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## Paper Session II-B - International Space Station Verification Program Enhancements

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**“International Space Station  
Verification Program  
Enhancements”**

**International Space Station  
Program Office**

**Integration, Test & Verification Team  
Houston, Texas**

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# **“International Space Station Verification Program Enhancements”**

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## **Abstract**

The International Space Station ISS is a unique aerospace program. The ISS spacecraft will not be completely assembled and tested on the ground prior to being delivered to orbit. The spacecraft elements and distributed systems are developed by eight different major Product Groups and International Partners and are assembled over 56 months with approximately 38 assembly flights. Consequently, unique and high-technology applications were derived to ensure the verification of the Space Station could be provided. This paper addresses two of the techniques employed to ensure verification could be effectively and efficiently accomplished.

## **INTRODUCTION**

The Space Station verification complexity equates to a formidable task relative to spacecraft testing and verification. The classical approach to complete hardware and software ground testing prior to launch is both cost prohibited and logistically unfeasible. Recognizing these constraints, ISS program engineers conducted a number of individual studies called Element-to-Element Systems Interface Integrity (EESII).

The goal of EESII was to determine the adequacy of the ISS integration and verification approach, and establish a limited, affordable and feasible core set of ground tests. This was done by reviewing ISS plans for physical and functional interface verification, from requirements through compliance phases of the program.

As a result of the EESII study, two relatively distinct processes were instituted to assist in the verification activities of the ISS:

- (1) Digital Preassembly (DPA) - techniques for physical interfaces, and;
  - (2) Quantitative Functional Analysis (QFA) - functional interface evaluations.
- These two distinct processes are elaborated below.

## **Digital Preassembly**

### **The Challenge**

In the 39 year history of manned space exploration, the world's engineering community has never been faced with the challenge now before us in the deployment of the International Space Station ISS. Deployment of most previous space vehicles has involved launch of the entire space vehicle where mating of the space vehicle is accomplished on the ground, e.g. Apollo-Saturn, Skylab, etc. In the past, mating of space vehicles requiring on-orbit assembly has traditionally been demonstrated by the physical mating of on-orbit mating components prior to launch, e.g. Apollo-Soyuz, Shuttle-Mir, etc.

The International Space Station, the world's largest space vehicle, designed, built, tested and launched by six space agencies from around the world, will require 44 launches from three launch sites around the globe, to deliver all the components to orbit where the most extensive on-orbit assembly procedure ever attempted will be required.

The total interfaces to be mated on-orbit number 76, reference Revision A to the ISS Assembly Sequence, dated 9/28/94. Of these, 37 have been identified through a risk management analysis to be a high risk. That is, the likelihood of a mating anomaly can be expected and the consequence is unacceptable, e.g. cannot achieve major program milestones. These 37 interfaces involve 74 major space vehicle components produced at contractors across the United States, Russia, Japan, Italy, Canada and Europe. The 'traditional' approach to demonstrating the mating compatibility of these components by performing a physical mate prior to launch has created an enormous logistical, cost and schedule dilemma for ISS Program Managers, therefore some mechanism had to be devised to mitigate the risks.

### **A Solution**

The Boeing Company, Prime Contractor for the ISS has brought their experience as the builder of the most advanced and complex airliner in the world, the 777, to the challenge. The 777 program required Boeing to completely rethink the design, mockup and build process in order to eliminate the high rate of redesign required using this traditional technique. Their solution involved the development of a 'digital preassembly' process whereby the 'pre-design' could be assembled in a three-dimensional (CAD) environment, identifying incompatibilities and interference's prior to release of the engineering pre-empting the need for a full scale mockup. On the 777 program, this process was targeted to reduce 'after release' engineering changes by 50%, the actual achieved reduction was greater than 85%.

The ISS on-orbit mating involves considerably more of a challenge. Many of the ISS major components are already designed and under construction at sites around the world. And with deployment of the ISS program spanning a period of fifty-six months, some components would be on-orbit before their mating components are built. This requires additional capability be added to the 777 process to give ISS Program Managers and engineers the confidence needed to commit to launch major components which are required to mate on-orbit without first physically mating them pre-launch.

Using the 777 digital preassembly process techniques as a basis, a process was developed to enable the Test and Verification engineers to assess the mating compatibility of major space vehicle components after they are built and without logistically moving them great distances. The ISS Digital Preassembly Process was created.

