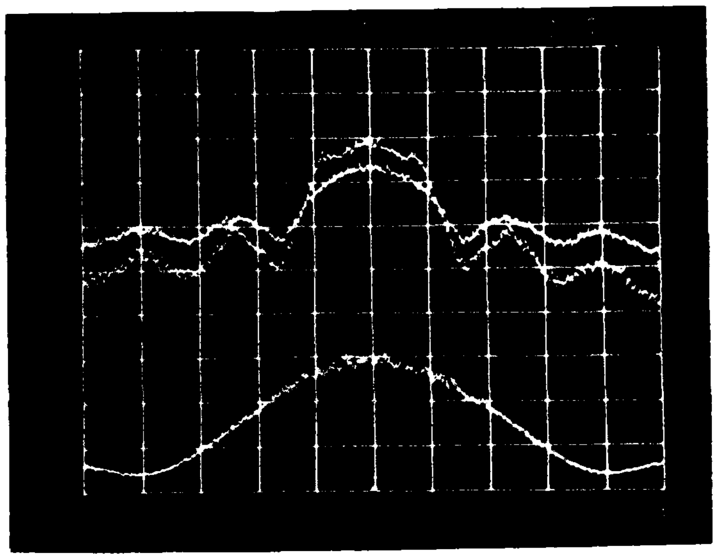
INTERFERENCE MODULATION PARAMETERS: 25 MHZ BW CTR 70 MH

POWER LEVELS: dbm|mw

SIGNAL:
-7.7 DBM, .171 MW

INTERFERENCE:
-18.6 DB, 14 UW

INTERFERENCE
+SIGNAL:
-7.0 DBM, .20 MW



BIT ERROR RATE:
NA

3PR ERROR RATE:
NA

DATA RATE:
8 MBPS

DATA COLLECTED ON

07-SEP-82 / 11:54:23

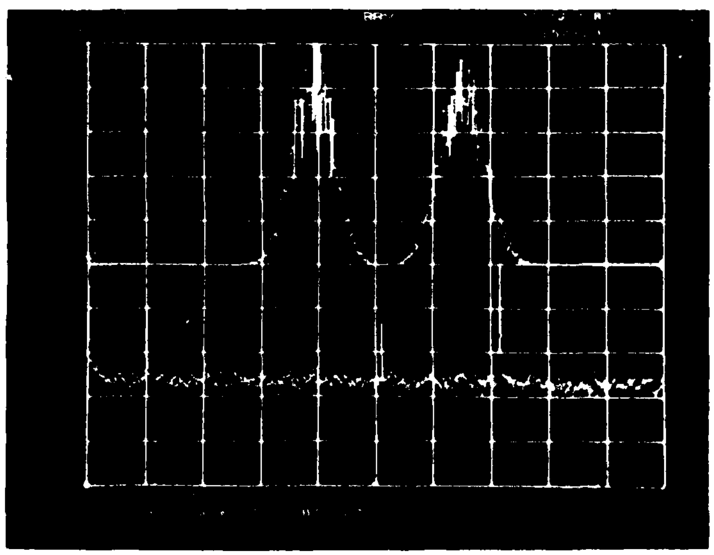


Figure 3-7:

QPSK Plus White Noise

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: B DICK

DATE|TIME: 07-SEP-82 | 14:51:19

SETUP FILE: SETH.DAT

DATA FILE: QPFMT1.DAT

SIGNAL TYPE: QPSK

INTERFERENCE TYPE: FM TONE

REMARKS

100 BUFFER HISTOGRAM AND DEC FDBK SPEC. TONE CTR FREQ SLIGHTLY BELOW 70 MHZ. ATTEN 20 DB.

INTERFERENCE MODULATION PARAMETERS: .5 MHZ RATE, 3.1 MH

POWER LEVELS: dbm|mw

SIGNAL:
-7.7 DBM, .171 MW

INTERFERENCE:
-18.6 DBM, 14 UW

INTERFERENCE
+SIGNAL:
-7.0 DBM, .200 MW

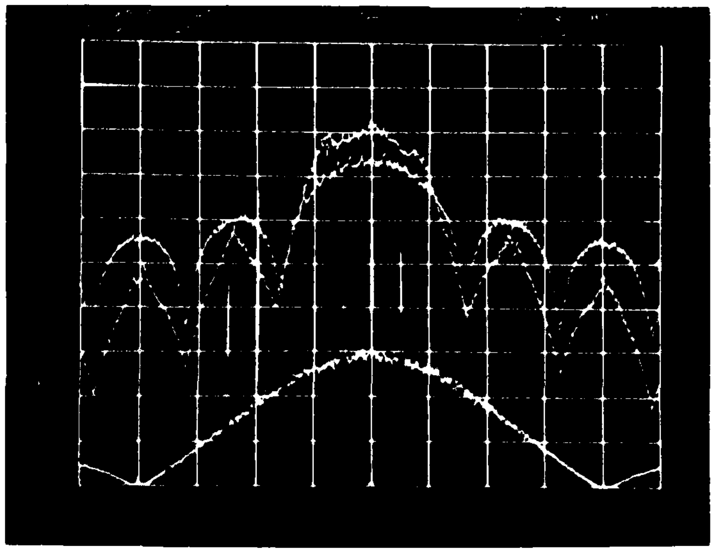
BIT ERROR RATE:
0.0 E-7

3PR ERROR RATE:
NA

DATA RATE:
8 MBPS

DATA COLLECTED ON

07-SEP-82 / 14:44:44



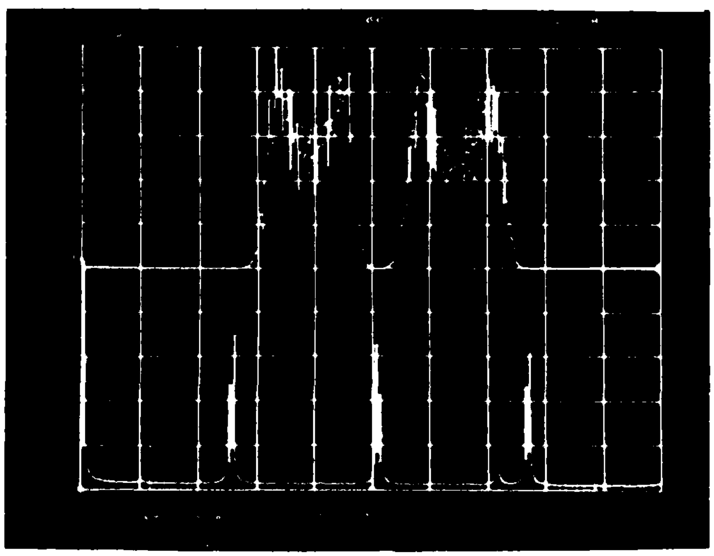


Figure 3-8:

