

Small Satellite Producibility, Affordability Approaches and TacSat 4 Design for Manufacturing and Assembly Results

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ABSTRACT

The Naval Research Laboratory (NRL) working under the direction of the Office of Force Transition (OFT) established an Integrated System Engineering Team (ISET) and satellite industry business team with the charter to develop small satellite bus standards. As part of this work a plan was developed to lower the cost of satellites thus enabling an Operationally Responsive Space (ORS) vision for flexible satellite missions. The vision is to increase ORS satellite rate production from ~1 satellite per year (lab provided) to ~5-10 busses per year and these would be provided by an industrial base using proven producibility and manufacturing methods. The OFT/NRL approach is to balance mission satellite utility with industrial know how given a set of reasonable standards in order to reduce cost and produce an affordable constellation of off-the-shelf satellites.

To assist in this vision, Raytheon Missile Systems facilitated a Design for Manufacturing and Assembly (DFMA) workshop with the ISET on March 6 and 7, 2007 using the TacSat 4 baseline design as the starting point. DFMA is a design methodology that considers manufacturing effort and cost as functions to be minimized, given the constraints of the customer requirements. The goal of the workshop was to identify current constraints affecting integration and assembly of satellite manufacturing today.

INTRODUCTIONS

Raytheon's integrated producibility approach represents years of experience in transitioning lean engineering designs into a production setting. Our design process incorporates lessons learned from our exo-atmospheric missile programs (EKV and SM-3) as well as our other missile programs to ensure a producible and affordable next-generation satellite.

Producibility and affordability approaches have been established in the context of system engineering integrated development. Trades that balance performance and cost while minimizing schedule risk are key to ensuring that the basic approach will meet program requirements and objectives. The system engineering process, including producibility and affordability interrelationships, leads to definition of hardware, software and interface requirements.

Traditionally, a design team will transition a design to a manufacturing team when the former believes the design has been completed and it is ready for production; however, much of the cost has been locked in by this time. As a result, the manufacturing team's influence on the final cost, quality, and schedule is about 20–30 percent. The team selects the manufacturing method, may negotiate purchase agreements with suppliers and selects raw materials based on design specifications. The design team has the most influence on total cost, as shown in Figure 1. During the design process, the design team selects the parts. The design specifications determine the process

to be used. The design decisions affect how complex the design will be. These elements determine 70–80 percent of the final costs, quality and schedule for the design.

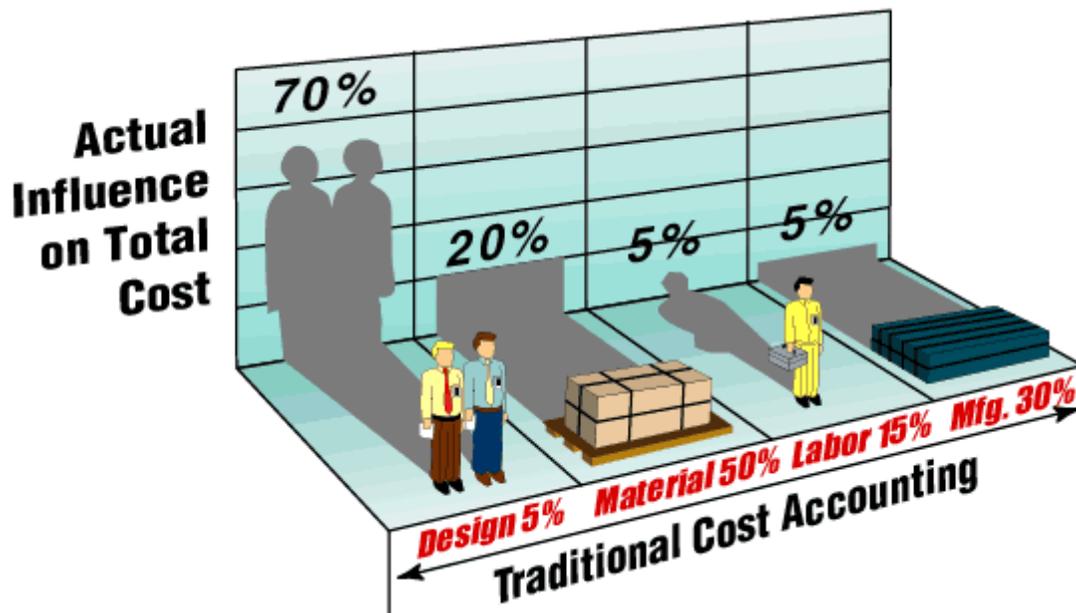
The measure of merit for producibility includes: integration, assembly and test cycle time; rework cycle time and rework probability; factory use; and unit-to-unit variability. These are traded against performance parameters such as margin allocations, weight, hardware functional partitioning, and producibility and affordability strategies.