### **The ISS Digital Preassembly Process (DPA)**

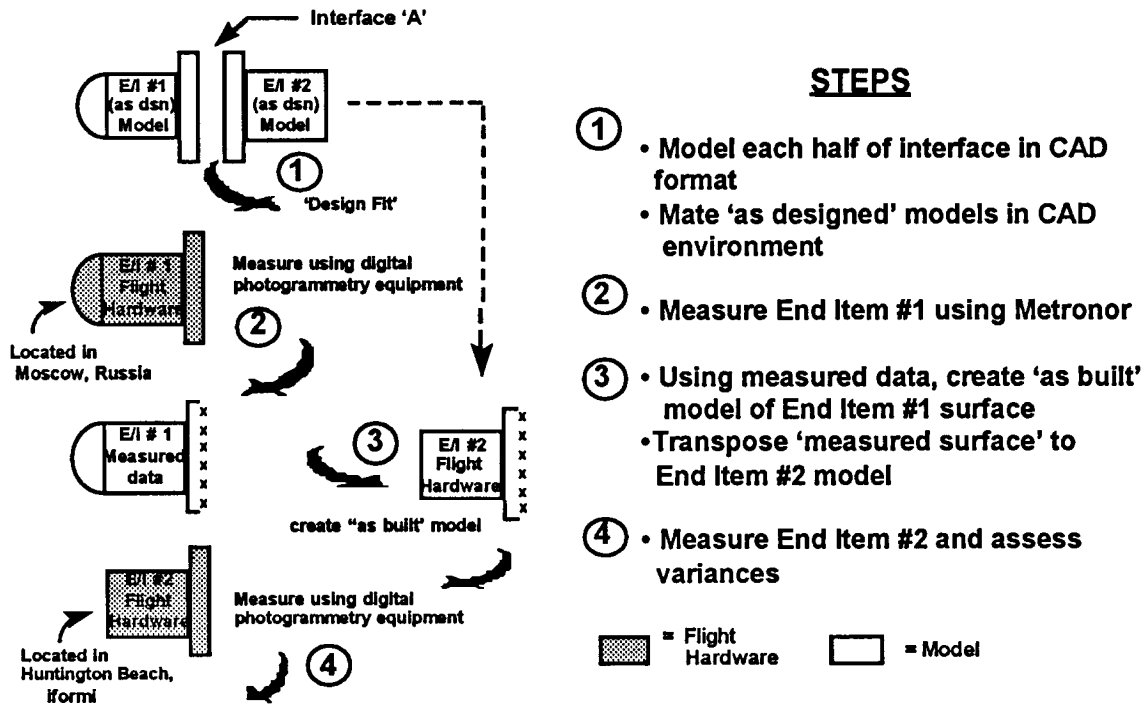
The DPA process is an original process created by extending the scope of the 777 process to include the actual measurement of as-built hardware and the comparison back to the design. The objective of the ISS DPA process is to identify, prior to launch: 1) off-nominal variances on the mating surfaces, alignment and latching components and 2) interference's involving externally mounted components, fluid lines, hand rails and deployable booms during the 'on-orbit' mating operations.

#### **THE 'AS DESIGNED' MATE**

The process begins with the creation of a three dimensional (CAD) model of each side of the interface using released two-dimensional component build drawings from the flight hardware manufacturer to assure 'pedigree' with current design, see figure 1. The models include not only the mating surfaces and hardware, but include all external peripheral components which are in the vicinity of the 'stay out' zone, an approximate one meter envelope. Once both sides of the interface have been modeled an 'as designed' mating is performed in a CAD environment. This early 'electronic' mating gives an important preview into the workability of the design.

#### **THE 'AS BUILT' MODEL**

One of the component models is then loaded into portable digital photogrammetry equipment ('Metronor', procured from Metronor AS, Box 238, N-1360 Nesbru, Norway), and shipped to the flight hardware location when that component has reached the assembly complete configuration, see figure 1. Measurements are then made and compared to the 'as designed' model and variances noted. These variances are then mapped back into the model (reverse engineering) creating an 'as built' model of that component of flight hardware.



**FIGURE 1 - ISS DPA PROCESS**

**THE 'ELECTRONIC MATE'**

The 'as built' model is then loaded into the Metronor and shipped to the mating component flight hardware location when that component is in the assembly complete configuration, see figure 1. Measurements are now made of this mating component referenced to the 'as built' model, an 'electronic mate'. This process allows an assessment to be made of 'actual' flight hardware-to-flight hardware without involving Interface Control Drawings (ICD) interpretations. From this 'electronic mate' of the component interfaces, interference and variance data is collected allowing an assessment to be made of the ability of these components to properly mate.