QPSK Plus Wideband Tone Modulated FM

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: B DICK

DATE|TIME: 07-SEP-82 | 11:42:20

SETUP FILE: SETH.DAT

DATA FILE: MEAS1.DAT

SIGNAL TYPE: QPSK

INTERFERENCE TYPE: BPSK

REMARKS

DFS VIA AP400, 100 BUFFERS, 10 BUFS DEC FDBCK, 20 BUFFS HIST. BBM RUN ABT 3 SECS. INTF DOWN 25 DB

INTERFERENCE MODULATION PARAMETERS: 71 MHZ CAR, .5 MHZ

POWER LEVELS: dbm|mw

SIGNAL:
-7.7 DBM, 1.71 MW

INTERFERENCE:
NOT MEASURABLE

INTERFERENCE
+SIGNAL:
-7.45 DBM, 1.81 MW

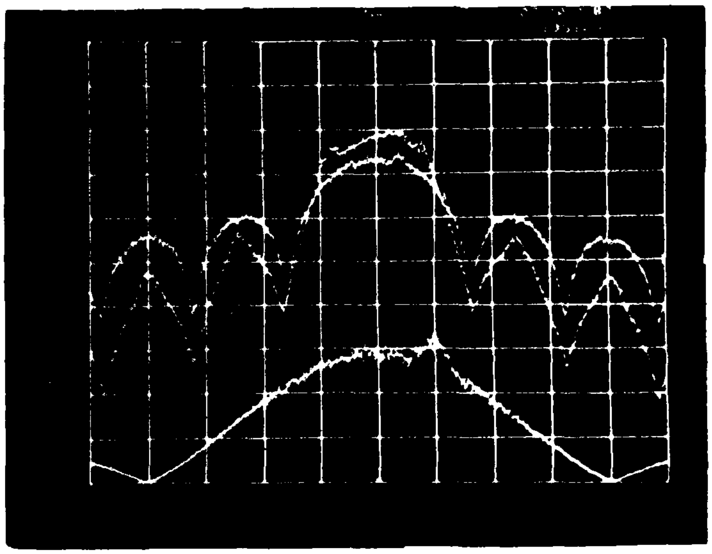
BIT ERROR RATE:
0.0 E-7

3PR ERROR RATE:
NA

DATA RATE:
8 MBPS

DATA COLLECTED ON

07-SEP-82 / 11:35:05



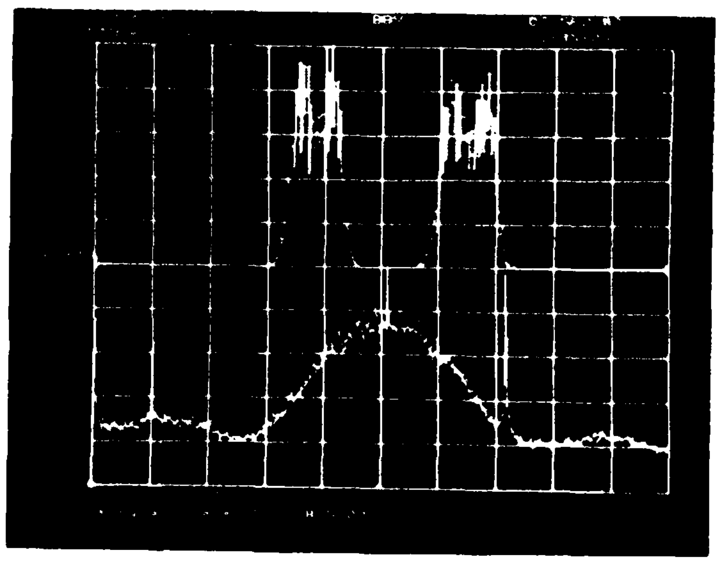


Figure 3-9:

QPSK Plus BPSK

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: BOB DICK

DATE|TIME: 02-DEC-82 | 08:10:31

SETUP FILE: TEST1.DAT

DATA FILE: A3BA52.DAT

SIGNAL TYPE: 3PR-AM

INTERFERENCE TYPE: BASELINE

REMARKS

BASEBAND SIGNAL MONITOR POINT CHANGED TO BE AFTER THE VICOM RECEIVER FILTER, NOW JUST BEFORE THE SLICERS. (Class "Med Low Baseline")

INTERFERENCE MODULATION PARAMETERS: NONE

POWER LEVELS: dbm|mw

SIGNAL:
-12.7 DBM

INTERFERENCE:

INTERFERENCE
+SIGNAL:

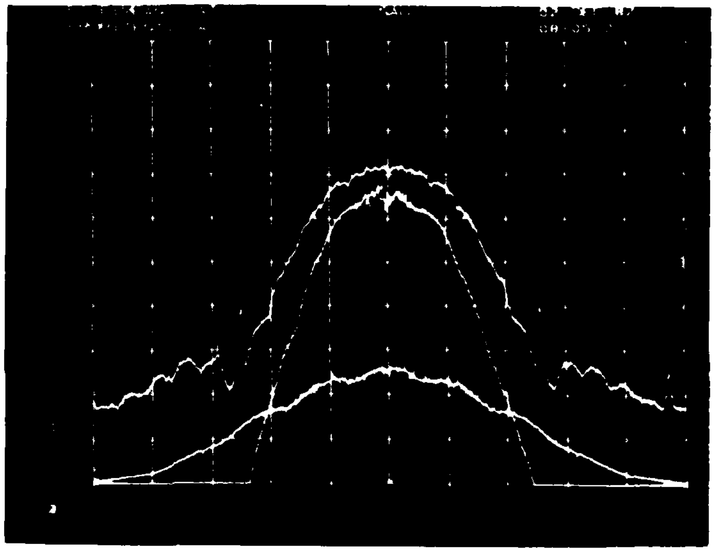
BIT ERROR RATE:
0.0 E-5

3PR ERROR RATE:
0

DATA RATE:
12.6 MB

DATA COLLECTED ON

02-DEC-82 / 08:05:07



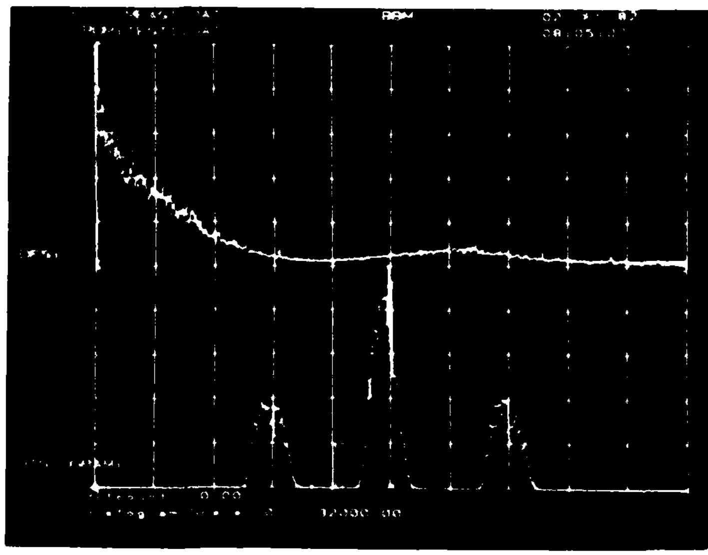


Figure 3-10:

Simulated QPR,

No Interference (Baseline)

count. In this case the count is zero, but lines showing the edges of the hit region appear anyway. The DFS here is typical of the no-interference Vicom T1-4000.

Figure 3-11 shows a case of pulsed CW interference. The pulse repetition rate (PRR) is one kilohertz, and the pulse width is 100 microseconds, giving a pulse duty factor of ten percent. The interference does not show up on the SAU power spectra. However, it is clearly visible in the DFS. The interference is visible as a low level of nonzero values extending over most of the histogram range. The interference is especially notable in the hit count, which has saturated at 32700. This case is a good example of the ESIM's power. The interference is not visible in the IF spectra, and would not be visible in an oscilloscope eye pattern display. Yet the Baseband Monitor (BBM) picks it up and shows that the interference is severe. The BBM also shows that the interference is pulsed with a low duty cycle.

3.8 FEATURE EXTRACTION

3.8.1 Introduction to Feature Extraction

Once a machine and human readable data base of measurements was compiled, the next step was devising and testing candidate features upon it. A feature is a many to one mapping used to reduce measurements to simpler forms. Feature extraction is an intermediate step between taking measurements and classifying patterns.

The design of features is an art rather than a science. A good approach is for an analyst to study a complete data base of human readable measurements and look for distinguishing characteristics of the various classes to be identified. Then the analyst designs candidate features which translate the presence or the degree of intensity of the characteristics into numerical form. It is important that the data base also be machine readable so that the same data is evaluated both by the human analyst and by the machine

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: BOB DICK

DATE|TIME: 02-DEC-82 | 09:39:54

SETUP FILE: TEST1.DAT

DATA FILE: A3PCW1.DAT

SIGNAL TYPE: 3PR- AM

INTERFERENCE TYPE: PULSED CW

REMARKS

CARRIER 69 MHZ, PRR 1 KHZ, PW 100 MICROSEC, ATTEN 40 DB

"ECM HIGH PULSED" 3PR ERROR LIGHT ON, OTHERS OFF

INTERFERENCE MODULATION PARAMETERS:

POWER LEVELS: dbm|mw

SIGNAL:
-12.9 DBM

INTERFERENCE:

INTERFERENCE
+SIGNAL:

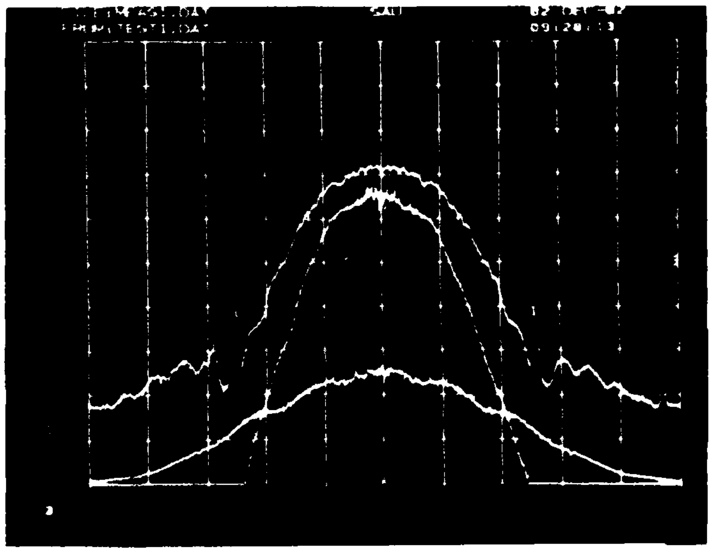
BIT ERROR RATE:
TESTER SYNC LOSS

3PR ERROR RATE:
"-32768"/(2 SEC)