DESIGN FOR MANUFACTURING AND ASSEMBLY (DFMA) OVERVIEW

The purpose of DFMA is to time-effectively collect and share knowledge about all manufacturability aspects of a design that will effect cost, quality and cycle time. The team needs to make early, collaborative design decisions that reflect consideration of design for manufacturability and assembly principles, defect reduction and affordability. The collaborative resources that are inclusive in DFMA are shown in the Figure 2.

RAYTHEON DFMA WORKSHOP

The DFMA process uses inputs from a wide range of collaborative team members. Homework is done before the workshop in key areas, as shown in Figure 2. These areas may include customer requirements and priorities, component options and obsolescence, costs of assembly, test and material, risks of change, variability analysis and tolerance analysis of specific design characteristics. During a DFMA workshop, the baseline



Courtesy Munro and Associates

Figure 1. An Integrated Product Team of Design, Manufacturing and the Business Elements of a Program can Influence 100 percent of the Satellite Production Cost.

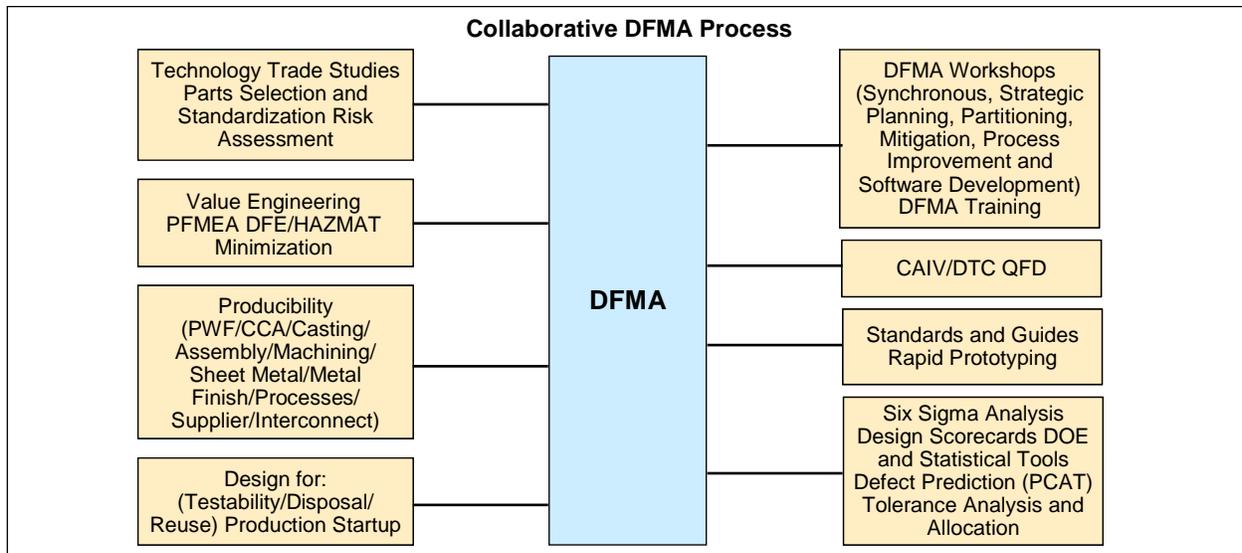


Figure 2. Collaborative DFMA Process Enables Individuals Working Together as a Team Using a Facilitated Process to Make Products More Competitive.