This process has been demonstrated by performing a 'pathfinder' exercise using ISS developmental hardware. This assessment is further enhanced by 'mapping' the measured data from the flight hardware into existing parametric models where an engineering evaluation can also be made under more dynamic thermal and pressure environment conditions.

## **QUANTITATIVE FUNCTIONAL ANALYSIS (QFA)**

### **Areas of High Criticality/Failure**

The goal of QFA is to analyze hardware and software integration (HSI) test and demonstration activities during system development cycles. The QFA process enables engineers to evaluate proposed and planned testing objectives. Specific analysis tools, known as “QFA tools” aid engineers in determining what testing is required and provides a quantitative feel for how well a system is being tested. Using the QFA process, engineers identify areas that are high criticality and/or high risk of failure.

### **Adequate Testing**

The test group uses the QFA process to ensure that the full system functionality is adequately tested at each phase of hardware and software integration. Testing performed early as part of a component qualification allows the greatest flexibility in changing system design at the lowest cost. Testing performed later in the program may result in design changes that are difficult and are relatively high cost. The QFA processes and tools assist the test group in defining a test program to meet the ideal condition.

Using the results of a QFA analysis, engineers recommend increased testing, testing modifications or, in the areas where testing maybe being performed with little added benefits, to delete testing from a verification program. Along with trade studies of the tests technical merit, cost, and schedule impact, the QFA process can assist program managers and test engineers in making test decisions.

### **QFA Process Development**

In order to begin a QFA process, it is first required to scope the process purpose and goals. Currently, the ISS has developed three different QFA type processes. The purpose of these processes are to (1) analyze HSI test activities of the U.S. Lab, a major ISS element, (2) a Station system level analysis to quantify the risk associated with inter-element functional integration of ISS data handling systems, and 3) evaluate Electrical Power System (EPS) testing across the ISS program. Each of these processes has required a unique implementation of QFA tools.

The goals of each of these processes are the same. They are to (a) evaluate the design and test programs with enough granularity to determine if problem areas exist, (b) provide a capability to diagnose given tests and prescribe “fixes,” and (c) provide recommendations early for augmentation of the verification program or design.

The basic characteristics of a QFA process are to first define the area to be investigated in terms of its complexity (what really matters about the subject)

and then to analyze the fidelity and extent to which the complexity is being addressed (how well do I deal with what matters). A QFA process has a basic five step approach. In working these steps the ISS program has implemented the QFA process relative to an interface perspective. The five steps:

- Step 1) Quantify the complexity of inter-element interfaces.
- Step 2) Quantify the fidelity of hardware and software used to test these interfaces.
- Step 3) Quantify the extent the interfaces are tested.
- Step 4) Determine minimal goals of fidelity and extent values
- Step 5) Compare the interface complexity to the test program fidelity and extent goals

The QFA process needs to establish complexity metrics; Engineering derived attributes to produce a measure of “Complexity”. As well as, the capability to assess interface testing and demonstration; Engineering derived attributes to produce a measure or “Blanket”. The word blanket is used simply because its attributes are analyzing the degree to which the complexity attributes are covered. Both the complexity and blanket are combined to quantify the relative merits of the planned testing. Recommendations for test and demonstration improvements will be developed when the “Blanket” indicates insufficient coverage of the “Complexity”. In order to develop both complexity and blanket attributes some guidelines were established. The following criteria are used to assess attribute candidates:

- 1) Meaningful - does it provide a quantifiable representation of the complexity.
- 2) Available - does it emerge naturally from the design process (no new work) and can it support the assessment in a timely manner.
- 3) Testable- can one look at the test program and discern how well the attribute is being addressed. This also provides a capability to diagnose the test program relative to the complexity criteria as well as prescribe adjustments, additions, or deletions to specific tests.
- 4) Sellable - will the rest of the program “buy-in” that the attribute reflects a real concern.

## **Complexity**

The purpose of defining the bus interface complexity is to establish a quantified representation of the relative importance of each interface in the ISS Program. Once this complexity is established for all of the ISS interfaces, they can be compared and addressed appropriately. To develop the complexity of a type of interface it is necessary to define attributes that reflect the concerns of the people associated with the design, operation and verification of the interface. “Brainstorming” is one technique that can be utilized to determine a potential list of attribute candidates. The final list will



prove to carry the essence of all the attributes that are on the preliminary list. It is helpful in attribute development that one strives to capture the “shadow” of the concerns, and not try to detail the exact concerns. This will enable the final list to be all encompassing without having a large amount of attributes.

