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Consistent Approach to Describing Aircraft HIRF Protection

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FOREWORD

This document constitutes the final report of the Fly-By-Light/Power-By-Wire (FBL/PBW) Integrated Requirements Analysis and Preliminary Design study, contract NAS1-19360, Task 52.

The NASA technical representative for this task was Charles W. Meissner, Jr.

The work was accomplished by Avionics/Flight Systems personnel of the Boeing Commercial Airplane Group.

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LIST OF SYMBOLS

SYMBOL	MEANING
<A>	Average antenna effective area
c	Speed of light
D	Antenna directivity
dBm	10 $\log_{10}$ [watts/mW]
e	Exponential
GHz	Gigahertz
ln	Natural logarithm
m	Antenna calibration factor
MHz	Megahertz
p	Power loss
p	Antenna polarization mismatch factor
$\underline{p}$	Average power loss
P_D	Power density
P_r	Antenna received power
P_T	Antenna net transmitted energy
q	Antenna impedance mismatch factor
sqrt	Square root
<U>	Average energy density

SYMBOL	MEANING
VSWR	Voltage Standing Wave Ratio
β	$10/\ln 10 = 4.343...$
γ	Euler's constant = 0.57721...
λ	Free space wavelength
π	Pi = 3.14159...
ρ	Reflection coefficient
η	Antenna efficiency

1.0 SUMMARY

HIRF related incidents on commercial transport airplanes are in contrast with HIRF requirements being proposed by regulatory agencies. This is the result of the inconsistent combination of factors that are used to describe aircraft HIRF protection. These factors include the external HIRF environment, the external to internal airframe attenuation, the internal RF field description, and equipment susceptibility or qualification levels and waveforms. An effort to describe and resolve these inconsistencies has been performed as Task 52 under NASA contract NAS1-19360.

Prior to assessing each of these factors, the overall HIRF certification process for critical flight equipment and systems as described in the section 8 of the draft HIRF Users Manual is compared with the certification process as completed by an airplane manufacturer. Notable differences make aspects of the ideal viewpoint incompatible with the realistic route to compliance. Idealized certification develops as a linear process and incorporates a recursive loop at the end of a program to incorporate corrective measures for possibly non-compliant equipment and systems. The realistic route to compliance develops as a set of parallel processes during the life of a new airplane program, and recursive corrective sequences are avoided because of the cost and delay they incur. Negotiations and cooperative efforts among suppliers, airframe manufacturers, and regulatory agencies are actively conducted by various liaisons to expedite equipment qualification. Incorporation of aspects of the realistic process into the idealized process is recommended.

The means of arriving at an external environment definition is based on a worst case scenario outlook tending to drive requirements to impractical levels. Alternative approaches to assessing the environment including the details of transmitter antenna and airplane approach geometry coupled with probability models may provide a more realistic evaluation of the threat.

Determining aircraft attenuation to HIRF and the properties of the internal environment requires both analytical and test methods currently applied to aircraft coupling and the internal environment. No currently available single test method or analytical tool is practical or applicable over the full HIRF threat frequency spectrum. Regarding modeling techniques, deterministic methodologies are important in the lower frequency range, e.g. below 200 MHz, whereas statistical models are more appropriate at higher frequencies where field variability obviates a deterministic approach.

Test methods similarly must be regarded as dependent upon sensor location and the frequency range of applicability. It is suggested that mode-stirring and wide band gaussian noise methods are suitable above 400 MHz and in many airframe cavities; however, the conventional low level swept frequency techniques are applicable at lower frequencies and/or constricted geometries.

It is recommended that statistical methods be used to assess the highly variable cavity fields and to correlate frequency and spatial averaging procedures at higher frequencies. These techniques are essential for the interpretation of mode-stirred and swept frequency data bases.

The final section focuses on equipment susceptibility test methods and the analytical and test methodologies used to probe the airplane internal fields. Bench level tests

begin early in an airplane program when requirements are initially set. System level tests tend to be expensive and performed late in an airplane program on integrated qualified components. As such they are for the present time considered to be of lower priority to bench level equipment tests.

Modeling of screen room and of airframe internal fields remains rudimentary. Statistical and mode-stirred approaches can in principle be designed to incorporate similarity concepts relating the screen room test environment to aircraft internal fields. Antenna correction factors determined from field measurements for these environments indicate that the sensor response to the internal fields in complex airframe cavities tends to be isotropic at the higher frequencies, an empirically validated conclusion.

Instituting the conclusions and recommendations proposed in this document to the modification of current certification processes will do much to provide a more consistent approach than presently exists.

2.0 INTRODUCTION

Evaluating commercial transport aircraft response to high intensity radiated fields (HIRF) has become an issue of importance with the advent of aircraft comprised of composite/plastic material structures and electrically controlled critical flight systems and components. Methodologies for assessing aircraft vulnerability to HIRF have had an impact on the certification process. Nonetheless, the HIRF compliance process development has also incorporated elements based on historical and other non-technical criteria that have heretofore lead to a certification process tending to be burdensome to the airplane manufacturer, technically inaccessible to regulators, and embodying factors lacking an overall mutual consistency. It is the purpose of the following document to address these issues, not to resolve them in their considerable complexity, but to provide a framework from which a consistent certification process may evolve. Much of the underlying structure now exists from which this evolution can proceed, but a coherent picture is lacking. It is a major objective of the following to provide such a perspective and thereby establish HIRF certification on a more rational basis than presently exists.

2.1 Background

A problem associated with the certification of airplanes to HIRF is illustrated in Figure 2-1. There exists a credibility gap between HIRF design effectiveness as determined from current assessment methods in contrast with HIRF incidents recorded in commercial airplane service history. A recent NASA publication [1] addresses many HIRF incidents that have occurred. Scrutiny of the document indicates that HIRF incidents in commercial transport aircraft are largely anecdotal, thereby raising questions as to the reality of the threat. This is not to ignore there have been serious HIRF related incidents, but these have been exclusive to military aircraft and helicopters. A source of the discontinuity between methodology and reality has been identified with the inconsistent combination of factors determining aircraft susceptibility to HIRF. In other words, it is clear that HIRF incidents are possible, but the conditions and probability for their occurrence have yet to be satisfactorily categorized.

This situation applies to current and future design and certification of new conventional aircraft, modifications to existing aircraft, and new innovative aircraft, such as the High Speed Civil Transport.

Aircraft HIRF protection design and certification has been based on specifying an external RF environment [2,3], assessing the internal airframe and installation attenuation of the environment, and then designing and testing equipment and systems to function in the internal environment [4]. While this approach is straight forward conceptually, the details of the process become complex and may drive the airframe, installation and equipment design to unrealistically high levels of conservatism.

The details that make this process complex include:

a. The external environment has several definitions, such as peak, average, peak rms, certification, normal, and all of these vary by frequency band.

b. The airframe attenuation is influenced by airframe structure, installed systems, cavity resonances, field incidence angle, and field exposure time.

c. Equipment and system susceptibility test results are sensitive to the choice of test method (anechoic chamber versus mode-stirred chamber [5], preset field strengths, monitored and leveled field strengths), equipment test configuration, modulation and time of exposure.

The approach to dealing with these variables has a significant impact on the airframe HIRF protection design requirements, the method of verifying the protection adequacy, and the format of the data used to certify the protection margins.

Since there are different groups and organizations that define and influence each of these areas, the overall protection design and certification must often deal with inconsistent data with which to base design decisions or certification plans. These inconsistencies may lead to insufficient HIRF protection, over-design, or unnecessary aircraft-level tests to verify protection performance.

2.2 Problem

Implementation of aircraft HIRF protection and subsequent regulatory certification requires assessment of the four factors delineated in Figure 2-2, including:

a. The external HIRF environment,
b. the external to internal airframe attenuation,
c. the internal RF field description, and
d. equipment susceptibility or qualification levels and waveforms.

The combination of these factors determine the overall protection effectiveness. Currently, each factor has an accepted convention for its description, but these conventions are not necessarily consistent when the overall protection design effectiveness is assessed.

Each factor requires a fairly complex description. For example, the severe external HIRF environment is a composite of a number of RF emitters [2,3], with the emitter having the highest intensity fields selected to represent the field strength for a particular frequency band. At high frequencies, the airframe supports a large number of airframe, wiring, and cavity resonances, which suggests a statistical representation [6-11] of the attenuation may be most technically correct. At VHF and UHF frequencies, the attenuation may be dominated by specific wiring and airframe resonances, which may not support a statistical assessment.

Similarly, equipment and systems may be tested in mode-stirred test facilities [12,13], or in semi-anechoic chambers [14]. Equipment susceptibility test levels must be comparable between these two different methods, taking into account room and test bench effects associated with the two methods.

Assessing the aircraft HIRF protection margin does not follow by simply arithmetically summing all factors for a particular frequency. Any statistical assessment must provide a rational method to represent the overall aircraft protection, both for determining the aircraft design requirements and for verifying the HIRF protection margins for aircraft certification.

2.3 Objective

The overall objective of Task 52 to NASA Contract NAS1-19360 has been to propose activities leading to a consistent approach for expressing HIRF airframe protection margins, to support aircraft design decision and aircraft certification. Methods for describing the factors associated with aircraft HIRF interaction are needed, so that the resulting HIRF protection margins realistically describe protection performance. This means that each individual HIRF protection factor, such as RF environment description or equipment susceptibility, will be expressed in terms that are technically consistent. This is not only as individual factors, but also in relation to the other HIRF protection factors.

2.4 Scope

Each factor identified in this report is sufficiently complex to require a separate study in its own right. Therefore the scope of the following work is limited to discussing those issues that drive the current certification process (i.e., external and internal environment, equipment and airframe attenuation test methods) and which heretofore have been based on incongruent assumptions. These assumptions will be identified and discussed in detail as will the consequences of current technical approaches in assessing the HIRF threat. Suggested alternatives will be proposed, e.g. statistical assessments, about which it will be argued a HIRF certification process can be developed that reflects a consistent overall approach for describing aircraft HIRF protection effectiveness.

2.5 Approach

Figure 2-3 outlines the Task with respect to its constituent elements. The diagram implies that each element is related and a consistent certification process will be arrived at when each of these elements is addressed and integrated into an overall process definition.

Section 3.0 compares the airplane certification process as viewed from the idealized perspective of the SAE-AE4R Users Manual for AC 20-xx with the realistic process as perceived to evolve during a new airplane development program from the point of view of one airplane manufacturer. The ideal process will be seen to differ with the realistic process and potentially may in fact drive airplane production to non-competitive levels. It is recommended that elements of the realistic process be incorporated into the ideal process so as to reflect actual airplane development and certification.

Section 4.0 considers the external environment and its impact on other factors. The external environment reflects a worst case compilation of HIRF emitters throughout the U.S. and Western Europe. Consequently, the environment has tended to be fixed at rather high levels especially in frequencies above one GHz. Furthermore, there is not as yet a unique choice for the environment, but the definition has tended to evolve over time. Here are discussed the multiple definitions (severe, certification and normal, peak and average) with a few comments pertaining to the probability of exposure to the environment [15]. It should be emphasized that statistical and probabilistic concepts run a common thread throughout this document wherein it is proposed that this point of analysis be given more credence in assessing HIRF test requirements.

Section 5.0 speaks to two important factors that are central to developing a consistent certification process. Current methods of assessing the internal environment and the airplane attenuation of the external field have led to several consistency issues. The fields excited within the complex airframe cavities have been shown to be highly variable as a function of frequency and spatial position. Furthermore, resonances are set up in the cavity that both contribute to this variability and the difficulty in interpreting the nature of the internal fields. For example, questions remain as to whether the internal fields and associated attenuation be represented by the average or minimum (worst case) attenuation, or should an alternative statistical description be given the fields. Sensor properties within the cavity environment are ill defined in that antennas may respond isotropically or retain some directionality within the cavity. In addition, an airframe attenuation is defined once a suitable reference measurement has been defined. This operation has not been standardized however and a consistent attenuation definition is not possible until one has been established.

Section 6.0 addresses issues pertaining to equipment susceptibility test methods, requirements and data. A consistent certification process is one in which laboratory equipment tests can be related to the internal airplane environment, otherwise there is the risk of designing equipment to unrealistic protection margins. Current FAA equipment test requirements (100 or 200 v/m) are largely based on precedents set in earlier (usually military specification) documentation, and on calculations founded on assumptions about the shielding effectiveness of the airframe to the external environment. As discussed above this is at present an ill-defined number which may have at best a statistical significance. Furthermore, the relationship between tests performed in anechoic versus reverberation chambers is not well defined with antenna correction factors currently not agreed upon.

Section 7.0 will present the following conclusions:

Compounding worst case requirements in arriving at a certification process is not the only means of arriving at requirements and is most likely not a realistic or even correct approach.

The idealized process envisioned by regulators deviates significantly from the realistic process as practiced by airframe manufacturers. It is recommended that aspects of the realistic dynamics be incorporated into the process definition and flow.

Test and analysis provide a means to define the internal environment and relate equipment level tests to the internal field. These results may be used to provide more realistic requirements on equipment level testing.

Test and analysis methodologies are a function of test configuration and frequency. A single attenuation assessment methodology is not sufficient for the entire airplane or over the entire 10 kHz to 18 GHz threat range.

Each quantitative factor contributing to assessing the overall HIRF protection margin may have a statistical element. For example, airplane attenuation as measured in the flight deck is not represented by a single number but at the higher frequencies may be defined by a distribution function which may be fairly well characterized. In suitably defined frequency ranges, assessing distributions for each factor and appropriately convoluting these is a candidate method that may provide a more realistic picture of HIRF susceptibility of airplane electronics and thereby lead to more realistic requirements. Criteria delimiting statistical methods are yet to be determined.

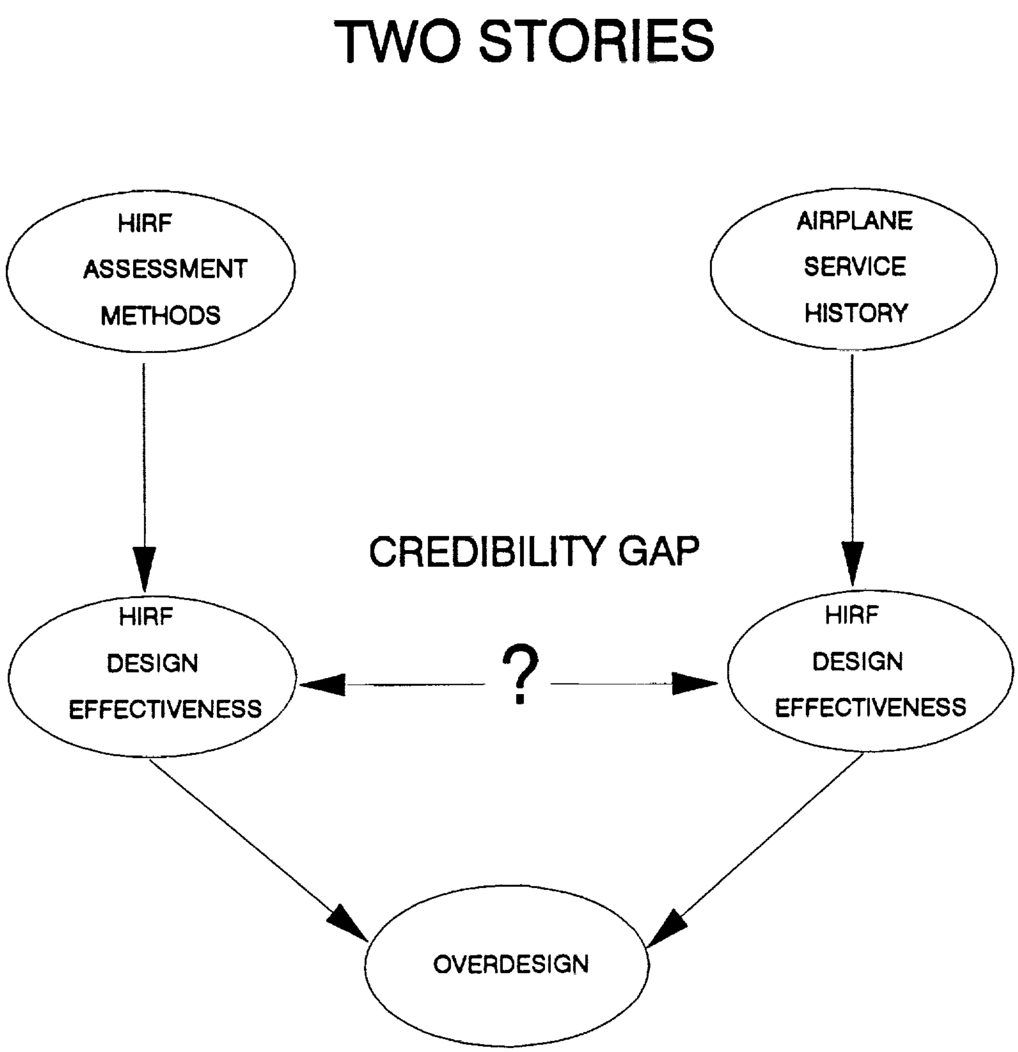

Figure 2-1 Aircraft Vulnerability to HIRF

FACTORS DETERMINING MARGINS

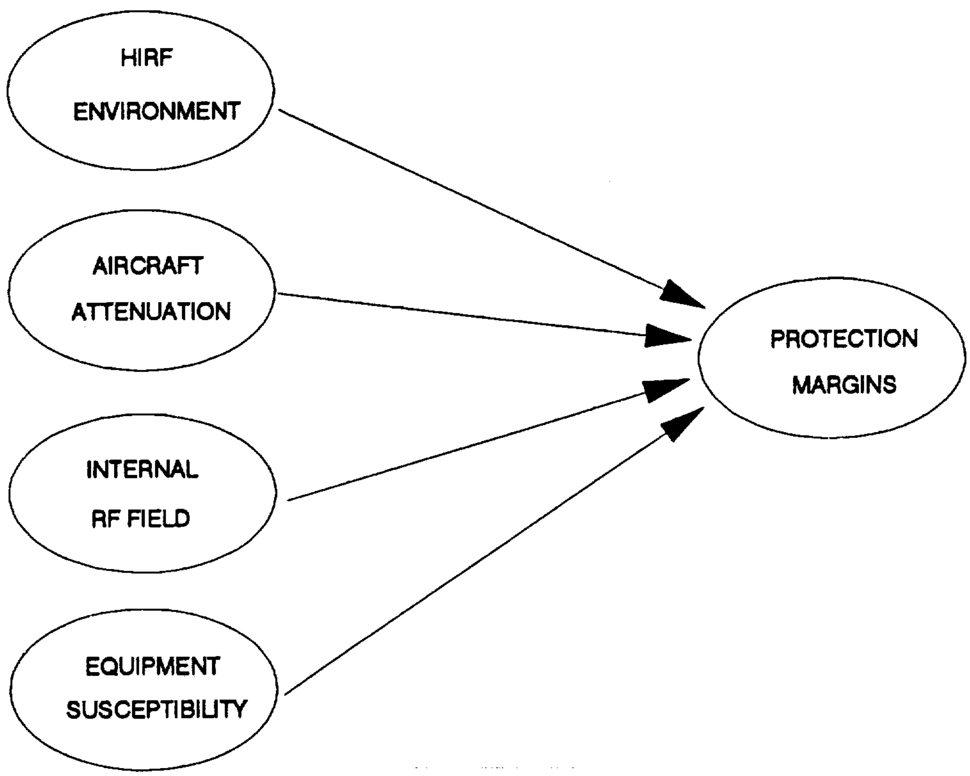

Figure 2-2 Consistent Protection Margins

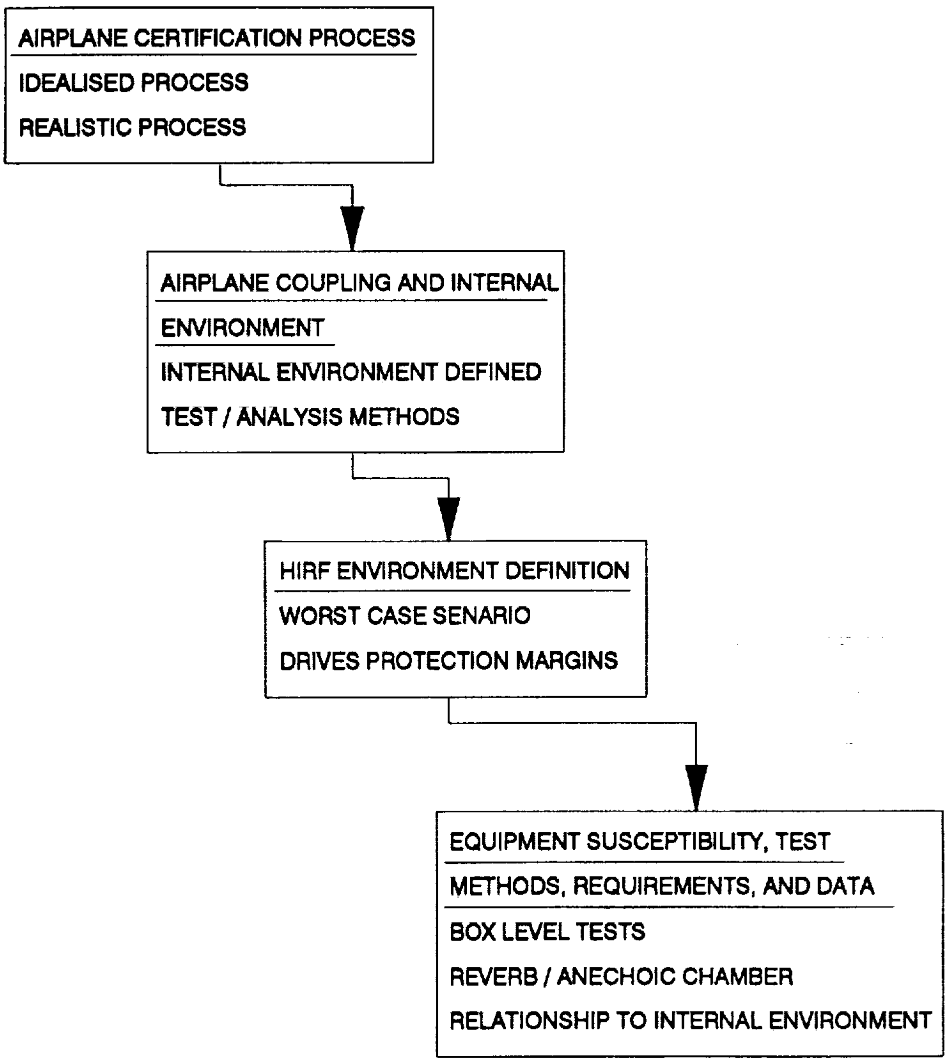

Figure 2-3 Task 52 Elements

3.0 AIRCRAFT CERTIFICATION PROCESS

There exists a need for a realistic assessment of the commercial aircraft certification process with respect to the HIRF environment. This section reflects the compliance process for large transport airplanes integrated with information retrieved from HIRF related documentation issued by industry and the regulatory agencies (FAA and JAA) responsible for HIRF oversight and certification. It is written from one airframe manufacturer's perspective, but is intended to be sufficiently generic to apply to transport aircraft in general.

This section provides an overview of how in practice an airplane is certified for HIRF. Certification is accomplished by examining: the identification of airplane critical functions; the development and release of certification plans; the comparison, issue and integration of FAA and JAA requirements; the assessment of supplier bench level tests; the assessment of airplane level tests; the compilation and release of the airplane HIRF certification document; and the final Type Certificate award. Many of these tasks are interrelated and performed in parallel.

The objective of the following is to integrate experience gained in the development and assembly of new generation aircraft into a representation of a consistent process leading to the demonstration of compliance to HIRF certification requirements. A comparison is made with the idealized process as detailed in section 8 of the SAE AC 20-xx Users Manual [3]. Such a comparison is essential to the development of a consistent compliance process.

3.1 Idealized Process

Figure 3-1 is the flow schematic of the process used in airplane certification programs to demonstrate compliance as proposed in the SAE Users Manual for AC 20-xx. These steps are summarized in the following, details can be found in the User's manual. The requirement for demonstration for any specific system or equipment installed in an aircraft is related to the criticality of the function performed by the system/equipment. The identification of systems/equipment functional criticality results from the application of a Functional Hazard Analysis developed in accordance with AC 25.1309-1A or AMJ No 25.1309. This analysis establishes Catastrophic, Hazardous/Severe Major and Major failure categories which may be related to system/equipment for the purpose of compliance demonstration.

The certification level requirement is related to the failure condition category. Electrical and electronic systems whose failure would cause or contribute to a failure function resulting in catastrophic failure are defined as being at Level A certification level, whereas those resulting in hazardous/severe-major failure condition are Level B, and major failure condition are Level C. The User's Manual details criteria by which the appropriate compliance level is chosen.

Referring to Figure 3-1, the initial step for new or existing equipment is to determine the HIRF environment to which it is to be subjected. The HIRF environment so used is dependent upon the criticality performed by the equipment. This establishes the test level for the equipment test using procedures of ED-14/DO-160, *Environmental Conditions and Test Procedures for Airborne Equipment,* under section 20. The second step is to make a decision as to which demonstration process can be used for compliance demonstration. The test requirement decision is then made based on the criticality (Level A, B, or C) of the function of the equipment/system under evaluation.

In step 4 the test procedures of ED-14/DO-160C, Section 20 are used as a basis for the qualification of electronic systems and equipment. Step 5 is relevant for equipment performing Level A functions, for which further testing and evaluation at the system or sub-system level may be beneficial. Physical installation of the equipment in the rig assembly should be similar to that used in the aircraft.

Step 6 involves a decision as to test at the aircraft level. Systems performing Level A functions (see step 11) are generally subject to aircraft testing. Procedures discussed in section 5 are recognized to be practical and acceptable in the determination of data for verification of aircraft and associated system installations. The two main approaches to aircraft testing include low level coupling (options provided by steps 7, 8 and 9), and high level tests radiating the aircraft at levels equal to the Certification HIRF environment (step 10). In the latter test, all systems performing Level A functions should be fully operational and the aircraft placed in various simulated operating modes.

Step 11 is an acceptable means of demonstrating compliance for systems performing functions categorized as Level A but performing display or non-control functions only. It cannot be used for Level A control functions. The objective of the test is to demonstrate that when the aircraft is exposed up to the Certification environment, any failures must not result in the loss of a Level A Display or Non-control function or the display of hazardously misleading information. For functions categorized as Level B, the test level to be used during equipment testing may be based on the Normal environment with allowance made for aircraft attenuation using either aircraft measurements or generic transfer function/attenuation curves. Lower level requirements are stipulated for Level C testing.

Similarity and other methods including analysis are options available for certification, but primarily for Levels B or C functions. Similarity cannot be used for Level A functions.

Finally, the ideal process assesses the results of the selected option through an electromagnetic evaluation (EMV) process (step 16) and a decision made to correct non-compliant systems or to certify. A possible corrective measures loop (step 15) is apparently a central aspect of the ideal process.

3.2 Realistic Process

Recent history pertaining to aircraft HIRF certification has provided a general framework defining the route to compliance for future fly-by-wire/fly-by-light commercial airplanes. The purpose of the following is to assemble and elaborate on disparate elements of the certification process as it has historically evolved and thereby provide a coherent picture of the aggregate process. The general stages and time line for aircraft certification and HIRF certification specifically are represented in Figure 3-2 and include:

1) Safety assessment process instituted. Airplane architecture (function criticality, etc.) and electrical configuration are defined. These include equipment and airframe design requirements.

2) Level A (critical) systems are declared. The FAA/JAA may issue Special Conditions, in this case regarding HIRF.

3) FAA/JAA and the airframe manufacturer coordinate requirements.

4) A certification plan is provided by the airframe manufacturer.

5) Tests are performed to demonstrate compliance:

   Equipment (bench) Level Tests: Performance and pass/fail requirements set. Suppliers perform equipment level HIRF qualification tests.

   Airplane Level Tests: The airframe manufacturer performs system/airplane level tests.

6) The manufacturer reports to regulatory agencies throughout the program as part of the certification process definition.

7) Final documentation including analysis, test, and certification reports are compiled and submitted to the regulatory agencies.

8) Compliance is complete when certification requirements have been met.

Not discussed above are possible post-certification changes and tests which have some historical precedents in the certification process.

FAA and JAA compliance options run concurrently and requirements differ. Typically aircraft manufacturers have maintained consistency by performing tests that satisfy the most demanding set of requirements which repeatedly have been levied by the JAA. Negotiations between the JAA/FAA and industry regarding a uniform set of requirements are in progress. Incorporating FAA and JAA compliance processes into Figure 3-2 results in the expanded version Figure 3-3. Reference to Figure 3-3 will be made in the following.

3.2.1 Initiate Airplane Program (Block 1)

Functional hazard assessment is performed. Aircraft architecture and electrical configuration are defined. Preliminary electromagnetic susceptibility analysis and models are assessed. Airplane engineering program go-ahead is given. Electromagnetics staff is organized. A design requirements document is released. The regulatory agencies are informed of proposals.