design is presented along with the supporting homework analyses. An overview is provided on the key producibility characteristics driving design affordability. This information is used by team members during the workshop to identify design changes with understood facts and data. The team votes on each proposed design change based on the following improvement criteria:

- Recurring cost improvement;
- Nonrecurring cost and return on investment;
- Implementation schedule;
- Assembly and cycle time schedule improvement;
- Performance improvement; and
- Quality improvement.

On completion of the workshop, design recommendations are captured in an executive summary plan. These changes are prioritized by their producibility merit. The changes are also characterized by their benefits to the program. The executive summary is presented to management to secure commitment and buy in to move forward with the implementation plan.

DFMA 12 PRINCIPLES

Raytheon has defined the DFMA process with 12 principles. They are outlined at the opening of the DFMA workshop to provide guidance to the workshop team. These principles assist the team in the decision-making process. As shown in Figure 3, Albert Einstein defined simplicity as the key to producibility. The 12 DFMA principles are:

1. Minimize the number of parts;
2. Minimize the number of fasteners;
3. Standardize;

4. Avoid difficult components;
5. Use modular subassemblies;
6. Use multifunctional parts;
7. Minimize reorientation;
8. Use self-locating features;
9. Avoid special tooling and test equipment;
10. Provide accessibility;
11. Minimize operations and process steps; and
12. Eliminate blind assemblies.

The following section breaks down the 12 DFMA principles key points:

1. Minimize the number of parts

- Essential part or not?
- If the items function is only to fasten, secure or connect other items then the item is nonessential
- Relative to all parts already assembled



Figure 3. Achieving Simplistic Designs Takes Out of the Box Thinking

- Does it have to move?
- Does it have to be a different material?
- Is it required for assembly or disassembly?
- If the answer is no to all three questions, then the part is a candidate for elimination or combination with other parts
- Using fewer parts results in reduced assembly time, fewer parts that may require troubleshooting, reduced potential part removal and less rework — a part that is designed out can never fail

2. Minimize the number of fasteners

- Most frequently disregarded principle
- Most costly operation in assembly
- Fasteners reduce automation opportunities
- Fasteners require work station support
- Fasteners contribute to carpal tunnel syndrome
- Most frequent cause of product failures

3. Standardize

- Simplifies engineering design and assembly documentation efforts
- Reduces procurement, inspection and inventory
- Allows for automation
- Reduces cost by increasing volume buys — economies of scale
- Eliminates defects caused by confusion
- Promotes design reuse
- Standardize components, subassemblies, materials, processes and part orientations
- Use a standard parts list
 - Stable list with strong criteria
 - Minimizes obsolescence
 - Supported by suppliers
 - Supported by supplier management teams
 - 65 percent industrial or commercial parts

4. Avoid difficult components

- Difficult components include
 - Components that cause difficulty during assembly resulting in increased handling, insertion time or both
 - Components that require more than one hand to grasp, are delicate, heavy, flexible, sticky, tangle, nest, sharp, abrasive or slippery
 - Components whose orientation is difficult to see

5. Use modular subassemblies

- Modular subassemblies are assemblies that stand alone. These assemblies can be assembled, inspected and tested independently.
 - Reduces complexity at final assembly

- Accomplishes functions common to many products in common subassemblies
- Improves disassembly and repair
- Reduces customer downtime
- Allows plug-and-play
- Allows design reuse
- Allows for future upgrade of current design
- Improves testability
- Allows break points for outsource
- Improves quality and reliability

6. Use multifunctional parts

- Multifunctional parts are parts that can be used in more than one place for the same or multiple functions
 - Design parts that can be used in multiple places
 - Design parts to perform more than one function
 - Reduces inventory support activities
 - Combine several parts in one part
 - Make left-hand and right-hand parts identical
 - Use symmetry when possible
 - Reduces development and production cycle time
 - Reduces assembly defects
 - Minimizes assembly tooling
 - Increase production volume of parts — economies of scale

