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VERIFICATION AND VALIDATION OF RF ENVIRONMENTAL MODELS - METHODOLOGY OVERVIEW

Systems Simulation and Development Directorate
Advanced Simulation Center
US Army Missile Laboratory

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U.S. ARMY MISSILE COMMAND

Redstone Arsenal, Alabama 35809

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I. INTRODUCTION

Radar guided missile simulation is one of several key methods employed to gain as thorough an understanding as possible of radar missile performance within an operational environment. Simulation is valuable whether in the design, development, evaluation, or deployment stages of a missile life cycle because it permits conducting a larger number of carefully designed trials in a controlled environment than is possible in flight tests. For the results of simulation to be a meaningful representation of actual missile performance, however, it is essential that the models of the system and its physical environment, which form the building blocks of simulation, have a demonstrable correspondence to reality. Among the models are ones characterizing the RF environment which stimulates the missile seeker. Verification and validation (V&V) of the underlying models in a formal program is therefore a necessary ingredient in a successful missile simulation effort.

The Radio Frequency Simulation System (RFSS) program for V&V of the RF Environmental Models utilized in hardware-in-the-loop (HWIL) radar guided missile simulation at the MICOM Advanced Simulation Center (ASC) is the subject of this document. The RFSS, the Electro-optical Simulation System (EOSS), and the Infrared Simulation System (IRSS) comprise the three physical effects simulators that surround a hybrid computing complex. The RFSS is unique in its capability of presenting the RF environment to the device under test. Included in its capabilities are the following:

- o 2 to 18 GHz frequency coverage.
- o polarization diversity.
- o four simultaneous, independent targets.
- o 42° instantaneous field-of-view presented to a device under test.
- o real-time range delay for coherent signal processors.
- o tapped delay lines and modulators for RF model implementation.

These capabilities allow the simulation (in real-time) of any RF guidance mode, including coherent or noncoherent active, semi-active, passive, command, beam-rider, and track-via-missile (TVM). The reader is presumed to be familiar with RFSS simulation operations and capabilities as described in the RFSS Users Guide [1] and the RFSS Capabilities Summary [2].

The RF Environmental Models form one of the basic building blocks of the overall ASC guided missile simulation. RF environment refers to the composite of electromagnetic signals, which stimulate the missile antenna during flight, and includes target scattering returns, clutter, multipath, and ECM signals. During a simulation in the RFSS, RF signals are generated in real time and transmitted across the anechoic chamber to the seeker mounted on a three-axis flight table. To properly exercise the missile seeker hardware during simulation, the signals presented to the seeker by the Environmental Models ideally should be indistinguishable from those encountered during an actual combat flight. Because of incomplete knowledge of the physical phenomena involved and constraints in time and budgets, it is possible to achieve this goal with only limited success. Within such limits, the RFSS Environmental Model V&V Program is designed to assure that the signals presented to the seeker are as realistic as possible and, furthermore, to quantify this degree of realism.

V&V has become an integral part of the modern approach to the development of large software-based systems. Although the specific objectives and requirements of RF environmental modeling differ significantly from those of software system development, the RFSS approach to V&V utilizes the same well-planned, time-phased approach to V&V which has been proven successful by software engineers.

The first stage of Environmental Model V&V is *verification* of the correct implementation of the models. This is accomplished in three stages:

- o Model Design Requirement Review.
- o Model Implementation Verification.
- o Periodic Calibration/Diagnostic Maintenance.

Design review checks that the mathematical models developed for a particular simulation meet the requirements agreed upon by both the simulation customer and RFSS System Leader in planning the simulation. Verification measurements assure that this mathematical model has been correctly implemented in real-time hardware/software in the RFSS. Calibration/diagnostic maintenance is a routine series of tests made on a daily or weekly basis during simulation operations to check that the models continue to function properly. If verification standards are not met at any stage in this process, corrective action is taken before proceeding to the next step.

Environmental Model *validation* addresses the much broader issue of model realism. The central issues are how adequately do the correctly implemented models emulate the real-world environment and what are the model limitations. These issues are addressed by comparing simulation predictions with actual field data or other independent results. The extent and nature of these comparisons are highly program specific. Depending upon the quantity and type of data provided to the RFSS by the simulation customer for validation, various quantitative measures of agreement between simulation predictions and reality can be computed and levels of confidence in the simulation results established.

As applied to RF Environmental Models utilized in HWIL simulation in the RFSS, the following definitions are appropriate:

- o Verification--the process involving acquisition and analysis of RFSS measurement data which assures RF Environmental Models implemented in the RFSS meet their design objectives.
- o Validation--the assessment and quantification of the degree to which RF Environmental Models are adequate representations of physical reality.

The general topic of V&V is discussed in Section II, both as it applies to guided missile simulation and as it has evolved from earlier work in software systems development. The specific RFSS approach to V&V of RF Environmental Models is delineated in Sections III and IV, respectively.

II. V&V FRAMEWORK

A primary objective of HWIL seeker simulation is to contribute to the development and assessment of weapon system performance. The aggregate expense of missile flight tests, including costs for fabrication of both developmental missile hardware and target drones and costs for operations of the test ranges, makes more than a limited number of flight tests economically infeasible. HWIL simulation can be used to maximize the information obtained from these tests by predicting through preflight simulation those scenarios critical to missile performance envelope assessment and by contributing through post-flight simulation to the analysis and understanding of flight test results.

It is also important that HWIL simulation be used to gain an understanding of missile system performance in those situations where avoidance of flight test cost is not the motivation; for example, where it is required to estimate performance versus projected threat capability, where quick reaction performance assessments are needed, or where special security requirements preclude tests susceptible to monitoring by a potential adversary. Simulation supports systems analysis, permits examination of "what if" issues, and contributes to the lowering of design risks. Results help to increase confidence in system performance and generally provide a data base for proper management decision-making.

To achieve these and other simulation benefits, it is mandatory that the realism of HWIL simulation be demonstrated, so that a high degree of confidence can be placed in simulation predictions and results. The V&V process of both the overall simulation and the component simulation modules provides an orderly framework for evaluating the degree of simulation realism and determining the level of confidence which is appropriate to the results.

A. V&V Hierarchy

As illustrated in Figure 1, a number of factors are involved in predicting the performance of a candidate weapon system. The ultimate measure of realism is performance in a real-world combat situation. Flight testing closely emulates reality, although even in this case a surrogate target is typically substituted for an actual threat vehicle. Target realism vis-a-vis the threat is an issue which must be satisfactorily demonstrated before flight test predictions can be accepted with great confidence.

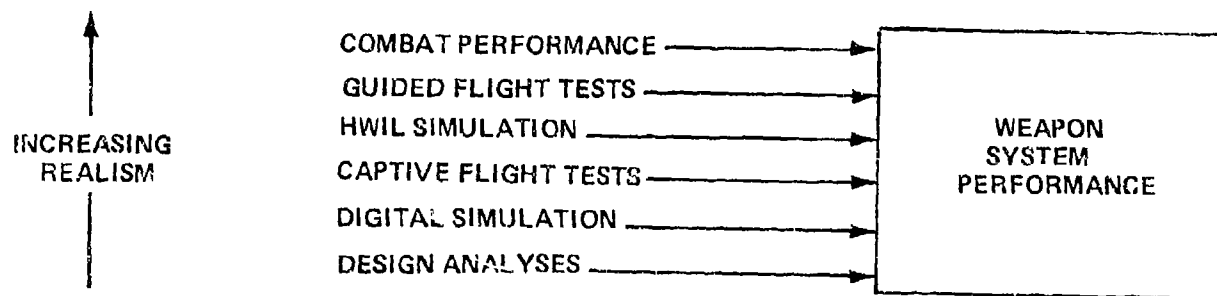


Figure 1. Hierarchy of performance evaluation methods.

In the remaining evaluation methods--HWIL simulation, captive flight testing, digital simulation, and design analysis--certain aspects of reality are replaced by models to gain scientific control over engagement scenarios and the large number of variables which can affect missile performance. The degree to which each method contributes to an understanding of overall missile performance is dependent upon the validity of these models. For an RF guided missile, a division can be made into three major elements which contribute to missile performance. As depicted in Figure 2, these are the RF environment, which stimulates the seekers; the sensor/signal processor, which processes the seeker's outputs; and the missile flight dynamics system. RF environment refers to the composite of electromagnetic signals that is available to excite the missile antenna and includes target return, clutter, multipath, and ECM signals. The sensor/signal processor includes both the missile microwave receiver and the target acquisition and tracking logic circuitry and/or computer. Finally, the flight dynamics system includes the remainder of the missile system (autopilot, actuators, etc.) and the aerodynamic coupling to the surrounding atmosphere.

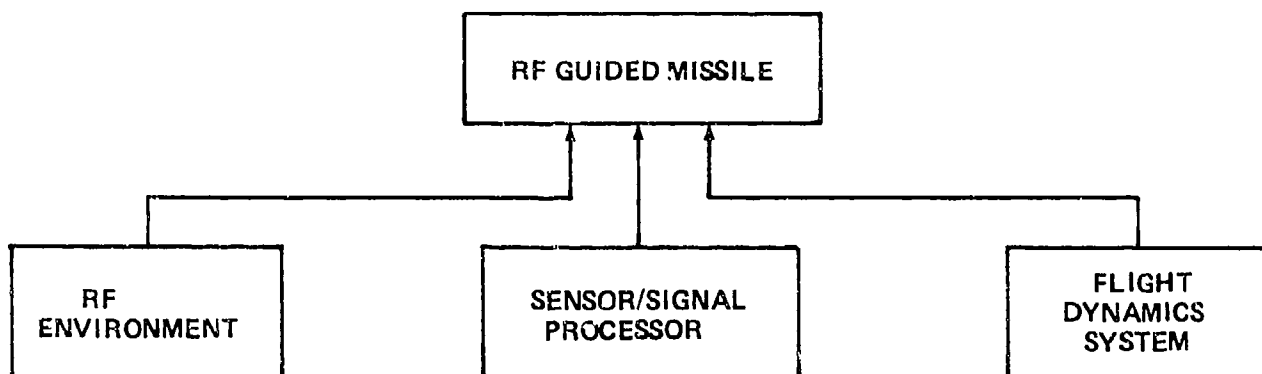


Figure 2. Major missile performance elements.

The tasks of V&V apply not only to overall missile performance but also to each of these elements. Moreover, in a missile simulation, it is impossible to establish with a high degree of confidence the credibility of simulation results without first verifying the correct implementation of the individual models and validating the correspondence of model predictions to reality.

The specific application of these concepts to RFSS HWIL simulation is discussed in paragraph II.B.