3.2.2 Critical Functions (Block 2)

Criticality of functions and equipment are determined by engineering groups responsible for each system in a safety and functional performance assessment. Level A, B, and C systems are determined in part by reference to rules provided in the FAA advisory circular AC 25-1309-1A. Final agreement on Level A, B, and C systems takes place after the assessment is complete and after the FAA has approved certification plans. Working lists are supplied to the FAA and JAA to aid with a final agreement. Applicable regulatory agencies may issue preliminary special conditions based on events reflecting aircraft vulnerability or general modification to airframe architecture. The manufacturer comments on the special condition which in this case relates to airplane electronics HIRF susceptibility. The special condition is released providing airplane requirements to meet Federal Aviation Regulations, (FAR). Special conditions supplement the existing FARs, thus providing additional airplane requirements.

3.2.3 Set Requirements (Block 3)

When new model airplanes are proposed, the manufacturer sets initial equipment subsystem test levels to be used by suppliers. Test level requirements are recommended based on preliminary model analysis, estimated airframe attenuation and known electromagnetic test capabilities. For example, the peak external HIRF environment may be as large as 6800 volts per meter over a given frequency interval, whereas the typical upper limit test capability is 600 to 1000 volts per meter. Design, pass-fail criteria, and test plans for early-on equipment level tests are negotiated with suppliers and approved by the respective manufacturer/supplier liaison. EMC data and in-service history are provided for off-the-shelf equipment. Nonetheless, any off-the-shelf Level A , B, or C equipment is required to be qualified for HIRF. Negotiations concerning requirements for items identified by the FAA/JAA are conducted between the airframe manufacture and the FAA and JAA until a final version of these requirements is agreed upon. Negotiations and reports are exchanged with regulatory agencies in part through the agency of the Designated Engineering Representative (DER). Furthermore, DERs often contribute pertinent information in these negotiations. Those issues relating to airplane safety are deemed non-negotiable.

3.2.4 Certification Plans (Block 4)

Certification plans are submitted to the FAA and the JAA. Major features of a plan include:

1) Unique features of the aircraft

2) Differences from previously certified aircraft

3) The methods for establishing compliance

4) A schedule of events.

<u>FAA Requirements and Means to Compliance</u>

Currently two methods for compliance have been offered the FAA, including airplane level tests (Method 1) or laboratory level tests (Method 2) on Level A system elements and their associated wiring. The choice by the aircraft manufacturer of Method 2 requires system components and their wire harness withstand an EM field strength in excess of, e.g. 100 volts per meter, without the benefit of airplane structural shielding in the frequency range of 10 kHz to 400 MHz, and e.g. 600 volts per meter between 400 MHz and 18 GHz. Figure 3-4 is a schematic of the FAA compliance process for performing equipment qualification level testing.

JAA Requirements and Means to Compliance

JAA verification requirements and means to compliance include both bench level testing of Level A, B, or C equipment and airplane level tests. Bench level tests begin as early in the program as possible, whereas airplane level tests must be performed near or at program completion. Integrated systems comprised of qualified components must pass any additional qualification tests. Typically, higher level integration tests such as full aircraft tests, have simpler pass/fail criteria but are not straightforward to perform.

Airplane level tests require that attenuation of the external environment during Low Level Swept Continuous Wave (LLSCW) tests or Low Level Direct Drive (LLDD) tests by the airframe demonstrate adequate shielding of Level A systems to the HIRF environment. The test method of choice is to a large degree a function of the airframe manufacturer. For high level pulsed tests, Level A system performance is monitored and must show no adverse effect.

Figure 3-5 is a schematic of one view of the JAA Certification process in performing both equipment and system level qualification tests, and airframe attenuation tests. Significant differences exist in the compliance requirements and procedures on comparing the FAA with the JAA. The JAA process tends to emphasize a worst case scenario which is more burdensome on the manufacturer. It also subsumes the FAA process in terms of equipment qualification levels (in addition to involving the airplane level tests). By performing tests to JAA specifications, FAA requirements are automatically satisfied. Nevertheless, test plans, reports and documentation and final Certification Report, are separately written and filed.

3.2.5 Test and Analysis (Block 5)

Equipment Level Tests

Equipment or bench testing is performed throughout an aircraft program. The manufacturer may perform tests on certain critical systems, e.g. flight controls, very early in a program to assess equipment response to estimated HIRF levels. Level A, B, or C systems are classified by the manufacturer and pass-fail criteria are defined by the supplier and approved by the airframe manufacturer's equipment liaison. Test procedures, design, verification goals, objectives and requirements are provided to suppliers in the form of a EMI/HIRF requirements document. Suppliers provide test plans and procedures which are then reviewed by the equipment liaison. Supplier tests may be witnessed or alternatively, the manufacturer may conduct laboratory validation tests. Equipment failure or deficiency requires re-design followed by re-test until requirements are met. The manufacturer reviews and approves supplier test reports. Supplier-manufacturer interaction is central to the certification process as it is now practiced. There is almost continuous supplier-manufacturer communication regarding test requirements and verification test results negotiation which proceed until design goals are met. Tests begin early-on in part because design goals and attendant requirements may change in the course of the program.

Airplane Level Tests

During several airplane developmental programs, low level swept frequency tests have been performed on airframes or airframe testbeds. These tests served two purposes. The aircraft attenuation tests were part of the certification process. Testbed tests also served to develop test procedures and as engineering validation tests to assess suitable low level test methods, evaluate airframe shielding techniques and associated payoffs. Both swept frequency and mode-stirring techniques have been shown to be acceptable methods for assessing airframe attenuation to low level incident fields.

Low level direct drive injection (LLDD) tests have been performed to measure internally induced cable currents by externally injecting surface currents. The corresponding transfer function provides an attenuation assessment. Low level direct drive (LLDD) tests are performed between 10 kHz and 30 MHz, and low level swept continuous wave (LLSCW), mode-stirred (LLMS), or frequency stirred tests are performed in the 30 MHz to 18 GHz frequency range.

Pulsed high level tests have also been performed on production aircraft at isolated frequencies to complete the certification process. Level A equipment must function without adverse effect while the airframe is illuminated with the full threat level field at specified frequencies. The preceding four options are available for airplane level certification tests. One method is usually selected and performed near program completion.

Alternative Certification Process

For selected equipment, e.g. second or third source engines, tests may be performed in the laboratory with high level pulse fields suitably attenuated as determined by the measured LLSCW levels. This reduces test cost particularly when modifications have been made to the airplane equipment configuration.

Similarity and Analysis

The similarity option may be exercised on selected Level B and C equipment with which there is documented experience, and in testing redundant or duplicate equipment. Tests are performed on a single equipment model and the pass/fail determination is accredited to equipment of the same type contingent on the response of the tested component.

Analysis may be used in conjunction with test for example to relate skin currents to the external field or to predict cable currents. Although difficult in practice, analysis may also be used in place of test to assess Level B and C equipment immunity under pulse level conditions.

Analysis and code development in general act to support protection design option tradeoffs, test design and the interpretation of test results. There is an on-going transfer of test data and analysis between test and model development impacting airframe design on HIRF attenuation and HIRF test development.

3.2.6 Manufacturer Regulatory Agency Interaction (Block 6)

Through the auspices of the DER, the manufacturer periodically apprises the FAA of qualification test results as they are completed and documented by suppliers. The manufacturer monitors supplier test methods and test reports. The airframe manufacturer negotiates and incorporates regulatory agency input into the certification process relating these to supplier test houses. Contrary to Figure 3-1, the realistic process does not have a corrective measures feedback loop. Qualification tests and any required re-design are performed by the supplier and manufacturer before documentation is released and before airplane level testing is performed as implied by the idealized process. In other words, once qualification tests have been satisfactorily completed, the respective equipment is qualified. Regulatory agencies may witness high level tests and review the corresponding documents.

3.2.7 Certification Documentation (Block 7)

The FAA certification documentation requires submittal of a criticality list, a HIRF certification plan including schedule, and a final HIRF certification report. The latter includes the necessary data appropriately summarized to substantiate qualification levels and performance of Level A (critical) systems. Suppliers submit test plans and test reports, the results of which are summarized in the final certification document. Results are in part submitted via FAA Form 8110-3.

JAA documentation supporting compliance include a criticality list, an airplane level test plan, interim milestone reports and summaries, and final reports summarizing tests relevant to compliance.

3.2.8 Compliance (Block 8)

Certification is complete with the qualification of Level A, B, and C systems to acceptable RF susceptibility/immunity levels as reported in the final certification document.

3.3 Process Comparison

Figure 3-6 is a schematic representative of the general route to compliance based on aircraft manufacturer experience and procedures compared with the ideal flow as represented in Figure 3-1. The realistic process is consistent with regulatory agency requirements and process recommendations. From this Figure, the following can be ascertained:

1) The Realistic Process integrates all aspects of the routes to compliance as inferred in the AC 20-xx. Catastrophic Level A, critical control, is analogous to the manufacturer route as programmed to satisfy JAA requirements, whereas Level A, critical display/critical non-control follows the aircraft manufacturer plan for FAA compliance for all Level A systems. However, as discussed above, these are in reality part of the same overall process. Similarity and analysis are integrated into the certification process and do not necessarily constitute separate routes to compliance. On new airplane programs, similarity is a relatively insignificant option. Possibly the most important observation is that the realistic process is not a linear one as indicated by Figure 3-1. Once critical functionality has

been determined, qualification testing, analysis and subsequent equipment certification are parallel processes.

2) Industry, supplier, and regulatory agency interaction is achieved through industry liaisons such as the FAA Designated Engineering Representative (DER). These individuals monitor test plans and results, participate in the formulation of requirements, and communicate requirements between regulators, designers, and suppliers. They are a very active element in the certification process from the initial stages of aircraft development, during the ongoing negotiation of compliance procedures and requirements, to the final type certification issuance. The ideal process apparently does not consider this or similar human dynamics that proceed in the realistic process.

3) Equipment supplier and airframe manufacturer interaction is explicit in the realistic process. Meeting design and regulatory requirements is fundamental to test success and can be accomplished through close supplier and manufacturer interaction. It is the responsibility of the airplane manufacturer to act as a conduit to accurately communicate manufacturer and regulatory agency requirements. Negotiations at this level are ongoing and begin early in the certification process. Once requirements are set, suppliers must meet qualification test levels. There is no end of the program corrections loop for equipment that fails to meet requirements as implied by the idealized process, although there is limited historical precedence for post-certification design changes and subsequent qualification test. A realistic certification process explicitly accounts for post-certification processes.

4) Test methodology development is performed on a continuous basis during the realistic certification process. Emerging technologies and scientific breakthroughs may simplify test procedures or provide a more accurate representation of the HIRF threat. An important component in the process is model development and analysis which is most effective when implemented in concert with test. New test and analysis technologies are given more emphasis in the realistic process.

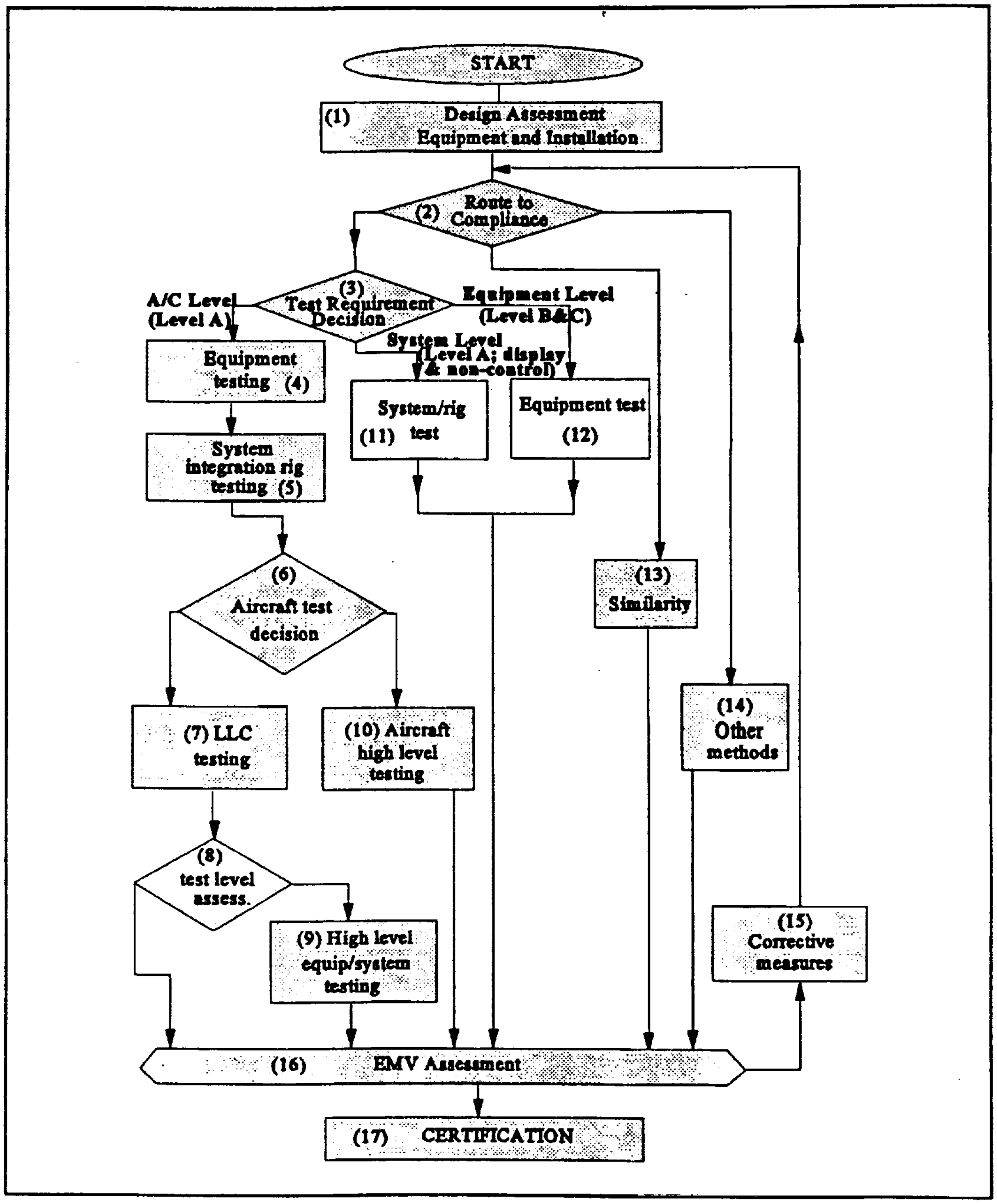

Figure 3-1 Idealized Routes to Compliance

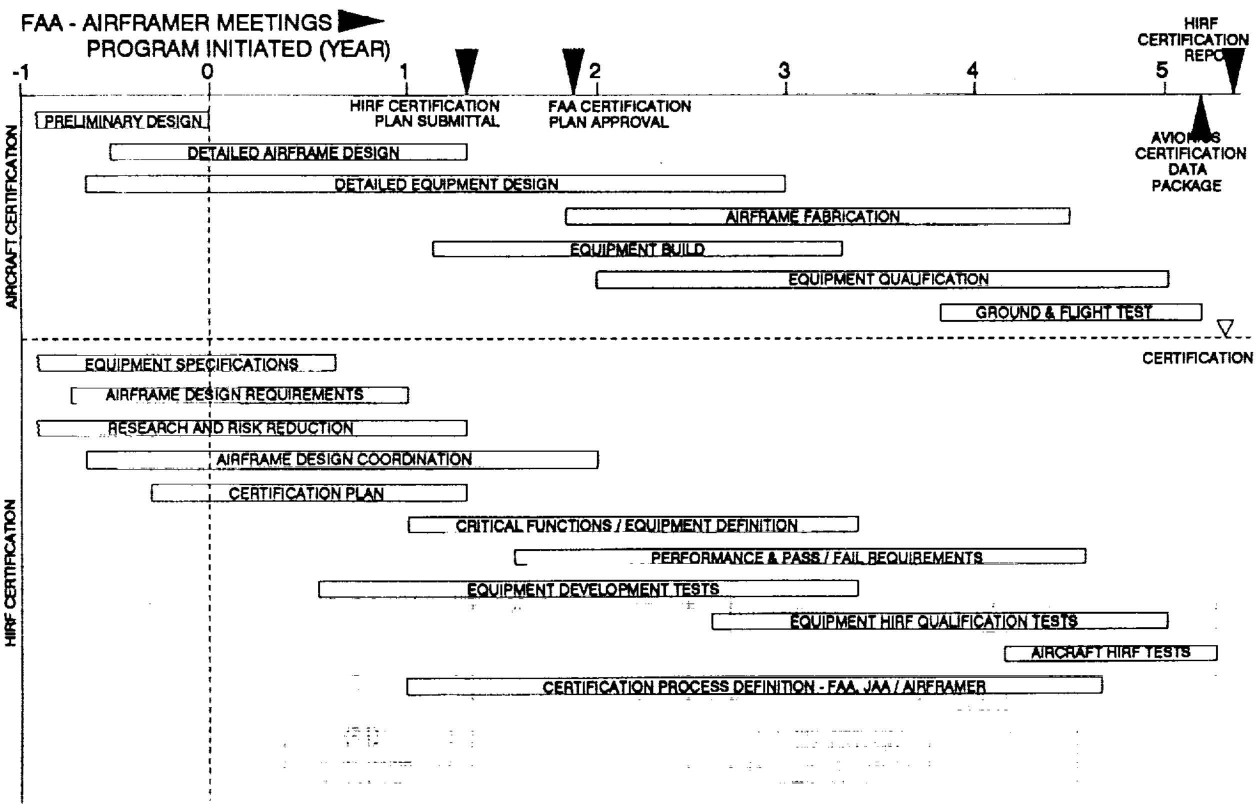

Figure 3-2 HIRF Certification Process Flow

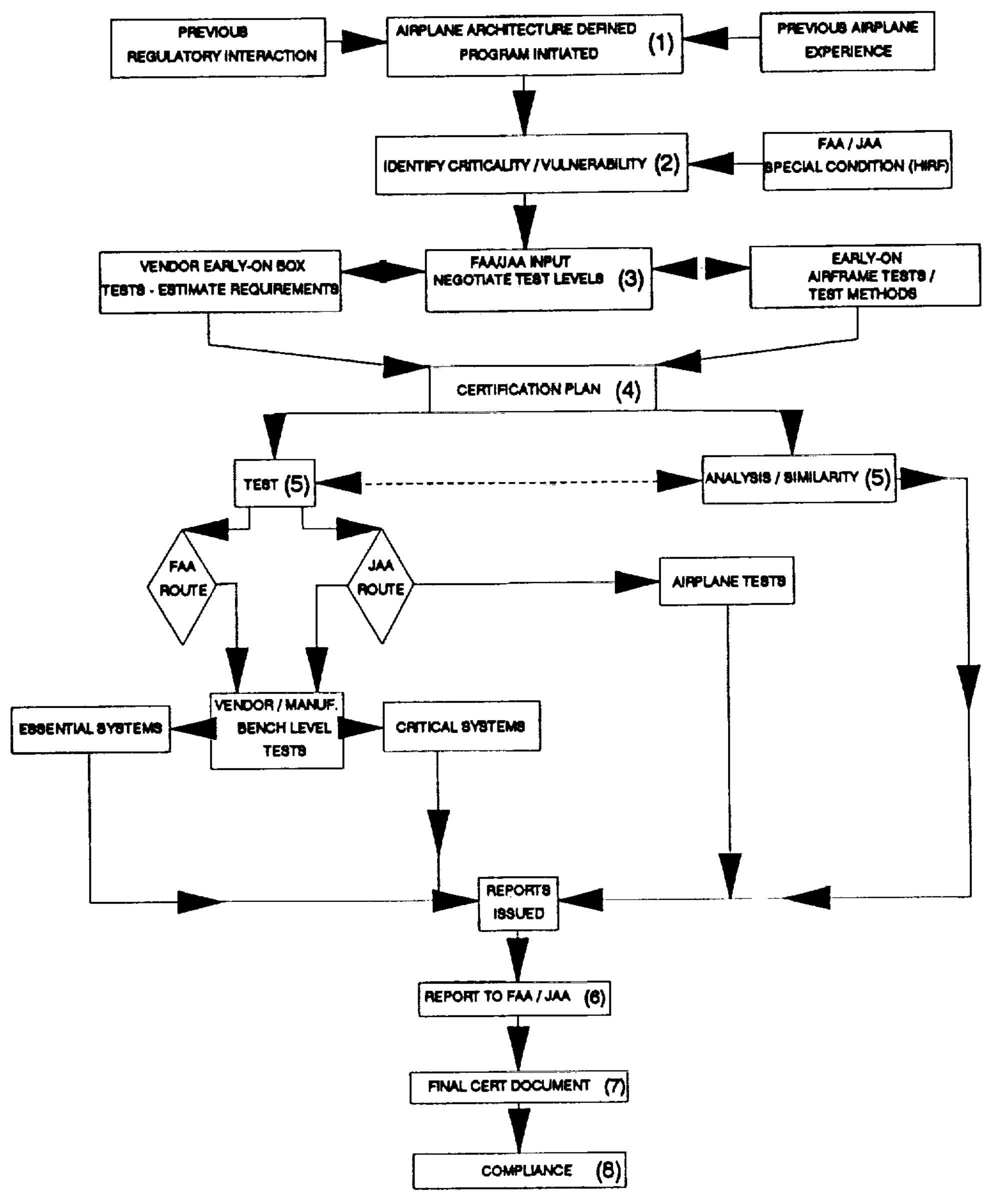

Figure 3-3 Realistic Compliance Process

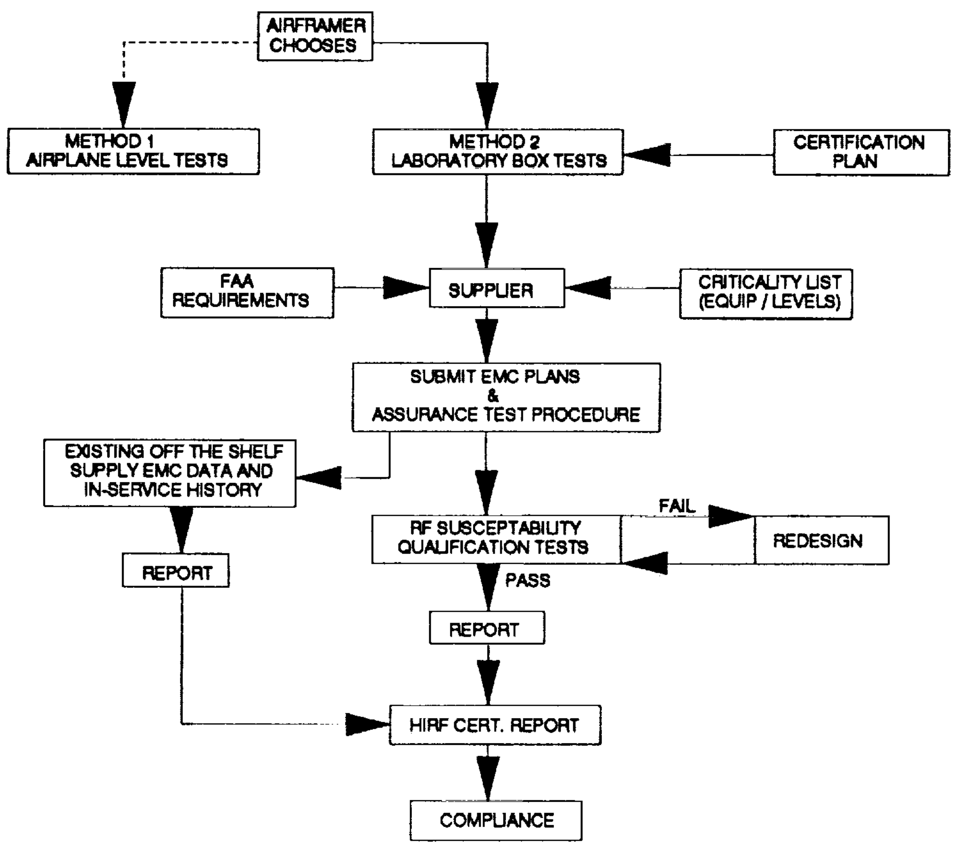

Figure 3-4 FAA Compliance Process

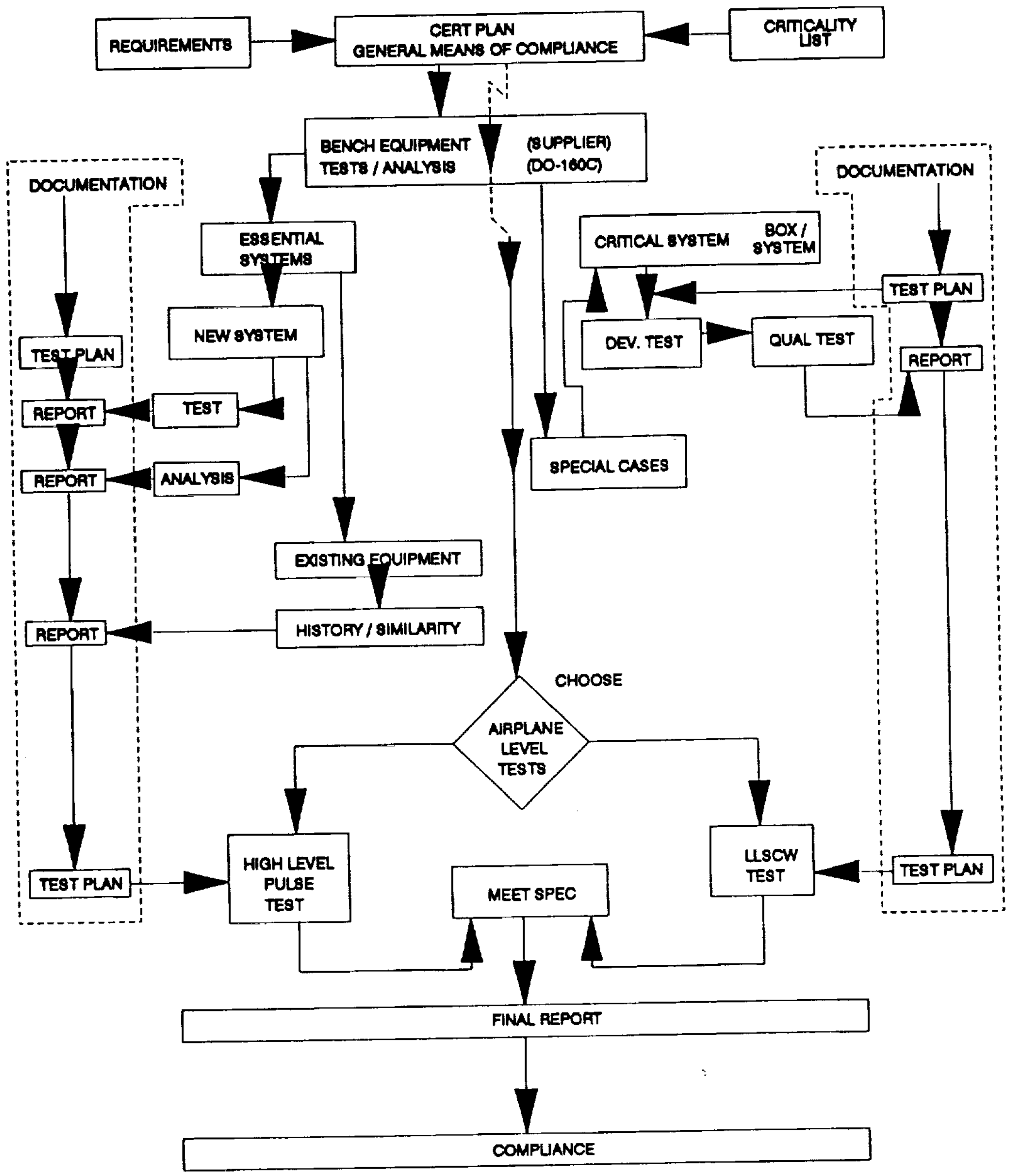

Figure 3-5 JAA Compliance Process

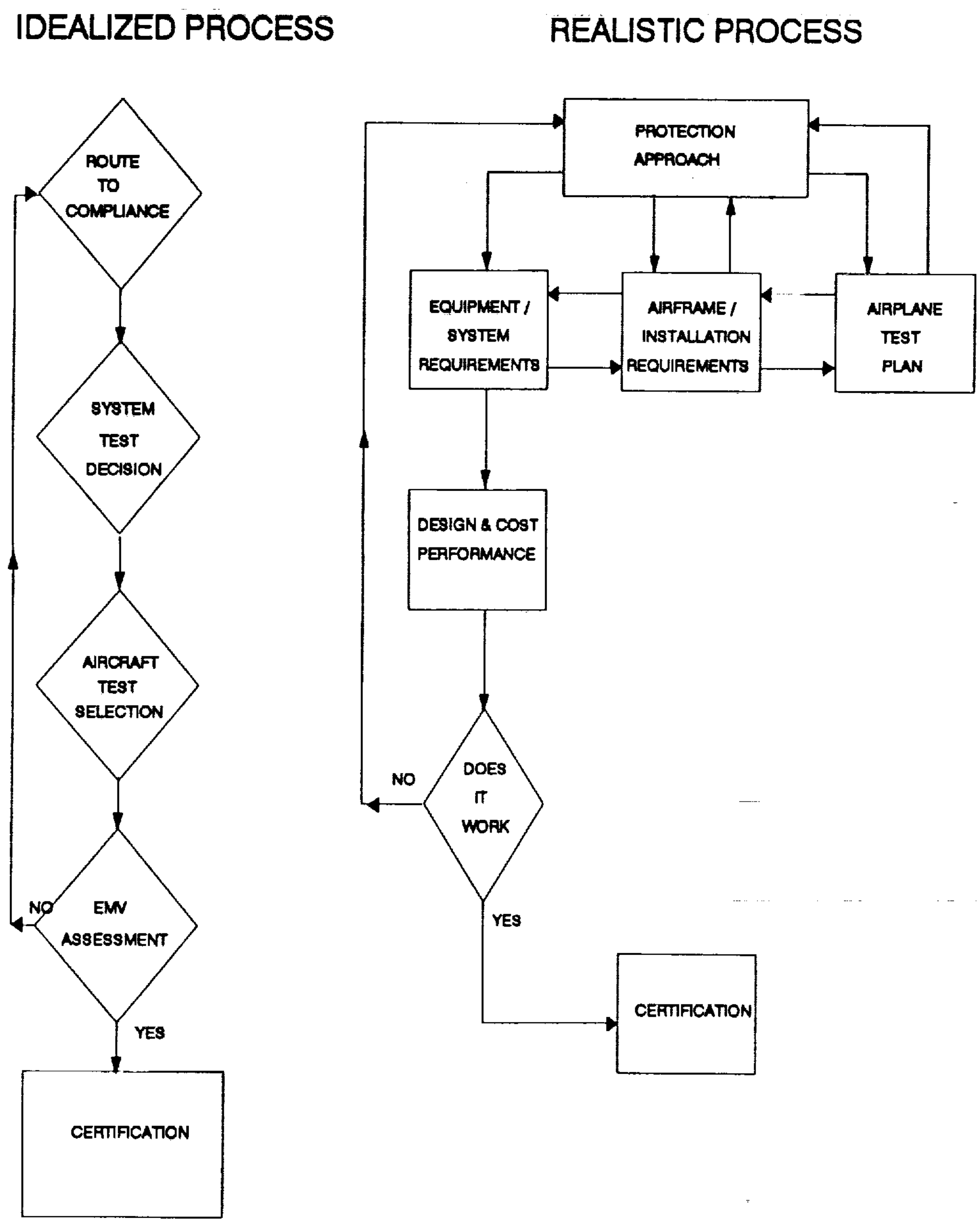

Figure 3-6 Process Comparison

4.0 EXTERNAL HIRF ENVIRONMENT

Assessing the external HIRF environment is a challenging albeit controversial component of the HIRF certification process. As will be discussed below, a consistent process has been lacking in part because of the approach in the determination of representative external HIRF environment levels. In the past, setting these levels has been a function of many factors including airplane type, regulatory agency approach, and field level definition. Consequently the environment definition has not been unique with respect to establishing HIRF protection and certification margins.