DATA RATE:
12.6 MB

DATA COLLECTED ON

02-DEC-82 / 09:28:13



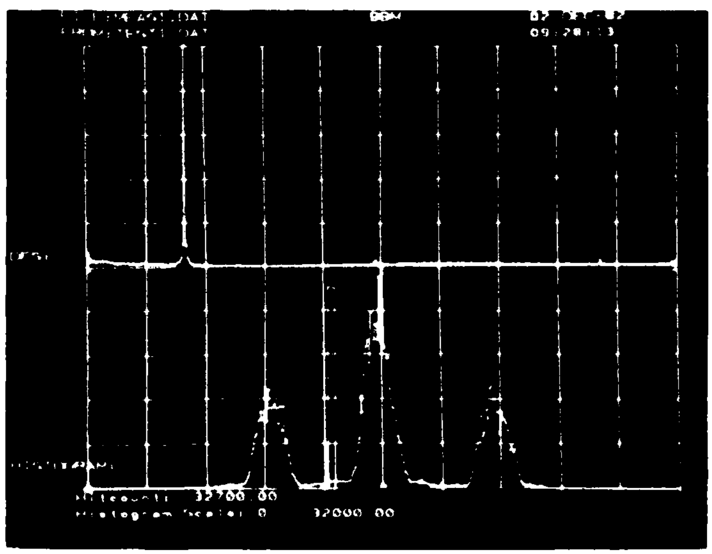


Figure 3-11:

Simulated QPR plus Pulsed CW

implemented candidate features. Next the analyst examines the numerical results closely on a case by case basis, to see how well the numbers correlate with his own estimates of the presence or degree of intensity of the characteristics. Some features will fail to produce appropriate numbers and will therefore be discarded. Other features will be more successful. The process is repeated for a variety of candidate features until a set of good features is developed, adequate to represent enough distinguishing characteristics to resolve the pattern classification problem.

In the present ESIM effort, several pre-processing techniques were tried out, aimed at bringing out certain characteristics of the data prior to feature extraction. We will first discuss the pre-processing, then the spectrum analyzer (SAU) features, and finally the baseband (BBM) features.

3.8.2 Measurement Pre-processing

The earliest pre-processing technique tried during the present project was subtraction of a reference spectrum from a measured power spectrum of signal plus interference. This subtraction was especially effective when it brought to human attention seemingly minor pertubations in the signal plus interference spectrum. Such perturbations could be significant if the interference power is concentrated in the main lobe of the signal power spectrum.

While the reference spectrum subtraction method is useful for revealing characteristics to human observation, it is of less value as a preprocessing technique for machine implemented feature extraction. The reason for this is that the difference of the two spectrums depends on the shape of the signal spectrum as well as the interference spectrum. To properly interpret a difference trace it is necessary to refer back to the characteristics of the reference spectrum. In particular, a difference trace peak may be due to a reference spectrum valley and not to an interference peak in the observed spectrum.

Another measurement pre-processing technique bordered on being a feature extraction method. This involved a routine that estimated the locations of peaks and valleys of a function. The routine worked as follows. It required that the user specify an amount by which a peak should exceed a valley. It would go through a curve from left to right looking for the first peak that exceeded the initial value of the curve by at least D. The first peak was taken to occur at the first local maximum such that the local maximum was both preceded and followed by points D or more below it. Then the first valley was taken to be the first local minimum such that it followed the first peak and was itself followed by a point at least D above it. After the first valley, the second peak was found, and so on. The preprocessing resulted in a list of peaks of the curve, giving locations and amplitude. Here again, interpretation of the results required cross-checking against the reference and measurement spectrum, and so this technique was not a true feature extractor. One refinement of the technique when applying it to the difference of two spectra was to compare the list of difference trace peaks to a list of reference trace valleys. This helped rule out declaring an interference peak where there was in fact no interference peak but only a reference trace valley.

A third preprocessing technique may be termed noise floor fitting. This technique aims at estimating what level of white noise may be present. It is a true feature extractor in that it produces only one or two numbers when applied to power spectrum measurements. It was not used in the final feature extraction only because a different method of curve fitting was found to give superior results.

Figure 3-12 illustrates the effect of white noise on a log scale power spectrum. It is seen that the observed spectrum (top trace) is at each point approximately the larger of the values of the signal spectrum (middle trace) and the flat white noise spectrum. This fact can be used to estimate the white noise level. In noise floor fitting a constant K and a gain G are found such that for (log scale) reference spectrum R(f) and (log scale) observed

Figure 3-12: 3PR-FM Plus White Noise

spectrum O(f), max {G+R(f),K} is the best approximation (in the mean square error sense) to O(f). Provided white noise is the dominant interference effect, this method will give a good estimate of the intensity of the white noise interference.

It should be noted that the goodness of approximation of noise floor fitting depends on the shape of the signal spectrum. In particular, the approximation was better for the 3PR-FM and QPR spectra than is was for the QPSK spectrum. Figure 3-7 (above) illustrates the effect of adding white noise for a log scale spectrum from the Harris modem QPSK signal. The presence of multiple sidelobes in the spectrum makes the noise floor fit less exact. It suggests a different approximation for the effect of white noise on the spectrum. This is that for stretch factor S and position parameter P, for (log scale) reference spectrum R(F) and (log scale) observed spectrum O(f), S·R(f)+P approximates O(f), for appropriate values of S and P. Calculation of optimal S and P parameters in the mean squared error sense is straightforward. S and P were in fact found to be valuable features, and so will be discussed further as SAU features.

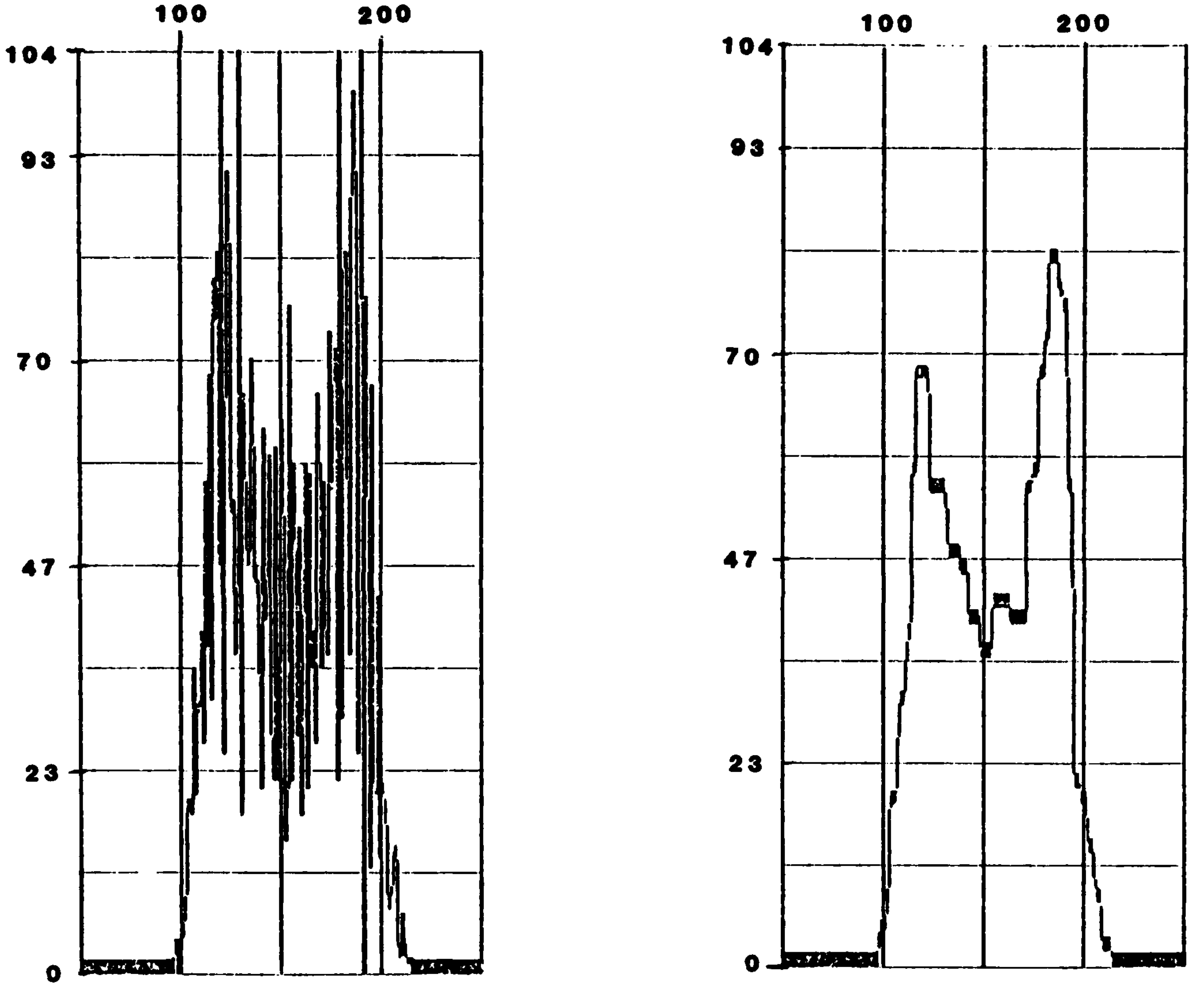
In addition to SAU preprocessing, a method was found for bringing out characteristics of BBM histograms for human observation. This method is known as median filtering. In median filtering a window of odd length n is slid along a data function. A new function is generated such that the value of the new function at a point is given by the median value in the window of length n centered on the point and applied to the old function. An example may clarify this. For window length 3 and function (1,4,2,3,8,7,2), the contents of the first window are 0 (appended to the function), 1, and 4. The median is 1, so the new function starts with value 1. The second window contains (1,4,2) and has median 2. The third window contains (4,2,3), with median 3, and so on. The filtered function that results is (1,2,3,3,7,7,2). The filtered function may be filtered again, in this case resulting in no change.