B. V&V Applied to HWIL Simulation

The motivating factor behind HWIL simulation is that an RF sensor/signal processor performs highly complex functions which are extremely difficult to model realistically on a computer. By inserting actual hardware into the simulation, the performance of this subsystem is by definition valid. The impact of this approach is that the environmental and flight dynamics models must not only be modeled realistically, but they must couple with the seeker and must execute in real time.

In an all-digital simulation, various levels of detail may be appropriate for the seeker model, depending upon the objectives of the simulation. To determine miss-distance statistics or false alarm probabilities via Monte Carlo techniques, a simplified model of seeker performance which executes in real-time is often appropriate. Detailed parametric studies of seeker performance versus variations in the RF environment, however, require complex seeker models which typically execute hundreds or even thousands of times slower than real-time. It is obvious that the V&V criteria applied to each of these extremes must reflect the different simulation objectives.

Similarly, different levels of detail are appropriate for the RF Environmental Models, depending on simulation objectives. To determine acquisition range, for example, a simple point target may suffice; but to determine end-game seeker performance, a realistic extended target model is required. In either case, the validity of the overall simulation is contingent upon utilizing RF Environmental Models, Seeker Models (or actual seeker hardware), and Flight Dynamics Models which have been both verified and validated over the range of parameters covered in the simulation.

1. Flight Dynamics Models

The missile dynamics models utilized by the RFSS in HWIL simulations are developed and implemented by the MICOM ASC. Verification of these models is of great significance; for example, an error in the model output, which drives the three-axis flight table on which the actual seeker is mounted, can result in actual physical damage to the seeker. These models are implemented through a step by step integration of previously verified submodules

until a completely verified flight dynamics model is assembled. This process which uses a previously verified all-digital flight dynamics model as the verification baseline, is described in detail in the *RFSS User's Guide* [1]. The Flight Dynamics Model is validated by comparing a time history of deflection commands to the missile control surfaces generated by the model with corresponding signals telemetered from actual flight tests or generated by a previously validated simulation model. Individual subsystems, such as the autopilot, can be independently validated if special provisions are made to include the appropriate signals in the flight test telemetry data package.

2. Seeker Models

As an adjunct to specific HWIL simulation programs, digital seeker models may be formulated by using open-loop seeker characterization test data obtained by the SSC in the RFSS. Based upon program requirements, a hierarchy of models of increasing realism and complexity can be developed. The simplest elements of this hierarchy, intended to model high level functional seeker system performance, may be required to run in real-time as part of the HWIL simulation of other missile components. More detailed members of the hierarchy are intended to accurately model seeker subsystems. The most realistic model, which generally requires significant computational resources to execute, is the detailed subsystem model that is integrated into a full seeker system performance model. Seeker characterization data obtained in the RFSS can be used to validate digital seeker models built from seeker design criteria, thus assuring that seeker hardware fulfills its design objectives. Seeker characterization measurements in the RFSS can also be used in conjunction with digital seeker models to assess and exploit threat hardware.

3. RF Environmental Models

Flight dynamics modeling is an established discipline, and experience has shown that validated models can be developed with a high degree of confidence. The problem of validating a radar seeker model is avoided in HWIL simulation by using actual seeker hardware. The critical factor, therefore, in establishing the credibility of RFSS HWIL simulation results lies in the V&V of RF Environmental Models.

The general approach to environmental modeling followed at the RFSS involves forming hierarchies of generic models for each RF environment

element. These hierarchies - which exist for targets, clutter, jet engine modulation, propeller and helicopter blade modulation, multipath and chaff - range from simple to complex, with corresponding ranges of applicability and realism. They are generic in the sense that their formulation is driven by specific data bases generated empirically or analytically which are appropriate for both the weapon system and the target or threat vehicle being simulated. The target model hierarchy, for example, consists of four types:

- o Isotropic Scatterer Model
- o Empirical Scatterer Model
- o Statistical Model
- o Deterministic Multiple Scatterer Model.

The simplest, the Isotropic Scatterer Model, consists of a point reflector located in space at the target centroid with a fixed radar cross section (RCS). The Empirical Scatterer Model allows for slow variation with aspect angle of both the target RCS (amplitude scintillation) and apparent angular position (low-frequency glint or bright-spot-wander). The Statistical Model adds to the Empirical Model high frequency amplitude scintillation (rapid variation with aspect angle) and angular glint components which may be either aspect or aspect-rate dependent. The final and most realistic member of the hierarchy, the Deterministic Multiple Scatterer Model, treats the target as a collection of point scatterers. Each scatterer can have aspect-dependent amplitude and phase scattering properties, with the total target return computed as the coherent superposition of the returns from the individual scatterers illuminated by the radar transmitter. This results in the seeker receiving realistic amplitude scintillation and range and angle glint.

Each of these models is driven by an empirical or semi-empirical data base, and the extent to which a particular model realistically represents the radar signature of a particular target or threat vehicle depends in large measure upon the quality and completeness of the available data base. The degree of realism required in the simulation is also dependent upon the seeker processing logic. It is the joint responsibility of the customer and the RFSS Systems Leader to agree during the coordinating and planning stage of the simulation development cycle upon model specifications which both satisfy the customer's test objectives and are implementable in the RFSS. The customer is responsible for providing the data from which the models are constructed or

for agreeing to use an existing RFSS data base. The RFSS Systems Leader is responsible for correctly implementing these models; i.e., to verify that the RF signals presented to the seeker-under-test meet previously agreed-to specifications. The RFSS approach to Environmental Model Verification is discussed in detail in Section III.

The credibility of the simulation results--the degree of confidence which one places in these results--is largely dependent upon the realism of the environmental models. Establishing this credibility is the purpose of the model validation effort. One of the first steps in the validation process is to demonstrate that the models reproduce the data from which they are derived. A more comprehensive validation procedure involves the quantitative comparison of model outputs with independent measurements or theoretical analyses. It is important that the RFSS customer help to identify the level of validation appropriate for his specific program and take the necessary steps to provide the required validation data. The general RFSS approach to environmental model validation is discussed in Section IV.

4. Overall Simulation

Verification of the overall simulation is accomplished by demonstrating the correct interface among independently verified component models. Validation of the overall simulation is also contingent upon the validity of the component models and is accomplished by comparing flight test results with simulation results. For example, the comparison of fin deflection commands which served in paragraph B.2 to validate the Flight Dynamics Model could also be used to validate the overall simulation of realistic RF Environmental Models are used in the simulation.

C. V&V As An Existing Technical Discipline

V&V techniques have been heavily used in the software systems environment for several years. Although many such techniques have been extrapolated to hardware or mixed software/hardware environments, there are differences. In the pure software situation, the actual item to be evaluated is usually available and can be used, while in the hardware-type situation some portion (ranging from none to all) of the hardware may exist or may need to be simulated. However, the general software V&V techniques can, to some degree, be transferred to the mixed software/hardware V&V domain. They are

reviewed here as pertinent background to the development of V&V methodologies specific to the RFSS and particularly the RF Environmental Models.

1. General V&V Concept

The main purpose of V&V is to assure that a developed product satisfies the user's requirements. To assure objectivity, the V&V team is at times composed of members who are independent from the system designers, developers, and implementers. The V&V process, ideally, should be accomplished in a series of steps that interface with the system development. Several steps constitute a phase of software system development, and each phase provides a definitive, verified baseline for the next phase. Verification is an interactive process aimed at determining whether the product of each step and/or phase of the development cycle fulfills all the requirements levied by the previous step and/or phase, while validation is the process of testing the developed system and comparing the results to the required performance.

2. Software V&V

The described V&V process is well suited for assuring that developed computer software products actually fulfill the role for which they were intended. It helps to prevent software costs from escalating by providing start-to-finish traceability. The production and documentation of each phase of V&V are compared with those of earlier ones, and a report of the results is prepared. Figure 3 presents a simplified view of such a V&V process. The development of a product can begin at any one of several points: initial concept formulation, research and development design, operational production, etc. Sometimes verification involves comparing several steps or phases rather than just two; the same is true for validation.

Software verification involves reviewing and analyzing all system software-related deliverables for correctness, completeness, consistency, and pertinence. The analyses are the result of comparing the contents of the system deliverables with the requirements, design documents, specifications, and standards established by:

- o Purchase Description or Statement of Work
- o Outline Acquisition Plan
- o Pertinent Military Standards and Regulations

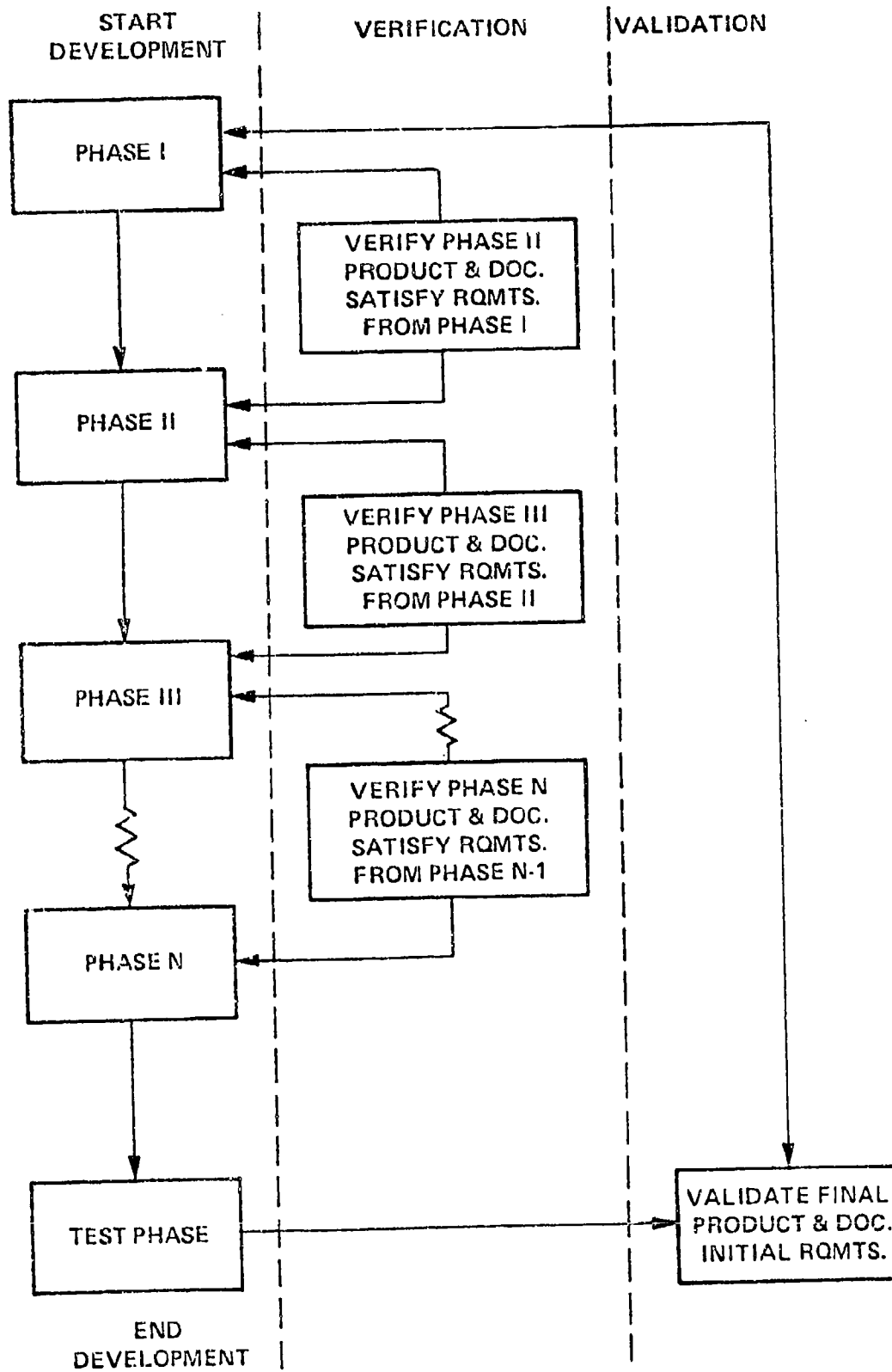


Figure 3. Simplified view of the V&V process.