Final understandings and the previous mentioned criteria consolidated the list down to six complexity attributes for one of the QFA studies. These are:

- 1) Number of devices
- 2) Number of hardware (HAN) and software (SAN) suppliers
- 3) Data traffic across the interface supporting each function
- 4) Number of CSCI functions and the criticality of the functions
- 5) Tight performance tolerances: Timing and Accuracy
- 6) Interdependencies of the devices on the bus: Closed Loop, Trigger, or Resource

Other examples of complexity attributes for data busses are number of algorithms involved and algorithm size. For power busses, Steady State load characteristics and Transient load characteristics are good candidates.

Numerical (quantitative) values for each of the attributes are now developed. The values need to have a perceived range and are mathematically manipulated so that the final QFA value for each attribute range is relatively the same. This is done in order to ensure that any single attribute does not numerically overshadow the others. After all, all of the attributes have been determined to have contributions to the overall complexity of the interface. The attributes are then weighted. The weighting is performed so that the relative importance the attribute contributes to the interface complexity is indexed to provide the right “shadow”. In the QFA study used as an example for this paper the nature of the interdependencies held heavier weighting than that of the number of hardware and software suppliers. To graphically represent the complexity of each bus, a complexity monolith is generated. The monolith is simply a box whose height is based on the value of complexity as generated in the complexity analysis. Each complexity attribute has a sub-monolith that represents the amount of bus interface complexity that is associated with that attribute. Reference Figure QFA-I

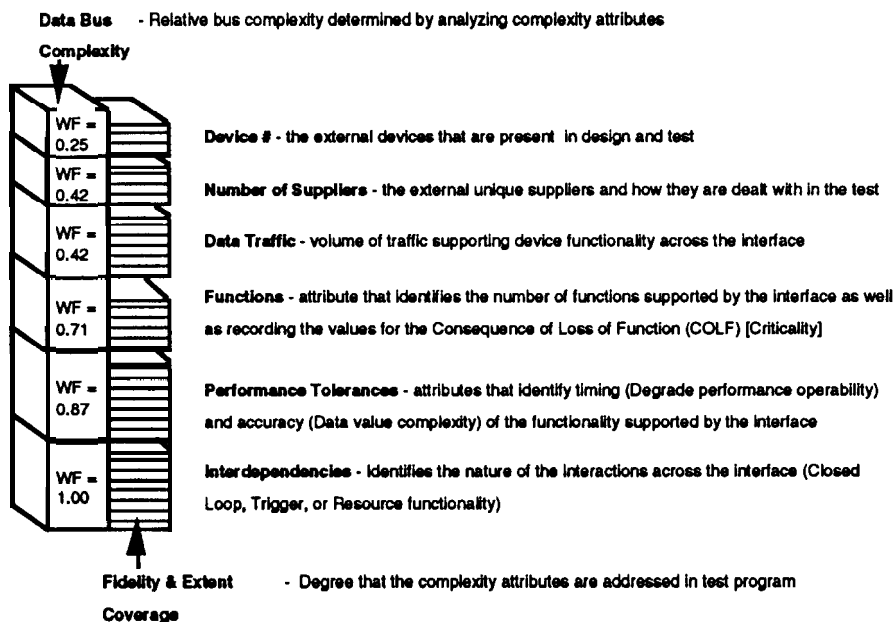
### **Fidelity and Extent “the Blanket”**

After the complexity of the interfaces is generated, it is necessary that the test program be analyzed to establish how well each of the interface complexities is addressed. A method to assess the completeness of the test program is developed and it utilizes two measures to gauge each test. One is the fidelity of hardware and software utilized in the test. The other is the extent that the attribute is exercised as a part of the test. The resultant of these entities for all tests of a given functional interface produces the measure of complexity coverage or “the blanket”.

**Fidelity** - the exactness or precision, relative to the design of the actual flight elements, to which the hardware and software are represented in the test in question.

**Extent** - the degree to which the complexity attributes are addressed in the test in question.

These measures are prejudiced to assess tests from an interface basis, similar to the complexity analysis. The method does not assess the ability of a test to meet other program criteria, e.g., specification compliance. It is only a method to address the goodness of the test with respect to the interface complexities described above.