Figure 3-13 illustrates the value of median filtering applied to a spikey histogram. Part a shows a histogram hump before median filtering, and part b shows the filtered version. In this case three passes with window length nine were done. The median filtering has a dramatic effect in clearing away spikes from the histogram. This histogram resulted from a sine wave. This is a particular case of a general class of histograms, namely those produced by constant envelope interference, which (for AM signal modulation) always produces a U shaped hump. Theoretically it is a $(1-U^2)^{-0.5}$ shaped function for $-1<U<1$. However, the sharp peaks of this function are rounded in practice, producing a rounded and somewhat irregular U shape.

As the figure shows, median filtering can bring out the U-ness of a histogram hump and make it obvious to human observation. It was thus a good candidate to be an aid to feature extraction. However, as discussed below in Section 3.8.4, it turned out that a good estimator of histogram hump U-ness was found which works directly on the (possibly spikey) histograms. Median filtering was thus found not to be necessary for machine extraction of features, even though it may be a valuable aid to human analysis of histograms.

3.8.3 Spectrum Analyzer Features

The first spectrum analyzer unit (SAU) feature tried was a refinement to the peaks finding routine described in Section 3.8.2. In this refinement the width of a peak was found, that is, how far to each side of the peak is the first point a fixed number of dB below it. That is, for threshold T dB, the algorithm finds the two points closest to a peak that are T or more dB below it. Then the distance between the two points so found is taken to be the T dB width of the peak, also known as the T dB bandwidth of the peak. This width-of-peak feature turned out to be of limited usefulness. For one thing, when applied to a signal plus interference trace it does not distinguish between peaks due to the signal and peaks due to the interference. When applied to the difference trace (difference of newly observed spectrum versus reference



a) HISTOGRAM OF SINE WAVE

b) HISTOGRAM AFTER 3 PASSES
DEDIAN FILTER, LENGTH 9

Figure 3-13: Effect of Medu Median Filtering on Histogram spectrum) it does not distinguish peaks due to interference peaks from peaks due to reference valleys. Figure 3-14 illustrates another problem. Here white noise pulsed with a 50 percent duty cycle has resulted in a very large number of spectrum peaks, visible in the photograph as shaded areas. For a spectrum such as this the peak finder routine finds a very large number of peaks, most having very narrow bandwidths. Thus the peak finder and bandwidth estimator often do not simplify the measurements. Wide bandwidth peaks may be due to signal or interference, while narrow bandwidth peaks may be present in large numbers.

Another SAU candidate feature was aimed at (and succeeded in) overcoming these difficulties. This was the use of template matching to find spikes in the received spectrum. Since the signal spectrum does not normally have spikes, any spikes found can be ascribed to the interference. By use of guard bands in the template, closely packed spikes (which may be termed spectral shading) may be rejected. The spike template matching algorithm operates as follows. The computer attempts to set a spike template on top of a spectrum in such a way that the spectrum touches the center point of the template, but falls below all other points. Wherever this turns out to be possible, a success is declared and a spike is considered located. A refinement of this technique is that after a spike is located the template may be stretched until both the center point and at least one other point of the template touch the spectrum, but at no point of the template does the spectrum exceed the template.

An example will illustrate how the technique works. Suppose the template is (0,0,4,5,4,0,0) and the spectrum is (1,2,3,3,10,6,3,2,1). The first attempted fit is with the template at the left of the spectrum. The smallest constant is found such that the template plus the constant rests on the spectrum. In this case the constant is 6, because (6,6,10,11,10,6,6) just rests atop (1,2,3,3,10,6,3). No spike is found here, because the template plus constant does not touch the spectrum at the center point of the template. The second attempted fit is with the template one point from the left into the

ECM SIGNAL MEASUREMENTS REPORT

WRITTEN BY: B DICK

DATE|TIME: 25-AUG-82 | 16:09:32

SETUP FILE: SETH.DAT

DATA FILE: QPPWN1.DAT

SIGNAL TYPE: QPSK

INTERFERENCE TYPE: PULSED WHITE NOISE

REMARKS

PULSE REP RATE 1 KHZ, DUTY FACTOR 50 PERCENT

25 MHZ BANDWIDTH DOWN 15 DB

INTERFERENCE MODULATION PARAMETERS:

POWER LEVELS: dbm|mw

SIGNAL:
-7.5 DBM, .18 MW

INTERFERENCE:
-14.1 DBM, 39 UW

INTERFERENCE
+SIGNAL:
-6.5 DBM, .227 MW

BIT ERROR RATE:
5.7 E-4

3PR ERROR RATE:
NA

DATA RATE:
8 MBPS

DATA COLLECTED ON

25-AUG-82 / 15:57:54

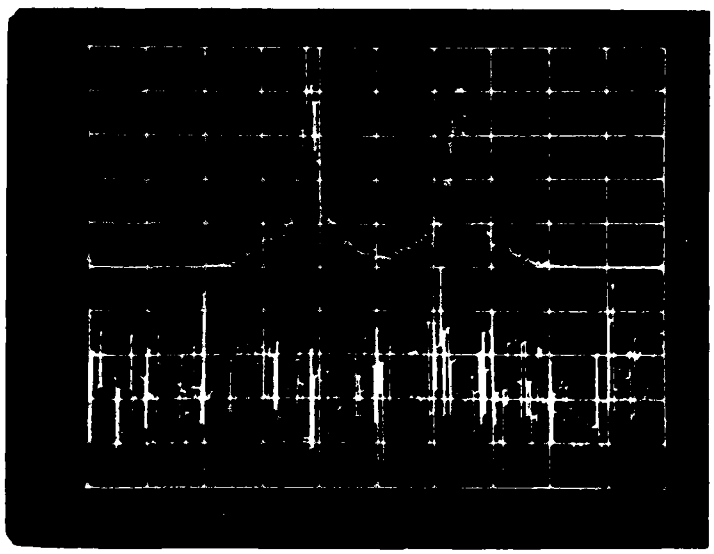


Figure 3-14:

QPSK Plus Pulsed

White Noise

spectrum. The constant needed is 5, giving template plus constant of (5,5,9,10,9,5,5) versus spectrum section of (2,3,3,10,6,3,2) with the difference of (3,2,6,0,4,2,3). Here a spike is detected, because the template plus constant touches the spectrum at the center point of the template. It turns out that the template many be stretched by a factor of 1.4 and still fit. That is, constant 3 plus stretched template (0,0,5.6,7,5.6,0,0) just fits atop (2,3,3,10,6,3,2) leaving a difference of (1,0,5.6,0,2.6,0,1). Note the presence of multiple zero values in the difference. Continuing the slide of the template along the spectrum, no other spikes are found. The result is that one spike is found located at position 5 of the spectrum and with amplitude 1.4 versus the spike template. Note that with this example template, spikes located closer together than 4 points apart will tend to mullify each other. For example, for spectrum (1,2,3,10,4,3,8,3,2,2), the template matching finds no spikes. This is an intentional feature of the template matching.