Furthermore, the external environment definition has been based on assumptions that often lead to a worst case evaluation of the threat. The importance of this observation lies in the fact that the environment, once fixed, drives the protection margins, and if unrealistic, tends to drive airplane over design and cost. Current environment definitions are fairly well established but their determination has been a matter of historical evolution.

Nonetheless, aside from arguments as to the validity of the levels as a function of frequency, as discussed in section 6, there are aspects of the defined threat that are not consistent with airport operations and attendant airspace restrictions. The task that follows is to point out these inconsistencies, their impact in the certification process, and propose alternative approaches to assessing the HIRF threat.

4.1 Environment Definition

The HIRF external environment definition has evolved over a several year commitment by the SAE AE4R and EUROCAE WG-33 committees, and the FAA, with inputs from the Electromagnetic Compatibility Analysis Center (ECAC), to compile the threat. Details to the history and reasoning leading to the threat assessment are provided in the HIRF User's Manual [3] section 4 and will be referenced in the following. Issues related to the certification process pertain to the assumptions leading to environment definition, the selection of the field levels (peak or average), and the uniformity of the certification requirements definition.

There are upwards of 500,000 licensed HIRF transmitters in Western Europe and the United States. Assessing the threat from the available data base is a significant task although only a fraction of these HIRF sources are of consequential power levels. The environment definition is divided between general and specific assumptions. The general assumptions provide an overall HIRF threat envelope across the 10 kHz to 40 GHz range as determined from the US and Western European transmitter power level statistics, whereas the specific assumptions are based on aircraft to transmitter distance criteria.

Figure 4-1 is a schematic showing the relationships between the general assumptions made by the FAA and JAA that drive the composite HIRF envelope definition. A detailed discussion justifying this set of assumptions is given in the Users Manual [3] and will not be repeated here. It is important to point out that based on what are considered safety issues, several of the assumptions are introduced on a worst case scenario basis. In particular, the representative field strength for each band is chosen to be that of the emitter with the maximum field strength (band drivers) for all transmitters within that band. The envelope functions are the peak field strengths as determined from peak rms values, and the average field strengths as determined from the average transmitted power.

Figure 4-2 relates how specific assumptions concerning transmitter target separation contribute the environment assessment. The principal difference between the severe and certification environment is that in the US, the FAA has introduced special use areas (SUA's) which have been eliminated from the severe environment definition to arrive at the certification environment. The normal environment is a lower level field strength and is determined from field strengths in the airspace in and around airports in which routine departure and arrival operations take place. Ultimately it is the latter two environments that determine the aircraft systems and equipment certification test levels. The JAA used the same data base but ascertained the environment from a probability analysis of the airplane exposure from shipboard and ground based transmitters close to airports. The assumptions in the analysis are not given in the User's Manual nor are they published so that a critical assessment cannot be made. The International Severe, Certification, and Normal HIRF Environments as presented in Figures 4-3 to 4-5 are determined by combining the FAA and JAA environments.

Methods of assessing the environment by introducing additional factors that may influence its determination are currently being examined. Among these factors are included transmitter and antenna system losses particularly as reflected in field strength calculations in the HF levels, antenna structure heights, exposure time, incorporation of restricted airspace around some drivers, and checking airport driver emitters to establish whether antennas are further than ground rule distances. Results of this analysis are preliminary and are currently unavailable.

4.2 Environment Definition Impact on Aircraft Certification

Figure 4-6 represents the relationship between factors that drive the HIRF certification process. There it is stressed that in the process, each of the factors is interrelated except the environment definition which tends to drive the evaluation of the other factors. A typical example is illustrated by Figures 4-7 and 4-8. Figure 4-7 compares the HIRF certification environment with typical equipment susceptibility test levels. The resulting airframe attenuation requirements given by the difference between the environment and the test levels are shown in Figure 4-8. Since equipment qualification test levels are necessarily chosen early in an airplane program development, and airframe attenuation can at best only be approximately estimated, there is some risk in not meeting attenuation requirements. A worst case assessment of the environment therefore has a significant potential impact on HIRF assessment methods and design requirements. This concept is illustrated by Figure 4-9 in which it is shown that the protection margins are primarily driven by the relative shielding of the aircraft and internal installation protection to the assessed environment. The choice of environment definition and level, i.e. severe, certification, normal, peak or average, and how these are to be applied to airframe attenuation, and equipment susceptibility assessments has a major influence on test and design requirements. At the present time a uniform definition is evolving making a consistent certification process problematic.

Another issue concerns the equipment test levels and equipment response properties as a function of frequency. Below 400 MHz critical equipment are typically tested by suppliers to, e.g. 100 v/m, which is higher than the environment definition even without the benefit of airframe attenuation. The environment levels increase above 400 MHz and in particular above 1 GHz. Test levels between 1 and 18 GHz typically are 600 to

1000 v/m, therefore performance margins are a strong function of airframe attenuation and internal installation protection. A lack of sufficient attenuation would imply HIRF vulnerability and therefore impact airframe/equipment shielding design. It is an interesting and possibly relevant observation that presently, most critical equipment apparently are not affected by the high frequency fields above 1 GHz, at least at the current 600 to 1000 v/m test levels.

Furthermore, there is considerable engineering judgment in part based on airplane service history and test experience leading to the conjecture that HIRF may not be a factor at these higher frequencies and field levels, e.g. 6800 v/m peak. Should this be the case, there is the risk of setting excessive design goals based on either the peak or average certification environment in the higher frequencies with respect to current equipment design. It is essential to validate certain of the above assumptions for example by testing equipment in chambers where sufficiently high field levels can be attained at these frequencies. This is one method that may resolve the choice of certification environment levels that in the contemporary context are worst-case driven.

Both the environment and equipment response are dynamic quantities that will change in time and with new airplane programs and as the HIRF source data base expands worldwide. A consistent process should be open to modifications based on up-to-date technical information suitably analyzed to give a realistic HIRF threat.

4.3 Probability of Exposure

Assessing a realistic HIRF threat not only provides a basis for determining HIRF protection margins, but is essential to developing a consistent HIRF certification process that represents the airplane response to the HIRF environment. One candidate method for assessing the threat other than the choice of a worst case scenario, (or the addition of special use areas), includes probabilistic models for the threat. This approach has not been adopted by the FAA, but has been employed by the JAA in developing their representation of the HIRF environment. Unfortunately, the assumptions that underlay the JAA models have not been available preventing a critical evaluation of their results. Crucial to any statistical or probabilistic model is an understanding of the assumptions that formulate the model, otherwise they are of little or no value.

Such an approach has a precedent. A recent calculation [15], apparently used by the JAA in its HIRF environment assessment, addresses the probability of aircraft and transmitter separation. This function can be used to assess the probability of exposure to various HIRF levels in the environment. The calculation is based on two concepts. First, the geometric relationship between a transmitter and airplane position relative to the runway is modeled. Secondly, the positions of the two are considered to be independent random variables having empirically derived distributions. The airplane position distribution function is determined from airport tracking flight path data for take-off and landing at selected European airports. For the derived geometric relationship, this distribution is found to be a normal variate. A similar procedure is used to ascertain the distribution for HIRF transmitters within a fixed radius of the runway. The probability of separation is then taken to be the product of these two normal distributions (although a convolution of the two distributions may be the appropriate procedure). It is further recognized that other factors may play a role in assessing the vulnerability of aircraft in the HIRF environment which account for possible failure modes. This remains to be analyzed.

This model, while a first step in assessing the statistical aspects of the HIRF environment, needs further development. First, it is prudent to expand the data base to include flight path data and transmitter locations indicative of a larger sample. For example, an alternative data base to assess airplane location in space and flight path distributions near HIRF sources may be community noise tracking paths. Secondly, a correlation analysis must be performed to assess the basic assumption of independence. Conditional distributions accounting for possible dependence can then be developed and provide a more rigorously determined assessment of the HIRF external environment. For example, factors which impact the form of the distribution such as time of exposure, and intensity variation, should be evaluated. These factors are in turn based on empirically derived distributions. As argued above, it is crucial that the basic hypotheses of any probabilistic model be clearly stated and tested to provide a quantitative level of confidence in their predictive ability. Such a rigorously determined probabilistic model does not currently exist.

Should an acceptable form be determined, its initial application may be to justify certain test levels to demonstrate compliance with HIRF protection requirements for selected equipment and systems, i.e. a factor in the HIRF analysis should be the probability of exposure.