7. Minimize re-orientations

- Assemble in Z-axis motion
- Eliminate holding parts in place for subsequent assembly
- Use gravity as an advantage, not a disadvantage
- Reduce injuries — bending, stooping, reaching and tugging
- Allow automation
- Avoid multiple turns or handling

8. Use self-locating features

- A self-locating feature is a physical feature of a component, module, or subassembly that provides a positive indication that the component, module, or subassembly has been assembled correctly
 - Chamfers
 - Staggered leads
 - Conforming features
 - Lips
 - Shoulders
 - Tapers
 - Tab-in-slot
 - Keys
 - Dog-point screws

9. Avoid special tooling and test equipment

- Avoid:
 - Nonstandard hand tools
 - Complex fixtures
 - Special assembly and test equipment
 - Features requiring custom tooling for fabrication
- Use hand operated fastener for access to maintenance items

10. Provide accessibility

- At assembly
 - Allow space around parts and components for tools
 - No stacked components or modules
- At test
 - Bring test points to the outside of modules.

11. Minimize operations and process steps

- Each sequential fabrication and assembly operation adds to the product cost and schedule:
 - Design to use in as is or as finished condition
 - Reduce and eliminate chemical treatment requirements
 - Perform tolerance allocation and process capability planning
 - Minimize plating and surface coating requirements
 - Design for no-clean operations
 - Avoid dissimilar materials
 - Minimize:
 - Fastening
 - Etching and plating
 - Joining and bonding
 - Hand soldering
 - Cleaning

- Surface coatings
- Finishing
- Deburr and touchup

12. Eliminate Blind Assemblies

- What is a blind assembly?
 - Blind assemblies include items that must be installed or adjusted without the operator having a direct view of the components or tools being applied

Each additional process step or manufacturing and assembly step adds to the cost and time required to produce a product, increasing opportunities for defects. Look at the processes required to build a design to evaluate if any can be eliminated or combined. Consider any processes or operations driven by unnecessary bells and whistles features.

RAYTHEON DFMA EXAMPLE

A series of DFMA workshops were conducted for the Tactical Tomahawk (Tomahawk Block IV) design for the explicit purpose of reducing product cost. Figure 4 shows the Tomahawk Block III design characteristics and compares them with the Tactical Tomahawk design attributes. These Tactical Tomahawk design changes reduced the missile cost for the customer by two-thirds when compared to the Tomahawk Block III design, and the customer, in turn, has provided larger lot procurements to Raytheon.

During the Tomahawk workshop the following producibility topics were a focus:

Use Parts and Material with Lowest Total Cost

Design in parts and material with the lowest total cost. The lowest total cost includes:

- Purchase price per piece
- Assembly costs
- Test cost
- Rework costs

<i>How High Tech Cuts Costs</i>		
<i>Block III Tomahawk</i>		<i>New Tactical Tomahawk*</i>
11,500	Total parts	7,500
3,750	Missile assemblies	1,000
2,500	Fasteners	800
45	Circuit card assemblies	25
22	Harnesses	12
160	Connectors	45
610	Assembly and test hours	193
Reduced Cost by Sixty Seven Percent		
*Preliminary figure		

Figure 4. DFMA Transformed Tomahawk Missile from a Traditional Aircraft Design to a Modular Configuration.

- Cost of yield losses
- Cost of supplier late shipments
- Cost of defective product arriving at incoming receiving

Minimize Interconnects

Minimizing interconnects results in:

- Less cables to buy and assemble
- Less interconnects to loose, brake or get dirty
- Multiple functions combining onto one board
- Multiple interconnects combined together, e.g., bundling (ganging) connectors together

Design for Modularity Assembly

Design for modularity assembly includes:

- Snap together construction
- Hardware with captive washers
- Parts with common form code and body sizes
- Parts packaged for automated assembly
- Modules designed for Z-axis assembly — top down

Design for Mistake-free Assembly

Designing for mistake-free assembly makes it difficult to place the wrong part in the wrong location and includes:

- Robust marking and identification
- Connector keying
- Captive hardware
- Design of simple, standard tools

Design for Reworkability

The removal, repair and replacement of equipment must be considered when designing hardware. This includes designing mechanical and electrical connections to withstand multiple assembly and disassembly sequences. The need for reworkability may be driven by defects, failures or design changes.