- o Pertinent Documentation Standards
- o Pertinent Department of Defense Directives

After reviewing and analyzing individual system documents, deficiencies resulting from noncompliance and nonconformance with the established requirements, specifications, and standards are noted; deficiencies are reported in technical reports with changes recommended to correct the deficiency. Subsequent versions of software-related documents are reviewed to ensure that the customer-directed changes have been included.

Validation involves activities which ensure that the system software is adequately tested and meets established user requirements for performance and reliability. Validation activities include independent tests, system software contractor's tests, independent comparative analyses, and acceptance testing.

A typical approach to a software V&V plan results in a six phase effort:

- o System Design Verification
- o Software Design Verification
- o Computer Program Configuration Item (CPCI) Verification
- o CPCI Validation and Integration
- o Specification Verification
- o System Validation

For each phase a chart similar to a Program Evaluation Review Technique (PERT) chart is valuable to portray graphically all software-related V&V activities, time-lines, deliverables, milestones, and their inter-relationships within the program.

3. Applicability of Software V&V Techniques to RF Environmental Models

V&V for pure software systems is more straightforward than for the mixed hardware/software configurations used in HWIL simulation. These configurations are not fixed--they must often be changed to satisfy specific customer requirements. The RFSS does not produce a product in the traditional software sense, so that many of the procedures outlined are not applicable; moreover, certain items (Outline Acquisition Plan, Pertinent Military Standards

and Regulations, etc.) are not available to serve as V&V standards. However, the planned phased approach employed in software V&V is broadly applicable to V&V of RF Environmental Models and is used in the following sections.

III. VERIFICATION OF RF ENVIRONMENTAL MODELS

A. General

Verification as applied to RF Environmental Models in the RFSS has the goal of assuring that the electromagnetic fields presented to the seeker-under-test during simulation meet the specific design objectives agreed to by the customer and RFSS Systems Leader at the beginning of the simulation development cycle. Validation addresses the broader issue of whether or not these correctly implemented models are an adequate representation of the real-world RF environment. Verification has, in a sense, a binary output; if a particular design objective is not met by verification testing, corrective action is implied. This action can be accomplished either by correcting errors or otherwise improving the model or by relaxing the design specification if demonstrated to be overly ambitious.

A typical simulation of an RF guided missile in the RFSS is accomplished in the following phases:

- o Coordination and Planning.
- o Simulation Development.
- o Integration and Checkout,
- o Simulation Operations.
- o Analysis and Documentation.

There are three distinct verification tasks which apply to each RF environmental model and which occur at different stages in the simulation development cycle. These are:

- o Model Design Requirement Review.
- o Model Implementation Verification.
- o Periodic Calibration/Diagnostic Maintenance.

Model Design Requirement Review occurs during the Simulation Development phase. It consists of verifying that the mathematical models (typically non-real time FORTRAN computer programs) developed for the simulation, satisfy the objectives set forth in the coordination and planning phase. This task

is important from a technical review perspective, particularly in its role to identify and isolate high risk areas which could later impact schedule milestones.

The second task, Model Implementation Verification, assures that environmental models have been correctly implemented in the RFSS. This implementation involves various processes, including microcoding of the mathematical model into real-time software, digital-to-analog signal conversion, in-phase and quadrature weighting, time delays, amplitude modulation, doppler modulation and amplification and radiation of the appropriate range attenuated RF signal from the proper position on the RFSS array. Verification of the implemented model is accomplished by measurement at various stages of signal generation. Final verification is accomplished by measurement of the actual signals presented to the seeker-under-test, utilizing the RFSS Verification Receiver Measurement System (VRMS). Verification measurements are discussed further in paragraph III. D.

Model Implementation Verification occurs during both the Simulation Development and the Integration and Checkout phases of the simulation. Real-time software and signal generation through the RF stage are verified during Simulation Development. By accomplishing this before missile hardware is scheduled to arrive in the RFSS, problems are detected and corrected with minimal impact on schedule milestones. This increases the productive use of missile hardware during the period when it is in the RFSS, and enhances the efficiency and effectiveness of the simulation program. Verification of the propagated RF signal using VRMS (which requires dedication of an aperture in the RFSS chamber) is generally performed during Integration and Checkout.

The final element of environmental model verification occurs on a periodic basis during the Simulation Operations phase of the simulation cycle. This task consists of a variety of daily and/or weekly calibration and diagnostic maintenance checks which are designed to assure that the environmental models continue to meet their design objectives. As with previous verification tests, failure to meet a specification implies corrective action before the simulation proceeds. Near real-time checks of the seeker output are also possible during simulation using an HP5451C Fourier Processor. This capability is designed both to contribute to environmental model verification and to facilitate on-line analysis of seeker performance.

B. Model Configuration Management

The environmental modeling objectives agreed to by the customer and the RFSS Systems Leader during the Coordination and Planning phase of simulation development, may consist of both model performance and model construction specifications. These specifications define the type and range of parameters over which the model is to be exercised. For a target model, for example, factors such as type of target, range of azimuth and elevation angles, maximum turning rate, and minimum missile/target distance at which the model must be realistic might be specified. The performance specification should define how accurately each model output variable can and should be simulated. For example, it might be required that target model radar cross-section as a function of azimuth angle agree with a known set of scattering measurements to within 3 dBsm. Specification of the model construction sets forth the technical approach defining how the model is to be formulated.

Some environmental modeling objectives are ambitious and may require elaborate measurement programs, advances in environmental modeling technology, or the development of new signal generation hardware. Therefore, it may become necessary to readjust these objectives during Simulation Development or Integration and Checkout. Model Configuration Management, which consists of documentation of Model Performance and Construction Specifications, is the responsibility of the RFSS Systems Leader, and is essential to the RFSS V&V program.

C. Implementation of RF Environmental Models

A hierarchy of generic models for targets, clutter and blade modulation are available for use in the RFSS, and are discussed in the *RFSS User's Guide* [1]. Models have also been developed for multipath and ECM, and the option exists to utilize actual jammer hardware to drive the RFSS ECM and/or main arrays. As discussed in paragraph II.B.1, these models are generic in the sense that they are driven by customer-supplied data bases which are appropriate to the particular seeker, threat vehicle and operational scenario of interest.

The implementation of these models, as illustrated in Figure 4, generally proceeds in a two-stage process. A FORTRAN computer program not required to execute in real-time is first produced; this form of the model is shown to satisfy the Design Requirement. The FORTRAN program then becomes the

standard against which the real-time version of the model is verified.

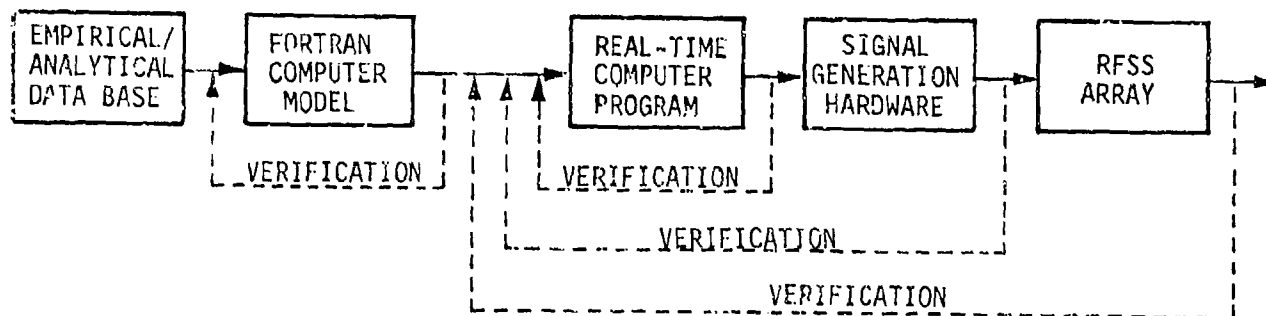


Figure 4. RF environmental model development and implementation.

An implemented model can be subdivided into three general sections: software which may reside on more than one computer, IF signals which undergo various analog processes in order to generate a signal with the proper doppler, waveform characteristics and time delay, and RF signals which are amplified and transmitted from the RFSS array to the seeker-under-test. Verification tests are designed to assure that the proper model outputs are produced after each of these stages.

First, the digital output of the real-time software is compared with the output of the FORTRAN math model. Next, the analog output of the amplitude modulators is measured to ensure that digital in-phase and quadrature voltage commands are correctly converted into analog signals and summed. Additional tests are performed at each stage of IF mixing when appropriate; for example, spectra of clutter signals are verified using a spectrum analyzer. Figure 5 illustrates the results of a typical clutter verification measurement. Twenty time slices of analog signals designed to simulate the clutter return detected by a CW semi-active radar missile are measured at IF, transformed using a DFT (discrete Fourier transform) spectrum analyzer, and the spectra averaged to reduce random fluctuations. The resultant averaged spectrum is then compared to the intended spectrum. The amplified RF signal is measured before radiation to verify the correct input to the array switching network. Finally, the signal is propagated across the chamber and measured at an aperture using VRMS to verify that the correct signal is presented to the seeker-under-test.