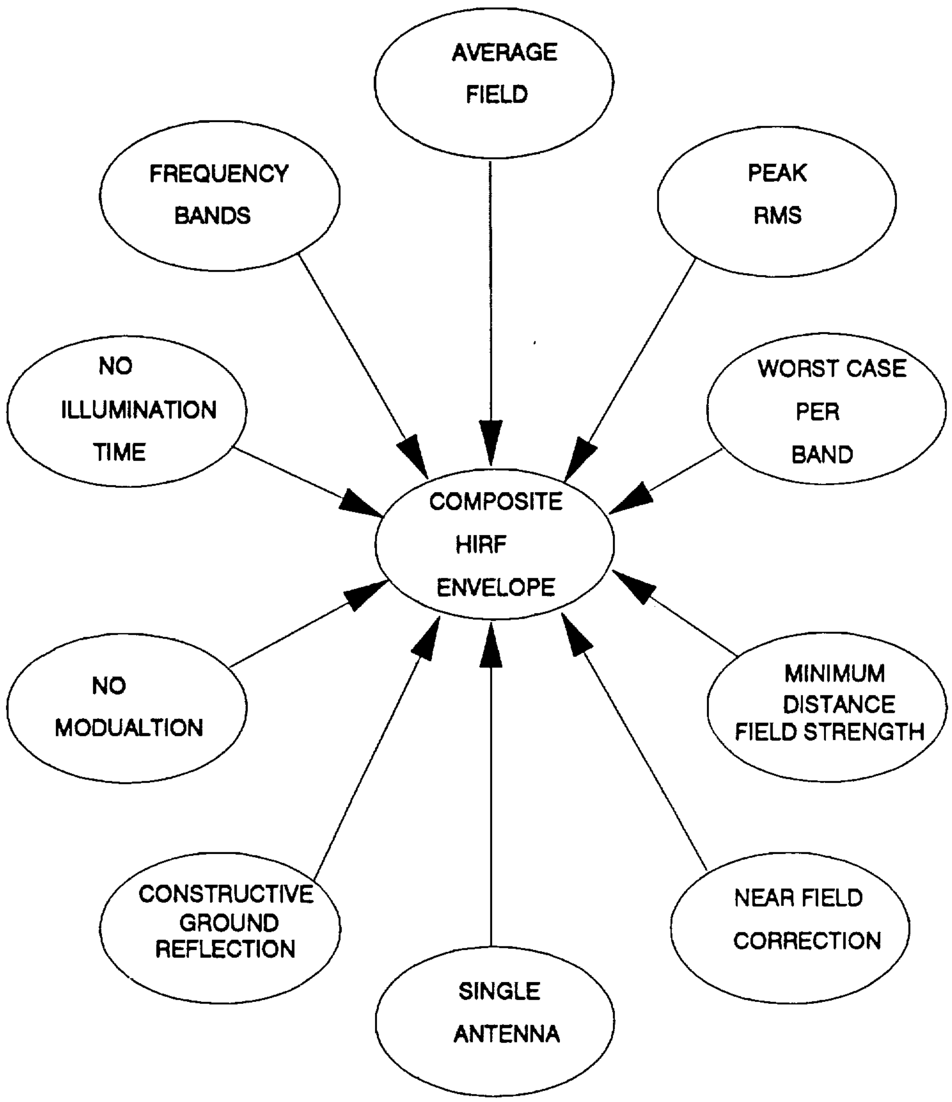

Figure 4-1 General Assumptions Defining HIRF Environment

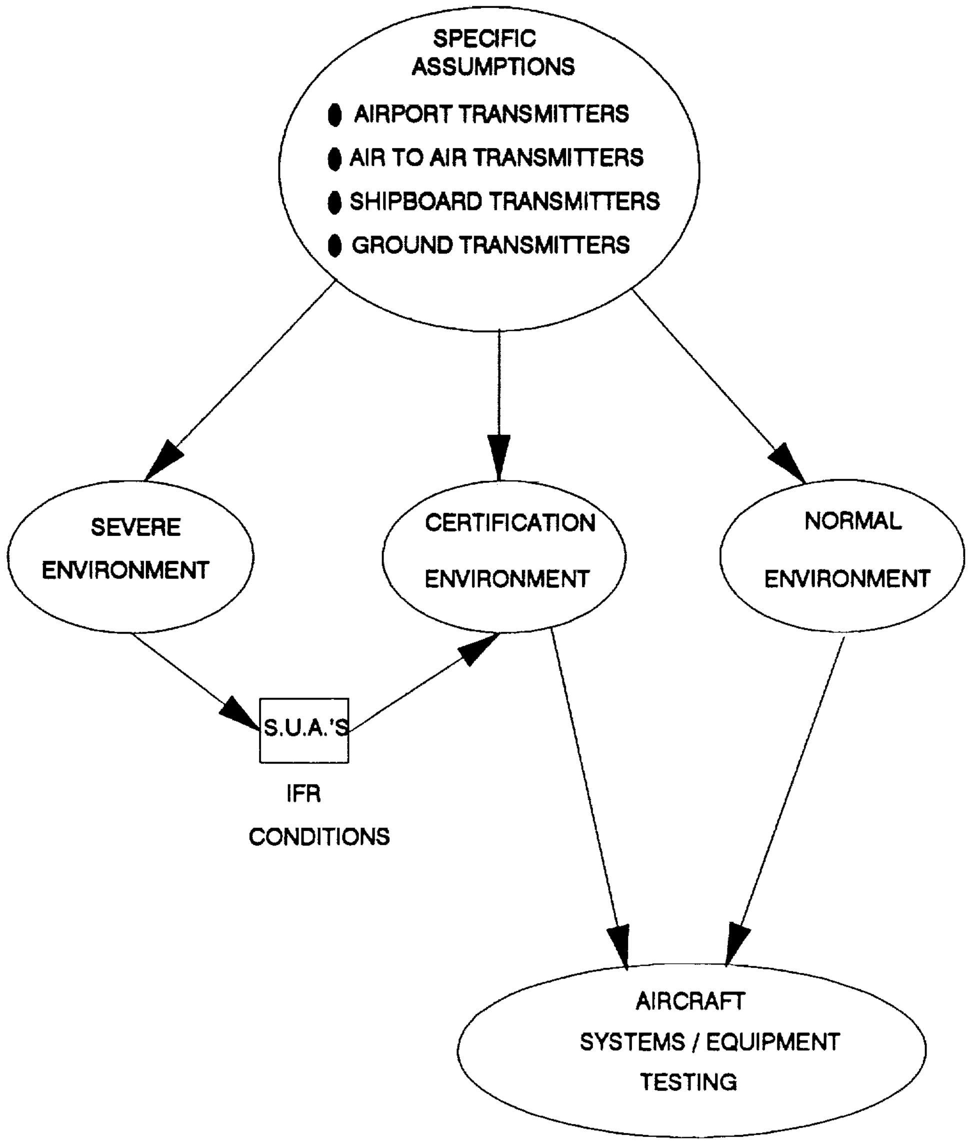

Figure 4-2 Specific Assumptions Defining HIRF Environment

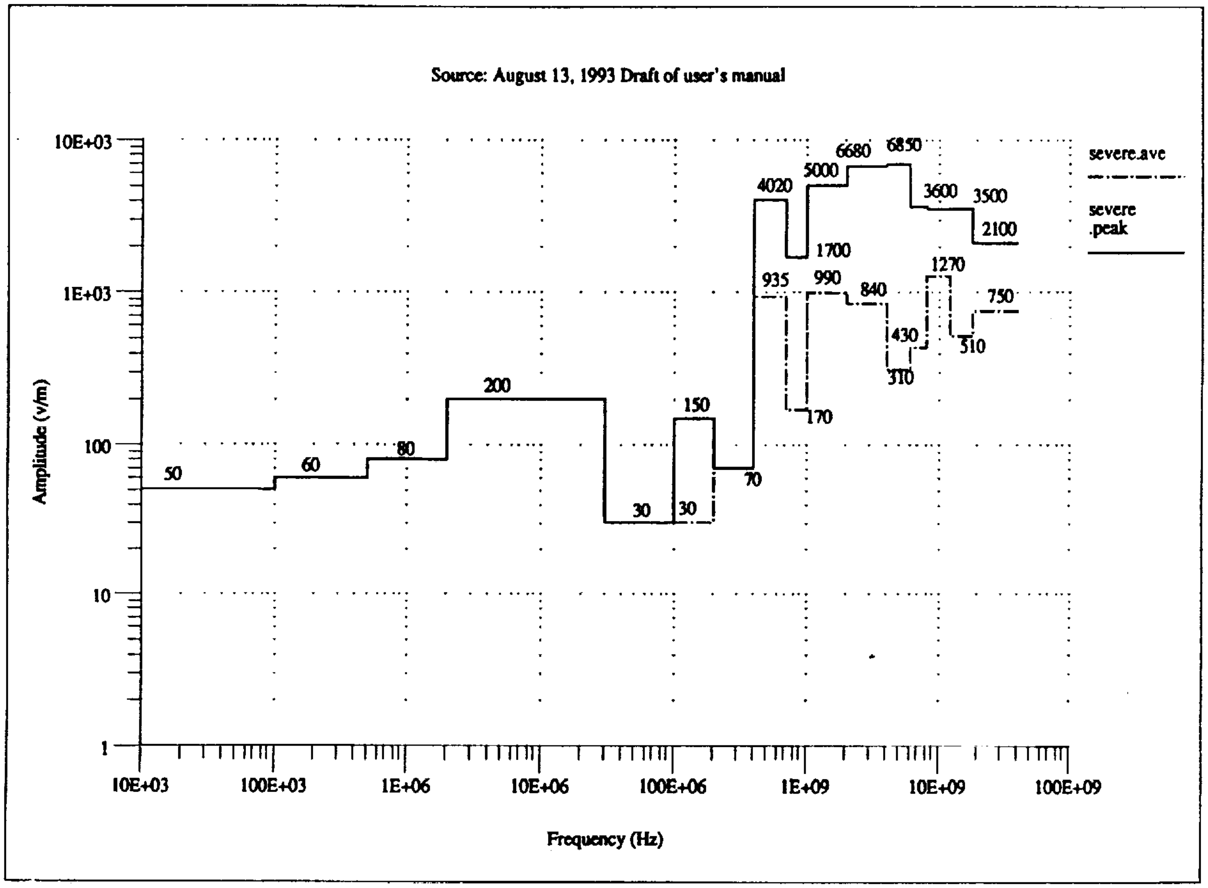

Figure 4-3 Severe HIRF Environment

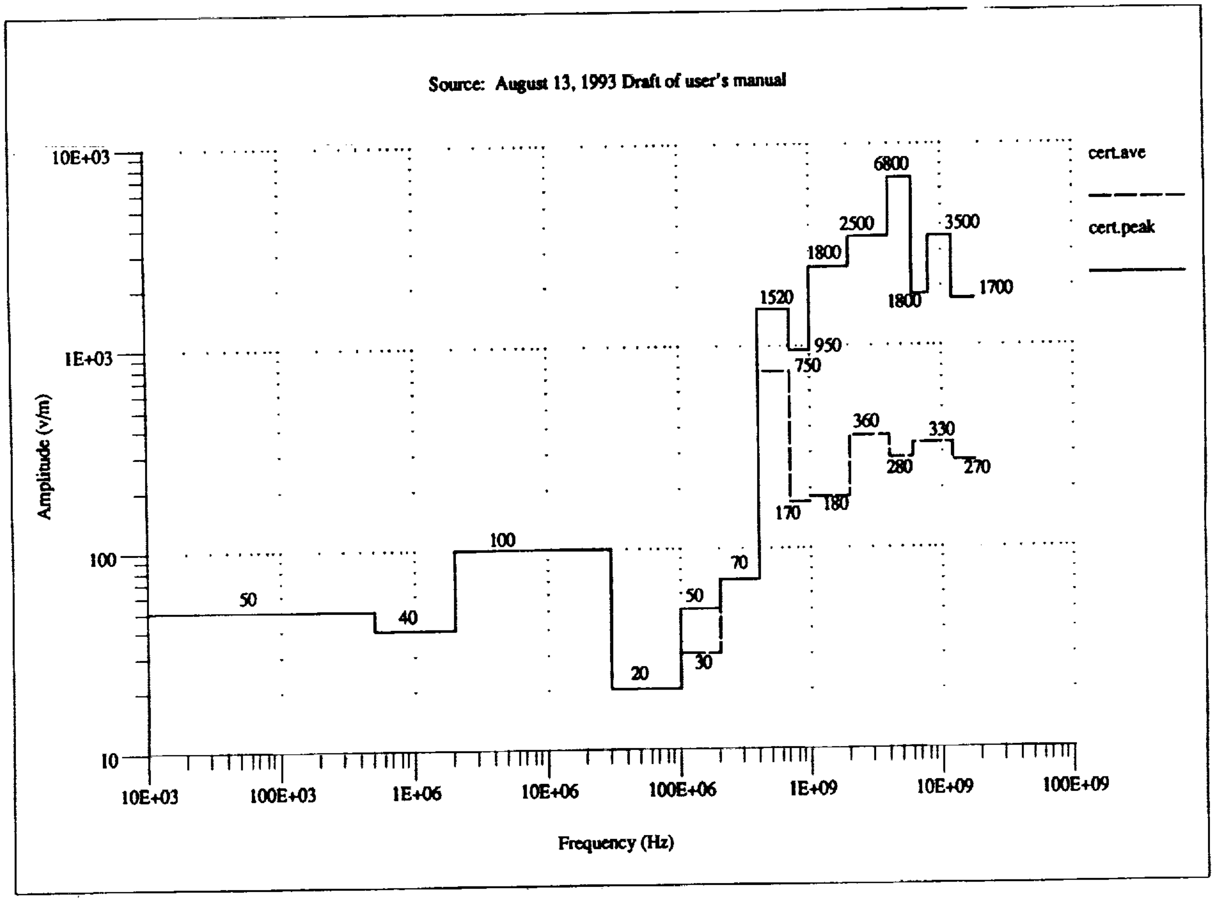

Figure 4-4 Certification HIRF Environment

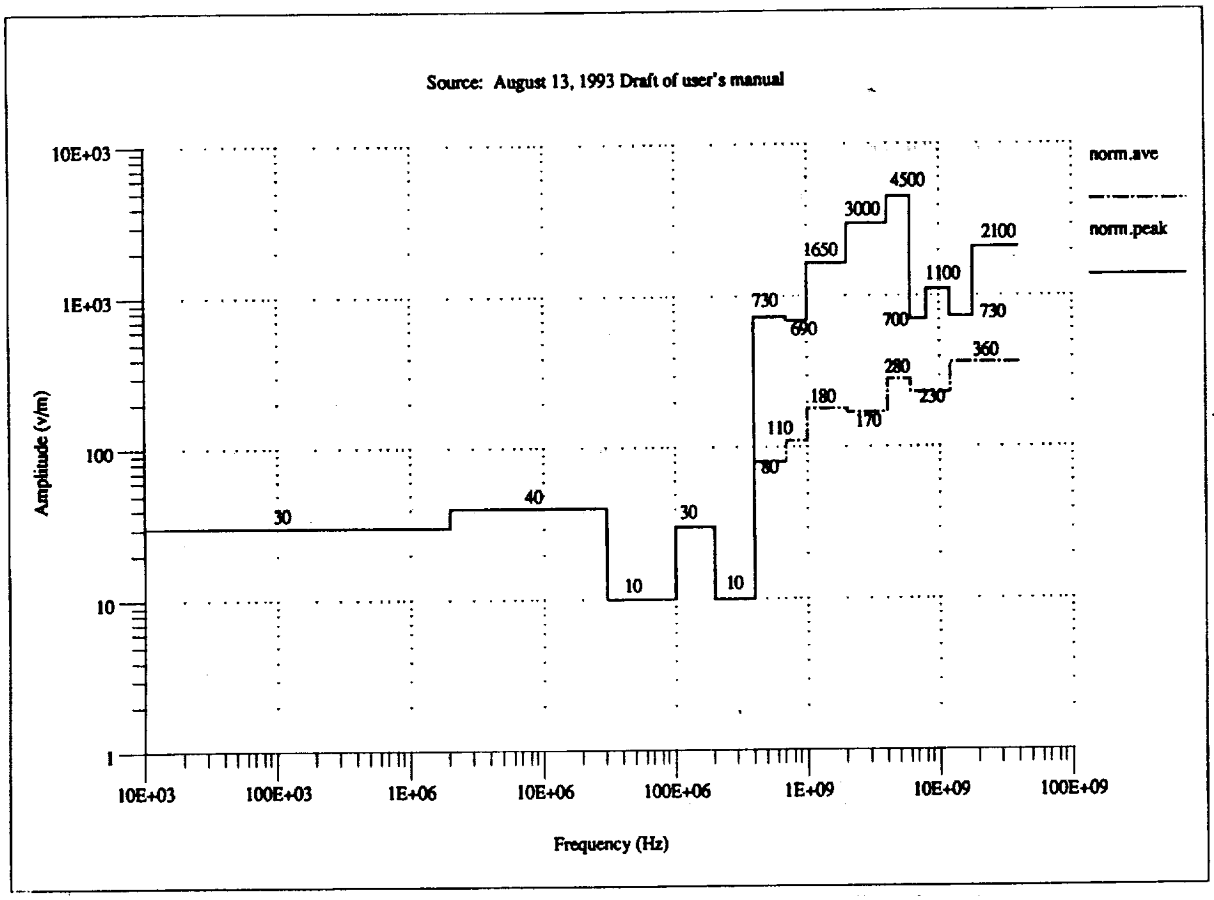

Figure 4-5 Normal HIRF Environment

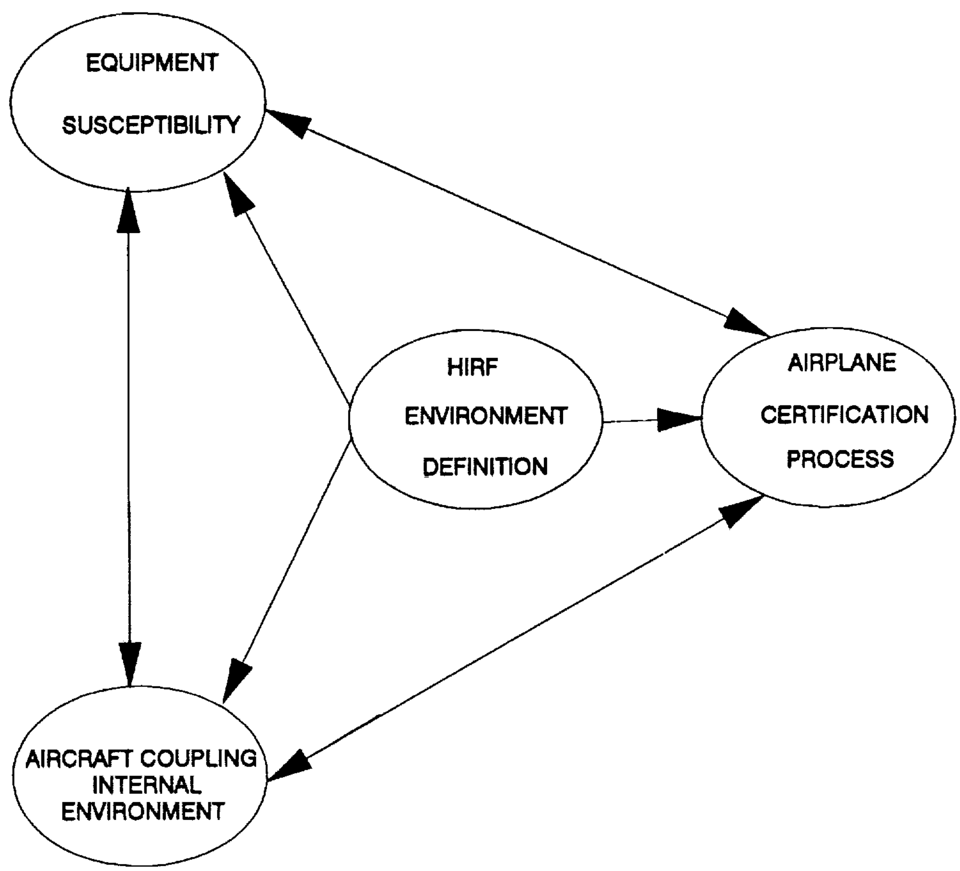

Figure 4-6 HIRF Environment Drives Certification

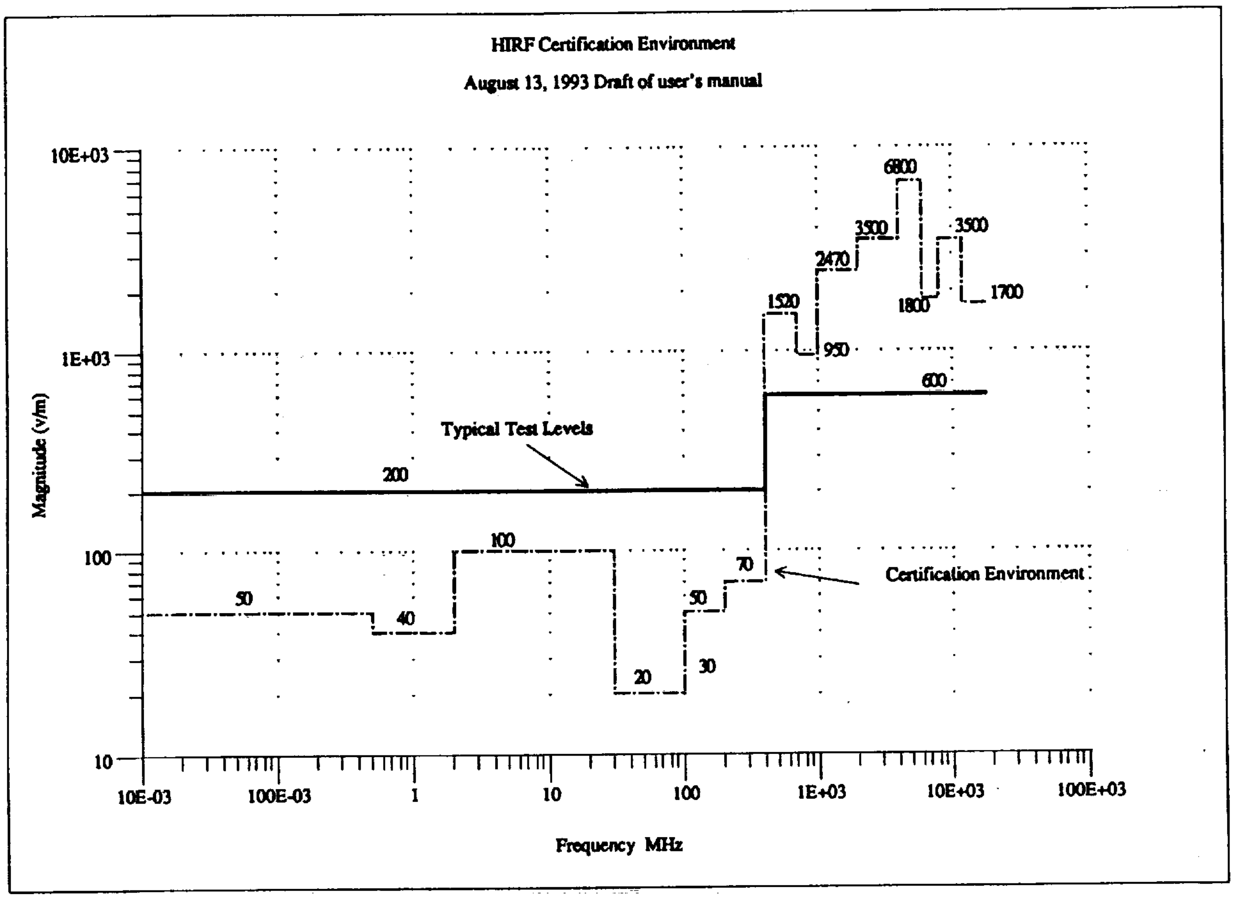

Figure 4-7 Typical Bench Test Levels Vs Environment

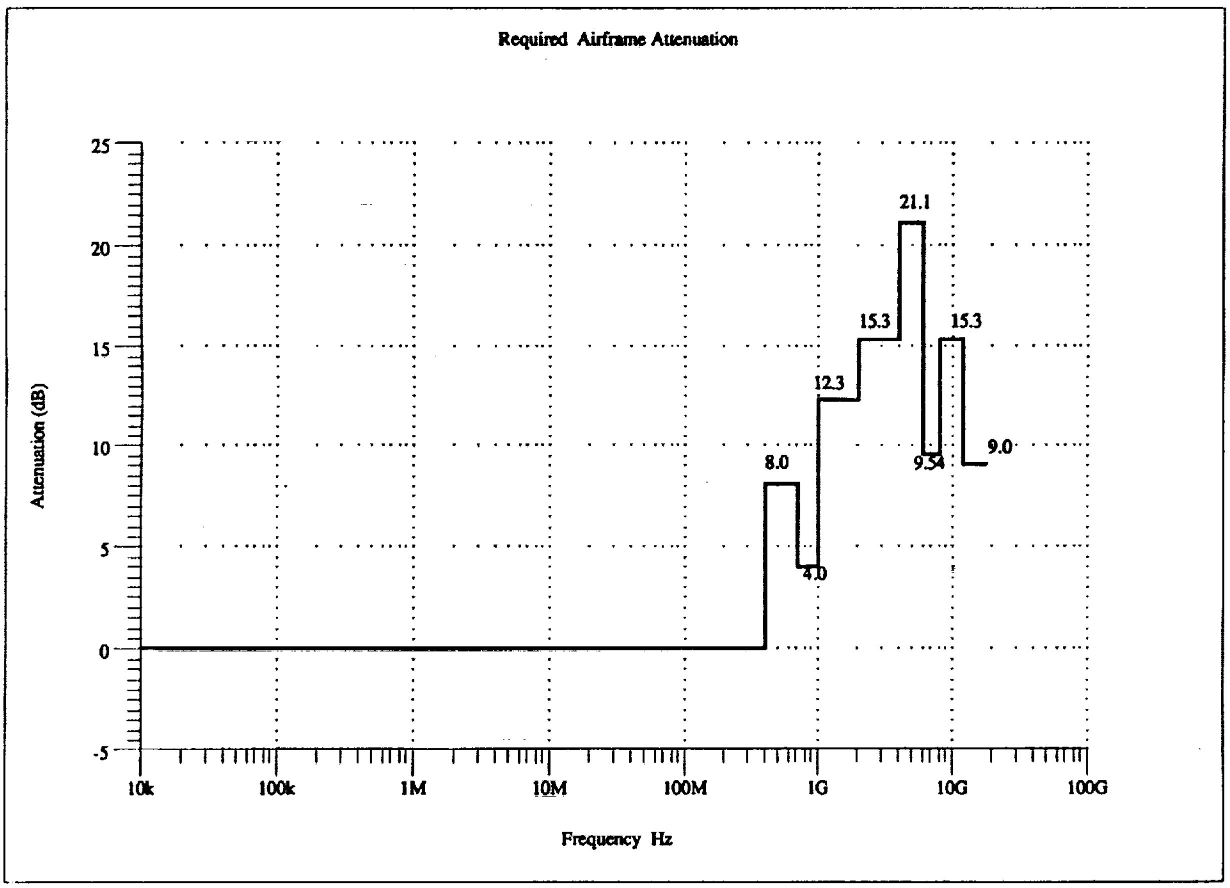

Figure 4-8 Typical Airframe Attenuation Requirements

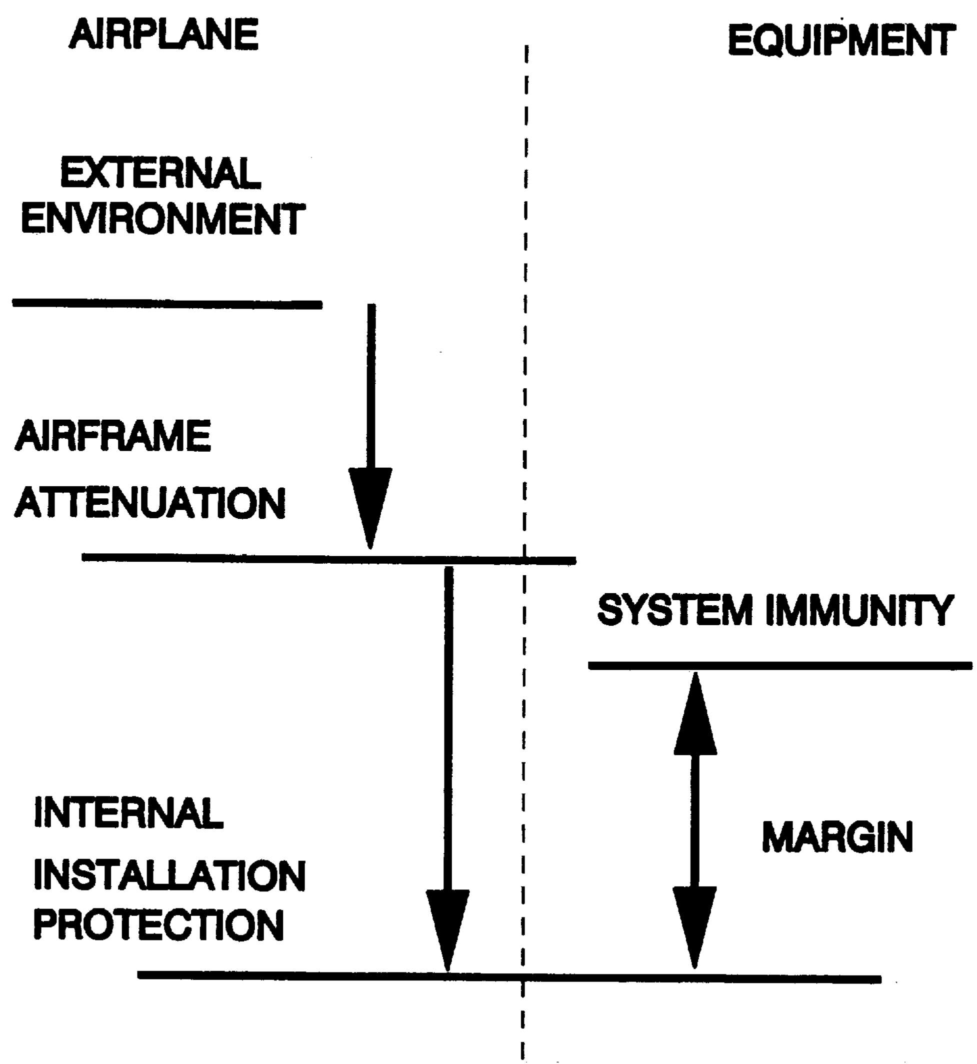

Figure 4-9 Driving Factors Determining HIRF Protection Margins

5.0 AIRCRAFT COUPLING/INTERNAL ENVIRONMENT

As discussed in section 4.2, HIRF aircraft attenuation requirements are based on worst case external HIRF threat levels and equipment susceptibility test levels. A rational basis for creating a consistent certification process requires several currently missing elements. First a uniform definition of the HIRF environment should be provided and as importantly, the probability of encountering this environment ascertained. Second, equipment level susceptibility tests requirements should be determined that are consistent with the aircraft internal HIRF environment. Standards should be revised to depict requirements based on rigorous technical knowledge and judgment. This requires a combination of deterministic and statistical analyses to assess the component response to the highly variable fields excited within the aircraft by the external HIRF environment. Finally, a consistent aircraft attenuation response may be assessed by taking the ratio of an internal field measurement (statistically determined where appropriate), with respect to an operationally defined external reference field measurement.

Assessing the attenuation properties of an aircraft to the external HIRF environment has become increasingly important with the advent of FBL/PBW aircraft and the potentially vulnerable critical electronic systems. In addition, there is concern for aircraft structurally conFigured with lower conductivity composite materials suggesting reduction of the airframe shielding effectiveness. Investigating fields excited within airframe cavities due to incident plane waves is a complicated problem to unravel. Experience has shown that alternative test methods are required in different test article configurations, and that a realistic HIRF assessment of an aircraft requires a combination of test and analysis. It is the purpose of the following section to propose how test and analysis may be used to provide a HIRF attenuation evaluation of an aircraft.

Several factors contribute to the difficulty in evaluating internal aircraft coupling to the external HIRF environment over the 10 kHz to 18 GHz certification frequency range. While in principle full threat level testing of an aircraft can be performed, such tests are expensive and performed long after aircraft completion thereby increasing the risk for re-design and retrofit. Therefore, in the certification process, the airframe manufacturer usually favors a combination of equipment bench level testing, low level swept frequency (LLSCW) and low level direct drive (LLDD) tests to assess aircraft vulnerability to the HIRF environment.

Furthermore, the structural complexity of the aircraft and its coupling to the test environment mandate the development of analytical tools not only to optimize airframe design with respect to HIRF protection but, along with test, to adequately evaluate the response of the internal environment to the external threat. To correctly perform this assessment, the assumptions made in performing equipment level susceptibility tests should be consistent with those used in the test design for airframe level attenuation evaluation. The current basis for setting requirements has lead to the development of an overall process that tends to compound worst case requirements. For example, there is evidence to suggest that aircraft flying through the HIRF environment expose on-board electronics to a mode-stirred field distribution. Laboratory susceptibility tests, on the other hand, are performed in fixed field level static configurations for which any dynamic cavity response simulating for example aircraft motion in the HIRF environment, is neglected. Consequently, it is incumbent on test and analysis to define a functional relationship between equipment level testing and airframe attenuation tests that more realistically represents the coupling of the external to internal environment. A consistent certification process may not be possible until this relationship is realized.

Section 5.1 of the following gives an overview of attempts to assess the field attenuation by an airframe. Two principal test techniques, standard low level swept continuous wave (LLSCW) and mode-stirring are compared in section 5.2. Between 400 MHz and 18 GHz, the mode density is sufficiently high to warrant a statistical approach over the usual deterministic modeling of the fields excited in certain airframe cavities. Section 5.3 discusses recent attempts to statistically model these fields, whereas it is argued in section 5.4 that recent mode-stirring test results can be used to assess these statistical models. Section 5.5 conveys a means by which appropriate test and analysis may provide a rational basis for establishing HIRF protection margins and protection performance.

5.1 Overview of Analytical Tools and Test Methods

Using low level fields to evaluate the attenuation of an airframe is based on the assumption of linear scaling to a full threat level. The HIRF certification environment increases dramatically above 400 MHz as does the excited mode density within aircraft cavities. The combination of bench level testing and aircraft low level swept continuous wave (LLSCW) testing is the preferred route to compliance. The following is a brief overview of the predominant test and analysis methods currently used to assess airframe attenuation and the attendant internal field response. These are provided to reveal options that not only support design against the HIRF threat, but also give a physically based rationale for establishing consistent requirements addressing HIRF.

Evaluating the many methods of HIRF analysis [16-18] indicates there is no single methodology or HIRF code that adequately assesses airframe attenuation to HIRF across the full 10 kHz to 18 GHz frequency threat spectrum. Indeed, the complexity of the HIRF and airframe interaction precludes using a single spatial point response function to deterministically represent HIRF attenuation throughout the entire aircraft or within an aircraft section over the full spectrum. The concept of a statistically based HIRF assessment has not been fully integrated into analytical approaches currently used to model HIRF response functions. A limitation of the deterministic approach is particularly apparent in the difficulty of modeling efforts to adequately interpret the variability of HIRF attenuation data and the high sensitivity to airframe configuration and orientation. In addition, predicting airframe attenuation levels and attendant coupling to internal cables and devices is computationally demanding and as yet very approximate over certain threat frequency intervals.

A consistent HIRF certification process will be possible when analysis is sufficiently sophisticated to correlate airframe attenuation in the HIRF environment to the simulated HIRF test environment. Furthermore, equipment level testing localized in the laboratory can be reliably compared to the internal airframe level measurements only when basic assumptions and test conditions are thoroughly analyzed and understood. For example, equipment level tests for critical functions are performed in the antenna near field at e.g. 100 volts/meter below 400 MHz and referenced to a near field measurement within the reverberation or anechoic chamber, whereas airframe attenuation tests are performed in the antenna far field, referenced to a calculated or open field measurement. By open field is meant a measurement at the approximate receive antenna position, but without the airplane in place. These two test scenarios are not consistent with the actual dynamic response that pervades an airplane exposed to the HIRF environment.

It remains a challenge as to how to correctly relate the worst case HIRF certification environment to the probability of equipment upset or damage as assessed from a combination of bench level testing and calculated and/or measured airframe attenuation. There is an apparent disconnect between present HIRF vulnerability requirements and reality as illustrated by the fact that third generation aircraft are in operation with fly-by-wire engine controls tested to 20 v/m, well below the HIRF threat less some reasonable assumption for nacelle attenuation, yet no incidents have been documented.

5.1.1 Analytical Tools Used to Assess HIRF Attenuation and Response

A number of analytical tools and computer codes are currently being applied in a quantitative and qualitative evaluation of airframe cavity and cable response to HIRF. Principal methods include those based on method of moments codes, transmission line codes, finite difference time domain codes, finite element codes, analytically closed form models, and probabilistic models.

Method of moments frequency domain codes are used in the wire grid modeling of aircraft surfaces and cables. Their primary application to HIRF studies is to calculate induced surface currents on the aircraft excited by an incident plane wave. Their limitations are largely frequency dependent. The wire segments are required to be less than a sixth of a wavelength making models exceedingly large and the computer requirements excessive for high frequencies and sizable objects. The software is restricted to conducting elements and cannot model dielectric structures. The upper frequency limitation is determined by the length of one-sixth wavelength relative to airplane dimensions or approximately 50 MHz for a large transport aircraft.

Frequency domain transmission line codes were for the most part originally developed to study EMP and subsequently applied to evaluate lightning effects on aircraft. They are used to model cable currents, through-braid couplings, electrically small apertures, conductors and dielectrics, and in general any configuration where transmission line analysis is valid.

Finite difference time domain (FDTD) codes have been developed to numerically solve the Maxwell equations employing finite difference techniques. They incorporate material properties and therefore are applicable to bodies comprised of conductors and dielectrics of a variety of geometric configurations. FDTD models are capable of modeling cable currents, cavity resonances including the effects of apertures, surface currents, and the corresponding transfer functions. They are limited by requirements on the finite difference cell size which must be less than a tenth of a wavelength along a given Cartesian direction, and therefore can be demanding code to run in terms of computer time and memory requirements. For a commercial aircraft, these considerations currently limit the applicability of these codes to less than approximately 200 MHz.

Finite element modeling (FEM) with boundary integral (BI) or absorbing boundary conditions (ABC) can be applied to HIRF studies to calculate induced surface currents or internal fields of the aircraft excited by an incident plane wave. This method yields either a large sparse matrix (FEM-ABC) or a combination of sparse and dense matrices

(FEM-BI). In either case dielectric structures can be modeled. As with straight method of moments techniques, this method is limited by relative wavelength to airplane dimensions, or to frequencies less than 100 MHz for large transport aircraft.

Analytically closed form models solve the Maxwell equations in the frequency or time domain within simple geometries such as rectangular, spherical, or cylindrical cavities. Apertures can be included, as well as loss mechanisms and dielectrics by incorporating an effective (phenomenologically determined) damping factor. These models provide field distributions within a cavity excited by an incident plane wave, and can model cavity resonances and cable currents. Models become computer intensive with the increase in frequency, but can be easily run on PCs and workstations. Results to date qualitatively match measured transfer functions from testbed tests.

Each of the above methods finds application over some well defined frequency range and for geometric configurations representing an aspect of the airframe electromagnetic field interaction. Nevertheless, they are deterministic and as currently configured are limited in their ability to predict the highly variable fields that are measured in the complex cavities occupied by aircraft electronics and critical systems. This observation underscores the need to extend traditional analytical approaches by incorporating probabilistic (or stochastic) and statistical methods into the analysis of HIRF data; the former to develop predictive tools based on probabilistic concepts, the latter to better assess the highly variable HIRF test data sets and their relationship to the HIRF environment. Statistical methods have been applied to airframe HIRF attenuation data reduction and thereby assess the overall electromagnetic characteristics of HIRF excited cavities. This will be discussed in detail below.

The above approaches each contribute to a better understanding of how the external HIRF environment excites the internal fields produced at the local equipment level surroundings. Analysis coupled with test may also impact present HIRF environment assessment and result in more realistic HIRF certification requirements than the worst case scenario now in place.

5.1.2 Test Methods used to Evaluate HIRF Aircraft Coupling

Test methods suffer from similar limitations ascribed to analytical methods discussed above in assessing how the external HIRF environment correlates with the local equipment level electromagnetic field environment. A reliable test methodology must address the questions of data variability and sensitivity to test configuration referred to above. To do so requires that the assumptions and conditions leading to given test results be clearly delineated in addition to their linkage with analysis.

There are five principal methods of measuring the internal coupling of aircraft cavities to externally impressed fields. These test methods have been applied over restricted frequency ranges dependent on test equipment or test methodology limitations. Included among candidate techniques are high level pulsed power tests, low level swept continuous wave (LLSCW) tests, low level direct drive (LLDD) tests, low level mode-stirring (LLMS) tests, and narrow band gaussian noise (frequency-stirred) tests. A brief description of each method is given in the following, with a more detailed account of the latter three provided in the subsequent section.

High Level Pulsed Power Tests

High level pulsed power tests are performed at fixed selected frequencies in the 400 MHz to 18 GHz frequency range. Equipment susceptibilities are monitored as the aircraft is exposed to the full threat level fields from several directions. They are expensive to conduct, the exposure area is small, current tests are performed at spot frequencies, and the number of test facilities is limited.

Low Level Direct Drive (LLDD) Tests

Low level direct drive testing is normally performed between 10 kHz and up through the first few airplane resonances, e.g. 30 MHz. The excitation is by current injection onto the exterior fuselage. The external surface currents and the internal cable currents are measured and the surface current to internal cable current transfer function is evaluated. The surface current is calculated from the external field using a method of moments code. Combining the measured and calculated transfer functions determines the field to wire transfer function.

Low Level Swept Continuous Wave (LLSCW) Tests

The conventional method for assessing the attenuation characteristics of aircraft to HIRF in the 200 MHz to 18 GHz range is the LLSCW test technique as represented in Figure 5-1. The procedure is to first measure the electric field at a reference point in space with the aircraft absent. The measurement is repeated with the aircraft in place within the test site and the antenna positioned at the reference point within the airframe, engine nacelle, or other component. The ratio of the measurements defines a transfer function and a corresponding attenuation of the external field. Measurements are typically performed over the 200 MHz to 18 GHz range partitioned into frequency bands. The external transmit antenna is usually fixed in position as is the receive antenna for a given test although both vertical and horizontal polarization responses are measured. In practice electric fields are ordinarily measured. Magnetic field measurements can be performed but are difficult above one GHz due to the paucity of suitable receive sensors. Electric field measurements are position and polarization sensitive and are highly variable as a function of frequency. Figure 5-2 is a typical LLSCW flight deck measurement. Many of the peaks are interpreted as effective cavity resonances due to overlapping cavity modes excited by the impressed field. Composite Q factors associated with these resonances increase as the square root of the frequency and ordinarily vary from as low as 10 or 20 below one GHz to over a thousand above six GHz. Evaluating the importance of resonances is an unresolved issue. Contemporary post processing techniques have focused on frequency smoothing routines, spatial averaging, and spatial maxima envelope fits to deal with the resonant structure and the associated data variability. However, there is not as yet an agreed upon procedure to represent airframe attenuation.

Low Level Mode-Stirring (LLMS) Tests

A recent addition to low level continuous wave test methodology is the adaptation of mode-stirring for assessing aircraft attenuation to external fields. The test configuration adapts reverberation chamber techniques to conform to the LLSCW methodology previously discussed. Figure 5-3 is a schematic of one possible test scenario based on the LLSCW test system suitably modified to accommodate mode-stirring software and controls. Alternative systems have been developed that use the peak-hold characteristics of a spectrum analyzer to obtain attenuation data.

The principle of the method is to measure the fields at a fixed location in the cavity at a fixed radiated frequency as the stirring paddle cycles through one revolution. The paddle is designed to perturb the fields within the cavity so that during one revolution all possible amplitudes and phases for excited modes pass though an arbitrary point in the cavity, sufficiently separated from the conducting walls. The receive antenna measures the cavity fields at equally spaced rotation angles of the paddle. From these field levels and the measured reference field, the airplane attenuation is calculated. The number of paddle positions required for acquiring data is suitably large to statistically sample the fields. The peak, mean and minimum attenuation are calculated at each frequency as well as other statistical measures of the cavity response. Success criteria and test antenna configuration requirements are the same as those for mode-stirred chambers. The response function becomes insensitive to receive antenna polarization and position with the increase in frequency and attendant increase in mode density. A typical cavity response is shown in Figure 5-4. Since the response of the antenna within the cavity is approximately isotropic, reference measurements are made with respect to a low directivity antenna and with ground reflections averaged out to obtain a consistent attenuation factor.

A related technique [13] that does not rely on the use of a stirring device is the band-limited gaussian noise or frequency stirred method. The principle of the method is to use gaussian band-limited noise to modulate the radiated carrier frequency when illuminating the test object. The radiated signal excites many modes over the bandwidth of the noise source in the test object to create a real-time, homogeneous field distribution. In contrast, mode-stirring creates a time averaged, homogeneous field distribution by using a mechanical stirrer and statistics. The result of frequency stirring provides the average power distribution in a cavity and is approximately the same as the mode-stirred average transfer function. This methodology may find use in statistically accessing the fields for those frequencies and geometries not suitable for mode-stirred methods. Frequency stirring is finding development in reverberation chamber work, and has recently been applied to attenuation tests and does hold some promise.

As with the assessment of analysis methods, several issues are paramount with regard to the acquisition and interpretation of HIRF attenuation data. It is evident that different techniques apply to different experimental situations and airframe configurations. No single method provides a global HIRF attenuation evaluation of the aircraft. While mode stirring is superior to LLSCW spatial mapping of the fields in cavities of sufficient size and excited modal density, it is limited by the size of the stirring paddle and the associated frequency range for which the stirrer is functional. LLSCW or possibly frequency stirring techniques are alternatives that may be required for low level evaluation of, e.g. an engine cowl. Furthermore, as illustrated with the LLDD test method, a combination of test and analysis may be required to evaluate the HIRF attenuation for a particular configuration.

5.2 Low Level Swept Frequency Test Compared to Mode-Stirred Test

The above brief description of LLSCW and LLMS test methodologies gives the essential characteristics of the two test techniques. Figure 5-5 shows swept frequency data and mode-stirred data on the same plot for measurements between 9.5 and 10.5

GHz as performed on an airframe testbed flight deck. The swept frequency data is bounded by the mode stirred minimum and maximum attenuation across the band of frequencies and varies on average about the stirred mean. This is typical for measured responses above one GHz and except for isolated frequency intervals involving dominant modes, also represents the response between 400 MHz and 1 GHz. Mode-stirred test statistics provide auxiliary information on the attenuation properties of an aircraft cavity. In addition, experience with the two test methods suggests the following comparison.