Design with Captive Fasteners

Captive fasteners used to mount the assembly are preferred. Captive fasteners should be repairable and replaceable from the top side of the assembly. The assembly should not have to be removed to rework and replace damaged captive fasteners.

AFFORDABILITY

We have created a culture that guides development and manufacturing decisions to balance performance and cost to meet customer affordability objectives. Raytheon has a successful track record implemented and executing Design-to-Cost (DTC) and Cost As an Independent Variable (CAIV) using processes and tools directly applicable to the instrument unit. Raytheon's DTC process emphasizes meeting specific cost targets at various stages in a product life cycle by applying the principles of CAIV. Raytheon's DTC approach is drawn from commercial, aerospace and Raytheon

internal best practice and lean practices adopted from Delco, GM, Toyota, Texas Instruments, and others. DTC drives engineering, manufacturing, material, finance and others variables to identify and eliminate extra cost.

Affordability Processes and Procedures

Raytheon applies a coordinated suite of business practices and IPT processes to implement DTC. These processes are tailored to specific programs objectives and used in concert for maximum benefit. They include:

- Design of experiments (DOE)
- DFMA
- Virtual and rapid prototyping and manufacturing
- Customer focus
- Design for six sigma manufacturing
- Use of commercial off-the self (COTS)
- Non-development items (NDI)

Metrics

Producibility metrics are generated during the early program phases and goals are established for each assembly. At a minimum, the following metrics are tracked:

- Defects per unit (DPU)
- Product manufacturing sigma
- Design to unit production cost (DTUPC)
- Cycle time (including touch time)
- Test selects
- Total parts and total part numbers
- Fastener types and quantities

VERIFICATION OF PRODUCIBILITY

Verification of producibility is performed by Manufacturing Engineering and is reported to the program. At a minimum, verification of producibility is reported at the scheduled design reviews. Verification of producibility is quantitative and qualitative.

Quantitative Verification

Quantitative verification is performed using DTUPC analysis, cycle time predictions and discrete event simulation.

DTUPC Analyses

DTUPC analyses are performed for all levels of assembly, e.g., PCBs, modules, units (stacks), panels and satellite. The DTUPC analysis addresses the following metrics:

DPU, sigma, DTUPC, test selects, touch time, percentage of mass reflow leads (PCB level only), percentage of auto place parts (PCB level only) and total parts and part numbers.

Cycle Time Predictions

Cycle time prediction analyses is performed for all levels of assembly e.g., PCBs, modules, units (stacks), panels and satellite. The cycle time prediction analysis will supply information to the discrete event simulation.

Discrete Event Simulation

Discrete event simulations is performed for all levels of assembly e.g., PCBs, modules, units (stacks), panels, satellite and total program including major subcontracts. The discrete event simulation will supply information to address the cycle time metric.

Discrete event simulations supplies useful information related to resource use (labor and machines), factory size requirements, what-if scenarios and overall process yields.

Qualitative Verification

Qualitative verification is performed during the manufacturing engineer's day-to-day involvement in the design activities. Qualitative verification can be in the form of comments and opinions expressed by the manufacturing engineer during involvement with commodity teams, design meetings, design reviews, exchange of e-mail and impromptu discussions.