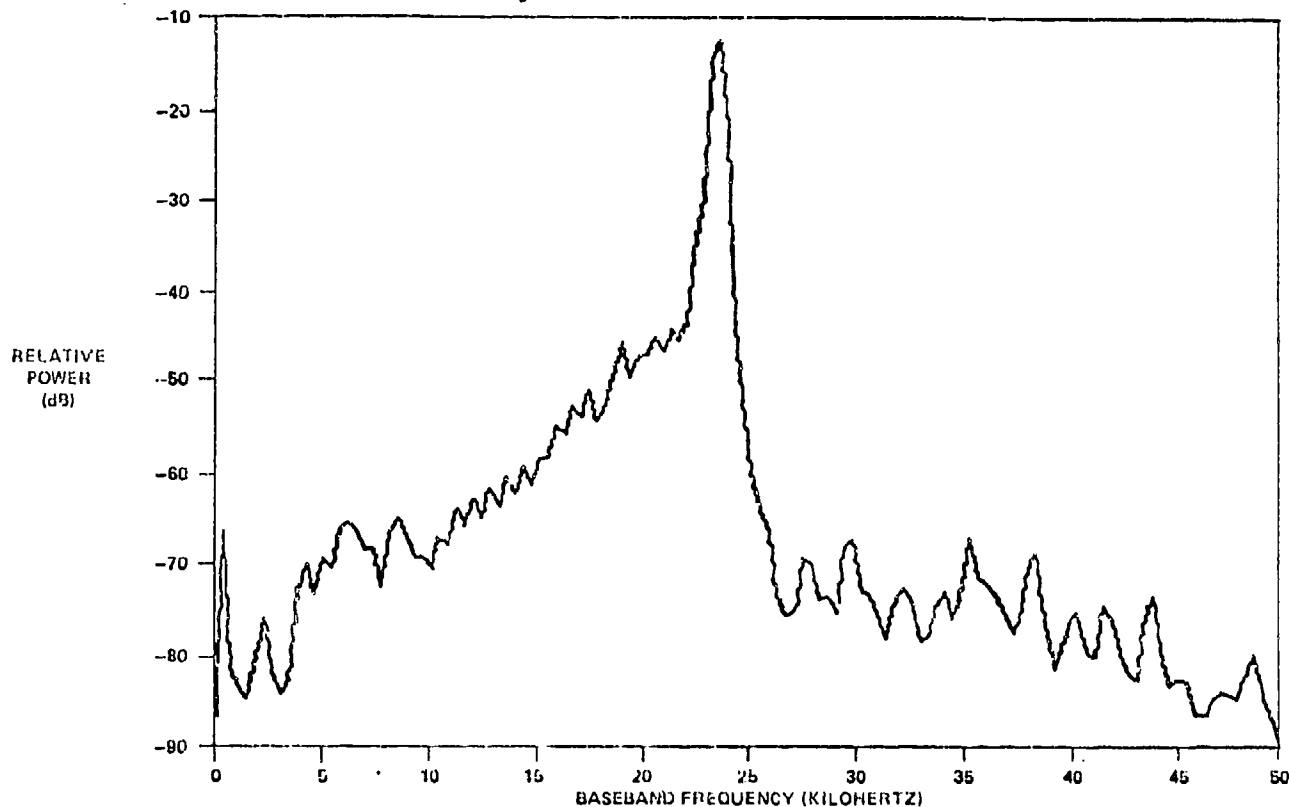


Figure 5. Fourier analysis of RFSS clutter signal generated by real-time software for a time slice of a simulated flight.

Verification tests are designed in this modular buildup fashion to facilitate the isolation of problem areas. Thus verification testing serves as a diagnostic tool and assists in the process of correcting errors or oversights.

D. Verification of Propagated RF Signals

The ultimate verification test of RFSS environmental models is the measurement of electromagnetic fields at the seeker aperture and the demonstration that these signals meet the model design requirements. These measurements are made using the VRMS. The specific waveform characteristics which are measured are dependent upon the characteristics of the seeker whose performance is being evaluated. For a semi-active CW doppler-tracking missile, for example, it is sufficient to verify the power and spectrum of the RF signal and the apparent angular position from which it is being radiated. For pulse-doppler missile with multiple range gates, it is also necessary to verify proper time-delay and phase coherency between the signals in the range intervals being

simulated. Current and projected RFSS verification measurement capabilities are outlined in the following subsections.

1. VRMS-I

Current RFSS verification measurements are accomplished by replacing the seeker-under-test by one of two instruments, the Calibration Sensor (Cal Sensor) or the Active Test System. The Cal Sensor is a four or five horn (dual configuration) interferometer which measures angular position on the RFSS array of a CW signal in the 2 to 18 GHz range. The receiver can measure signal polarization and can measure angular position as a function of polarization. Absolute accuracy of this device is a function of frequency, polarization and angular displacement [3]. The Active Test System generates a 20 W peak pulse modulated signal with variable pulse repetition interval and duty factor. This signal is transmitted across the chamber where it is received by the array and processed as in an HWIL simulation. The retransmitted signal is received, range-gated, and processed by a heterodyne receiver. The output consists of video and detected IF signals. Detected IF is used to verify time-delays and the video signal is passed to a spectrum analyzer for Environmental Model spectral density verification.

Current verification measurements are generally limited to a static target scenario; that is, neither of these devices is capable of tracking a target flying an arbitrary trajectory across the array. Verification of RF environmental models in a dynamic situation is therefore done inferentially utilizing the seeker-under-test. After the performance of the seeker is established versus the verified static environmental models, a number of baseline dynamic scenarios are run. If the seeker performs as expected based upon the static tests, the environmental models are considered verified in the dynamic situation.

Figures 6 and 7 illustrate the use of seeker-derived data to accomplish RF Environmental Model development and verification. In Figure 6, the power spectrum of a time slice of the monopulse sum-channel wideband video signal telemetered during a missile flight test is presented. The analysis was performed in the RFSS using an HP5451C Fourier Analyzer. This data was used in the formulation of RF environmental models. In Figure 7, the results of a similar analysis using data obtained during the simulated flight of the

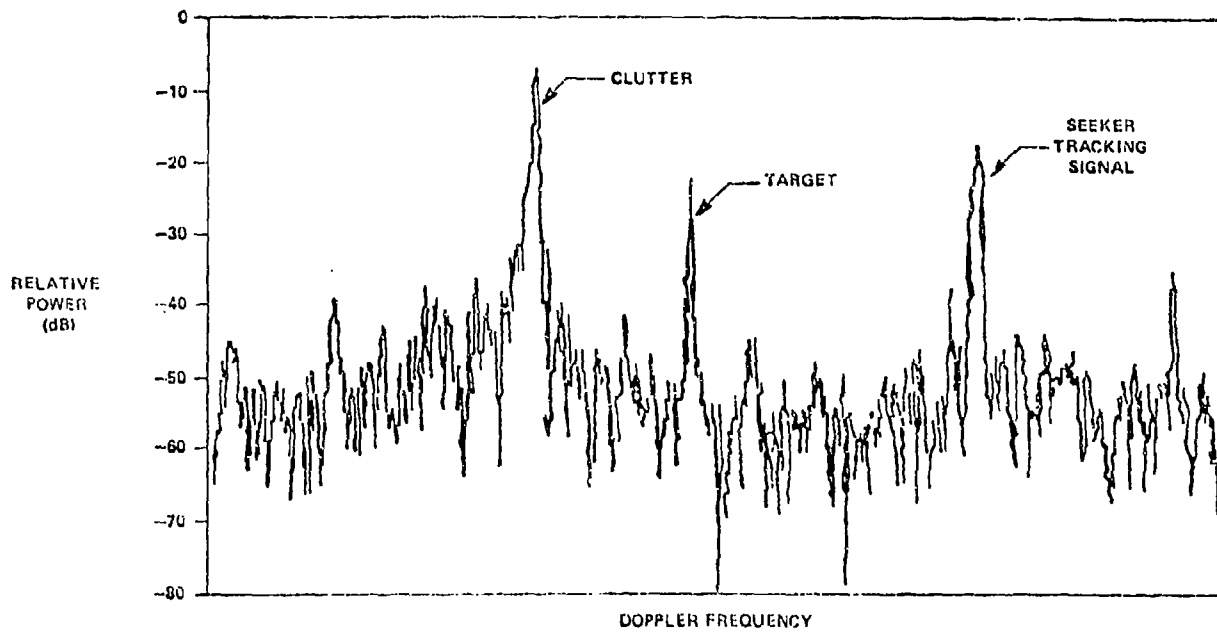


Figure 6. Fourier analysis of time slice of wideband video signal from a test flight.

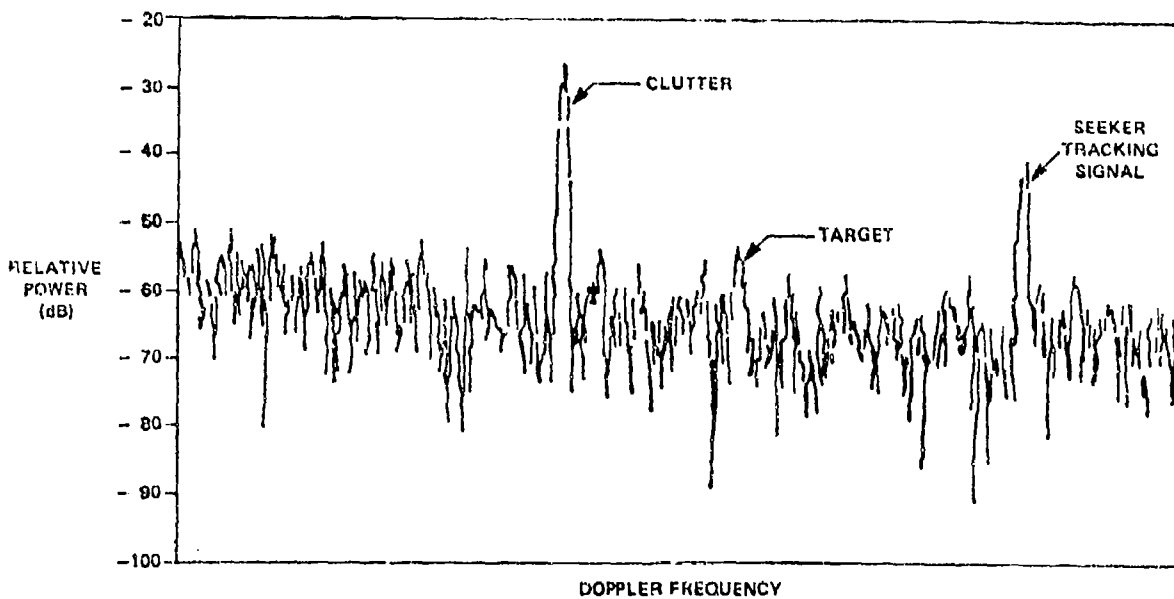


Figure 7. Fourier analysis of time slice of wideband video signal from simulated flight.

same seeker in the RFSS are presented. Use of the HP5451C in this manner permits rapid analysis of seeker performance during simulation.