The SAU fits all its power spectra within the limits of 0 to 1024 over a range of 1001 points. It was determined experimentally that a good template for SAU power spectra was a 17 entry vector of (5*0,25,5*50,25,5*0), where 5*0 represents 5 entries of value 0 and 5*50 represents 5 entries of value 50. This detects isolated spikes of height one half division or more on the ten division vertical scale. The spikes must be separated by at least 0.08 of one division on the ten division horizontal scale. Further, each spike detected could have width at most 0.07 horizontal division at height down one half vertical division from its peak value.

The spike template generally was most effective with the linear scale time averaged Spectrum 2 (also known as the Narrow Span Mode). It generally picked out the spikes due to CW, tone AM, and tone FM. It seldom picked out a spike in Spectrum 1 if the spike was located within the main lobe of the signal spectrum. However, it could pick out spikes in Spectrum 1 if they were very large in amplitude, or if they fell where the signal spectrum was low in amplitude. Because Spectrum 3 was designed to have a very large resolution bandwidth, a tone in the signal would result in a spectrum hump, not a spike. Consequently, the spike template was not used with Spectrum 3.

Another SAU feature extraction algorithm that turned out to work well was the use of gain plus offset to make the best fit in the mean square error sense between a reference spectrum and an observed spectrum. The gain, offset, and goodness of fit all turned out to be useful features. Theoretically the gain plus offset fit applies exactly to a linear scale spectrum (such as Spectrum 2) when the signal is perturbed only be additive white noise. In practice the gain plus offset fit worked well for log scale spectra also.

The mathematics of the gain plus offset fit is as follows. For reference spectrum r(f) and received spectrum g(f), let E denote the average value operator. That is, Er denotes average value of r(f) averaged over all f, Erg denotes the average value of r(f) times g(f) over all f, and so on. Let a denote the gain to be applied to r(f) and b denote the offset value to be added to it. Then a*r(f)+b should be as good a fit as possible to g(f). In particular, it should minimize $E(g-ar-b)^2$. The optimal a and b are easily found by basic calculus. They are

$$a = (Erg-ErEg)/(Er^2 - (Er)^2)$$

and

$$b = (Er^2Eg - ErgEr)/(Er^2 - (Er)^2)$$

The interpretation of a and b are that a estimates how much signal fading has taken place, while b estimates how much white noise has been added. In addition the quantity

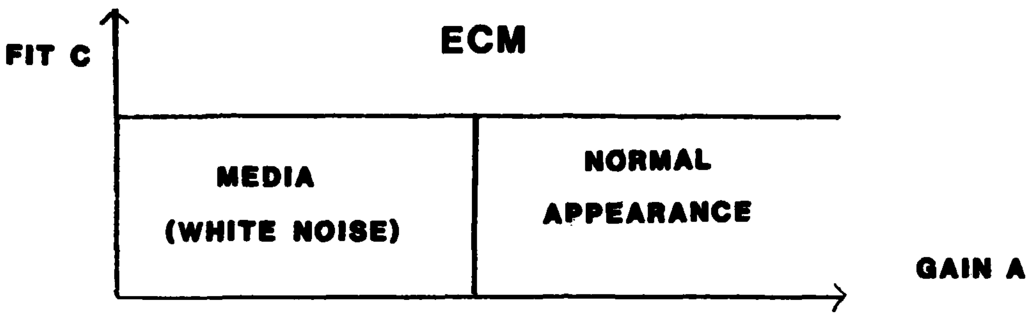
$$c = E(g-ar-b)^2$$

is an estimate of how well the data confirms the hypothesis that only fading and white noise have corrupted the signal. The smaller is c the more likely it is that the facts fit the hypothesis.

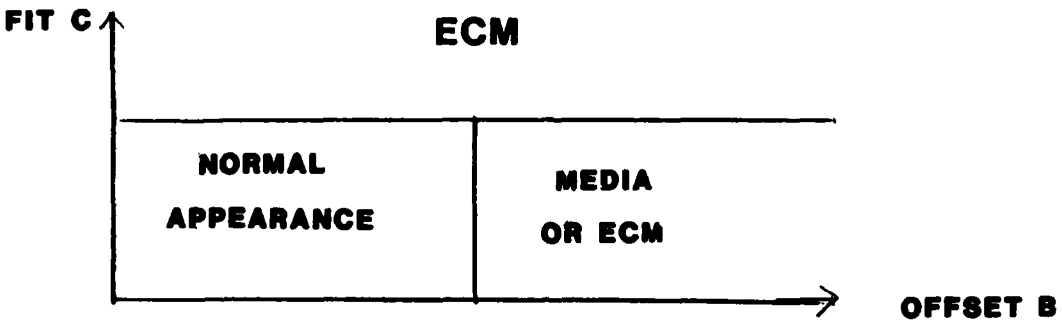
While the gain plus offset fit theoretically applies only to a linear scale spectrum, in fact it was found that it extracts features well for log scale spectra as well. Figure 3-15 illustrates how the gain a, offset b, and fit c may be used to divide up the space of all possible power spectra into decision regions. This way of classifying was arrived at by plotting the results for 25 diverse cases of noise and interference as they perturbed QPSK power spectra. For all spectra it turned out that very poor goodness of fit c was caused only by interference (in the figure ECM stands for any kind of interference, including RFI). Further, for the log scale Spectrum 1 a low value of gain (a) occurred only for white noise. (Note that fading would result in vertical displacement of a log scale spectrum, not in shrinking it). For the log scale Spectrum 3 a low gain occurred only for white noise, pulsed white noise, and swept CW.

The first classification logic (Logic I) made extensive use of the gain plus offset classes to classify the various types of interference. This is described in Appendix B. However, the classification turned out to be sensitive to variations in interference parameters, and not just to interference classes. This is why Logic I was not used in the software delivered with the ESIM system. Under Logic II the gain plus offset features were used to determine whether or not all three SAU spectra had a normal appearance.

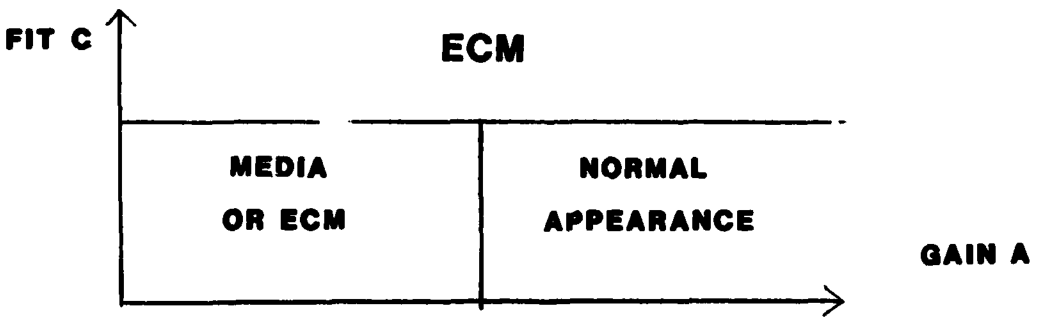
Another SAU candidate feature was termed the interference basis estimator. This was used in an attempt to quantify what fraction of the signal spectrum was submerged under the interference spectrum. One would expect a very low fraction when tonal interference such as CW was present and a large fraction when broadband interference was present. The feature was calculated immediately after the gain plus offset. It consisted of counting how many points of the observed spectrum were above the modified reference spectrum. In practice this feature turned out to be uninformative. Minor random variations in the spectra had a strong influence on this feature, so that this feature estimated that interference dominated 50 percent of the



A) SPECTRUM 1 CLASSIFICATION



B) SPECTRUM 2 CLASSIFICATION



C) SPECTRUM 3 CLASSIFICATION

FIGURE 3-15
USE OF GAIN AND OFFSET FIT
TO CLASSIFY INTERFERENCE

spectrum in nearly all cases. Consequently this interference basis feature was eliminated from consideration.

3.8.4 Baseband Monitor Features

One of the first baseband monitor (BBM) features tried is known as the U-ness estimator. It turned out to be quite successful and was used in both Logic I and Logic II. The aim of the U-ness estimator is to quantify the degree of concavity of a histogram hump. At first it was thought that concavity estimation would require preprocessing, such as median filtering. However, it turned out that the U-ness estimator worked well without any preprocessing.