Mode-stirred test times per frequency point are comparable to those for swept frequency tests. However, as can be seen from Figures 5-6 to 5-9, mode stirring is less sensitive to receive antenna polarization and position than the swept frequency method especially above one to two GHz. Figure 5-6 is a swept frequency measurement in which the receive antenna is displaced from its default position by 2.5 and 5 cm respectively. The response is seen to be position dependent. Figure 5-7 is an average mode-stirred measurement in which the receive antenna has been displaced several feet. The position dependence is not evident especially when distribution functions from data obtained at two different locations are compared. A similar conclusion can be drawn from Figures 5-8 and 5-9 which compare typical responses with the receive antenna polarization changed. To statistically access the equivalent data (i.e. determine minimum and average attenuation in the cavity at the specified frequency) with frequency swept methods would require position mapping of the cavity attenuation properties in addition to changing the antenna polarization. Such test procedures increase test time significantly.

Mode-stirring tests generally exhibit superior repeatability characteristics over time and lower data variability than swept frequency methods. More importantly, however, preliminary calculations indicate they present a test configuration that approximates the internal environment that evolves when a moving aircraft is exposed to HIRF.

Two limitations associated with using mode-stirred techniques on an aircraft include accessibility in certain test configurations, and measurements in the vicinity of walls. HIRF testing within, e.g. engine nacelles, is challenging using mode stirred methods for two reasons. First, fitting a suitable stirrer and antenna within such a cavity may not be possible. The stirrer must have dimensions on the order of half the longest test wavelength of interest. For alternative test configurations, this may restrict the use of mode stirring to frequencies well above one GHz. The second limitation is a consequence of requiring the receive antenna to be at least a third of a wavelength from the cavity walls. Wire bundles or other equipment within or near the walls would be outside the purview of mode-stirring methodology except for the highest frequencies, e.g. above 6 GHz.

Finally, one issue not fully resolved is the choice of the Figure of merit to represent airframe attenuation from the mode-stirred data base, that is, the average versus the minimum attenuation. Choosing the minimum attenuation would further compound the sequencing of worst case requirements. Such a choice is not necessarily well founded in that these numbers are in the extremes of the corresponding attenuation distribution. It is apparent that until each factor contributing to the HIRF threat is rationally determined beginning with the environment definition down to equipment level susceptibilities, the choice will remain problematic.

5.3 Cavity Mode Distribution Statistics

There has been considerable activity in recent years investigating the modal structure of complex cavities as excited by incident electromagnetic waves. A deterministic analysis of the cavity mode distribution is difficult except for the simplest geometries, i.e., spherical, cylindrical, and rectangular cavities. Consequently, non-deterministic or statistical approaches have been implemented to investigate those cavities and frequency ranges for which the mode density is sufficiently high, and for which loss mechanisms are present but do not overdamp the modal structure. Current theories indicate that for complex cavities and high mode densities, the power measured at a randomly selected point has a statistical distribution that is independent of the detailed geometry of the cavity. If this is the case, then similarity principles can be used to correlate the response of an LRU in a mode-stirred chamber with the statistically analogous internal field within an airframe cavity. This may resolve the current conundrum of relating laboratory susceptibility measurements to airframe internal field response functions, at least for continuous excitation. The question of pulse excitation remains open, however.

A modal description of a cavity is useful for assessing possible interactions with internal electronics and wiring, the field levels within a cavity and their distributions, interpreting low level continuous wave or mode stirred test results, and in relating frequency and spatial averaging of the fields within the cavity.

A statistical analysis of cavity electromagnetic response data provides a number of useful insights. First of all it is a method for sorting and evaluating the large and highly variable data base presented by swept frequency and mode-stirred tests. This method affords a means of comparing airframe attenuation statistics with reverberation chamber and theoretical cavity models. Random sampling from an empirically determined distribution provides with some level of confidence a possible cavity response. Consequently, should theoretical models match experimental distributions, they contribute a predictive tool to assess airframe attenuation. Furthermore, an analysis of the distribution functions may establish a relationship between frequency and spatial averaging procedures. This is particularly important to mode-stirring test interpretation where a statistical relationship exists between the mode-stirred response distribution and a spatial map of the cavity fields.

Historically speaking, early attempts to model cavity resonance distributions can be found in the work of H. Weyl in his investigations of the electromagnetic mode density within a rectangular cavity. Recent research specifically directed to modeling the modal distribution functions for complex cavities of arbitrary shape includes papers by Miller and Lehman [6], Avallo, et. al., [5], Kostas and Bovarie [7], Lehman [8], Price, et al,. [9], and Holland and St. John [10]. The following will summarize the most important of these models, their assumptions, limitations, and predictive aspects, and how they can be applied to assess HIRF levels in aircraft cavities.

5.3.1 Theoretical Distributions

Current statistical theories addressing the excitation of electromagnetic modes within complex cavities are based on four principal assumptions:

(1) The cavity is electrically large so the mode density is high.

(2) The cavity does not have apertures.

(3) The cavity is of complex shape for sufficient randomization of the fields.

(4) The cavity is lossy but has well defined resonances with reasonably large resonant Q values.

Within the context of these assumptions Lehman and others have derived probability density functions for the power loss distribution within a complex cavity. The power loss, p, is defined to be the ratio of the square of the internal field to the square of the external field without the airplane present (figure 5-1). The conventional theory for the cavity mode distribution at a fixed excitation frequency yields a chi square of two degrees of freedom. In a mode-stirred experiment this would correspond to the fields measured over one paddle revolution and would represent a temporally derived spatial distribution. When transformed to power units in dBm their result becomes:

$$f_{\mathbf{p}}(p) = (1/\beta)\, z(p)\, e^{-z(p)}$$

$$z(p) = e^{[(p-\underline{p})/\beta\, -\, \gamma]}$$

p = power loss (dBm) $\qquad$ $\underline{p}$ = average power loss (dBm)

$\beta = 10/\ln(10) = 4.343$ $\qquad$ $\gamma = 0.5772...$ = Euler's Constant

This is the simplest version of the statistical theories, nevertheless it illustrates most properties of the theoretical distributions and has been applied with some success to power loss distributions in reverberation chambers and airframe electronics bay cavities. It is a single parameter distribution requiring only the mean cavity energy density at a given frequency or over a frequency interval.

5.3.2 Theoretical Statistical Analyses

Limitations to the applicability of the above distribution to evaluating airframe attenuation to HIRF include the assumptions of no apertures and high modal density. Regarding the latter assumption, it is expected that experiment and theory will converge at higher frequencies as the cavity modal density (modes per unit volume) increases with the third power of frequency. At lower frequencies, determined by the ratio of the cavity dimensions to wavelength, e.g. 400 MHz to 1 GHz in an airframe electronics bay, corrections to the theoretical distribution incorporating higher statistical moments will be required. Such a theory has not as yet been developed.

An essential ingredient to a fully developed airframe model must include the effects of apertures. Whereas the complex cavity assumptions of Lehman and others explicitly neglects apertures in assessing a distribution function for cavity fields, to do so would comprise incorporating the respective conditional probabilities to evaluate internal field distributions as excited by an external source. At high frequencies model distributions fit empirical distributions regardless of apertures. General criteria for this observation have not been developed since the correlation must break down for apertures having sufficiently large cross sections compared to cavity total area. Furthermore, although theoretical models converge to the chi square distribution, other model distributions have been proposed [9,10] and arguments presented for their validity. The issue is not resolved.

5.4 Cavity Mode Distribution Experimental Results

Determining the statistical distributions for LLSCW or LLMS data reveal trends not apparent from raw data sets. Statistical distributions are an alternative means for comparing highly variable and complex HIRF attenuation data sets for other possible test configurations. In addition, the efficacy of statistical model predictions can be assessed from these data sets as a function of frequency and test configuration.

Mode-stirring experiments are particularly suited to evaluating the statistical properties of complex cavities. The collection and interpretation of mode-stirred data is fundamentally a statistical procedure. Stipulations that fields in a mode-stirred environment are uniformly distributed, or that measured response functions are independent of receive antenna polarization or position, are predicated on a statistical assessment of the data at a fixed frequency or over a frequency interval. As the stirrer revolves through one cycle, the field measured at an arbitrary point in the cavity (sufficiently removed from the walls) ranges over the possible amplitudes and phases of modes that are excited in the cavity at the excitation frequency.

In the statistical sense, and within certain uniformity bounds, a field mapping of the cavity is determined at a single receive antenna position. For this to be true, it is required that the cavity be electrically large compared to the excitation wavelength to ensure that a sufficient number of modes are excited; the cavity must support relatively high Q resonances so that the mode density is comprised of distinct, albeit effectively broadened modes. These are criteria for which the above statistical analysis is deemed to be valid.

Mode-stirring attenuation tests have been performed on a non-production forward fuselage testbed in part to verify the above assertions. Measurements were made with the test configuration shown in Figure 5-3. Results are for mode-stirred transfer function tests performed on a stripped electromagnetically shiny flight deck referenced to an external open field measurement performed with the airframe removed. The flight deck is not a completely closed cavity in that window apertures are present. The test configuration is representative of a possible airframe HIRF attenuation evaluation set-up. However for the reasons discussed above, the magnitude of the transfer function data is only approximate. These tests in part validated mode-stirring as a methodology for assessing airframe attenuation. The following results will illustrate several of the assertions made above concerning the statistical field distributions within the airframe cavity.

Figures 5-5 and 5-10 are typical mode-stirred measurements between 9.5 and 10.5 GHz and between 0.5 and 1.0 GHz respectively. The maximum, mean, and minimum attenuation are calculated at each measured frequency in the band. Figures 5-11 and 5-12 represent the probability density and cumulative probability curves for a single paddle revolution measurement at 9.75 GHz compared to the above theoretical prediction. The chi square goodness of fit test is satisfied to the ninety-nine percentile indicating the model distribution matches at these high frequencies regardless of the presence of cavity apertures (in this case windows of dimensions larger than a wavelength). The model distribution function does not fit the data as well at lower frequencies indicating higher order moments to the distribution may be required to obtain a suitable fit or another model formulated. Figures 5-13 and 5-14 compare the respective distributions at 0.901263 GHz where it is evident the goodness of fit tests are not satisfied.

Several factors contribute to the observed differences between fits at high and low frequencies. The two most important concern the increase in modal density with frequency and the attendant increase in effective Q values with frequency. For a rectangular cavity the mode density (modes per unit volume) increases proportionally with the cube of the frequency. A similar functional relationship can be shown to be true for the complex cavity examined here. Furthermore, Figure 5-15 is a plot of the average experimental Q determined from resonance structure between 1 and 18 GHz. This function increases with the square root of the frequency. Criteria for the validity of the rudimentary single parameter model distribution are met with the increase in frequency, however it is also apparent that below several GHz the statistical theory is not adequate and must be extended. Similar conclusions can be drawn for mode-stirred data representing polarization and position independence which is again verified with the increase in frequency and consequent statistical field uniformity.

5.5 Implications of Coupling Test and Analysis

A number of challenges exist in using test and analysis to determine the HIRF compliance of an aircraft.

First it is essential that the assumptions that determine equipment level susceptibility requirements have a rational basis with regards to the HIRF threat. As discussed in section 6, specifications have been set either arbitrarily or with respect to a worst case HIRF environment definition. Consequently, present airframe attenuation requirements combined with equipment susceptibility requirements tend to compound the required airframe attenuation requirements and drive overdesign of the aircraft and, it follows, weight and cost.

Second, different airframe test configurations, e.g. flight deck versus engine cowl, will demand alternative test techniques to assess attenuation. Evaluating airframe attenuation with mode-stirring or narrow band gaussian noise techniques and the attendant statistics may be methods of choice over the 400 MHz to 18 GHz frequency range where mode densities are high. However, LLSCW or narrow band gaussian noise techniques may be required in configurations or frequencies not accessible to the mode-stirring methodology either because of spatial restrictions (no room for a stirrer), or too low a mode density.

Third, several options are available for expressing the fields in the internal environment and the respective attenuation. The fields may be referenced to either a calculated or measured open field value. Disadvantages of the latter scheme are related to the incorporation of extraneous environmental sources such as ground reflections which create false resonance structure, and there are inaccuracies associated with the former procedure. Airframe manufacturers typically reference internal fields to an externally measured open field with extraneous contributions such as ground reflections smoothed or factored out.

It should be recognized that attenuation is a conceptually complex quantity that depends on the conditions and assumptions used in its evaluation. The spatial variability of attenuation measurements reveal it is not, however, a single number indicative of an aircraft's ability to shield against HIRF. Both deterministic and statistical methods should be used to assess airframe attenuation. Deterministic methods may bound the threat in localized configurations, whereas statistical methods give a global assessment of the aircraft response to the external threat. Contrary to the assumptions of past analyses, a consistent HIRF certification process should incorporate a Figure of merit based in part on the statistical assessment of the HIRF attenuation response of an aircraft.

In summary, conclusions regarding how test and analysis that assess aircraft coupling of external HIRF to the internal electromagnetic environment which may provide a more reasonable HIRF certification process include:

Test:

1. The test method selected depends on the properties of the test configuration, and the frequency range. For example, LLSCW or frequency stirring may be chosen for testing within engine nacelles where spatial dimensions would prohibit effective mode-stirring except for the very highest frequencies. Mode-stirring or frequency stirring have attributes that would be advantageous in larger airframe cavities such as the electronics bay or flight deck in assessing airframe attenuation.

   Stirring methodologies may also provide a consistent statistical assessment of the cavity fields that both approximates the dynamics of the fly-by fields and the field distributions without the need to perform field mapping. The latter would be required using LLSCW methods to obtain equivalent data. Non-stirred LLSCW field mapping tests are time consuming, expensive, and useful only if appropriately performed in conjunction with modeling efforts so as to give a representation of the expected field distribution.

2. Full HIRF threat level aircraft tests are expensive, inadequate in their spatial and (for the forseeable future) frequency coverage, therefore it is advantageous to the manufacturer they be avoided.

3. A consistent attenuation assessment is possible if suitably characterized reference and receive antennas are chosen. It is recommended that low level tests be referenced with respect to low directivity antennas. A consistent process will incorporate a standardized method for establishing a reference. Based on the somewhat homogeneous response of the receive sensor within a complex airframe cavity, the corresponding directionality of the reference measurement must be factored into the attenuation, and spurious ground reflection effects and effects of responses of test configuration elements, identified and removed.

4. Fly-by tests of HIRF transmitters by production aircraft would provide data needed to validate code and test methods simulating external to internal coupling dynamics and thereby contribute to a rational basis for assessing attenuation requirements. Such tests would potentially verify the hypothesis that the internal fields excited by a HIRF source approximates a mode-stirred environment.

Analytical and Statistical Models:

1. Analytical models are important to interpret test data and predict aircraft response to HIRF. No current methodology can provide a comprehensive aircraft model, although alternative techniques may be necessary to assess various component or configuration response functions over appropriate frequency intervals. Analysis and the corresponding codes require further validation.

2. Test data is inherently sensitive to position within the airframe. Most analytical methods are deterministic and may only give a qualitative representation of aircraft response functions in certain frequency ranges. Statistical approaches are needed to assess field variability, to interpret mode-stirred test data, and to assess shielding effectiveness as predicted by complex cavity field distribution functions. The applicability of statistics should be delimited.

3. Statistical models need to be improved to incorporate the frequency dependence of the complex cavity mode density function and thereby provide more realistic models at lower frequencies.

4. The overall usefulness of models is in their ability to assess the potential coupling of the external HIRF environment to internal component electronics. They will in turn provide a consistent representation of the external to internal response thereby impacting the formulation of more realistic equipment level susceptibility and airframe attenuation test requirements. Probabilistic approaches can provide a means to assess the overall HIRF threat and thereby provide a rational basis on which to construct realistic requirements. For example, as mentioned above, it is significant that third generation airplanes are in operation with fly by wire engine controls tested to 20 v/m, well below the HIRF environment less a reasonable assumption for airplane attenuation, yet no incidents have been reported. The threat can be partitioned into somewhat independent or conditionally dependent factors including:

   1) the probability of encountering the external HIRF environment (threat)

   2) the external to internal aircraft coupling

   3) the internal environment and the probability of coupling to equipment

   4) the probability of system upset

   Given sufficient statistical information it is possible to formulate probability distribution functions for each aforementioned factor that when appropriately convolved, yield a more realistic assessment of the HIRF threat. Such an analysis, routine to reliability studies, is predicated on acquiring accurate distribution functions. As these distributions become empirically or analytically defined [1], a statistical course of action is recommended to contribute to the development of more realistic HIRF requirements, and it follows, a consistent certification process.