2. VRMS-II

To upgrade the RFSS verification measurement capabilities, a new receiver is planned. VRMS-II will be capable of measuring polarization, doppler, angular position (azimuth and elevation) and range or time-delay. Additionally, VRMS-II may be positioned in the chamber near the seeker and be capable of making measurements simultaneously with seeker operation, lending obvious flexibility to both environmental model and seeker verification possibilities. Because it will not be necessary to dismount the seeker from the flight table and replace it with VRMS, significant economies in time are possible in the performance of both verification and routine calibration measurements.

This receiver will consist of an interferometer type multiple horn arrangement with a receiver and digitizer for each horn. Results are recorded and processed off-line in a timely but non-real-time mode, allowing maximum flexibility. Processed data is displayed in tabular or graphical form, with hardcopy available, and may be stored digitally for future analysis.

E. Typical RF Environmental Model Verification Plan

Measurements designed to verify the correct implementation of RF environmental models are documented in the RFSS Simulation Test Plan prepared during the Simulation Development Phase. These plans are ultimately reduced to step-by-step detail in the RFSS Simulation Test Procedures. An abbreviated version of typical test procedures utilizing VRMS-I to verify target model RCS and angular glint characteristics is presented in Figure 8.

IV. VALIDATION OF RF ENVIRONMENTAL MODELS

A. Rationale

To ensure credibility of RFSS simulation results and to define limitations and bounds on the interpretation of these results, the validity of the basic RF Environmental Models should be demonstrated. Specifically, these models, utilized within their domains of intended application, must be shown to match real-world environments within some acceptable level of accuracy. The intended application in turn dictates the degree to which complexities and subtleties associated with the physical processes being represented in the

TYPICAL TARGET MODEL VERIFICATION TEST PROCEDURES

- MOUNT ACTIVE TEST SYSTEM ON FLIGHT TABLE AND CALIBRATE.
- CALIBRATE AND VERIFY TARGET MODEL RCS PATTERN.
 1. SELECT PROPER PULSE MODULATOR PRF AND DUTY FACTOR.
 2. CENTER TARGET IN REFERENCE ARRAY TRIAD WITH TARGET CENTER OF GRAVITY (C.G.) AT REFERENCE RANGE (1000 FEET).
 3. CENTER ACTIVE TEST SYSTEM RANGE GATE ABOUT TARGET C.G. RANGE BY MAXIMIZING VIDEO OUTPUT LEVEL.
 4. MATCH RANGE GATE WIDTH TO TARGET EXTENT BY MAXIMIZING VIDEO OUTPUT LEVEL AND SIGNAL/NOISE RATIO.
 5. ADJUST RANGE ATTENUATORS TO OBTAIN A DETECTED IF OUTPUT APPROPRIATE FOR THE TARGET NOSE-ON CROSS SECTION AND C.G. RANGE.
 6. ROTATE TARGET IN 1° STEPS THROUGH RANGE OF ASPECT ANGLE FROM 0° TO 180° IN THE YAW PLANE.
 7. RECORD VIDEO AND DETECTED IF LEVELS AT EACH STEP. FOR STATISTICAL MODELS, OBTAIN SUFFICIENT DATA AT EACH STEP TO ESTIMATE MEAN WITHIN A 95% CONFIDENCE LEVEL.
 8. REPEAT FOR ROTATION OF TARGET IN PITCH PLANE.
 9. COMPARE CALIBRATED MEASURED DATA WITH RCS DATA.
- VERIFY TARGET MODEL ANGULAR GLINT PATTERN.
 1. MOUNT CAL SENSOR ON FLIGHT TABLE.
 2. CALIBRATE CAL SENSOR DIRECTION OF ARRIVAL (DOA) MEASUREMENT FOR REFERENCE TRIAD. (SHOULD BE THE SAME TRIAD USED FOR RCS AND TARGET MODEL CHECK-OUT).
 3. CENTER TARGET IN REFERENCE TRIAD (NOSE-ON).
 4. ALIGN CAL SENSOR WITH TARGET C.G.
 5. ROTATE TARGET IN 1° STEPS THROUGH RANGE OF ASPECT ANGLE FROM 0° TO 180° .
 6. MEASURE DOA OFFSETS FROM C.G. POSITION AT EACH STEP.
 7. COMPARE CALIBRATED MEASURED DATA WITH GLINT DATA.

Figure 8. Typical target model verification test procedures.

model must actually be present. Clearly, a radar seeker designed to be sensitive to some property of the environment must be exposed to a simulated environment which includes that property if the seeker is to be appropriately exercised. Thus, a hierarchy of RF Environmental Models emerges ranging from simple to complex in their characterization of the real-world environment. Model validation ensures that all "relevant" properties of the environment are, in fact, accounted for in the model and are accurately replicated. The term "relevant" in this context is thus generically dependent on the characteristics of the class of seekers. If the same models are to be used to exercise and compare different versions of a specific device under test, the models must incorporate properties which may be required by any of the versions. The degree to which such properties are important can be revealed by sensitivity analyses accomplished

through variation of model parameters. RF Environmental Model hierarchies are intentionally formulated to range from simple to complex in order to facilitate the identification of trends and limitations in seeker performance due to complexities in the RF environment.

Quantification of the validity of environmental models becomes a key factor for decision-making in simulation planning, by ensuring proper application of the models and by establishing the level of confidence to be associated with simulation results based on use of these models.

b. Data Requirements

Validation procedures necessarily are based on comparisons between model predictions and results of physical measurements. As illustrated in Figure 9, data produced by the physical measurements must be independent from those used in formulating the model whose results are to be compared with the data; otherwise, only model verification rather than validation will have been effected. The model must, of course, replicate the data used in its formulation (as verification ensures), but, more importantly, it must have predictive capabilities which the validation process demonstrates.

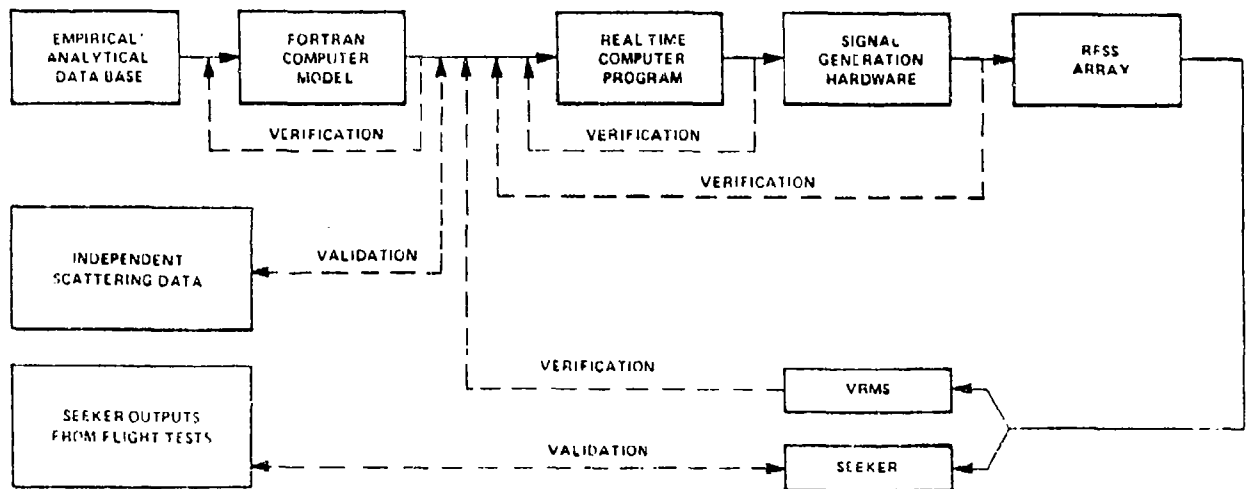


Figure 9. Validation of RF environmental models.

Validation of RF Environmental Models can involve both direct measurements of the environment itself and indirect measurements of the effect of the environment on a test seeker which incorporates target detection, discrimination and location logics. The seeker can be of generic design or a version of the seeker under evaluation. Thus, a variety of data acquisition and analysis activities can generate data to support the validation process. What data is actually specified is a function of what can be accomplished within reasonable time, cost, and technical feasibility constraints. Also, the availability of useful pre-existing data is another major consideration in determining what should constitute the data base for model validation.

In planning a model validation effort, recommending several levels of activity to acquire and process validation data may be appropriate if additional options become apparent to improve model credibility with increased effort. Such options should be identified along with the tradeoffs which link the increased levels of confidence in the model predictions and the costs incurred in achieving these gains.

C. Validation Procedures

It is clear that the validation process is basically open-ended-- that tests with increasing levels of sophistication and expense can be devised which will improve model credibility, albeit with eventual diminishing returns. Selection of specific procedures must be based on reasonable allocation of effort against the tradeoffs cited in IV.B. These procedures must be definitive in terms of what new data are to be obtained, how these measurements are to be made, what instruments are to be used in their acquisition, what data reduction and analysis steps are required, and what criteria are to be used in the validation assessment. If several independent data sets and analysis procedures are involved, an important issue is how the groupings of results are to be combined to arrive at a "bottom-line" assessment.

For example, measurements within the RFSS may be involved in which a simulated target is assigned a position on the array, then rotated stepwise in aspect angle. A measurement receiver at the intended location of the seeker-under-test in an RFSS aperture observes target position and both RCS and glint characteristics. The measured properties of the simulated target are then compared with those of the real-world target on which the model was based. If replication is satisfactory, the model implementation is verified for the

conditions tested; if not, the model is corrected and verification measurements repeated. Next, seeker hardware can be mounted and angle errors measured versus target orientation in open loop tests. If captive seeker test data are available against a real target rotated in space, comparisons of this test data against open loop simulation runs can produce validation results. More broadly, any experimental data which independently checks the predictions of the environmental model can be used for validation. Care must be taken, however, to ensure that the model is exercised within its intended range of application; for example, far-field target scattering data cannot be properly used to validate a near-field target model. Such procedures are particularly relevant when sensors used in the validation activity have identical or similar characteristics to those of the generic seekers which the environmental models are intended to exercise. This applies to models covering target characteristics, clutter, multipath, and ECM interference. Failure to achieve complete validation over an initial range of intended application may lead to refinement of the practical limits of model application.