TACSAT 4 DFMA WORKSHOP

The Naval Research Laboratory (NRL), working under the direction of the Office of Force Transition (OFT), established an Integrated System Engineering Team (ISET) and satellite industry business team with a charter to develop small satellite bus standards. As part of this work, a plan was developed to lower the cost of satellites thus enabling an Operationally Responsive Space (ORS) vision for flexible satellite missions. The vision is to increase ORS satellite rate production from approximately one satellite per year (laboratory provided) to approximately 5–10 busses per year. These satellites would be provided by an industrial base using proven producibility and manufacturing methods. The OFT/NRL approach will balance mission satellite utility with industrial know-how given a set of reasonable standards to reduce cost and produce an affordable constellation of off-the-shelf satellites.

To assist in this vision, Raytheon Missile Systems provided a DFMA workshop with the ISET on March 6–7, 2007. A DFMA workshop was selected because it is a design methodology that considers manufacturing effort and cost as functions to be minimized, given the constraints of customer requirements. The workshop goal was to identify current constraints affecting integration and assembly of satellite manufacturing today. Based on the constraints, a list of producibility recommendations was developed. These recommendations should enable improved supply chain cost management, high product quality and efficient manufacturing, resulting in enhanced communications between design, manufacturing, purchasing and management. The driving parameters that were

considered during the workshop were hardware technology, manufacturing and test processes, cost and schedule. The following is a summary of the recommendation categories generated from the workshop:

1. Functional test;
2. Assembly access;
3. Part and process usage;
4. Cable and harnessing;
5. Mechanical alignment;
6. Special tooling;
7. Center of gravity measurements; and
8. Hardware handling and lifting methods

TACSAT 4 DFMA WORKSHOP RECOMMENDATIONS

To achieve an affordable satellite from the DFMA process, the following recommendations are established from Raytheon best design practices. It is the manufacturing engineer's responsibility to see that any best design practices delineated in this document that are thought to be critical to the successful execution of an individual program are followed by that program. One way to guarantee that these best design practices are followed is to take the best design practices from this document and incorporate them into the program-specific requirement documents.

1. Functional test

- a. Provide adequate number of test access points
- b. Provide adequate access to the test points
- c. Provide built-in self-test and diagnostic resolution
- d. Maximize testability coverage at the lowest level of assembly possible
- e. Design test equipment for quick and reliable interfacing

2. Assembly access

The panel should be designed to allow access to all modules and units for removal and replacement at the panel level. The need for temporary disconnection and relocation of cables and harnesses should be kept to a minimum during module and unit removal and replacement.

Access to Hardware

Straight access to all mounting hardware should be maintained at the satellite level of assembly.

Module Installation and Removal

Module installation and removal should be from the top of the assembly. Modules must be designed to allow removal and installation at the panel level of integration. Modules must be fully connectorized and keyed for quick installation and removal.

3. Part and Process Usage

Use Fewer Parts

Fewer parts results in reduced assembly time, fewer parts that may require troubleshooting, reduced potential part removal and less rework — a part that is designed out can never fail.

Use Fewer Part Types

Fewer part types results in fewer parts to purchase, expedite, receive and stock, pick and setup on the assembly line, fewer stock locations to track and fewer suppliers to manage.

Use Low Defect Processes

Using low defect processes results in reduced troubleshoot and repair time that equals reduced production cycle times.

Defects can be lowered by:

- Eliminating hand soldering, hand assembly and hand cleaning steps
- Design out parts that require high defect rate processes

Replacement Parts

Replacement parts should be fully interchangeable with the parts that they are replacing. Replacement parts should be the same form, fit and function as the part that they are replacing. Replacement parts should not require excessive adjustments, tuning or shimming.

4. Cable and Harnessing

Cable and Harness Connectorization and Keying

Cables and harnesses should be connectorized and keyed. Connector keying may be in the form of physical keys, color coding, or some other type of mechanical differentiation. Quick connect connectors, gang connectors or both should be used when possible. Quick connect connectors must use a positive locking feature that is easily verifiable in a design. Avoid locating identical connectors near each other to prevent mismates.