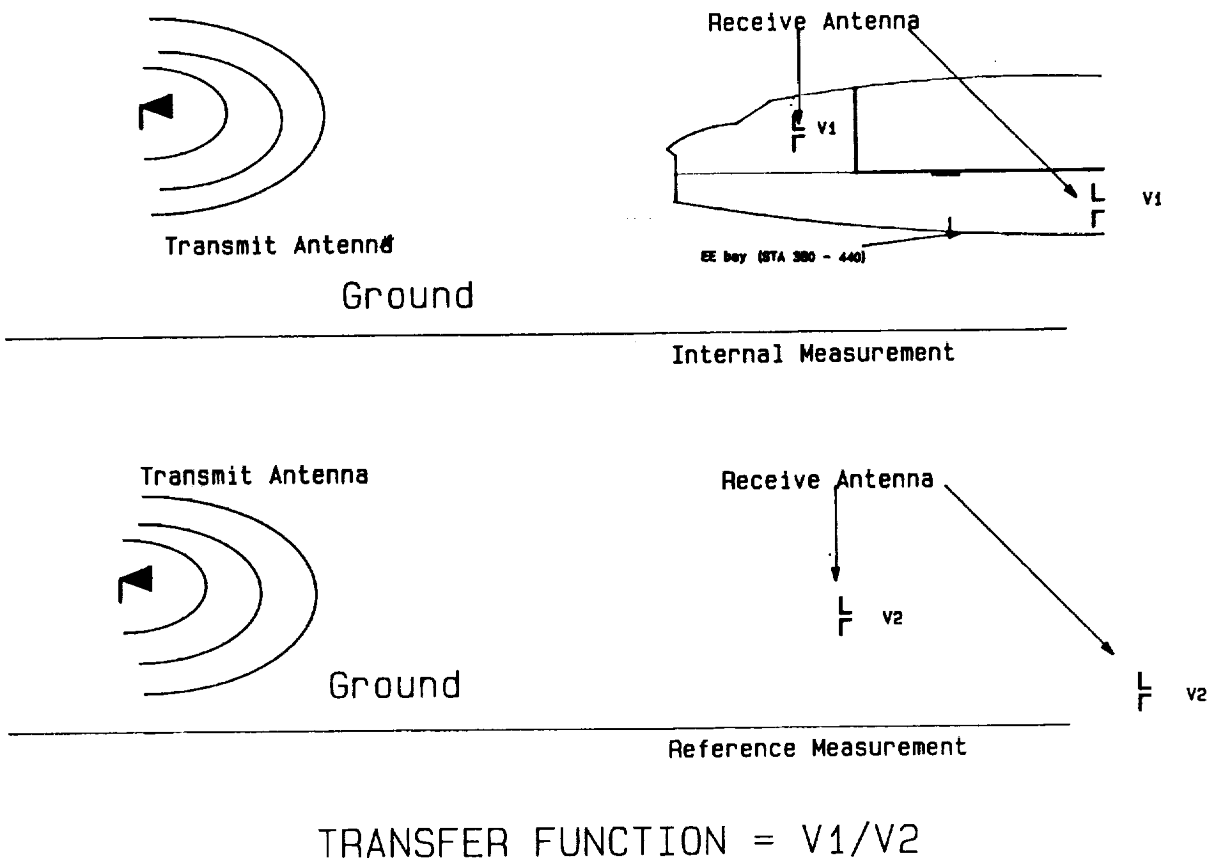

Figure 5-1 Transfer Function Measurements

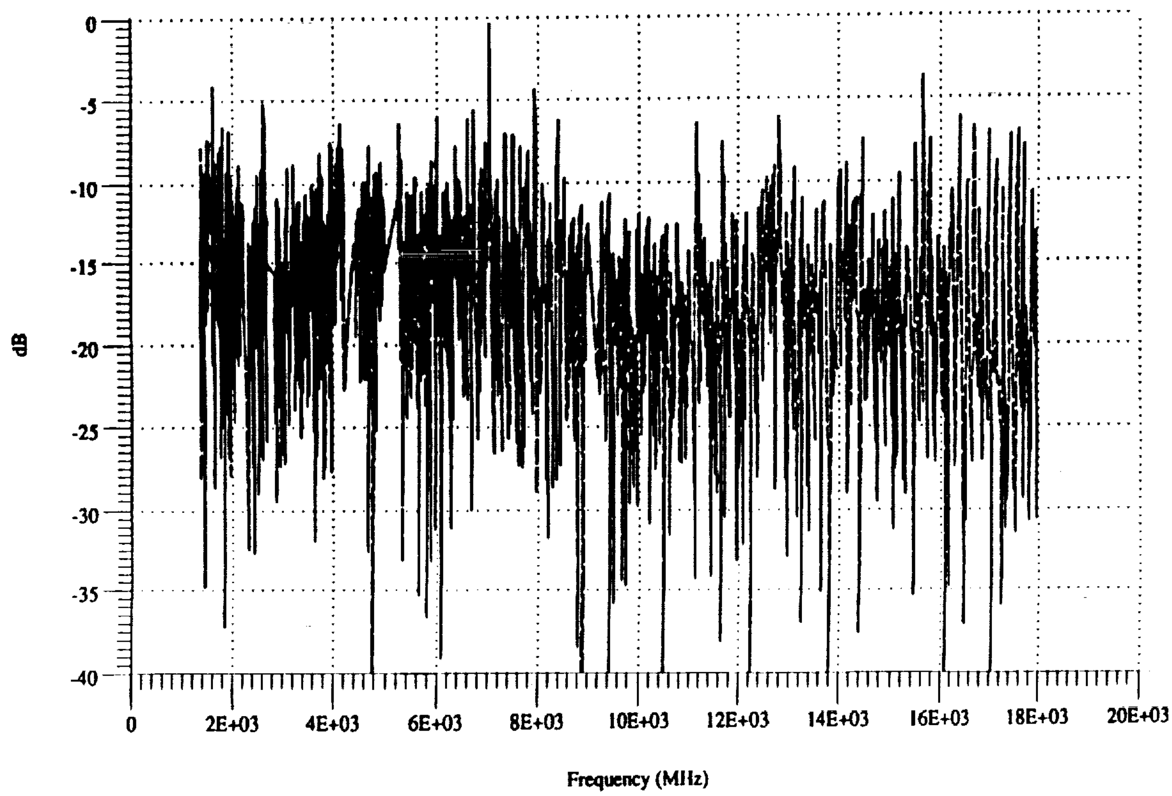

Figure 5-2 Typical Attenuation Measurement

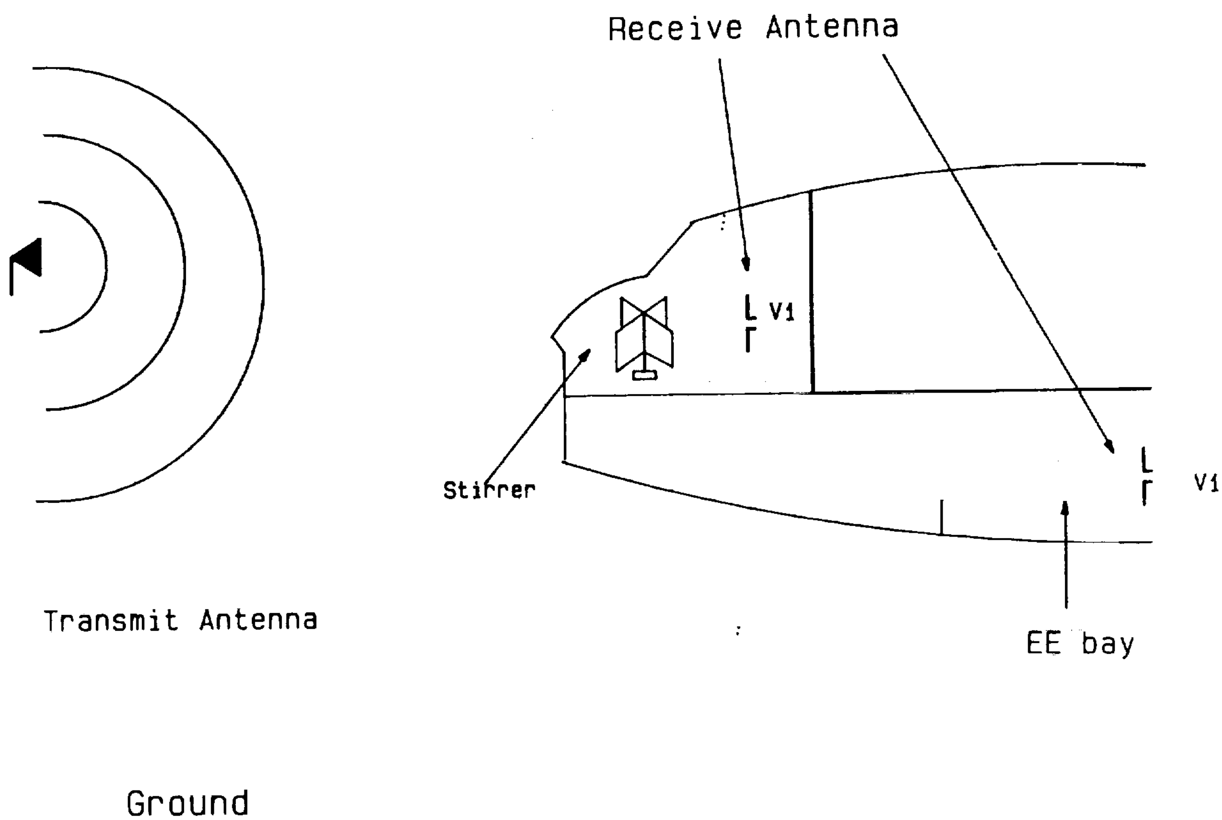

Figure 5-3 Mode-Stirred Attenuation Measurements

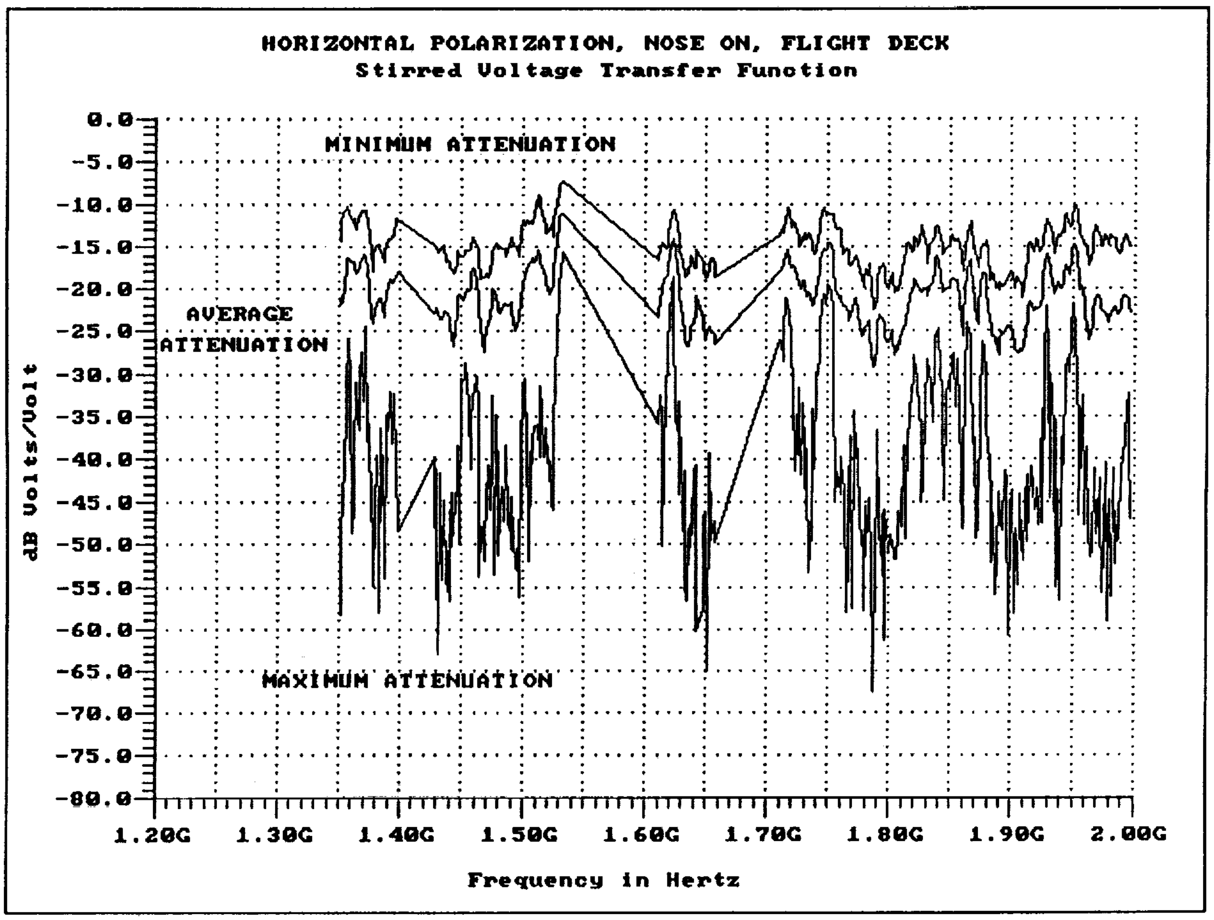

Figure 5-4 Mode-Stirred Flight Deck Attenuation

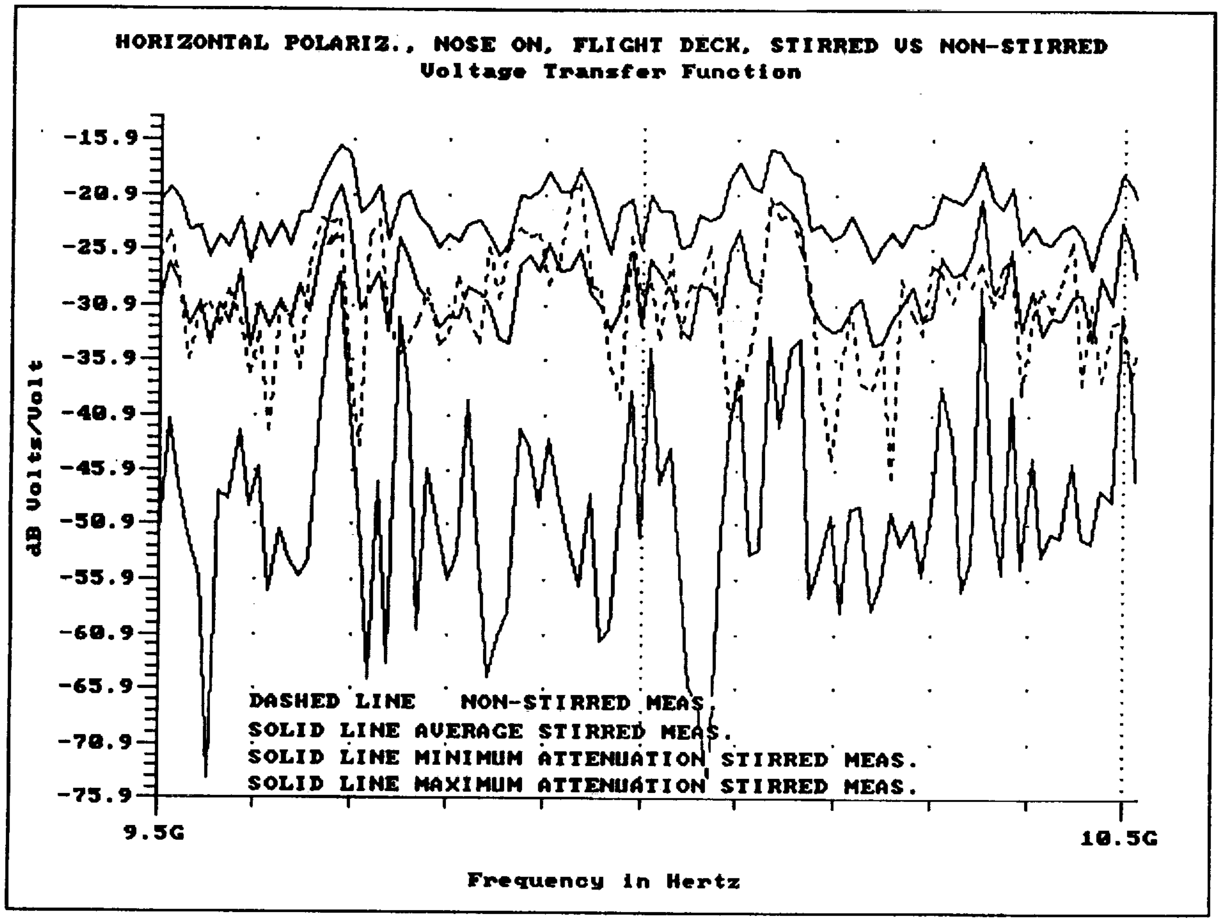

Figure 5-5 Stirred (Solid) Vs Non-Stirred (Dash) Attenuation

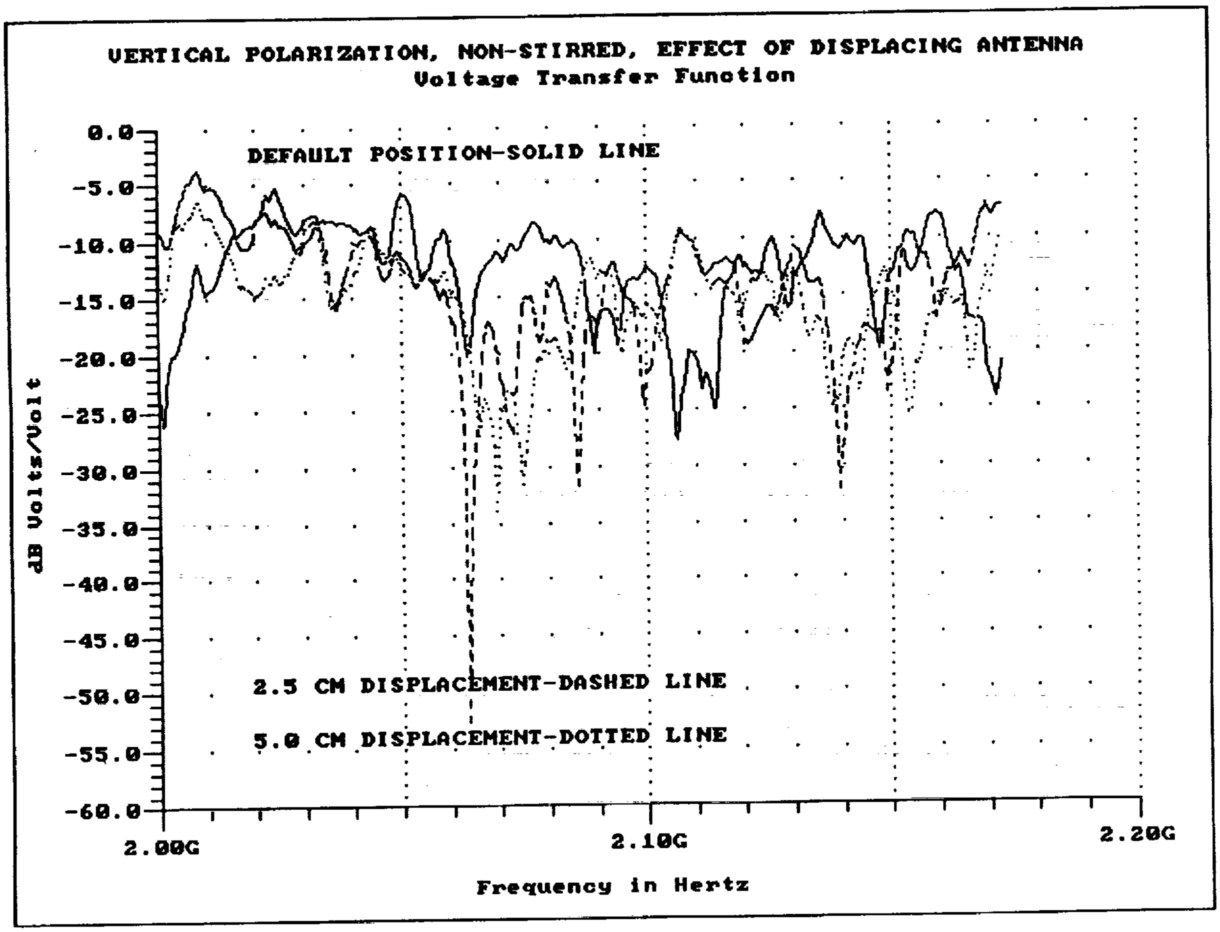

Figure 5-6 Non-Stirred Receive Antenna Position Dependence

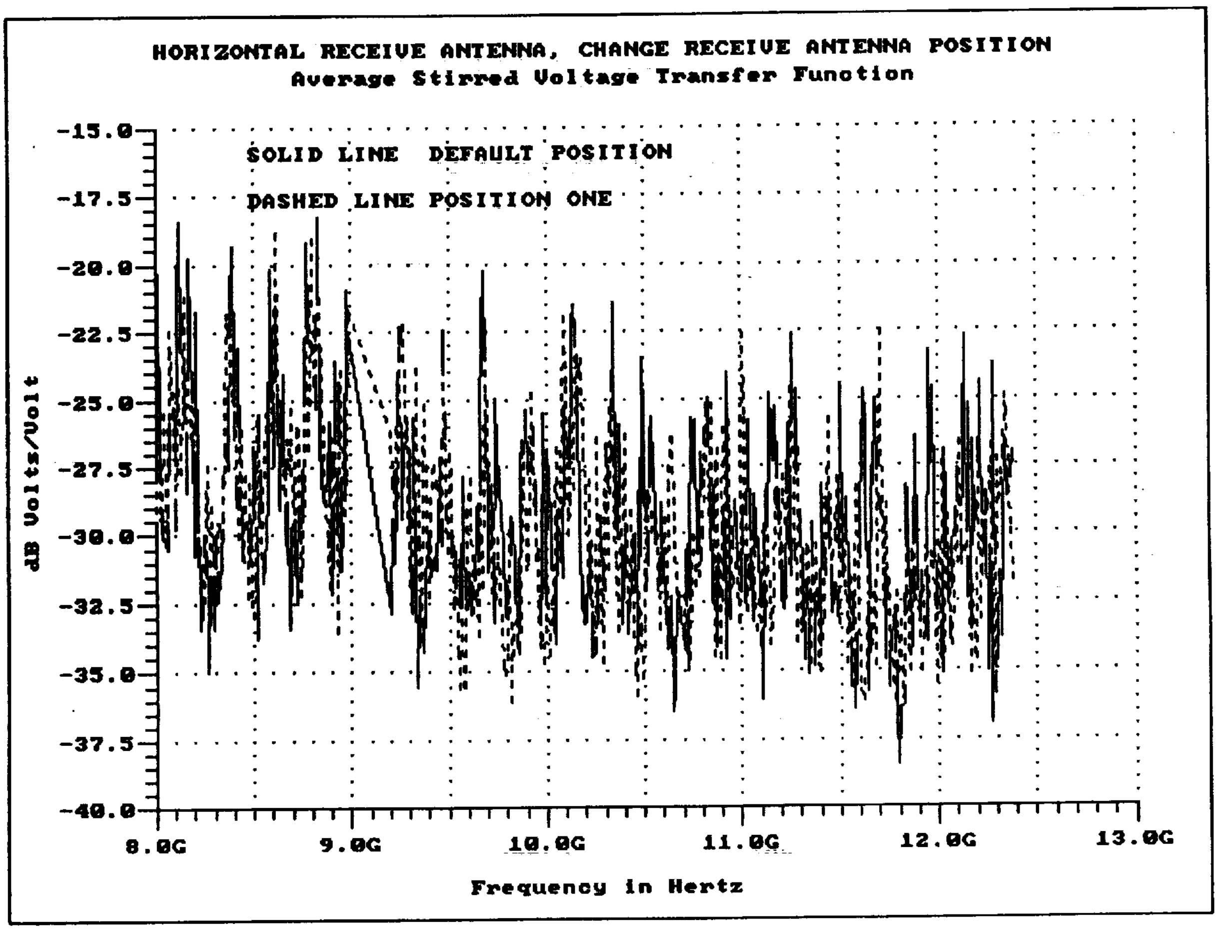

Figure 5-7 Stirred Dependence on Receive Antenna Position

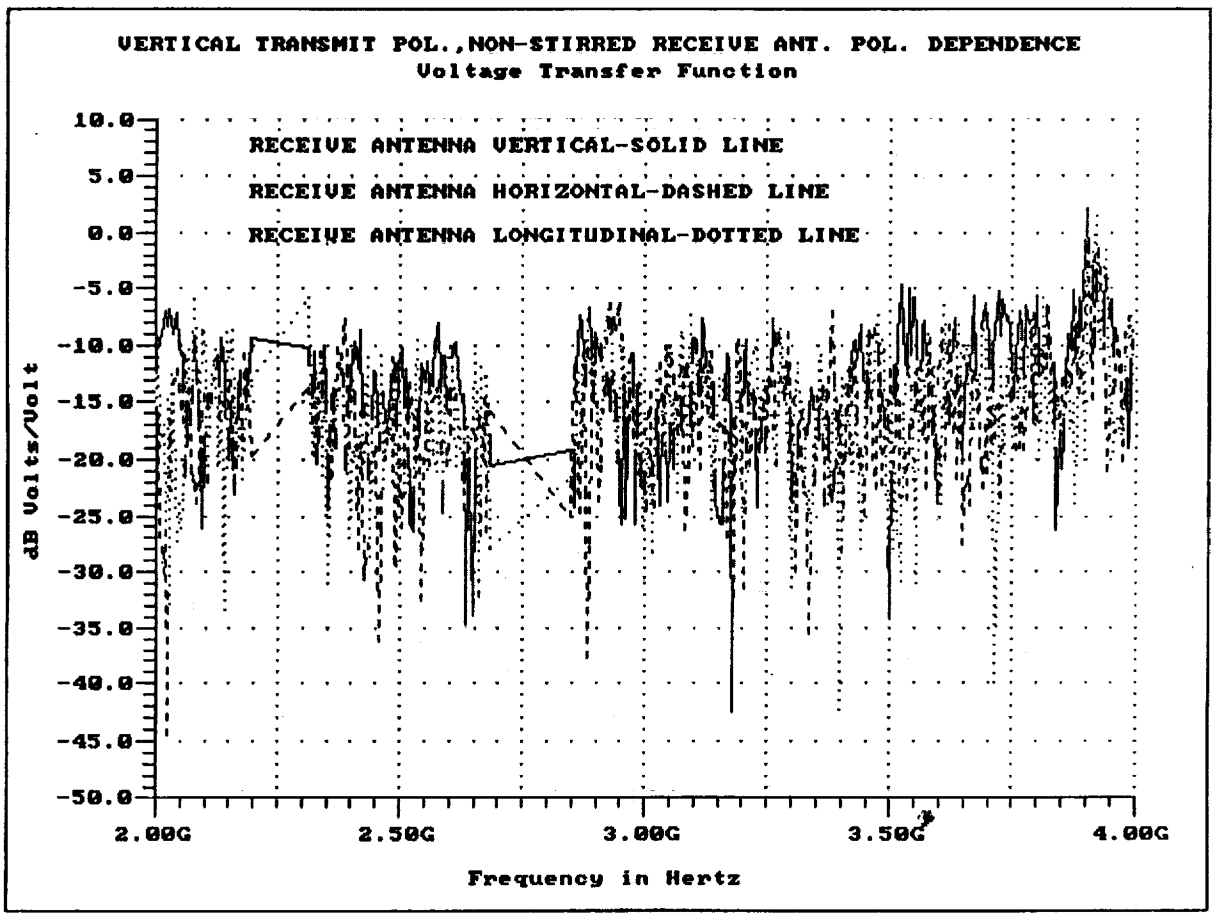

Figure 5-8 Non-Stirred Receive Antenna Polarization Dependence

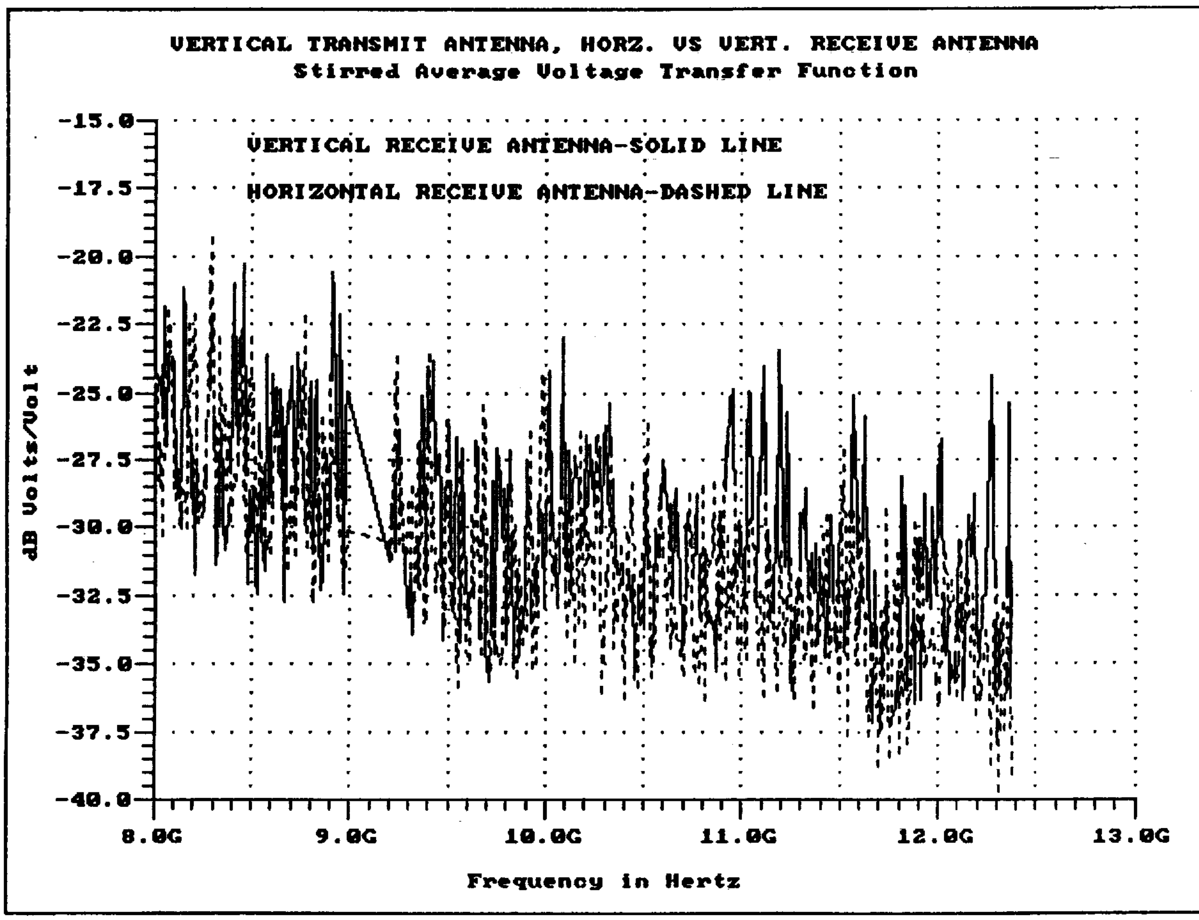

Figure 5-9 Stirred Receive Antenna Polarization Dependence

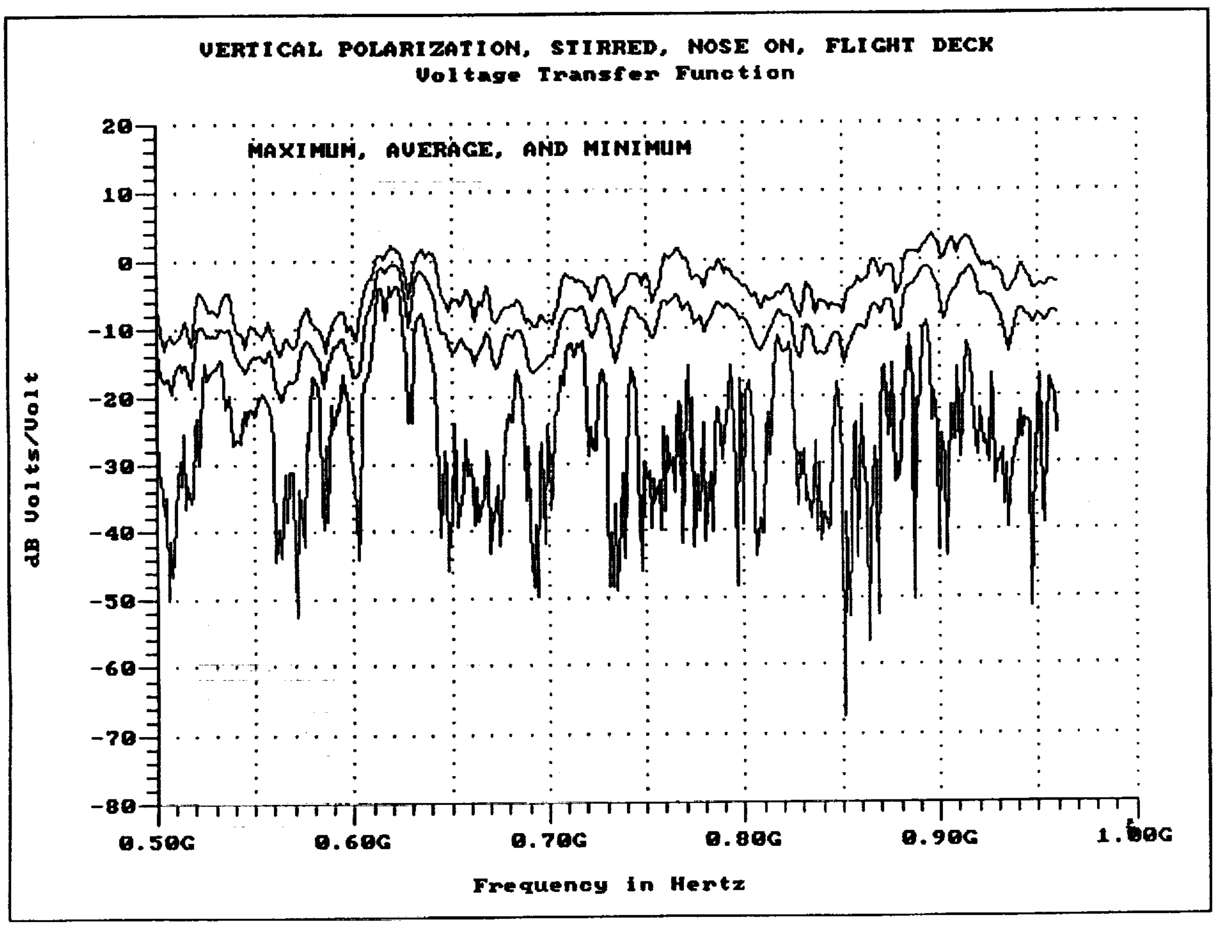

Figure 5-10 Mode-Stirred Transfer Functions (0.5 - 1.0 GHz)