In a specific V&V plan, the procedures have to be definitized so that steps covering data acquisition, processing, analysis and validation assessment can be scheduled and costed with responsibilities assigned. Implementation of specific V&V procedures may be accomplished partly by the RFSS and its contractors on the other hand and the agencies and contractors associated with the RFSS customer on the other. This is established by determining how and where the procedures are best carried out under the circumstances. The specific V&V baseline plan with its possible options delineate the recommendations for the V&V activity.

D. Model Accuracy Requirements

In performing a simulation in which random or pseudo-random effects occur, it is important to realize that it is not generally necessary to provide a simulation that exactly reproduces the behavior of the actual system. For example, consider a digital receiver whose input is a definite signal plus random noise. In simulating the input to the receiver, a random number generator can be used to generate noise. This noise can be made to have the same statistical characteristics as the real noise, such as mean, variance, amplitude distribution function, and correlation function; but it will not be identical to the real noise (of course, separate samples of real noise will not be identical).

either). Errors will not occur on the same bits in the simulation as in real hardware, but measured over a long period of time, error rates should be the same. Thus, the noise model can be made correct in a statistical sense, but does not yield identical results. Any comparison of the simulated and real results should account for the expected differences, and comparisons should be made using appropriate statistical parameters.

By the same token, the Deterministic Multiple Scatterer Target Model may not correctly predict the exact azimuth angle at which a null in the radar return occurs. However, it should predict the fact that nulls occur, along with their frequency, depth and approximate angular locations, and the nulls should vary with appropriate parameters, such as wavelength and target orientation and range. In comparing the simulation with flight test results, statistics derived from the results are important parameters to be compared in addition to the details of the fine structure of the return versus angle or time.

E. Quantitative Methods for Model Validation

To quantify the results of validation testing, a general procedure is outlined. The procedure focuses on the level of agreement between model predictions and observed real-world phenomena within the domain of intended application of the model. It also deals with the certainty with which such agreement levels have been established. These factors combine to produce probabilities that the model outputs are within prescribed limits set forth as performance specifications and/or design objectives.

Because the model outputs are describable in terms of a number of parameters, each of which is addressed in the specification, probabilities for each parameter are treated first, then combined to arrive at an overall probability that the model produces a satisfactory aggregation of realistic outputs. This probability serves as the index of model validation and is a function of the range of input conditions for which a single index is to apply. If the model operates over several regimes of input conditions, then a separate validation index should be derived for each regime. Thus, a target model, for example, might have a long-range, mid-range, and short-range regime--separately validated.

Before addressing details of this methodology, it is noted that model validity as defined above, becomes a function of the limits of acceptability for the various model output parameters as reflected in the design objective; this is as it should be. The limits of acceptability can be relatively wide for less critical parameters and tighter for more critical ones. In addition, because of the statistical nature of some of the measured and predicted parameters, a probabilistic treatment is warranted and leads to a continuum of possible values for the validation index.

If the various model output parameters are more or less independent (not systematically coupled), the probabilities of their falling within the design objective can be combined multiplicatively to arrive at an aggregate probability. If correlated, steps can be taken to form derived parameters which are uncoupled and independent. In general, the model output parameters to be examined may be instantaneous outputs or derived quantities such as statistical means and standard deviations obtained from a continuous time series.

More specifically, the procedure consists of

- o Identifying the range of model input conditions for which the outputs are to be compared with real-world observations or with independent analysis results.
- o Identifying the model outputs--specifically the set of parameters to be used to characterize the outputs.
- o Establishing the limits of acceptability for each parameter in terms of its replication of real-world phenomena.
- o Identifying the sets of data to be compared.
- o Performing comparative analyses and deriving key statistics including means and standard deviations for each set to be compared. For simulation runs, input conditions over the applicable range are varied to develop the requisite distribution of outputs.

- o Deriving measures of closeness of the parameters being compared (based on differences of the means) and certainty of the assessment (based on analysis of confidence limits as affected by the sparsity of the data).
- o Combining these two measures to compute the probability that the agreement is within specified tolerance.
- o Further combining such assessments as might be obtained from independent test series dealing with the same parameter, using a linear combinatorial scoring procedure in which weighting factors account for the adjudged relevance, comprehensiveness and reliability among the several tests. The result here is a best overall estimate of the probability that the model output parameter being examined is within tolerance.
- o Combining probabilities for all the parameters characterizing model outputs. Individual probabilities are multiplied for independent parameters. Correlated parameters are to be uncoupled by additional procedures.
- o Performing sensitivity analyses by varying the limits of acceptability in the model specifications and checking the degree to which validation indexes change.
- o Identifying potential problem areas in model assumptions and implementation factors; institute trial changes in model formulation to assess corresponding effects in model performance and recalculating validation indexes.

Figure 10 summarizes the key procedural steps involved in comparing model outputs with corresponding observation of real-world phenomena to arrive at an overall validation index. The sensitivity of the index to model assumptions, model inputs and specified tolerance on model/real-world agreement is also determined as part of the procedure to fine-tune the model performance requirements. The procedure is susceptible to iteration during weapon system development as new simulation and flight test results are made available. Such iterations tend to reduce risk and improve confidence in interpreting simulation results.

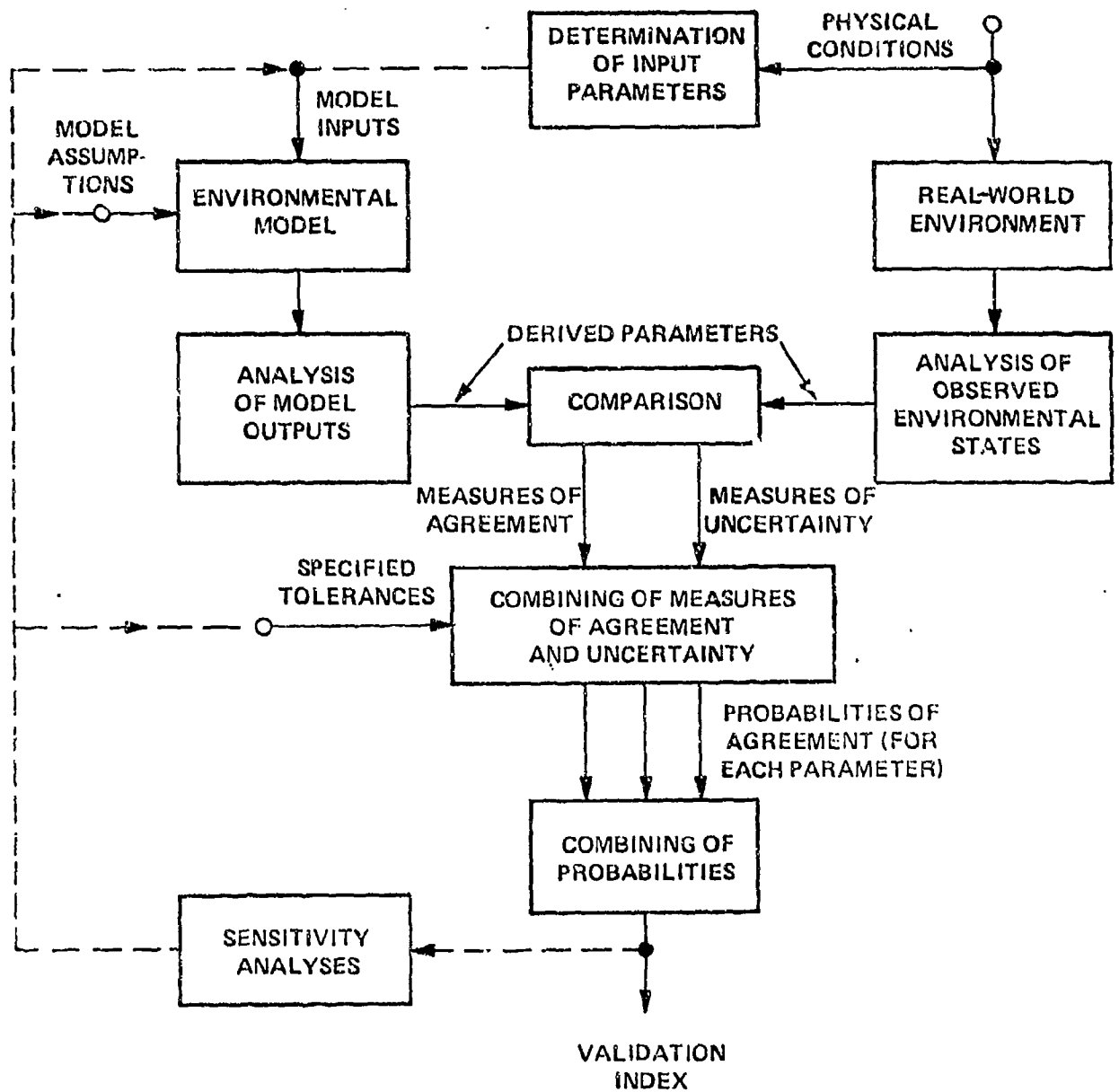


Figure 10. Quantification of model validation.

The analytical techniques and procedures for accomplishing the above steps are available to be utilized as applicable. It is recognized that the degree to which deployment of these procedures is warranted is highly dependent on the nature of the specific program and the availability of data for comparative analysis. The general methodology thus serves as a framework for subsequently defining procedural steps in quantifying validation results in specific programs.

One of the principal techniques utilized deals with comparisons of two finite-sample distributions representing, for example, a model-produced parameter and a corresponding observed real-world parameter. The technique involves computation of the finite-sample means and standard deviations; the differences of the two means serve as a best estimate of the agreement between the model and the real world with respect to that parameter. The well-known "t statistic" is utilized in an analysis which yields the probability that the true difference in means lies within a specified interval about zero difference (Appendix A outlines the basic procedure). This probability becomes the validation index for that parameter with respect to the allowed tolerance on model realism.

Appendix B outlines other techniques and procedures that have been studied for use in quantifying validation results. All relate to the comparison of measured data with simulation results obtained by operating directly on the data to be compared or on parameters derived therefrom. If the observed data is of the nature of a time series, there needs to occur a combining over the sample elements of the series in the comparison. The use of Thiel's Inequality Coefficients (Section B-1) and the Cross Correlation Coefficient (Section B-2) are two approaches to accomplish this. If the parameters to be compared are random variables, comparisons frequently are affected by data sparsity or by measurement errors; thus, the inclusion of measures of certainty of assessment in the procedure outlined in Figure 10. One possible technique to handle sparsity of test data in such cases is to utilize Bayesian Updating (Section B-3) to produce the probabilities required by means of hypothesis testing. Finally, in combining the results of several diverse comparisons dealing with the same physical parameters, appropriate combinatorial techniques are needed. Section B-4 outlines a simple linear scoring procedure involving weighting factors which can account for the relevance, comprehensiveness and

reliability of the various independent test results used in comparisons leading to a validation index.