**Figure QFA-1 QFA attributes**

The fidelity of a test is dependent upon the development level of the hardware and software used in the test. A separate hardware and software fidelity factor is determined for each device used in the test. The value for the fidelity factor is determined by the perceived amount of risk that still remains if the test program would be conducted at that development level, e.g., qualification hardware = .95 or a perceived remaining risk of 5%. All hardware and software factors are averaged to generate an overall fidelity factor for the entire test. Hardware and software simulators/simulations can have a full range of fidelity values based on how accurately they depict flight hardware/software. The assessment of Simulators/ Simulations fidelity is determined by the nature of the simulation and the degree of formal review and approval the Sims are involved with.

To determine extent it is necessary that the test program be evaluated in terms of the complexity attributes. Each complexity attribute is assessed from the aspect of the test program to determine how well the attribute was addressed i.e. the degree that these attributes were represented during testing. Extent is defined as a percent coverage of the complexity attribute (0 - 100%) and therefore the extent calculations will always include elements of the complexity calculations. The process for determining the extent values is performed for each complexity attribute. The method used to correlate fidelity and extent to complexity for multiple tests is illustrated in Figure QFA-2.

The analysis generates fidelity and extent values between 0 and 1 for each test for each attribute of the complexity. These values are then multiplied together to establish an area of coverage for each test. After all of the tests associated with a given interface are plotted, the shaded area represents the amount the test program has addressed the complexity of the interface. This is the "blanket". It represents the degree that the test program covers interface complexity. Reference Figure QFA-1.

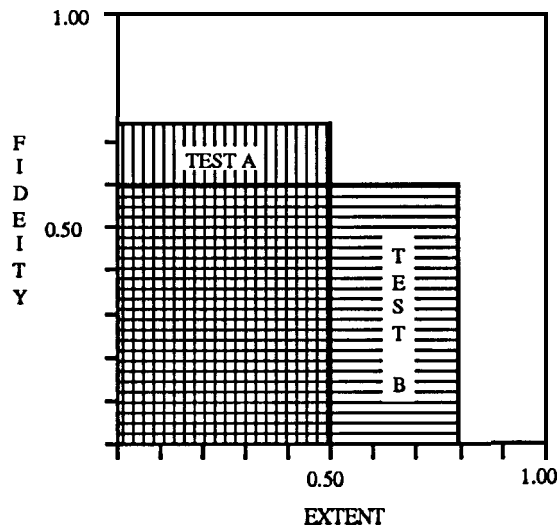


Figure QFA-2 Multi-test Coverage

### Implementation

The implementation of this process involves a great deal of data gathering and detailed investigations into the ISS test programs. To facilitate this effort a series of worksheets are developed for Complexity, Fidelity, and Extent. These worksheets allow the investigator to simply fill of a form with basic information. The worksheets then utilize macro's to calculate the various complexities, fidelities, and extents, as well as graphics. Final evaluations and decisions are based on comparing the study results with minimum

acceptable test levels. The Minimum acceptable levels are generated by utilizing the QFA process and inputting the desired minimums for fidelity, extent and the average complexity of the subsystems being analyzed. The process then is reduced to comparing graphical data as depicted in Figure QFA-3. When suspect areas are identified, these areas are considered to be at risk. Risk is present because the predefined conditions that are established as minimums have not been met. The risk value is a quantifiable. This enables the engineer to be able to prioritize the higher risk areas in the test program. For the areas of QFA risk, the details that have been captured as part of the data gathering process are reviewed from which recommendations are made.

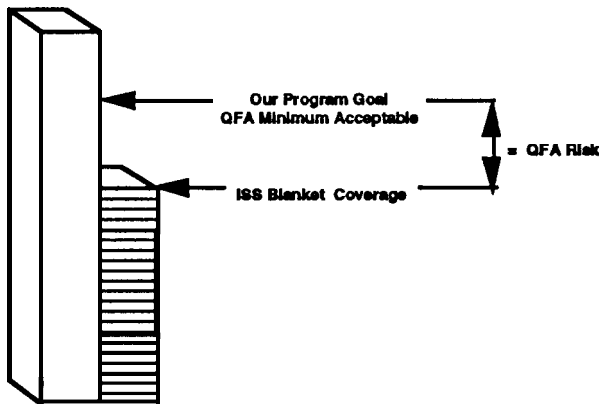


Figure QFA-3 Graphical Product