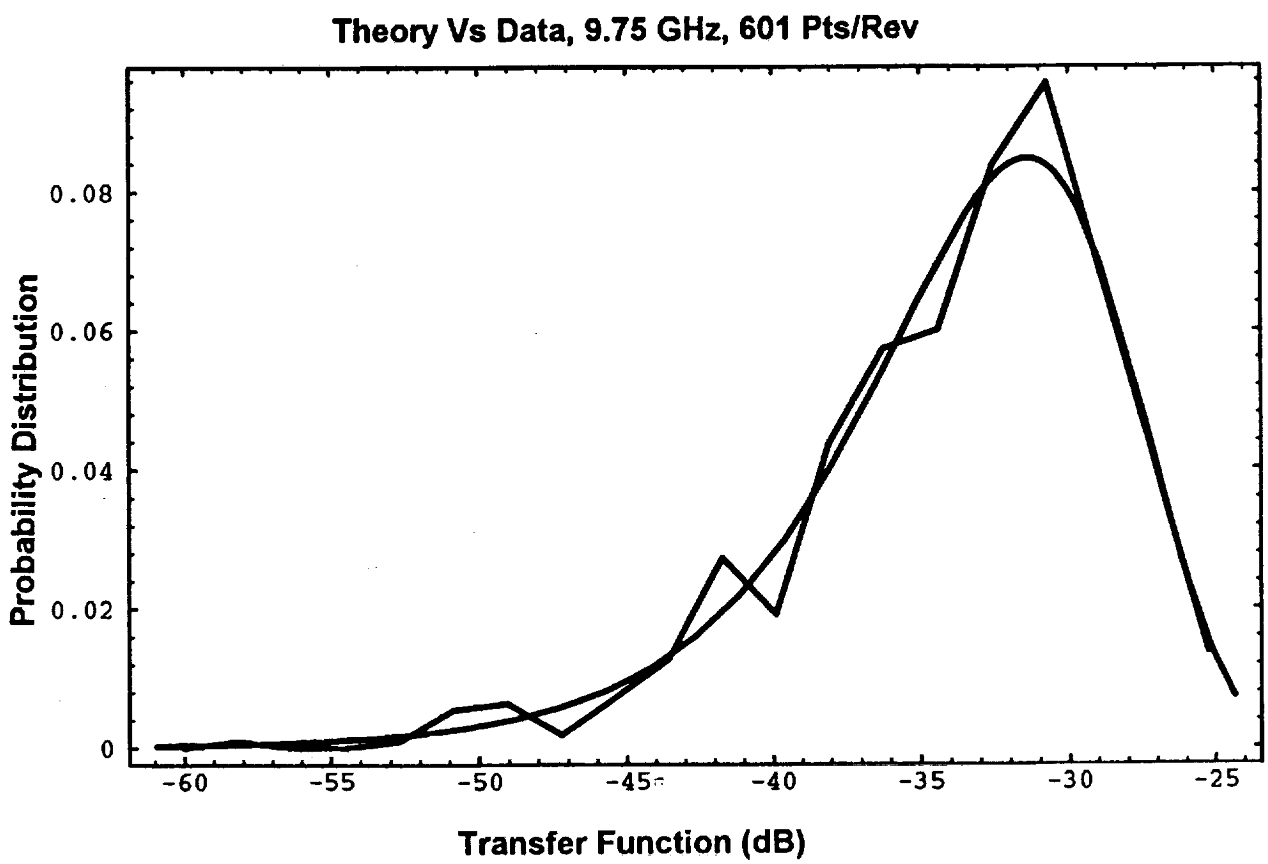

Figure 5-11 Theoretical Vs Experimental Distribution Functions

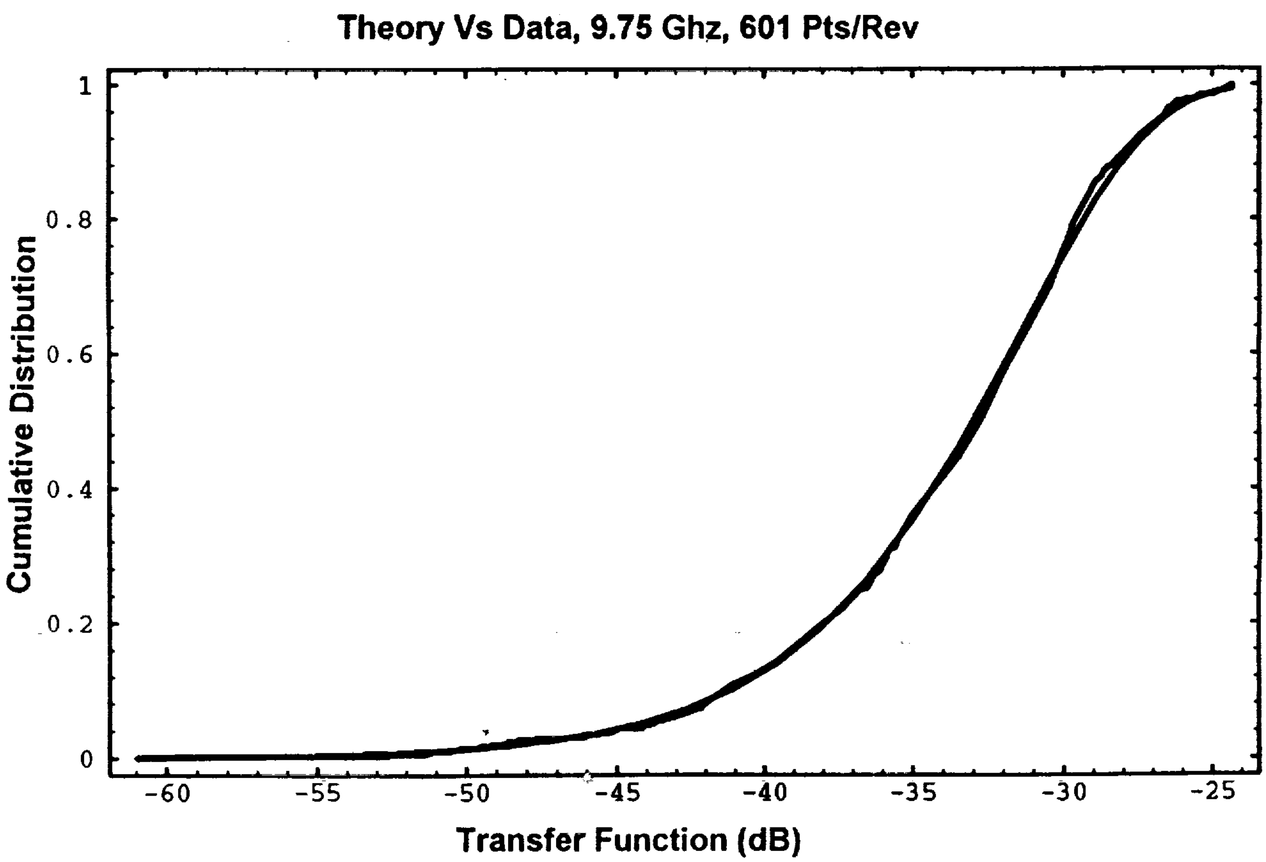

Figure 5-12 Cumulative Distributions - Theory Vs Experiment

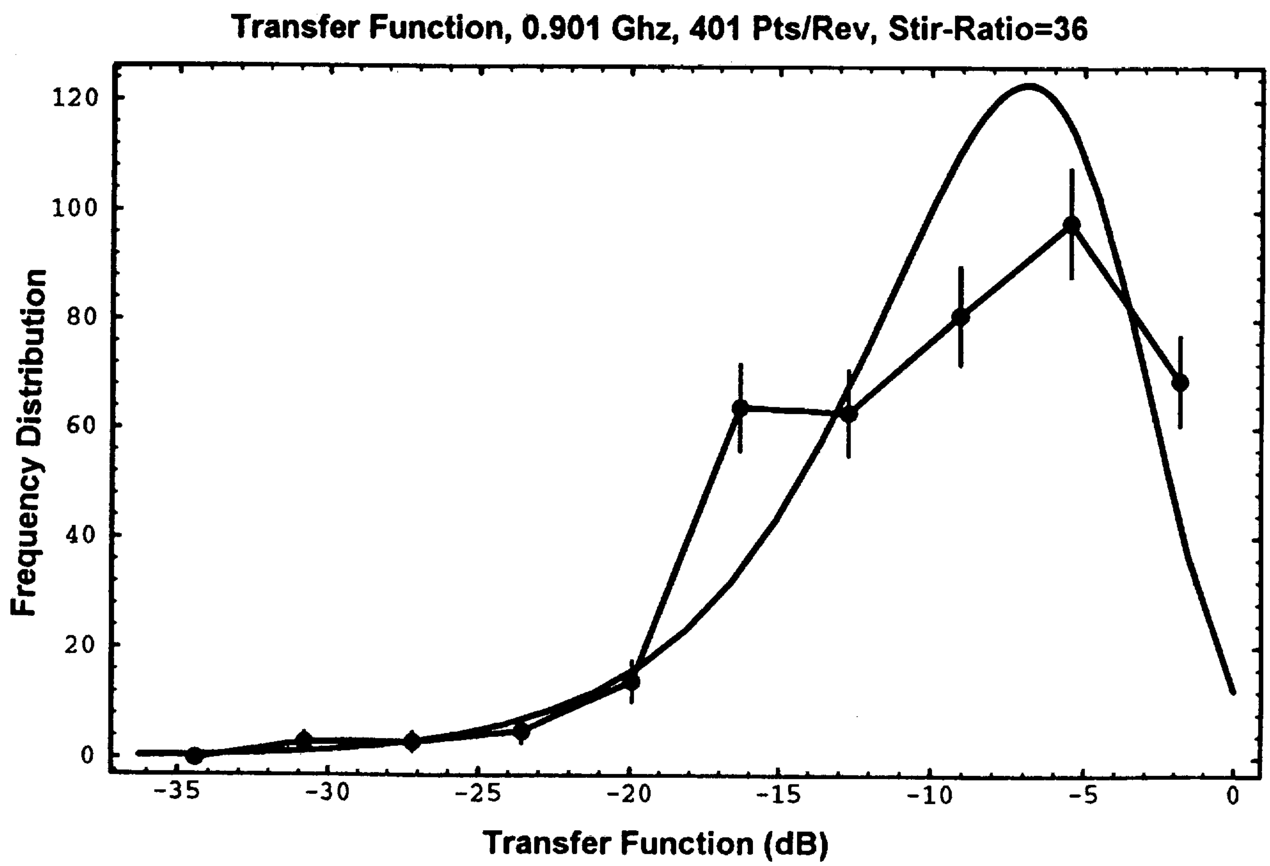

Figure 5-13 Frequency Distributions - Theory Vs Experiment

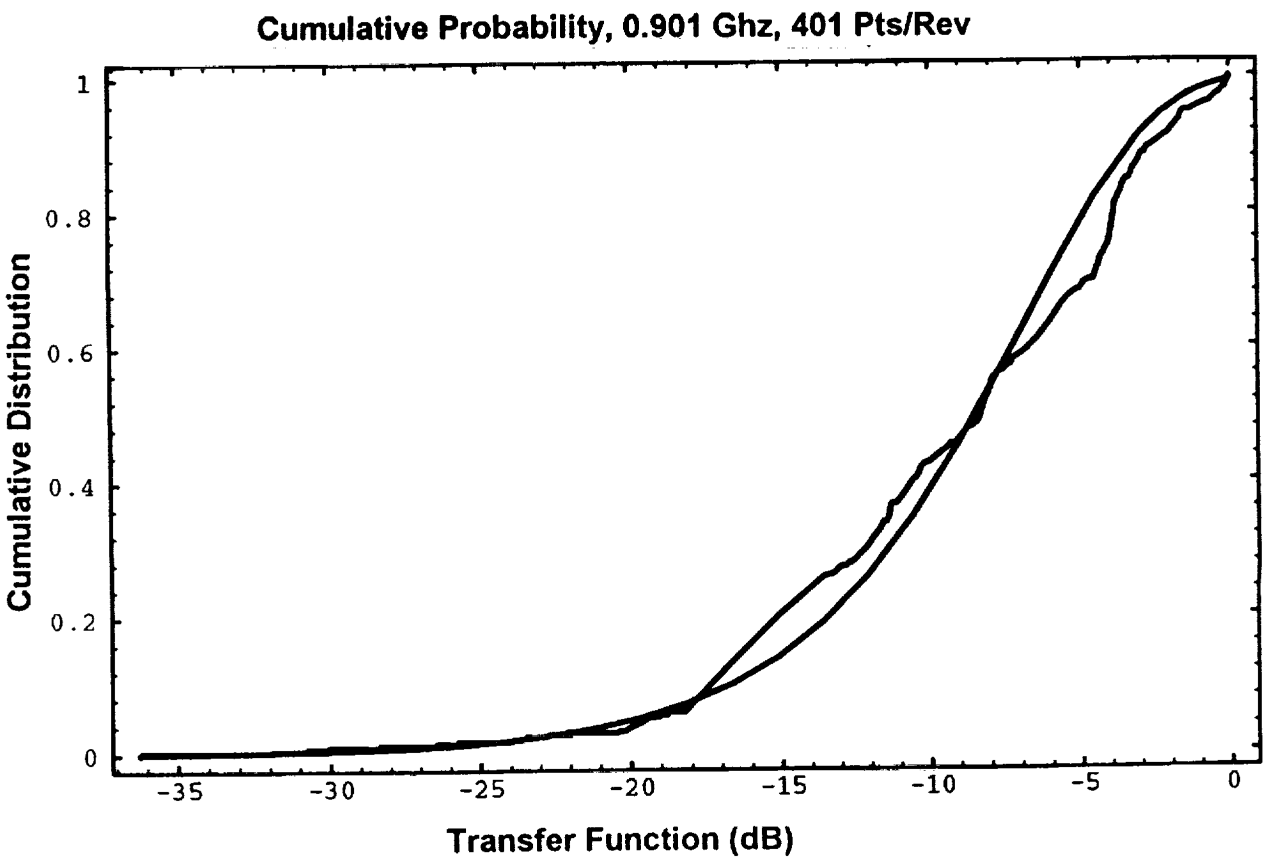

Figure 5-14 Cumulative Distributions - Theory Vs Experiment

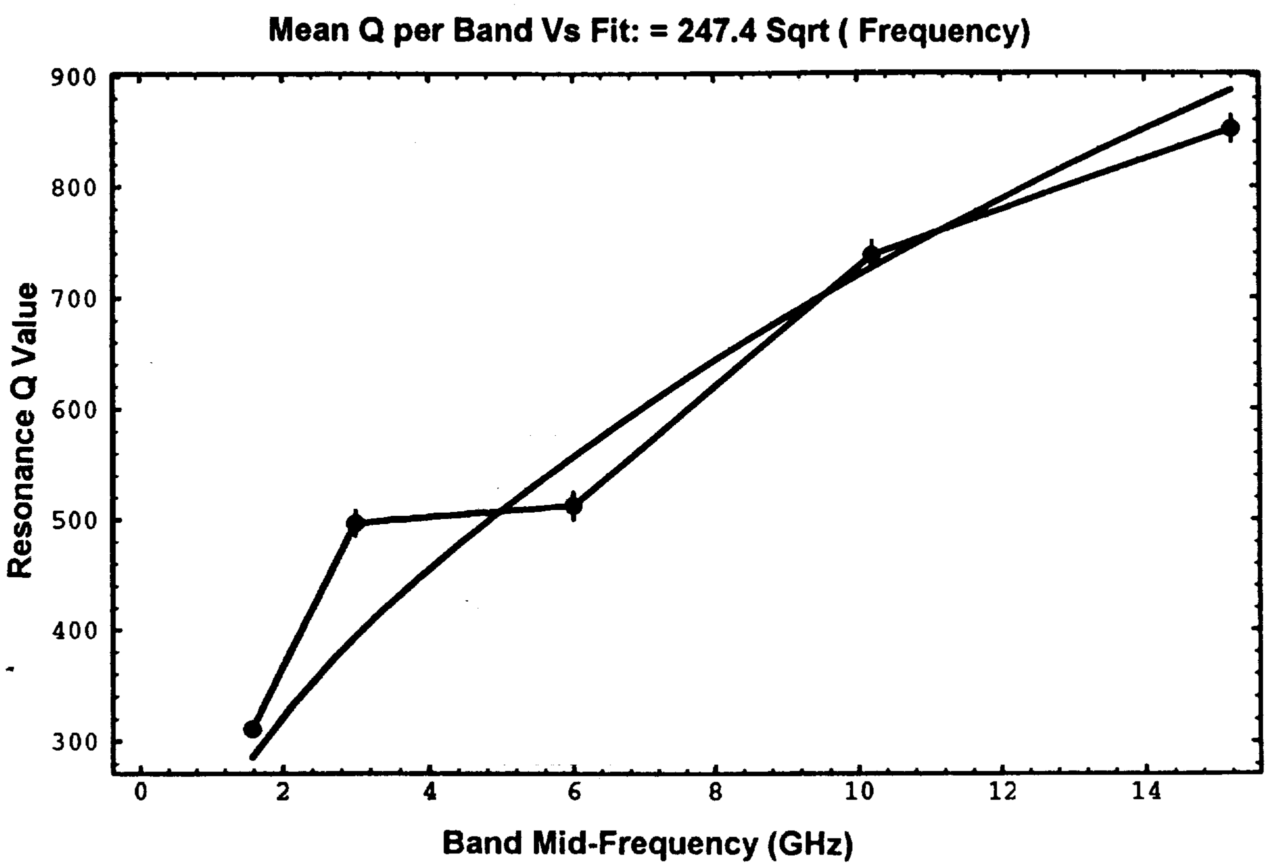

Figure 5-15 Mean Composite Q Vs Frequency (1.0 - 18.0 GHz)

6.0 EQUIPMENT SUSCEPTIBILITY, TEST METHODS, AND REQUIREMENTS

As discussed in section 3, the FAA and JAA have instituted somewhat different airplane certification requirements for both equipment level qualification tests and airplane certification tests. The rationale for this is to a large degree historical, although there is also a technical basis for some of the dissimilarity. Ongoing coordination continues between the regulatory agencies to arrive at a single certification process. Such a comprehensive process definition has not been completed, consequently airplane manufacturers have often elected to test at higher field levels and requirements indicative of the JAA process. This assures compliance albeit usually with a cost and time penalty.

Also discussed in section 3 was the fact that in the realistic process flow, equipment level requirements and qualification tests are set early in an airplane program so that the likelihood of compliance for the final integrated systems or airplane test is high. Nevertheless, significant questions remain concerning the bench level test methodology and attendant requirements. These have been based on somewhat problematic assumptions, and it is yet to be shown that these are consistent with the actual internal airplane environment. The combination of the external environment levels and the choice of bench level test requirements set the airframe attenuation requirements. Choosing a worst case scenario for the environment, and somewhat arbitrary equipment test levels have driven requirements for airframe attenuation to levels that may not be realizable at certain threat frequencies. This then requires possible excessive additional equipment level shielding and the attendant weight penalty.

The process is not rational in view of the history of the HIRF threat, or in view of the basic assumption of equipment level vulnerability. Laboratory tests to date have shown that for frequencies above 1 GHz, at which the external environment is most severe, current equipment designs do not respond in those cases for which the equipment functions below 1 GHz. Figures 6-1 to 6-2 provide overviews to pulsed and AM equipment under test (EUT) susceptibilities as a function of frequency.

Questions remain, therefore, as to the means of assessing equipment or integrated systems that will simulate the actual response in the airframe internal environment. Current screen room test levels, e. g., 100, or 200 v/m below 400 MHz, and 600 v/m above 400 MHz have been set either on the basis of historical (often military standard) levels, estimated airframe attenuation levels, and the capabilities of available test facilities. Furthermore, test methodologies used in anechoic versus mode-stirred chambers yield results that are difficult to relate to each other and to evaluate with current modeling techniques. The following section will discuss the challenges presented by susceptibility tests and the assumptions that have made a consistent certification process difficult to achieve.

6.1 Bench Level Test Procedures Assessment

Historically, HIRF equipment has been selected and sub-system laboratory tests have been performed using test procedures and test configurations that are consistent with DO-160C, Section 20. Figure 6-3 is a schematic representing the process by which equipment level test and analysis is formulated. The testing is conducted in shield rooms or anechoic chambers on individual LRUs with simulated loads. More recently, an attempt has been made to make the LRU test setup so that installation details, such as grounding, wire harness shielding, shield terminations, and equipment interfaces are consistent with the actual airplane installation.

An example of an equipment level test is shown in Figure 6-4. The system is setup in a shield room with anechoic absorber. The system setup, system procedures and capabilities, mode change description, and antenna positions/polarizations are explained within the supplier's qualification test plan (QTP). All transmit antenna positions and polarizations are centered and placed at one meter from the equipment under test (EUT).

In this particular example, during testing at each of the RF susceptibility discrete frequencies, the supplier's automated test equipment (ATE) is sequentially monitoring up to 15 input/output channels for either audio communications distortion, audio power output, or audio noise without signal, depending on the RF modulation type. A susceptible response is indicated automatically by the ATE when the appropriate data gathering mode is selected. In order for the ATE to capture any susceptibility, the setup is radiated at a test level for a minimum dwell time of 30 seconds. Any failures are automatically highlighted on a monitoring CRT by the ATE. Personnel continuously monitor the ATE for any such indications.

The RF susceptibility pass/fail criteria is provided by the supplier's representatives. During the RF testing, the supplier's personnel monitor the test system for upsets and provide the mode switching at each of the required RF test frequencies.

This is the common susceptibility test scenario and is advocated since practicalities and logistics drive this type of testing. Analogous to lightning susceptibility certification, HIRF is also difficult to simulate at full threat levels. Certification tests are therefore broken down into components. For the LRU tests a fixed voltage and current are specified and then sufficient shielding, cable routing, etc., is guaranteed by the airframe manufacturer to make sure the energy at the LRU (line replaceable unit) does not exceed this level.

Bench level tests may not simulate accurately the actual in-airplane environment but may be justified by means of a measure of electromagnetic hardness. This mode of certification can be maintained until on-going research and development efforts produce accurate modeling methods to predict internal airplane levels as a function of the external threat.

6.2 Compliance Using System-Level Testing Versus Equipment-Level Testing

A definition of system-level test is one in which qualified equipment have been integrated into a system to be tested at the appropriate susceptibility levels. Few system tests are actually performed because system integration usually occurs late in an airplane program. Although systems comprised of qualified equipment are at lower risk of test failure, such a system test where a failure occurred could have unacceptable consequences. Meaningful full-up system integration rarely occurs early enough for system level tests to be performed in a timely manner. This becomes a driving factor for the LRU equipment testing using simulated loads. There simply may be no chance of getting a full system for HIRF certification. Furthermore, systems tend to be physically large and electronically complex for which there are few test facilities of dimensions sufficient to radiate the system under test. Indeed, making the system operational outside the airplane itself may not be feasible thus limiting the types of systems available for test in any case.

One example of a system level test is the electronic engine controller or EEC. Figure 6-5 shows a block diagram of the EEC test setup. The EEC is housed inside a screen room, over a copper ground plane with on-engine devices (e.g., actuators, sensors, ignitors, etc.) tied to the ground plane through ground straps or through mounting bolts of on-engine devices, or to the low side of circuits simulating engine loads. The EEC itself is tied to the ground plane with a copper strap. The objective is to recreate the engine ground plane where possible. For this test, the aircraft interface cables under test (channel A and B) are supplied by the airframe manufacturer and the shields terminated at each connector with pigtails. The supplier monitors the position of engine actuators to determine EEC susceptibility to EMI or lighting induced transients. The positions of the actuators are determined by linear potentiometers linked to the moving parts of the actuators. The potentiometer signals are routed to a strip chart recorder through copper conduit. The EEC manufacturer test bench allows the EEC to operate in closed loop engine control at a particular operation point.

There has been expressed a concern on the part of the JAA that insufficient full HIRF system level tests are performed and they are conveying a strong desire for such tests to be done. However, there is no indication that the current approach to certification will change in the near future. Systems are becoming more complex and although this may drive the need for system tests, the complexity will increase the logistical difficulties. Furthermore, revision of requirements to accommodate system tests have yet to be established. The HIRF user's guide does describe tests using a systems rig; however, a comparable document to DO-160 for equipment tests has not been written.

There are no well developed models to predict shielding of components or systems. The only concrete points available are based on test results. Models are needed to predict field levels in, for example, the EE bay. Models and tests are even more limited for system tests. There is a need to establish a baseline and the conditions and circumstances where system level testing is absolutely required. This does not exist at the present time. Furthermore, LRUs are tested on the bench in a variety of states to simulate the system. In addition, modeling indicates that the wiring responds only to the local fields. The present method of equipment testing tends to be conservative, because susceptibility test levels below 400 MHz are typically at or above the HIRF threat environment without the benefit of shielding by the airframe racks, and the airframe itself.

The trade offs in performing LRU versus system level tests are significant. System tests require larger test facilities capable of achieving at least equivalent test fields and are therefore energy intensive. Few facilities are operational that can achieve the required high field levels with full system test rigs in place. Furthermore, it would be unrealistic to immerse a system having a large geometry in a uniform field. Requirements also become more demanding to perform tests which in all likelihood will include both manufacturer and supplier test personnel. The benefits of performing system tests may not justify the expense.

6.3 Assess Internal Field Baseline and Susceptibility Models

A significant issue central to developing an overall consistent certification process, is the relationship between the shield room test and the airplane internal HIRF environment. A typical scenario in performing airplane attenuation tests is to measure the electric field at the center of the cavity and then apply the attenuation to the requirements for radiated susceptibility to calculate the levels the equipment can withstand. This procedure represents a very conservative approach for several reasons. First, the electric fields are typically measured in the center of the cavity or away from the metal which neglects the shielding effects of the equipment racks. Bench level testing measures the total field on the bench due to the sum of both the transmit antenna and reflections from the environment. Therefore the drive level does not represent an incident plane wave field on the equipment under test (EUT). If the receive probe happens to be located at a null due to a wall reflection, the power is increased until the required field level is attained, which in some cases is not achievable.

A possible resolution of these difficulties is to use mode-stirring for both equipment level testing and airframe attenuation assessment. As discussed in section 5, should chamber and airframe cavity statistical distribution functions prove to be the same, similarity arguments can be made to relate the LRU response in these two environments [19]. That is, the mode-stirred chamber results may prove to be more representative of the airframe cavity environment. Mode-stirring has the additional advantage of producing higher field levels for a given input power than traditional screen room techniques.

Resolution of the internal environment problem can in principle be obtained from a combination of test and modeling of the equipment level test environment, in comparison with the HIRF internal environment. However, limited progress has been accomplished in modeling bench or system level tests or for that matter, airplane cavities. Recent attempts [16-19] give promising results for representing the fields within electrically large cavities driven by externally excited apertures. Furthermore, statistical models [5-11] also make contributions to the internal field assessment by providing trends and bounds to the cavity RF coupling.

As shown in Figure 5-2, LLSCW test data taken on a bare airframe cavity indicates that above 200 MHz, the internal environment behaves as a resonant enclosure containing a high density of excited modes. Simple analytical models of lossy cavities support this assertion. Figure 6-6 represents the modal structure within a lossy cavity excited by an internally positioned point dipole compared to LLCW test data. It is evident that there is qualitative agreement. The model may be overly simple to describe a real airframe cavity in detail, nonetheless it does support a conclusion brought out by the statistical analysis of the excitation of electromagnetic waves in complex cavities. There it has been shown that the distribution function for the modes within electrically large complex cavities is largely independent of the detailed geometry of the cavity.

There are unresolved questions that models need to address. An important problem concerns the antenna response and calibration [20-22] within a shield room or reverberation chamber as compared to the response within the airplane cavity. The calibration factor for a reverberation chamber is defined as [21]:

$$m = P_D/P_T$$

$$P_D = c \langle U \rangle \quad = \text{Power density}$$

where $P_T =$ Net energy transmitted

$c =$ Speed of light

$\langle U \rangle =$ Average energy density

The power density can be measured as a function of frequency inside the room. The received power is:

$$P_r = \langle A \rangle P_D$$

$\langle A \rangle =$ Average effective area

The effective area (A) of an antenna is defined as:

$$A = p\, q\, \eta\, D\, \lambda^2 / (4\, \pi)$$

where

- p is the polarization mismatch factor,
- q is the impedance mismatch factor,
- η is the antenna efficiency,
- D is the antenna directivity,
- λ is the free space wavelength.

The directivity, when averaged over all incident angles(<D>), is 1, where <> indicates an average over 4 π steradians. The effective area <A> is then:

$$\langle A\rangle = p\,q\,\eta\,\langle D\rangle\,\lambda^2/(4\pi)$$
$$= p\,q\,\eta\,\lambda^2/(4\pi)$$

Using a polarization mismatch factor of 1/2 and a directivity of one, the calibration factor becomes:

$$m = P_r/(\langle A\rangle P_T) = 1/(\eta q)\; 8\pi/\lambda^2\; P_r/P_T$$

There is a contention that empirical evidence indicates the above calibration factor is a factor of 2 too large. Without an answer to this question, the relationship between shield room susceptibility measurements and airplane internal field measurements remains unresolved. In other words, the correspondence between the field at the equipment under test in a shield room or reverberation chamber, and the field at the equipment located in the airplane cavity must be demonstrated. The answer to this question is a function of the antenna response in each of these environments.

Figure 6-7 provides a partial answer to this difficulty. The graph shows the respective transfer functions within the test bed flight deck for a monopole over a ground plane antenna compared with a directional horn antenna. Each has been respectively referenced to its open field measurement. The open field directivities of these two antennas differ on the average by 10 dB over the frequency range of interest. Figure 6-8 compares the two antenna airframe transfer functions after the corresponding open field references have been removed. Much of the directivity difference has been lost within the complex cavity; that is, the antenna response approaches isotropy.

This observation suggests the following argument for assessing the correct antenna calibration in the cavity environment [21-22]. Given that the antenna inside the airframe responds isotropically, then the appropriate reference for an internal airframe attenuation is an isotropic reference. The isotropic reference can either be measured or calculated.

The polarization mismatch factor for a randomly polarized wave incident on the antenna is 1/2 [22]. This is a result of the antenna coupling to only half the cavity energy. The other half of the cavity energy is cross polarized to the receive antenna. The average effective area is now

$$\langle A\rangle = q\,\eta\,\lambda^2/(8\pi)$$

The efficiency (n) and the impedance mismatch factor (q) limit the repeatability of a transfer function measurement made with two differing antennas. The impedance mismatch factor is given as:

$$q = 1 - \rho^2$$

where ρ = the reflection coefficient.

$$\rho = (VSWR - 1)/(VSWR + 1)$$

where VSWR is the voltage standing wave ratio. This quantity varies between antennas as a function of frequency and accounts for much of the variability (along with the secondary efficiency differences n) in transfer function measurements when using different antennas. In principle, the references can be calculated for different antennas using empirically determined antenna directivities, however these vary due to measurement inaccuracies. Therefore, a calculated reference may not yet be accurate enough for attenuation measurements since a few dB error in the attenuation may impact design.

An alternative to a calculated reference is to measure the transfer function with a low directivity antenna, such as an electrically small dipole (D= 1.8 dBi). This would minimize the effects of antenna directivity while not requiring any post processing of the data, and thereby provide a consistent picture of the airframe internal environment.