F. Specific RF Environmental Model Validation Plan

Where validation of one or more of the RF Environmental Models is required in an overall simulation program, a specific validation plan is formulated for an effort involving participation by both the RFSS and the customer. The initial plan, including options as appropriate, is drafted by the RFSS and reviewed by the customer. The approved plan reflects the final selection made among validation testing options, delineates schedules and costs, identifies the joint responsibilities of the RFSS, the customer, and supporting organizations, and should relate to the validation of the overall simulation.

The actual data to be utilized and comparisons to be made are highly program-specific; these depend on the availability and/or feasibility of acquiring various lab and field test data, computer simulation outputs and flight test results. The analytical procedures to be used in the quantitative evaluations are drawn from those delineated in paragraph IV.E, as applicable, and supplemented where necessary with other specialized techniques. The degree of specificity needed is comparable to that in the example of paragraph III.E.

The formulation of validation testing options in this draft plan implies a cost/benefit tradeoff in obtaining higher levels of confidence in the models at additional expense in time and dollars. The plan sets forth the tradeoff--making estimates of confidence level improvements based on analysis of the volume and quality of the data to be compared and the power of the data reduction methods to be used.

G. Relationship to Weapon System Validation

Evaluation and validation of weapon system performance is a cumulative, hierarchical process. The standard weapon system development cycle, as illustrated in Figure 11, is characterized by four phases and three primary program milestones at which Defense Systems Acquisition Review Council (DSARC) reviews are held and program continuation decisions made. The capability of the hardware to fulfill technical and operational requirements must be evaluated at each decision point. Simulation, both all-digital and HWIL, provides major inputs to this decision process.

PHASE	CONCEPTUAL	VALIDATION	FULL-SCALE DEVELOPMENT	PRODUCTION AND DEPLOYMENT
HARDWARE CONFIGURATION	EXPERIMENTAL PROTOTYPE (BREADBOARD)	ADVANCED DEVELOPMENT PROTOTYPE (BRASSBOARD)	ENGINEERING DEVELOPMENT PROTOTYPE	PRODUCTION ITEMS
GOALS	DEVELOP AND EVALUATE HARDWARE; DEMONSTRATE FEASIBILITY	VERIFY PRELIMINARY DESIGN AND ENGINEERING	COMPLETE SYSTEM DEVELOPMENT, ENGINEERING, FABRICATION AND TESTING	IMPROVE PRODUCT AT MINIMUM COST; DEPLOY
SELECTED SIMULATION CONTRIBUTIONS	AID IN DESIGN THROUGH SENSITIVITY TESTS	VERIFY SUBSYSTEM PERFORMANCE THROUGH CHARACTERIZATION TESTS	DETERMINE SYSTEM PERFORMANCE ENVELOPE THROUGH FULL-UP SIMULATION	EVALUATE AND OPTIMIZE SYSTEM PERFORMANCE VS. CHANGING THREAT CAPABILITIES
MILESTONES	▲ DSARC I	▲ DSARC II	▲ DSARC III	

Figure 11. Weapon System Development Process.

During the conceptual phase, when a system design is formulated to meet both technical and operational requirements, simulation, particularly all-digital, is a valuable tool in performing parametric system analyses. HWIL simulation is sometimes used during the validation phase to demonstrate that brassboard hardware meets its design requirements, and also to improve system performance. In combination with flight tests, simulation is an integral factor in determining the performance of the fully-developed system, and can make important contributions to the final DSARC decision to enter production. Finally, after the system is produced and deployed, simulation provides a timely, cost-effective and, if security requirements dictate, covert method of evaluating and optimizing system performance in new scenarios and against changing threat capabilities.

To contribute to the decision-making process, the results and predictions of simulation must be realistic and credible. RF Environmental Model verification and validation form part of the groundwork for a validated simulation, which in turn contributes to weapon system validation. Thus, a validation hierarchy can be constructed, with the validity of the top levels depending critically on the validity of each lower level.

The validation process, as illustrated in Figure 12, can be viewed as building a pyramid of confidence in weapon-system performance predictions. As new scenarios are introduced, sensitivity analyses performed, models improved, and simulation predictions corroborated with flight test data and

other independent analysis results, the knowledge base of the pyramid is broadened step by step and higher levels of confidence reached over a period of time. With simulation results supported by a carefully structured V&V foundation, technical and program managers are able to make difficult weapon system development decisions with increased confidence and decreased risk.

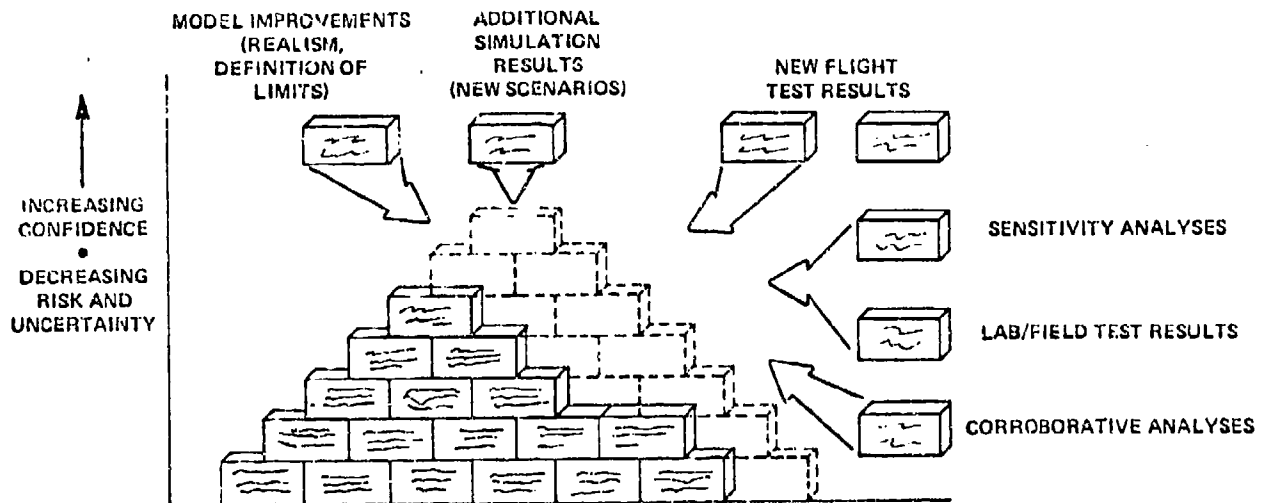


Figure 12. Validation - building a pyramid of confidence.

Validation cannot be achieved through a single experiment or flight test. Each input to the validation process generates new insights into system performance. As deficiencies are corrected and results begin to corroborate and support each other, confidence is developed about predicting performance. 100% confidence can never be reached because not all possible scenarios and contingencies can be explored in validation testing, but an iterative validation program carried out over a period of time can be made to reduce risk and uncertainty to acceptable levels.

V. SUMMARY

RF Environmental Models utilized in HWIL simulation of radar guided missiles at the MICOM ASC are developed in hierarchies ranging from simple to complex. These varying degrees of realism permit the parametric assessment of seeker sensitivity to features of the RF environment and facilitate the identification of trends and limitations in seeker performance. The RFSS approach to verification and validation of these models is based on the following multi-phase program, each phase building upon the results of the previous one:

- o Verification of RF Environmental Model design.
- o Verification of real-time hardware/software model implementation.
- o Routine calibration/diagnostic maintenance to ensure continued correct implementation during simulation operation.
- o Model validation using independent corroborative data and quantification of the degree of model realism.

Implementation of this program involves joint participation by the RFSS staff, the RFSS customer and various supporting organizations--in accordance with an approved V&V plan. Key activities include identifying, provisioning and analyzing data required for model validation. The V&V program provides the means for assessing the credibility of simulation results, and lays the foundation for properly interpreting simulation results as required for program planning and decision-making in weapon system development.

APPENDIX A
CONFIDENCE INTERVAL FOR DIFFERENCE IN MEANS

Assuming that samples are drawn from two populations, P and A , and that these populations are normally distributed and have equal variance, the following procedure can be used to determine the confidence that the true difference between the means does not exceed some specified tolerance value.

The statistic

$$t = \left[(\bar{P} - \bar{A}) - (\mu_P - \mu_A) \right] \cdot J$$

has the t-distribution with $m = n_P + n_A - 2$ degrees of freedom, where

$$J = \left[\frac{n_P n_A (n_P + n_A - 2)}{(n_P + n_A) (n_P S_P^2 + n_A S_A^2)} \right]^{1/2}$$

and \bar{P} and \bar{A} are the means of the samples. S_P and S_A are the standard deviations of the samples, n_P and n_A are the sizes of the samples (number of points measured) and μ_P and μ_A are the means (unknown) of the populations.

To find the 100 (1- ϵ)% confidence interval, enter the t-distribution table with ϵ and m degrees of freedom to find a value of t . Using this t , the confidence limits (symmetrical about $\bar{P} - \bar{A}$) are simply

$$(\bar{P} - \bar{A}) \pm \frac{t}{J}$$

For 50% confidence, the value t/J is the probable error.

On the other hand, there may be predetermined tolerance limits, L_1 and L_2 , within which it is required that the true value, $\mu_P - \mu_A$, lies. The tolerance limits may or may not be symmetrical about $(\bar{P} - \bar{A})$. For each limit, L_i , calculate

$$t_i = |(\bar{P} - \bar{A}) - L_i| \cdot J$$

Using this value of t_i , and m degrees of freedom, enter the t-distribution table and find by interpolation the corresponding value of ϵ_i . For most tables, ϵ represents the probability measure of both tails of the t-distribution, so each ϵ_i must be halved and then added together. Thus, the confidence becomes

$$100 \left(1 - \frac{\epsilon_1 + \epsilon_2}{2} \right) \%$$

that the interval defined by the limits L_1 and L_2 contains the true value of the difference between the means, $(\mu_P - \mu_A)$.

This approach has the advantage that it works with small sample sizes, although at least one sample must be of at least size two or more. It requires the assumption of normality, but is reasonably accurate for distributions that differ somewhat from normal. Finally, it assumes that the variance of both populations are the same, but the results do not appear to be sensitive to this assumption, particularly when the two sample sizes are similar. This latter assumption can be tested using the F-distribution, but that test requires at least two sample points in both samples.