The U-ness calculation proceeds as follows. Thresholds are set at fixed percentiles into a histogram hump. The distance between the thresholds is measured, and the zeroth, first and second moments of the hump as truncated by the thresholds are computed. These are used to compute the normalized second central moment. That is, for L and M the two thresholds, the zeroth, first and second moments (Z,F, and S respectively) are given by

$$Z = \sum_{i=L}^{M} H(i)$$

$$F = \sum_{i=L}^{M} H(i)*i$$

$$S = \sum_{i=L}^{M} H(i)*i^2$$

where H(i) is the observed histogram at point i. Then the normalized second central moment V is give by $V = (S-F^2/Z)/Z$. Finally, the U-ness estimate U is give by

$$U = \sqrt{12V/(M-L)}.$$

This has the property that the U-ness of a rectangle is 1. The maximum possible U-ness is obtained for a distribution large at L and M and zero in between. This maximum value is the square root of three. The lower bound to the value of U is zero.

The U-ness was computed for histograms obtained from a variety of distributions. It was found that truncation percentiles of 10 and 90 percent worked well. Using these truncations the U-ness estimator was found to agree well with human observation. That is, U values of 1 or more indicated a concave histogram hump, while U values less than 1 indicated a convex hump. In addition, it was found that U values of less than 0.8 indicated some kind of envelope modulation of the interference, particularly AM with a large modulation index or pulsing with a pulse duty cycle greater than 20 percent. Previous Figures give examples of histograms in the three ranges of U-ness. Figures 3-8, 3-7, and 3-14 show high, medium, and low U-ness respectively.

A second baseband feature aimed at estimating the spread of the BBM histograms. Given a threshold, it counted how many histogram bins between two nominal signal levels exceeded the threshold. This histogram spread feature was found to be a useful measure of interference severity. However, another technique, termed pseudo error counting, turned out to be more useful. Consequently, the histogram spread measure was not used.

A third baseband feature, termed pseudo error counting, turned out to be quite useful and played a significant role in both Logic I and Logic II. This feature was also sometimes termed pseudo hit counting. The principle of operation is as follows. A pseudo error is a received value that falls near a decision level in the demodulator. A received value falling near a decision level may or may not represent an error in transmission. However, it is very close to being an error in transmission, even it is not actually an error. That is to say, the interference amplitude for such a received value either exceeds the amplitude required for error or is very slightly below it. In particular, we may speak of a one dB pseudo error as representing a received value that is either an error already or else is within one dB of being an error. Specifically this is a received value representing interference that were it a ratio of 1.122 or more larger in amplitude it would have to result in an error. Similarly for a 2 dB pseudo error and and amplitude ratio of 1.259.

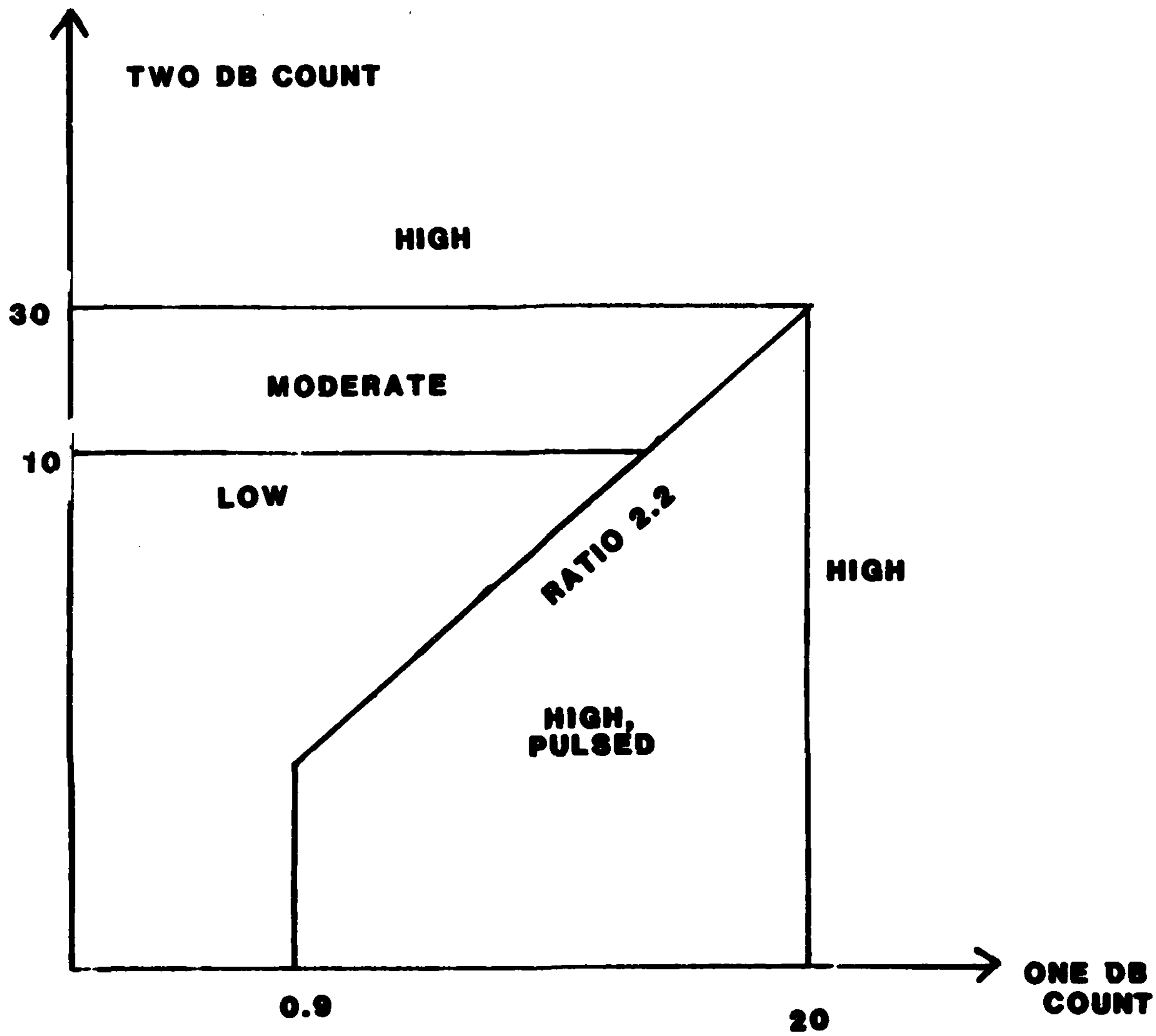
A one dB pseudo error thus represents either an actual error or something very close to being an error. This provides a quantitative justification for using the one dB pseudo error count as a measure of interference severity. When the one dB error count is high it is clear that the interference is severe, or at least on a thin borderline of being severe. Similarly to a lesser degree for the two dB pseudo error count.

The one and two dB error counts were plotted for a variety of noise and interference conditions. It was found that various degrees of interference danger could be characterized in the two dimensional space having the logarithms of the one and two dB hit counts as its coordinates. Figure 3-16 illustrates this result. The two dB pseudo error count was found to be good at estimating the severity of continuous interference. However, pulsed interference complicates the situation. Pulsed interference with a low pseudo-error count could produce quite a severe error rate. It was found that the ratio of the one and two dB count successfully separated the pulsed from the non-pulsed cases. The ratio of 2.2 formed the boundary. The explanation for this is that for pulsed interference the ratio of the pseudo error counts will be only slightly greater than the ratio of the lengths of the pseudo error regions, which is 1.89.

The difference between the pulsed and non pulsed cases turned out to be small. One modification which improved classification performance was to allow the two dB interval to slide over a limited range, with the final interval selected to be the one that produced the minimum count. The one dB range was then taken to be at the center of the selected two dB range.

3.9 CLASSIFICATION LOGIC

The development of the classification logic proceeded along with the development of the feature extraction. This is because the purpose of feature extraction is to aid the classification, and the value of a feature rests in the classification results which it enables. Some automated decision making



SCALE: COUNT PER THOUSAND RECEIVED VALUES

FIGURE 3-16

ESTIMATED DANGER GIVEN PSEUDO ERROR COUNTS has been presented in Section 3.8. Additional decision making resulting in a preliminary version of classification logic (Logic I) is described in Appendix B. Here we will describe the workings of the final logic (Logic II).

Figure 3-17 provides a summary of the logic in pseudo-code. The logic is organized along the lines of increasingly specific decision making. Its first decision is whether the interference is tonal or noiselike. The term tonal means that the interference has one or more spikes in its power spectrum. The term noiselike indicates that there are no spikes in the interference power spectrum visible to the spectrum analyzer unit (SAU). Given that one or more tones are detected, the interference is further classified by the number of tones found. One tone indicates CW interference, two or three tones indicate the single class of (tone modulated) AM/NBFM, while four or more spikes indicate (tone modulated) WBFM (wideband frequency modulation).