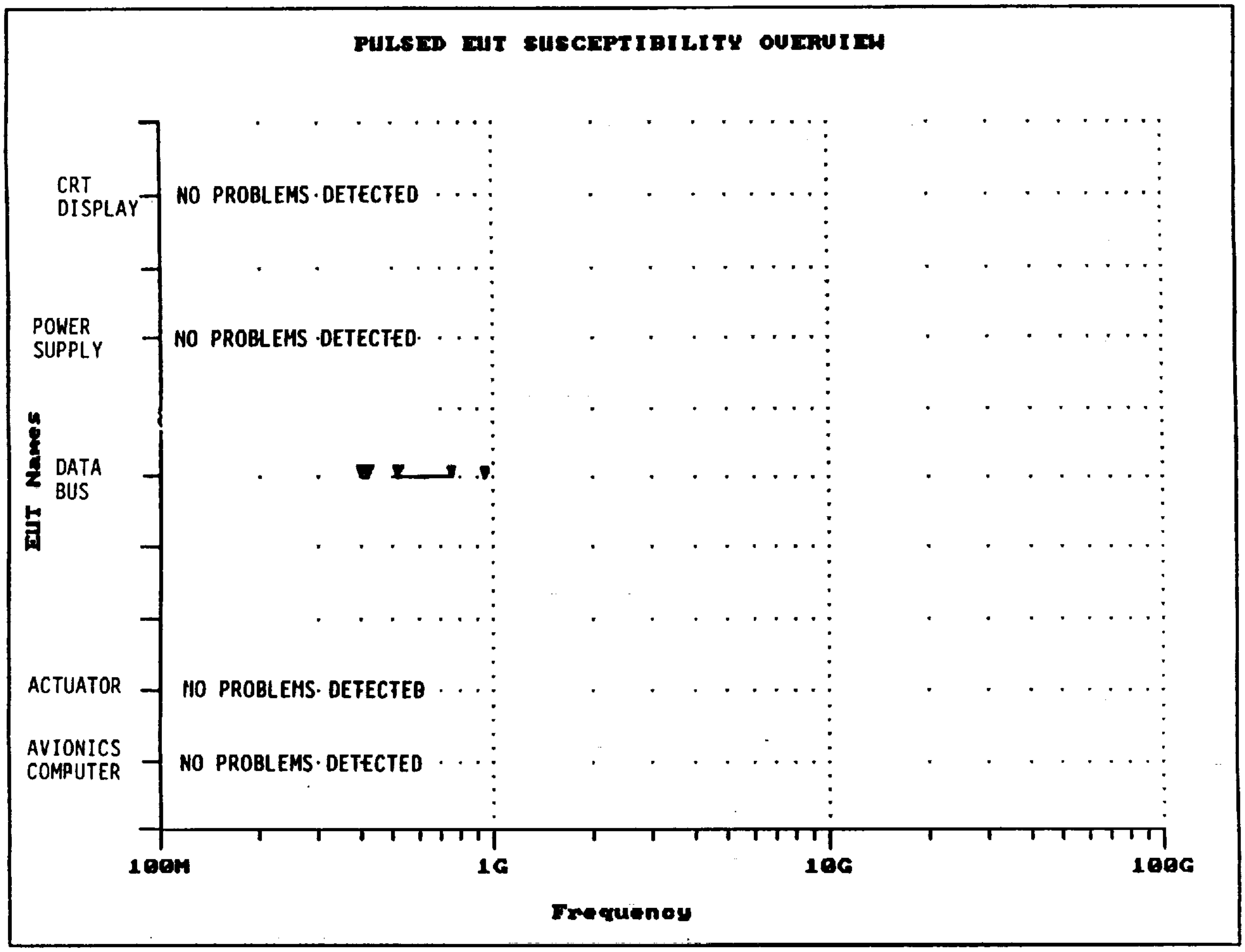

Figure 6-1 Pulsed EUT Susceptibility Overview

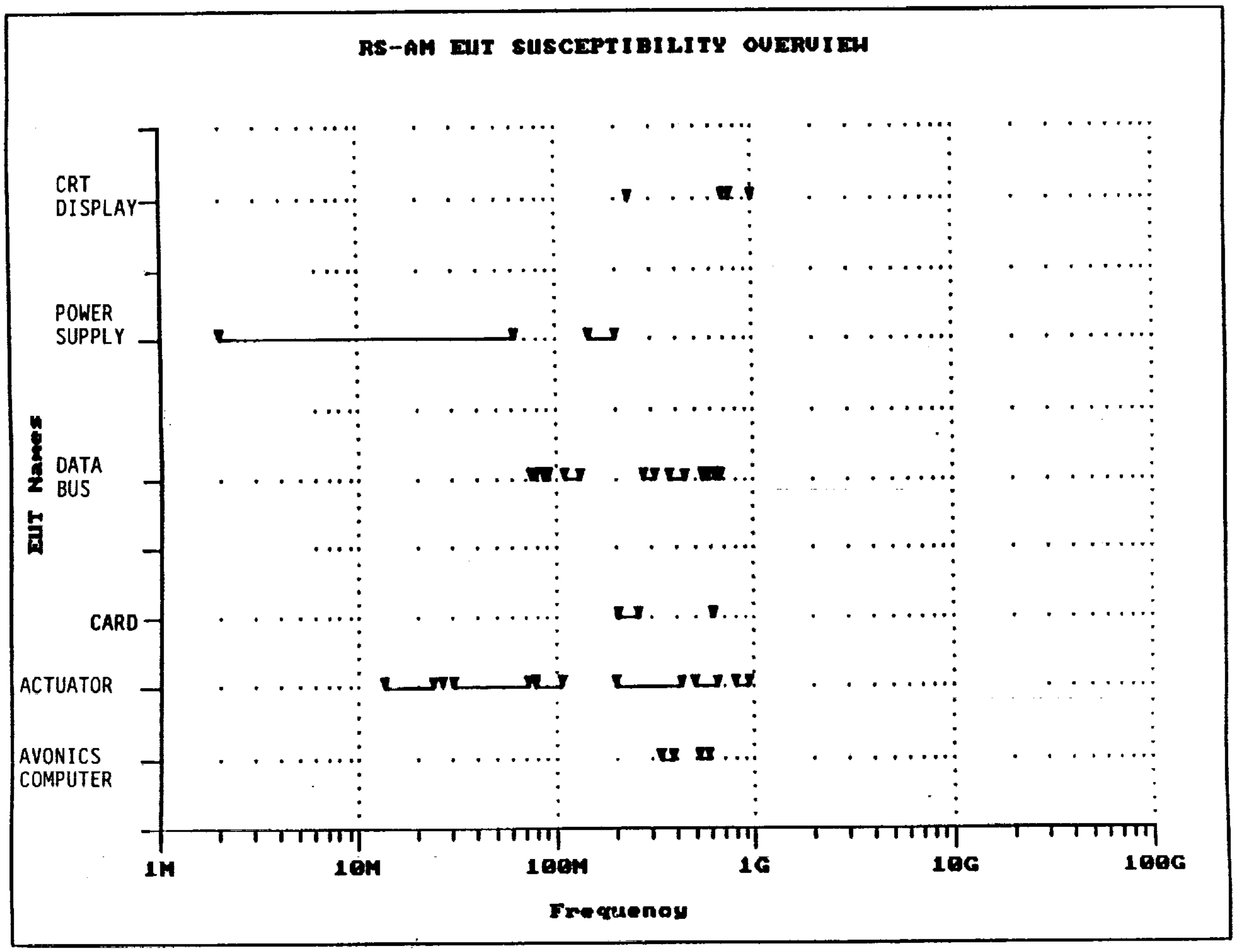

Figure 6-2 RS-AM EUT Susceptibility Overview

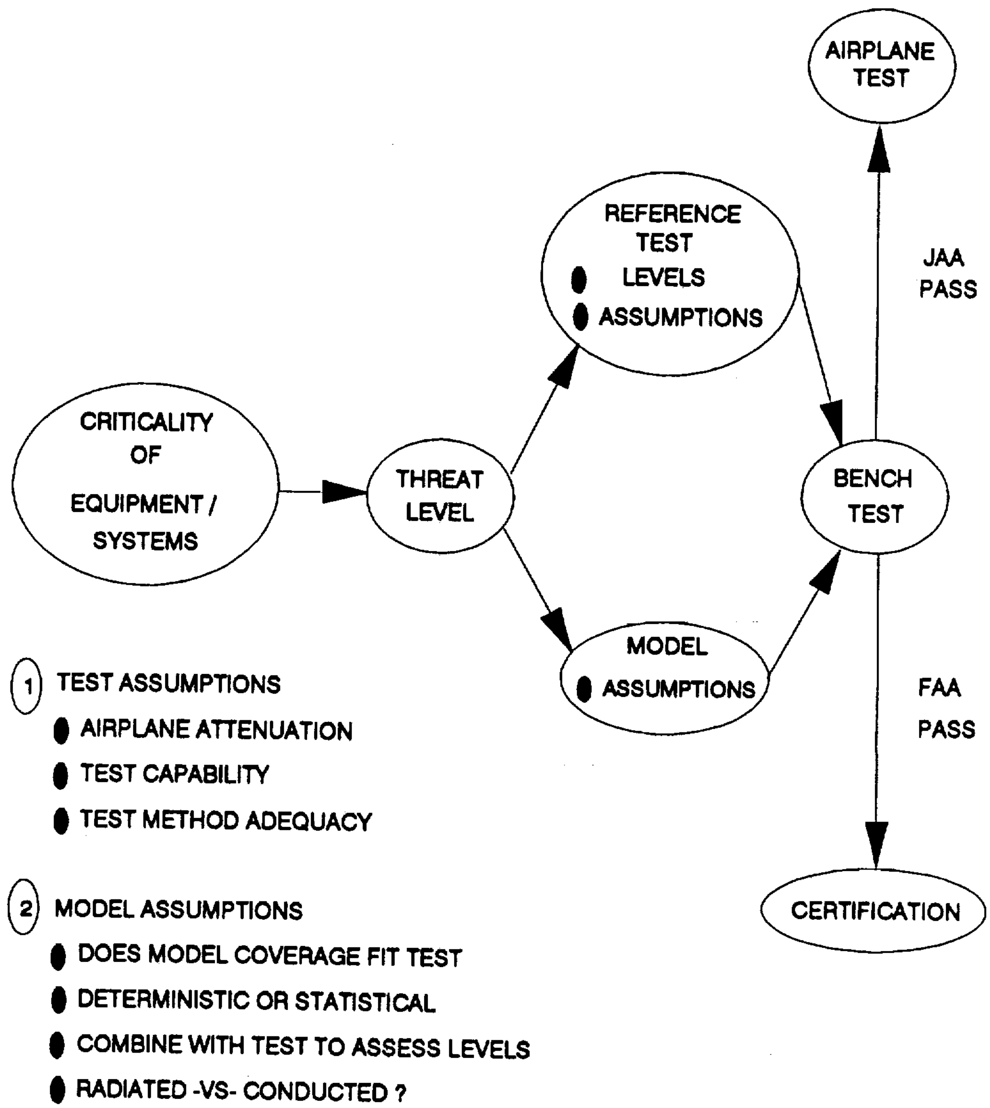

Figure 6-3 Equipment Vs System Tests

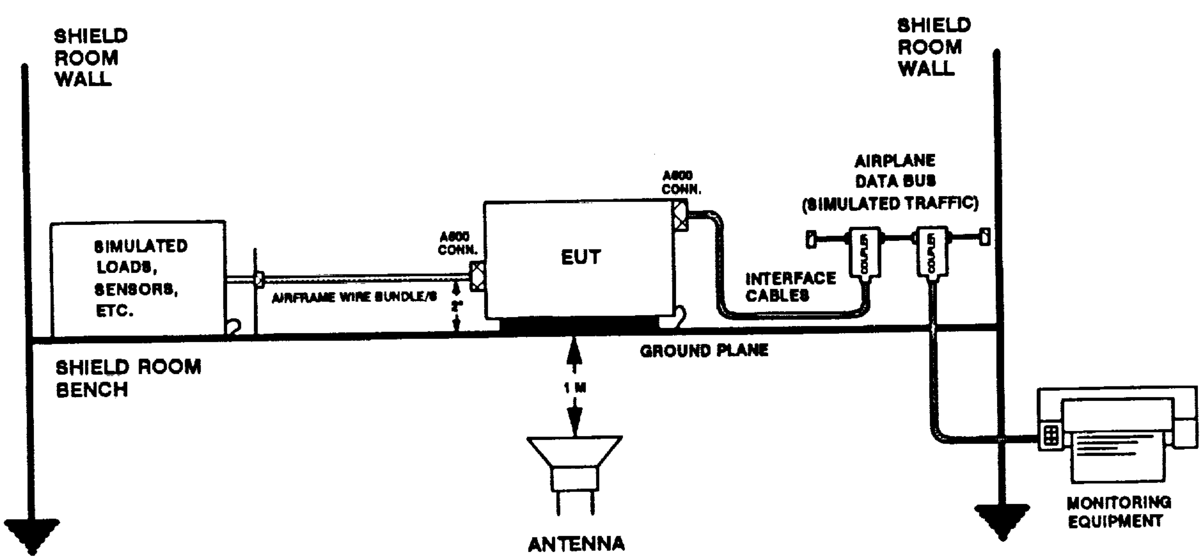

Figure 6-4 HIRF Black Box Test Example

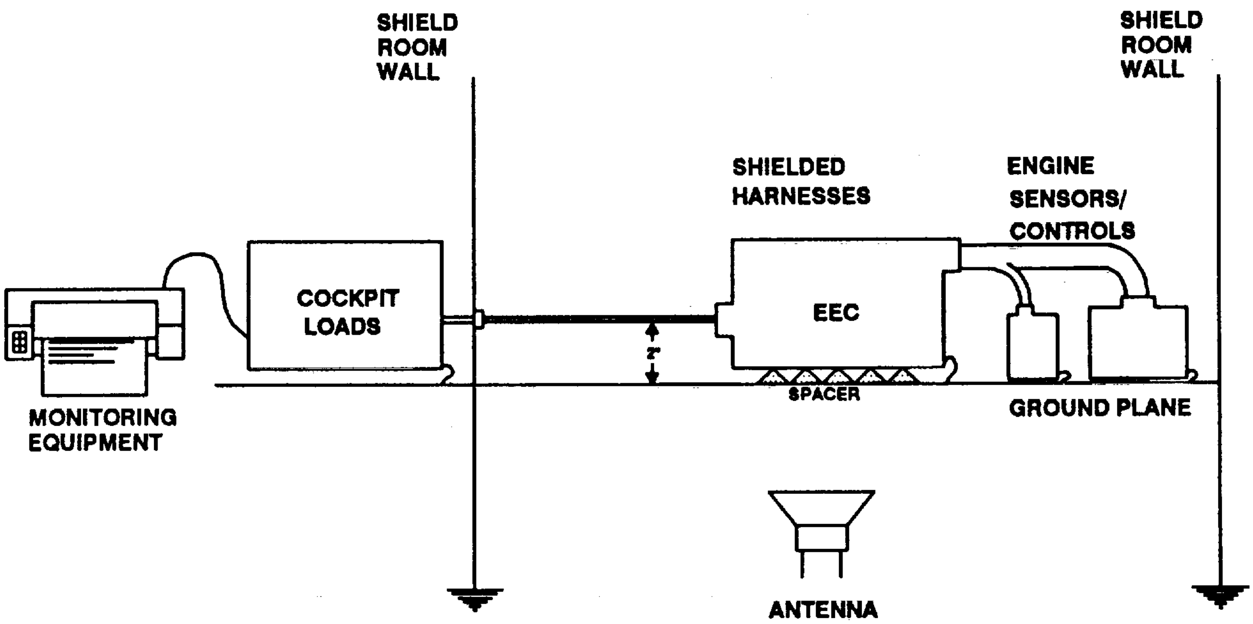

Figure 6-5 HIRF System Test Example - Electronic Engine Controller

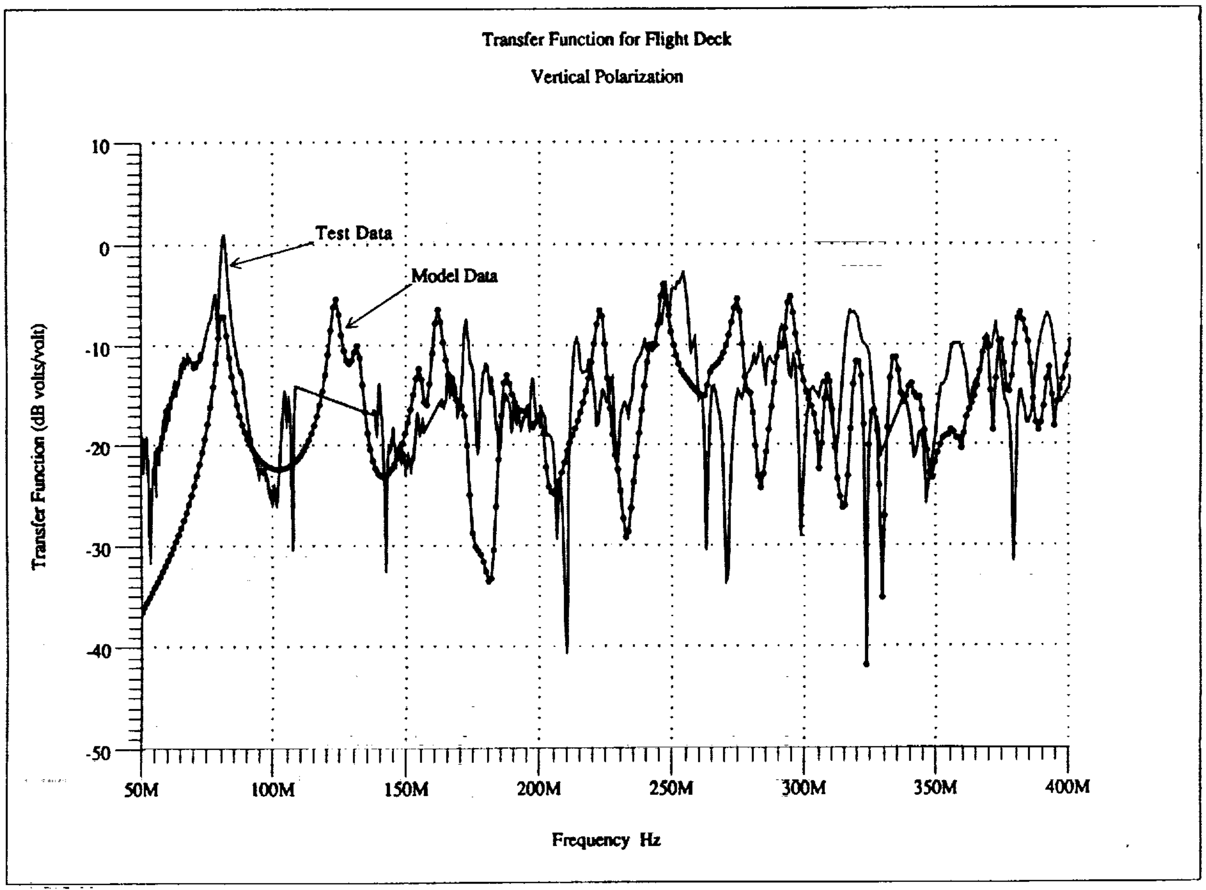

Figure 6-6 Cavity Model Vs Test Data

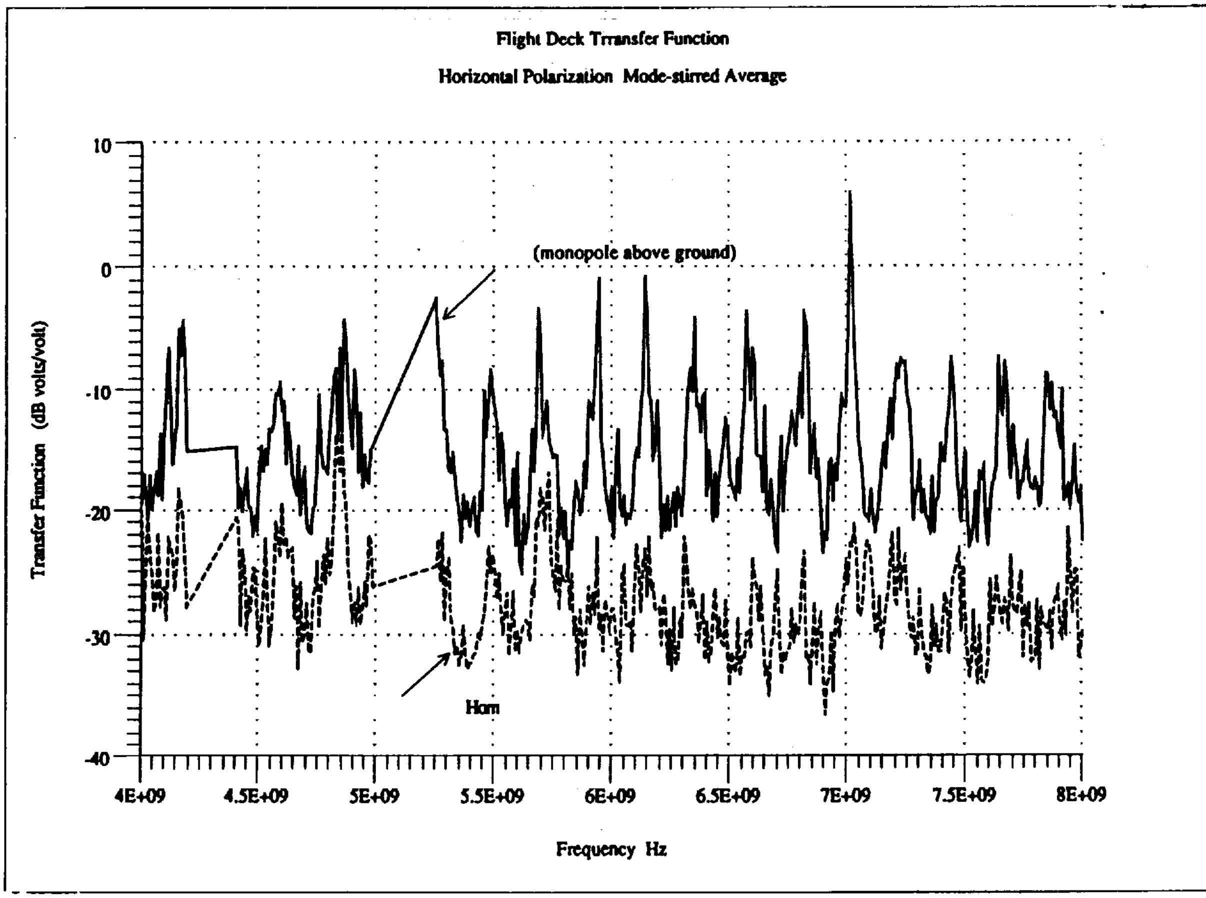

Figure 6-7 HIRF Test Dependence on Receive Antenna

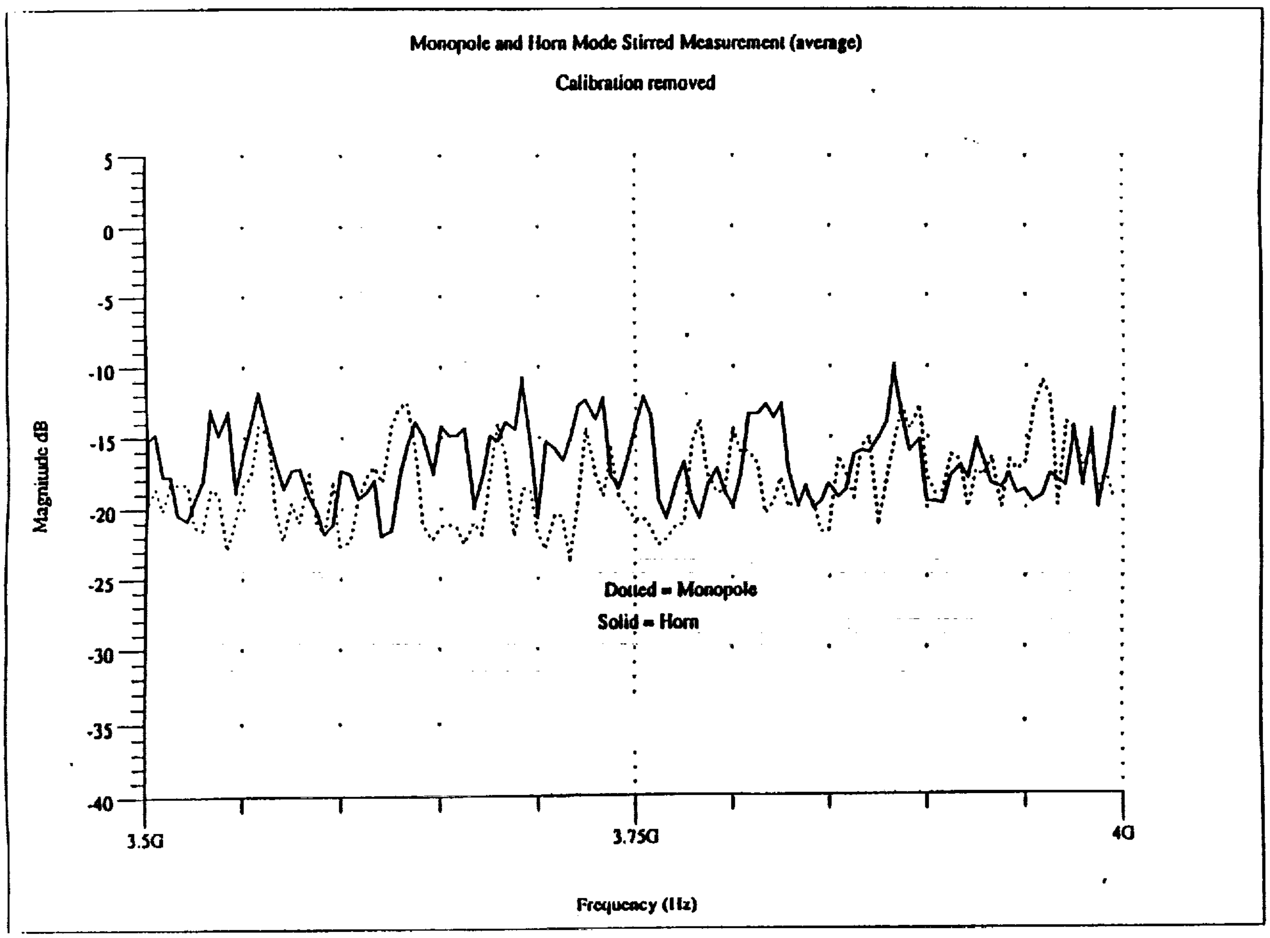

Figure 6-8 Receive Antenna Internal Response

7.0 CONCLUSIONS AND RECOMMENDATIONS

HIRF aircraft attenuation requirements are based on worst case external HIRF threat levels and somewhat arbitrarily determined equipment level susceptibility requirements. A consistent certification process requires several currently missing elements. First, a uniform definition of the HIRF environment that incorporates factors that affect the probability of encountering this environment is essential. Second, equipment level susceptibility tests requirements should be determined that are consistent with internal HIRF structure as assessed from test and analysis. Arbitrarily set standards should be revised. This will demand a combination of deterministic and statistical analyses to assess the component response to the highly variable fields excited within the aircraft by the external HIRF environment. Finally, a consistent aircraft response to the external field should be assessed by taking the ratio of a statistical or deterministic internal field measurement with respect to an operationally established reference field measurement.

7.1 Certification Process

Comparing the idealized commercial aircraft HIRF certification process as detailed in the AC-20xx Users Manual to the realistic process as practiced by a commercial airframe manufacturer, the following differences have been noted:

The realistic process is one in which test and analysis, requirements negotiation, equipment susceptibility qualification among other processes evolve in parallel. There is no recursive corrections loop at the end of a program in the realistic process as indicated for the idealized process. However there is the possibility of post-certification testing.

The importance of new test technology and modeling breakthroughs to assess airframe and component qualification is given more emphasis in the realistic process.

Generic airframe curves provided in the Users Manual as they are now formulated have been of limited usefulness in the realistic process. The concept, however, if developed for Level A, B, and C systems may simplify the overall process to certification which is a goal of formulating a consistent compliance process.

7.2 External HIRF Environment

The external HIRF environment is established by the distribution of worst case emitters as a function of frequency. Assessing the environment is ongoing. Incorporating additional factors such as transmitter antenna system losses, antenna structure heights, restricted airspace, and evaluating airport driver emitter location, will provide for a more realistic threat. Current probability based models for the HIRF threat are primitive and need to be improved. Their use for incorporating the probability of exposure into evaluating HIRF test requirements should be established.

7.3 Aircraft Coupling/Internal Environment

The test method selected to evaluate airframe attenuation depends on the properties of the test configuration, and the frequency regime. For example, LLSCW or frequency stirring may be chosen for testing within engine nacelles where spatial dimensions would prohibit effective mode-stirring except for the very highest frequencies. Mode-stirring or frequency stirring have attributes that would be advantageous in assessing airframe attenuation in larger airframe cavities such as the electronics bay or flight deck. These test methodologies at the higher frequencies provide a consistent statistical assessment of the cavity fields without the need to perform field mapping as would be required using LLSCW methods to obtain equivalent data. Non-stirred LLSCW field mapping tests are time consuming, expensive, and useful only if appropriately performed in conjunction with modeling efforts to give a representation of the expected field distribution.

A consistent attenuation assessment is possible if suitably characterized reference and receive antennas are chosen. Low level tests should be referenced with respect to omnidirectional antennas. A consistent process will incorporate a standardized method for establishing a reference. Based on the somewhat homogeneous response of the receive sensor within a complex airframe cavity, the corresponding directivity of the reference measurement must be factored into the attenuation.

Analytical and numerically based models are important to interpret test data and predict aircraft response to HIRF and need more emphasis in the certification process. No current methodology provides a comprehensive aircraft model, although alternative techniques may be necessary to assess various component or configuration response functions. Analysis and the corresponding codes require further validation.

Attenuation test data is inherently sensitive to position. Most analytical methods are deterministic and over certain frequency intervals provide only a qualitative representation of aircraft response functions. Where applicable, statistical approaches are needed to assess field variability, to interpret mode-stirred test data, and to assess shielding effectiveness as predicted by complex cavity field distribution functions.

Statistical models need to be improved to incorporate the frequency dependence of the complex cavity mode density function and thereby provide more realistic models at lower frequencies. Limitations to the statistical approach need to be established.

The overall usefulness of models is in their ability to assess the potential coupling of the external HIRF environment to internal component electronics. The result will provide a consistent representation of the external to internal response thereby impacting the formulation of more realistic equipment level susceptibility and airframe attenuation test requirements.

Probabilistic approaches can provide a means to assess the overall HIRF threat and thereby provide a global basis on which to construct realistic requirements. As this paper has indicated, the threat can be partitioned into approximately independent or conditionally dependent factors including:

1) the probability of encountering the external HIRF environment (threat)
2) the external to internal aircraft coupling

3) the internal environment and the probability of coupling to equipment
4) the probability of system upset.

7.4 Susceptibility, Test Methods and Requirements

Analogous to lightning, HIRF is a threat that is difficult to full threat simulate. Certification tests are broken down into components, with a few system level tests performed. Current bench level testing is more a measure of an equipment's electromagnetic hardness than a true simulation of the airplane internal environment. Consequently, qualification test levels are set based on historical precedence, estimated airframe attenuation, or test laboratory capabilities. Below 400 MHz, test levels tend to represent a conservative assessment. Above one GHz equipment do not appear to respond to the simulated threat when no problems are seen below one GHz. Data should be gathered to determine if this is a general trend.

Few large system tests are performed because system integration occurs late in an airplane program, and adequate test facilities are limited in capabilities and availability. The cost effectiveness of performing system tests should be established. Modeling efforts are not currently adequate to address system response to HIRF, and test results are limited.

Antenna calibration factors relating airplane internal fields to shield room and reverberation chamber measurements remain controversial. Empirical data indicates antennas respond isotropically in complex cavities containing large mode densities. Statistical models support this conclusion. Additional research is needed to resolve this issue.

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13. ABSTRACT (Maximum 200 words)
The HIRF certification process as currently implemented is comprised of an inconsistent combination of factors that tend to emphasize worst case scenarios in assessing commercial airplane certification requirements. By examining these factors which include the process definition, the external HIRF environment, the aircraft coupling and corresponding internal fields, and methods of measuring equipment susceptibilities, activities leading to an approach to appraising airplane vulnerability to HIRF are proposed. This approach utilizes technically based criteria to evaluate the nature of the threat, including the probability of encountering the external HIRF environment. No single test or analytic method comprehensively addresses the full HIRF threat frequency spectrum. Additional tools such as statistical methods must be adopted to arrive at more realistic requirements to reflect commercial aircraft vulnerability to the HIRF threat. Test and analytic data are provided to support the conclusions of this report. This work was performed under NASA contract NAS1-19360, Task 52.

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