APPENDIX B

QUANTITATIVE TECHNIQUES APPLICABLE TO VALIDATION TESTING

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In this Appendix several techniques are presented that are applicable in determining the degree to which the simulation agrees with measured performance.

B-1 THIEL'S INEQUALITY COEFFICIENTS

Thiel's Inequality Coefficients (TIC) are used to compare two sampled time series. The predicted time series P is intended to represent the actual time series A . The basic coefficient U is given by:

$$U = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - A_i)^2}}{\sqrt{\frac{1}{n} \sum_{i=1}^n P_i^2} + \sqrt{\frac{1}{n} \sum_{i=1}^n A_i^2}}$$

where P_i and A_i are the sampled values of the predicted and actual time series respectively, and n is the number of samples of each. U varies from zero to one, with zero corresponding to identical series and one corresponding to very dissimilar series.

U can be decomposed into three components:

$$U_m = \frac{\bar{P} - \bar{A}}{D} \quad \text{unequal central tendency}$$

$$U_s = \frac{S_P - S_A}{D} \quad \text{unequal variation}$$

$$U_c = \frac{\sqrt{2(1-r)} S_P S_A}{D} \quad \text{imperfect covariation}$$

where D is the denominator of Equation 1, \bar{P} and \bar{A} are the means of P_i and A_i , r is the correlation coefficient between P_i and A_i . Note that

$$U_m^2 + U_s^2 + U_c^2 = U^2$$

Equation B2 may be rewritten as:

$$U^m + U^s + U^c = 1 \quad (B3)$$

where

$$U^m = \left(\frac{U_m}{U} \right)^2 \quad \text{bias proportion}$$

$$U^s = \left(\frac{U_s}{U} \right)^2 \quad \text{variance proportion}$$

$$U^c = \left(\frac{U_c}{U} \right)^2 \quad \text{covariance proportion}$$

The TIC is easily extended to the case where there is more than one time series associated with the predicted and actual cases.

B-2 CROSS CORRELATION COEFFICIENT

The Cross Correlation Coefficient is a measure of the similarity of two sampled time series. It is given by:

$$R = \frac{1}{n} \sum_{i=1}^n \frac{(P_i - \bar{P})(A_i - \bar{A})}{S_p S_A}$$

where P_i and A_i are the predicted and actual time series, \bar{P} and \bar{A} are the means of the P_i 's and A_i 's, S_p and S_A are the standard deviations and n is the number of samples of each series.

R varies from -1 to $+1$, being $+1$ if the series P_i and A_i are identical, 0 if there is no correlation between the series, and negative if the series tends to be out of phase with each other.

B-3 BAYESIAN UPDATING

The correlation of simulation results and test data is frequently hampered by the sparsity of the test results in comparison with the abundance of available simulation outputs. A technique is needed for quantitative evaluation of the degree to which the model of the system predicts the performance of the real system as evidenced by actual test results. One possibility lies in the use of Bayesian analysis in which test data can be examined in terms of the probabilities that they derive from one of several hypothesized model formulations.

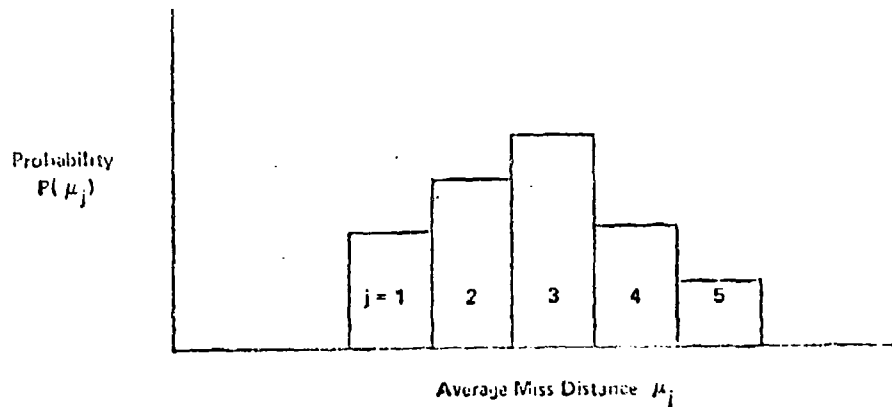
In this technique, a probability distribution is assumed for some problem parameter, only one unknown value of which represents the "true state" of the system and its environment. A particular value of the parameter in effect selects a hypothesis concerning the real-world state. The distribution represents a best estimate of the probability that a given value of the parameter will be the correct one, prior to any observations. When observations are made--however indirect or incomplete--the probability distribution becomes modified using a specific updating procedure. This posterior distribution is again susceptible to further updating if additional independent measurements pertaining to the same "true state" are made.

The quantity described by the prior and posterior distribution may itself be a parameter of another statistical representation. For example, if miss-distance were described by a one-parameter distribution (such as a Rayleigh), then the parameter expressed in terms of average miss-distance is a function of the various problem assumptions; any one set leads to a single value of the average miss-distance parameter. Stochastic processes consistent with that set of assumptions in turn account for the distribution of miss-distances about this average value. Furthermore, a number of sets of assumptions can be treated during simulation, each one associated with its own miss-distance distribution as derived from simulation results. The problem then becomes one of hypothesis testing, specifically to determine which set of assumptions is more likely to be correct.

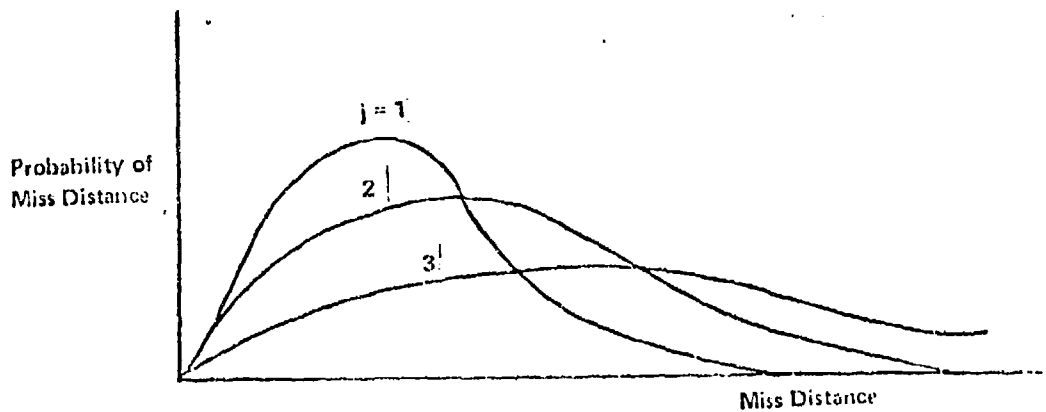
In the Bayesian updating process, the prior distribution relates to the probability of correct choice among the alternative sets of assumptions, with the observations tending to support or refute the candidacy of any given set. Of course, denser and higher quality data are more likely to sharpen the selection. However, the procedure does as much as is possible consistent with the available data; it is quantitative and permits sensitivity analysis with the respect to the assumptions. As more and more data is available regarding the "true state," the initial assignment of the prior distribution among these alternatives becomes less and less important and the final posterior distribution becomes increasingly independent of the initial assignment.

To be more specific, consider N hypotheses of a miss-distance distribution each of which by illustration could be characterized by a single distribution parameter μ_j . $P(\mu_j)$ is the initial assignment of the probability that

the j^{th} state is in fact the correct one, in other words that μ_j is the correct value of average miss-distance.



With the j^{th} set of assumptions being associated with μ_j , the miss-distance distributions corresponding to several values of j are derived from analysis and simulation as depicted below.



A limited series of measurements which correspond to a single "true state" is associated with a set of observations "O" of miss-distance. To determine which value of the index j best fits the observations, the Bayesian formulation is utilized in which

$$P(\mu_j|O) = \frac{P(O|\mu_j)P(\mu_j)}{\sum_j P(O|\mu_j)P(\mu_j)}$$

where $P(\mu_j)$ is the prior assignment of probability that the j^{th} hypothesis is true $\left[\sum_j P(\mu_j) = 1 \right]$.

$P(\mu_j|O)$ is the posterior probability that the j^{th} hypothesis is true, given the set of observations "O" $\left[\sum_j P(\mu_j|O) = 1 \right]$.

$P(O|\mu_j)$ is the probability that the set of observations "O" occurs, given the j^{th} hypothesis.

The quantity $P(O|\mu_j)$ can be calculated directly by first computing for each observation the probability that a given distribution would have produced the measurement, then aggregating the observations using joint probabilities. This can be done regardless of the sparsity of the data. That is, the methodology does not depend on statistics being derived directly from the observations--we deal only with the likelihood that the observed data came from one assumed distribution or another. In fact, the quantity $P(O|\mu_j)$ for the various j which yields the smallest value of $P(O|\mu_j)$ then compare the remaining P 's in the form of ratios, specifically called likelihood ratios. Likelihood ratios thus are a measure of the relative correlation of the measured data and the simulation results.

In short, Bayesian updating can provide a practical method for quantitative validation of simulation runs with sparse experimental data.

B-4 COMBINING OF VALIDATION SCORES OBTAINED FROM DIVERSE COMPARISONS

If several diverse comparison tests are conducted to check the ability of a model to produce realistic outputs, the individual validation scores can be combined using weighting factors accounting for the relevance, comprehensiveness and reliability of the individual data sets being compared. Combinations of weighted scores can be used to produce higher level scores which in turn may thus be further combined in a multi-level scoring methodology. A combinatorial approach permits logical grouping and treatment of as many parameters or factors as are judged relevant. Combining of scores can occur within a single level or over several levels.

In a linear combinatorial scheme, for example, all scores can be placed on a scale 0 to 100 and weighting factors on a scale 0 to 1. By so constraining these factors, the derived score also has values between 0 and 100 and is therefore in proper form for use in higher level combinations. A linear combinatorial scheme is most justified when the contributing factors are independent, but the scheme can provide useful results if dependencies are present but are unknown.

For a two-level scheme, a final score S is given in terms of first level scores S_i and weighting factors w_i by

$$S = \sum_i w_i S_i$$

subject to the constraint

$$\sum_i w_i = 1$$

Similarly, S_i is given in terms of second-level raw scores S_{ij} and weighting factors w_{ij} by

$$S_i = \sum_j w_{ij} S_{ij}$$

and

$$\sum_j w_{ij} = 1$$

This can be extended to as many levels as needed. The 0-to-100 scale chosen for each of the scores represents a progression with increasing values designating more favorable situations. The scale would represent, for instance, the estimated probability in percent that a model output is within prescribed tolerance. Also, various nonlinearities can be introduced such as setting unacceptable raw scores (below a pre-set limit) to zero for the next level of combination in the progression leading to a final overall validation score.

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