Given that no tones are detected (and hence the class Noiselike is decided), the one and two dB pseudo error counts are checked. If they are both very low, and if the SAU gain plus offset fits are all good, then the class Baseline is decided. If not, a class is assigned based on the U-ness of the histogram humps. High U-ness (greater than one) indicates constant envelope interference, such as multipath, or PSK or FM with bandwidth falling within the receiver bandwidth. Medium U-ness indicates bell-shaped curves in the histogram humps. This indicates Gaussian interference or wideband interferences such that only part of the interference bandwidth falls within the receiver bandwidth. Low U-ness (below 0.8) indicates strong envelope modulation of the interference, hence AM or pulsing.

Regardless of whether tones in the interference are detected, pulsing is tested for using the one and two dB pseudo error counts. If they are both moderate and if the two dB count is less than 2.2 times the one dB count, then pulsing of the interference is declared and the danger level is declared high.

Figure 3-17: Final Classification Logic in Pseudo-Code

```
ENTRY
IF (SPIKES IN SAU SPECTRA) TONAL
ELSE NOISELIKE
END IF
IF (TONAL)
   IF (ONE SPIKE) CW
   IF (TWO OR THREE SPIKES) AM/NBFM
   IF (FOUR OR MORE SPIKES) WBFM
END IF
IF (NOISELIKE)
   IF (PSEUDOERRORS FEW.AND. SPECTRA FIT) BASELINE
   ELSE
     IF (U-NESS HIGH) CONSTANT ENVELOPE
     IF (U-NESS MEDIUM) WIDEBAND/GAUSSIAN
     IF (U-NESS LOW) PULSED/AM
   END IF
END IF
IF (PSEUDOERRORS MODERATE WITH LOW RATIO) PULSED, DANGER HIGH
ELSE
   IF (QPSK)
        DANGER LEVEL SET BY PSEUDOERROR COUNTS
        IF (DANGER LOW.AND.HIT COUNT HIGH) DANGER MEDIUM
   ELSE DANGER LEVEL SET BY 3PR FORMAT VIOLATION COUNT
   END IF
END IF
IF (DANGER HIGH) TYPE ECM
ELSE
   IF (TONAL.OR.PULSED/AM) TYPE RFI
   ELSE TYPE MEDIA
END IF

EXIT
```

Figure 3-17

For QPSK which is not considered pulsed the danger level is set by the pseudo error counts, except that a high hit count will change a low danger level to moderate. For QPR and 3PR-FM the 3PR format violation count is an excellent estimator of the actual bit error rate occurring. Therefore this count is used to set the severity estimate.

Identification of Media, RFI, and ECM conditions is done primarily by danger level. Interference which is identified as producing a high danger level is declared to be ECM. Interference identified as producing a low or medium danger level is identified as Media or RFI, depending on the class. Constant envelope interference can be caused by multipath. Bell shaped histogram humps can result from fading in the presence of white noise. Consequently, the wideband/Gaussian and the Constant Envelope classes are identified as Media. Other interference classes producing low to moderate danger levels are identified as RFI.

The final logic was arrived at after a more specific logic (Logic I) was found to be sensitive to interferences parameters. It is apparent from human observation of the data collected that there is as yet untapped potential in the ESIM system. Further logic development is likely to produce improved results.

3.10 RECOMMENDATIONS FOR FUTURE ALGORITHM DEVELOPMENT

As previous sections have shown, the ESIM hardware and software system contains potential which has not yet been fully realized in the classification algorithms developed to date. The spectrum analyzer unit (SAU) is a sophisticated device capable of gathering data under a wide range of settings. The baseband monitor (BBM) can obtain a variety of measurements including data sample histograms, decision feedback power spectra (DFS), and hit counts. The histograms are especially valuable for estimating the severity of non-pulsed interference, while the hit counts are good for catching low duty cycle pulsing. The histograms also are useful for a limited amount of classification, distinguishing constant envelope from wideband or Gaussian interference, and distinguishing both these classes from high index AM or high duty cycle pulsing. The DFS shows potential, however its use is not straightforward due to low level background noise complicating the no-interference spectrum. Additional valuable measurements include radio alarms, with the 3PR format violation alarm being especially useful, and the radio received signal level (RSL).

The ESIM software has proved itself valuable for collecting, organizing, and reporting on ESIM measurements. The software can be used in part to collect measurements and store them in a machine readable set of disk files for later use. The software can also produce human readable reports summarizing the machine readable measurements. The software provides a framework for supporting feature extraction and interference classification logic. The use of disk files along with program modularity allows effective use of the computer's limited memory.

The feature extraction and pattern classification algorithms developed to date demonstrate some of the promise of the ESIM system. They give information about interference effects which would otherwise not be available. At the same time, they fall short of what a human observer is capable of inferring, given a look at the ESIM system measurements. Thus, while the existing system and its algorithms show promise, there is room for improvement, and evidence that improvement is possible.

There are three distinct but interrelated problems which future ESIM algorithms should address. These are the problems of first estimating interference severity, second deciding what class of interference is occurring, and third deciding whether or not the particular case of interference has appeared previously and been identified as unintentional interference (RFI). We will discuss each of these in turn.

Estimating interference severity is now a solved problem, given that it is known that the interference is steady state, that is, that the interference is not pulsed and does not sweep in and out of the receiver passband. This restricted problem has been solved by the present effort with its design, implementation, and use of the baseband monitor (BBM) and its histogram technique. However, interference need not be steady state, it may be time varying. Pulsing with a duty cycle of 10 percent or more is handled well by existing algorithms through use of the histogram. Pulsing with very low duty cycle may best be handled through use of the hit counter. In particular, a clear histogram but a high hit count indicates trouble. Current algorithms are somewhat error prone in that they tend to confuse a moderate level of steady state interference with a high level of low duty cycle pulsed interference. The difference is usually clear to a human observer of the histogram, so further feature development is likely to clear up this problem.

Deciding what class of interference is occurring is a more difficult problem. Even the definition of the problem may need some reworking. This is particularly illustrated by the present system's use of a "Wideband/Gaussian" class. The point behind this class is that a band limited section of a wideband constant envelope interference does not have a constant envelope. Possession of a constant envelope is not at all visible in the power spectra, but only in the baseband histogram, and this histogram is taken after the receiver filtering. Consequently some redefinition of the classes to be distinguished is required. For example, large bandwidth noise modulated FM cannot be distinguished from large bandwidth Gaussian noise.

The questions to keep in mind while establishing classes of interference are first (for the present) what kind of system could have generated the interference (the ECM), e.g. how sophisticated is it, and second (for the future) what radio counter-interference measures (ECCM) should be employed to negate the interference. The second question is more important in the long run, and for it the behavior of the interference within the signal passband is critical. If, for example, the interference is not constant envelope within the signal passband, that is a useful thing to know, even though the interference before filtering may be constant envelope. Thus some of the ESIM system's answers may be more useful than the answers that are theoretically right.

Deciding the class of interference also is rendered more difficult by signal masking of the interference, and by the wide variety of parameters and variations the interference can assume. The important question here is how to make the computer classify as well as a human can do, given the measurements.

Identifying a case of interference as one having been previously designated RFI is probably the most difficult decision problem. It requires analyzing the characteristics of an interference case finely enough to distinguish it from almost all distinct interferences, but not so finely that minor variations render it unrecognizable. In particular, the signal to interference ratio (SIR) should be variable over at least a limited range without negating recognition. This problem is mostly as yet unexplored, because it requires a finer and more accurate discrimination than does the problem of interference classification, and thus is approachable only after the problem of interference classification has been resolved.

The solution of each of the three ESIM algorithm problems should proceed along similar lines. Each should be handled with a five stage process that may be gone through not just once but several times. The steps are:

1. Collect design data base of measurements

2. Devise human-implemented algorithms for classifying

3. Devise features

4. Devise computer-implemented classification

5. Test the classification on both the design data base and new measurements

Iterating this procedure several times for each of the three decision problems should result in a logic that is robust, specific, and accurate.

3.11 REFERENCES

1. Honeywell Inc., "Digital Automated Technical Control (DATEC) Field Test and Evaluation of Baseband Eye Monitor," Honeywell Final Report, July 1980.

2. A. V. Oppenhein, R. W. Schafer, Digital Signal Processing, 1975, Prentice-Hall, Englewood Cliffs, New Jersey.

4. CONCLUSIONS AND RECOMMENDATIONS

This section outlines several areas for further research.