Cable and Harness Tie Points

All cable harness tie points should be predefined and prelocated with keepouts observed. An acceptable keepout area will permit direct access to the tie points at all times. The need for installing tie wraps around RF cables in the integration facility should be kept to a minimum. If tie wraps must be installed around RF cables in the integration facility then locations should be predetermined and special features should be built into the RF cable harnesses limiting the potential damage that could occur during the tie wrap operation.

Cable and Harness Bundling

All cabling and wiring should be in harnesses and bundles. The number of different harness and bundle assemblies should be kept to a minimum.

Cable and Harness Routing

Cables and harnesses should be routed to permit access to module and unit mounting locations to allow module and unit removal and replacement, the connection of module insertion and extraction tooling, and the connection of unit lifting tooling.

5. Mechanical alignment

No precision mechanical alignment should be required in the final integration facility. Precision mechanical alignment involves positional measurement, analysis of measurement results and subsequent tweaking of the alignment. This type of mechanical alignment process can be time consuming and highly variable.

A mechanical mounting process that requires no mechanical alignment is preferred. If mechanical alignment is necessary a go no-go gage block type of alignment is preferred.

6. Special tooling

Special tooling should be designed in parallel with the design of the satellite. Special tooling includes, but is not limited to, dollies and strong-backs.

7. Center of Gravity (CG) Measurements

No CG measurements should be required during production for modules or units. CG measurements during production for panels are discouraged. CG measurements during production for satellites are acceptable.

Weight measurements

No weight measurements should be required during production for printed circuit cards, modules and units. Weight measurements during production for panels and satellite are acceptable.

8. Unit lifting points

Lifting points required to interface with mechanical fixtures should be designed into all of the units. These lifting points must be accessible at the panel level for both unit installation and unit removal. Unit lifting points should permit vertical lifting and vertical rotations of the unit.

Lifting points required to interface with mechanical fixtures should be designed into the satellite. These lifting points must be accessible at all times during system level integration and at the launch site.

CONCLUSION

The TacSat 4 DFMA workshop outputs provide a framework that will improve satellite manufacturing cycle time, so that manufacturing and producibility issues are addressed up front during the design phase. DFMA focuses on cycle time reduction and commonality at all the manufacturing indenture levels. Approximately 70–80 percent of all manufacturing costs are determined in the early concept stages of design, and it is here that the DFMA contribution

begins. Using DFMA, engineering and design professionals, working with manufacturing experts, systematically evaluate individual components and assemblies as they relate to ease of assembly and manufacturing efficiency. As a result, costly practices such as sequential engineering and the use of single function parts, numerous fasteners and multiple prototypes are eliminated. Lessons learned through both the TacSat 4 satellite and Tomahawk missile DFMA provide a good overview of key producibility activities that benefit future satellite designs.

This effort directly supports the NRL vision of improving cycle time to market and lowering cost. The obvious advantage of this technique is to minimize variation through reduction in assembly steps and parts. Reductions in costs and in manufacturing cycle times that improve delivery and increase capacity are the resulting benefits.

ACKNOWLEDGEMENT

I would like to thank Michael Hurley from the Naval Research Laboratory in sponsoring the DMFA workshop and the ISET Business Team for their dedicated workshop support. The output of the workshop will provide guidance for future satellite designers for years to come.

REFERENCES

Raytheon Six-Sigma™ DFMA Principles – Open source training material

Traditional Cost Accounting Influences on Manufacturing Costs – Courtesy Munro and Associates

ACRONYMS

- CAIVCost As an Independent Variable
- CGCenter of Gravity
- COTSCommercial Off-the Shelf
- DFMADesign for Manufacturing and Assembly
- DOEDesign of Experiments
- DPUDefects per Unit
- DTCDesign-to-Cost
- DTUPCDesign to Unit Production Cost
- EKVExo-atmospheric Kill Vehicle
- IPTIntegrated Process Team
- ISETIntegrated System Engineering Team
- NDINon-Development Items
- NRLNaval Research Laboratory
- OFTOffice of Force Transition
- ORSOperationally Responsive Space
- PCBPrinted Circuit Board
- SMStandard Missile