The ECM detection and identification techniques developed under this effort are based on a limited sample of data collected during the course of the effort. Although an extensive data collection was undertaken at the start of the program, the nonexistence of the ESIM hardware at that time did not permit storage of raw data. Thus the data base consists mainly of scope photographs. The ESIM hardware configuration now permits much more flexibility in terms of data collection and even permits storage of the raw baseband data. Upon completion of the ESIM hardware, additional data were collected. It is primarily from this data that the logic was developed however. Due to time and funding constraints, the data base is rather limited in scope. Although the logic developed is fairly robust, it is difficult to predict its performance in a realistic electromagnetic (EM) environment. In light of the above, the following is recommended:

- Additional data collection, analysis and algorithm refinement using DICEF facilities.

- Extensive test and evaluation with a DRAMA radio when available.

- Test and evaluation in a realistic EM environment, e.q. Fort Huachuca, overseas DEB site.

Although the thrust of the effort was placed on developing an automatic ECM detection and identification capability, the system can also be used as a performance monitor for links not subject to jamming as well. The baseband measurements produced by ESIM can be used to provide a measure of signal to noise ratio, phase jitter and harmonic distortion as well as provide estimates of error rate. Unlike other pseudo error rate monitors, which assume gaussian noise statistics, the ESIM estimates the noise statistics and thus can provide a more accurate estimate of bit error rate. The ESIM can also be a useful test bed for evaluating proposed performance monitoring techniques as well. Recommended work in this area includes:

- Controlled collection and analysis of degraded radio equipment using the DICEF facilities.

- Evaluation of candidate performance monitoring techniques on the collected data.

- Field test and evaluation of the best technique(s).

The emphasis of the current program was placed on Line-of-Sight (LOS) microwave links. Extension to TROPO and Satellite links is possible but would require additional data collection, analysis and algorithm refinement due to the differences in propagation effects. Recommended work in this area includes:

- Controlled data collection and analysis using the RADC lab and field test sites and TROPO simulators

- Refinement of algorithms, test and evaluation at RADC and other field sites.

The ECCM radio of the future will most likely have the capability to reconfigure itself based on the current ECM environment (e.g. DCS ECCM Radio, TROPO ECCM MODEM, VHSIC Reconfigurable Modem). The ESIM environmental monitoring capability could provide an assessment of the interference environment for the radio. The computer based ESIM capability could be interfaced to a reconfigurable radio to not only provide a measure of interference but also to control the radio in laboratory experiments. Recommended work in this area includes:

- Determining optimal ECCM for various interference types using the Interactive Communications Simulator (ICS)

- Interfacing a multimode ECCM modem such as the ECCM TROPO modem to ESIM.

- Controlled data collection, analysis, test and evaluation using DICEF LOS, TROPO and ECM simulators.

Although the ESIM configuration which consists of two racks of laboratory measurement equipment provides much flexibility as a laboratory tool, its operational use in the field may be prohibitive because of its size and cost. Analysis has indicated that the basic signal processing required for environmental monitoring can be implemented into a microprocessor based radio applique. Recommended work in this area includes:

- Design of a microprocessor based radio applique which incorporates the ESIM and possibly other performance assessment algorithms.

- Fabrication, Test and Evaluation using DICEF facilities.

- Field test, evaluation and demonstration of its utility to the operational community.

A. ESIM SYSTEM SPECIFICATIONS

The following specifications reflect minimum performance standards for the ESIM system.

ESIM is a hybrid, hardware/software, system. These two areas will be treated as one in regards to specifications thus presented.

A.1 SYSTEM OPERATING SPECIFICATIONS

Input Parameters

IF Input:	Impedence	50-78 ohms
	Level	0.5 vp.p nominal into 50 ohms
	Channels	8 radios maximum or 4 radios each having two channels
	Frequency	70 MHz
BB Input:	Impedance	50-78 ohms
	Level	1 v p-p maximum
	Channels	8 radios maximum or 4 radios each having two channels
	Frequency	(data rate) 1-13.25 Mhz
	Ext Clock Input	TTL Positive true
Alarm:	Total of	16 interrupt lines
	3 per radio	latch input; 12 total
	1 per radio	state changes low-high, high-low 4 total
	1 error counter	switches to 1 of 4 radios; counts in-going pulses for a programmed time period.

A.1.1 Command Mode Selection

Help - Lists command modes

ESIM - Starts Automatic Mode

Hardcopy - ESIM Status printout

Exit - Returns to RT-11

Set up - Parameter setup

Manual - operator selects radio

Poll - Automatic cycle through radio

Poll/Interrupt - radio selection through interrupt from radio alarm

A.1.2 Output Processing

Display Panel	Radio Status;	on/off line
	Frame Sync Loss;	yes, no
	Interference type media,	RFI, ECM
	Danger to communication disruption;	low, med, high
CRT Display	Radio parameters	
	Radio Status on/off line	
	Modulation type	
	Bit Rate	
	ESIM parameter	
	Interference Status	
	Interference type	
	Danger level	

- Hard copy can be obtained for above CRT display, (Figure 3-1)

- CRT display can be routed to remote terminal

A.1.3 ECM Interference Type

- Baseline
- AM Tone
- Repeat Jamming
- Wideband noise
- Bandlimited nose
- FM Tone Wideband
- FM Tone Narrowband
- FM Noise Wideband
- FM Noise Narrowband
- Swept CW
- PSK
- CW
- Pulsed versions of the above
- Repeat jamming

A.2 ELECTRICAL

A.2.1 Primary Power

115-125 VAC single phase 60Hz

A.2.2 Current

19 amps peak start up

15 amps average running

A dedicated 20 amp minimum circuit should be provided for ESIM. The term dedicated circuit is defined as that which is supporting no other equipment and whose source is free from high current transient producing devices such as welders, compressors, etc.

A.2.3 Secondary Power (DC)

Each ESIM subassembly contains internal power supplies for generating voltages. An exclusion exists in the IF couplers C1A3 which provides +24 vdc to the BB couplers C1A4. The interconnecting cable is designated as C1A3 P2 to C1A4 P2.

Secondary voltages used are: +25 vdc, +/- 15 vdc, +5 vdc, -5.2 vdc.

A.2.4 Grounding

All ESIM subassembly power supply ground leads are connected to the chassis. Each chassis is in turn grounded to the rack. Grounds terminate at the power distribution assembly C1A10 where a ground cable can be connected and attached to the site ground bus.

A.1.3 ECM Interference Type

- Baseline
- AM Tone
- Repeat Jamming
- Wideband noise
- Bandlimited nose
- FM Tone Wideband
- FM Tone Narrowband
- FM Noise Wideband
- FM Noise Narrowband
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A.3 MECHANICAL

A.3.1 Size

Overall size (with protrusions) length 47" height 70 1/2" depth 48".

A.3.2 Volume (less table)

Cabinets C1 and C2	56.4 cu. ft.
Cabinet C3	15. 56 cu. ft.
Total	71. 96 cu. ft.

A.3.3 Weight

Cabinets C1 and C2	est. 650#
Cabinets C3	est. 225#
Total	875#

A.4 ENVIRONMENTAL

A.4.1 Ambient temperature range

Operating +55°F to +89°F
Storage 0°F to +150°F

A.4.2 Relative Humidity

Operating 10-90% with maximum wet bulb temperature 82°F and minimum dew point 36°F

Storage 10 to 95% non-condensing

A.4.3 Heat Dissipation

6115 BTU/Hr. max. (based on 1800 watts)

A.4.4 General

The ESIM system should be operated in a computer type environment. This includes relatively dust free conditions and minimal ambient temperature changes.

Appendix B: Preliminary Version of the Classification Logic

An initial version of a classification logic was developed based upon measurement collection runs with a variety of interference conditions imposed upon a QPSK signal. This version used a number of preliminary classification based on features which were known to discriminate various classes of interference. The features used were (see sections 3.8.3 and 3.8.4):

a. The U-ness test

b. The SAU spectra spike template matching

c. SAU Spectrum 1 gain plus offset matching

d. SAU Spectrum 2 gain plus offset matching

e. SAU Spectrum 3 gain plus offset matching

f. One and two dB pseudo error counts

For each feature the range of possible values was divided into preliminary decision regions, and a vector of preliminary decision results was determined for each measurement run in the data base. The result was a table which gave a unique signature for each class in the data base, except that FM noise was not distinguished from PSK. The Baseline, White Noise, and Multipath classes were declared to be Media, with all other classes designated as ECM. It was left to a later date to distinguish RFI from ECM by means of a library of features files representing operator identified cases. The severity of interference was decided by use of the one and two dB pseudo error counts.

The preliminary logic worked very well on the data base of measurements upon which it was designed. However, when it was tested on a variety of new interference parameters, most of the time the new vector of preliminary classification failed to match any of the sample vectors stored in the data base. Thus the preliminary logic was insufficiently robust and so was greatly revised to produce the final logic.

END