Cross-Industry Characterization of Spacecraft Integration and Test Discrepancies: Transforming Discrepancies into Product Development Improvements

Annalisa L. Weigel\(^1\), Joyce M. Warmkessel\(^1\)

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

This paper presents the results of cross-sector benchmarking research on discrepancies encountered during spacecraft system-level integration and test. Analysis results demonstrate which subsystems have the highest occurrence of discrepancies, which integration and test environments precipitate the greatest number of discrepancies, and what the leading causes are of discrepancies. In addition, the paper presents cost data for spacecraft discrepancies, and concludes with a discussion of important factors to consider in evaluating the cost-benefit trade of upstream preventative investment to avoid problems before they occur versus downstream reactive measures after problems occur.

**Introduction**

Toyota quality philosophies say that mistakes are very valuable, for they indicate areas for improvement. Taking this to be true, there is a lot of "value" contained in the discrepancies encountered during spacecraft integration and test, beyond the immediate and obvious value of identifying the problem at hand on the current spacecraft. These discrepancies can point to more systemic problems in an organization, such as fundamental design deficiencies, documentation inaccuracies, workforce training needs, and so on. Thus, an analysis of these discrepancies, with a view to reduce or eliminate them, can lead to product design improvements, process improvements, cycle time reduction and cost savings.

There is little insight across the space industry on the kinds and distribution of discrepancies encountered. If these discrepancies are to be addressed, their frequency reduced and ultimately eliminated altogether, more data is needed. Research began at the Lean Aerospace Initiative (LAI) to answer this need. The Lean Aerospace Initiative (LAI) is an active research partnership among the U.S. Air Force, the Massachusetts Institute of Technology (MIT), defense aerospace businesses and organized labor. Formally launched in 1993, the initial research focused on the aircraft sector. Following very positive results, LAI welcomed the U.S. Air Force's Space and Missile Systems Center, NASA and major U.S. space companies into the research partnership in 1998. Work in the partnership now involves both the aircraft and space sectors.

**Research Purpose and Methodology**

The purpose of the research presented in this paper is to characterize the distribution of system-level integration and test (I&T) discrepancies. System-level I&T is defined as the time on the factory floor from payload and bus mate to spacecraft ship, including all environment and functional tests. This top level of assembly was chosen for the research because the system-level I&T portion of spacecraft development is a large part of the development schedule and approximately 35-50%\(^2\) of the total recurring costs on a program. In addition, finding defects at the system level are more costly than finding defects at lower levels of assembly, with the costs to fix a defect growing by an order of magnitude at each level of assembly. Any progress that could be made on reducing discrepancies at the top level of assembly would have the greatest payoff in terms of schedule and cost.

\(^1\) Research Assistant, Department of Aeronautics and Astronautics.
\(^2\) Senior Lecturer, Department of Aeronautics and Astronautics.

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Data was gathered through vendor-maintained discrepancy reports on each discrepancy they recorded against a spacecraft during I&T. For each discrepancy, the following data were collected:

- Spacecraft pseudonym
- Mission area (communications, navigation, space science, weather, remote sensing, or early warning)
- Open date, close date and open duration of the discrepancy
- Affected subsystem
- I&T activity being performed at the time of discrepancy occurrence
- Immediate fix action taken on current discrepant spacecraft (disposition)
- Root cause of the discrepancy
- Long-term corrective action taken to prevent recurrence of this problem on future spacecraft

Over a two-year period, a data set was amassed consisting of over 23,000 discrepancies, representing at least 20 programs and product lines that included over 225 spacecraft. There was a mix of mission areas as well as a mix of government and commercial programs. The date range spanned 1973-1999.

In addition to the discrepancy report data, over 50 interviews were conducted with spacecraft system and subsystem engineers, I&T personnel, program managers and quality assurance to provide the proper context and understanding necessary to analyze the discrepancy reports.

This paper presents the results of this cross-sector benchmarking research on discrepancies encountered during spacecraft I&T. Analysis results demonstrate which subsystems have the highest occurrence of discrepancies, which I&T activities precipitate the greatest number of discrepancies, and what the leading causes are of discrepancies. In addition, the paper presents cost data for spacecraft discrepancies, and concludes with a discussion of important factors to consider in evaluating the cost-benefit trade of upstream preventative investment to prevent problems before they occur versus downstream reactive measures after problems occur.

**Categorization System**

An important part of the research was developing a categorization system for 6 attributes of discrepancies: Mission Area, Activity or Test, Subsystem, Disposition, Cause, and Corrective Action. This characterization system is derived from existing vendor codes, DoD military standards documents, and interagency working group products. Internal spacecraft vendor coding systems for these attributes were mapped to the master categorization system presented here. This made a cross-organization analysis possible.

**Mission Categories Description**

These categories describe the primary mission of the spacecraft on which the discrepancy occurred.

- **Communications** – any spacecraft whose primary mission is to provide communications, including direct broadcast, relay satellites, telephony, etc.
- **Other** – all other missions, such as weather, remote sensing, early warning, navigation, etc

**Activity or Test Categories Description**

These categories describe the I&T activity that was taking place at the time of discrepancy occurrence.

- **Acoustic Test** – includes setup and post environment activities, as well as the acoustic test itself.
- **Vibration Test** – includes setup and post environment activities, as well as the vibration test itself.
- **Acceleration Test** – includes setup and post environment activities, as well as the acceleration test itself.
- **Shock Test** – includes setup and post environment activities, as well as the shock test itself.
- **Thermal Vacuum Test** – includes setup and post environment activities, as well as the thermal vacuum test itself.
- **Thermal Cycling Test** – includes setup and post environment activities, as well as the thermal cycling test itself.
- **Ambient Integration and Test Activities** – Any activity taking place from payload and bus mate up to spacecraft ship, that is accomplished in an ambient environment and not included in the categories above. This includes initial and final functional tests, as well as other functional tests not associated with environmental exposure.

**Subsystem Categories Description**

These categories describe the part of the spacecraft the discrepancy was written against [2].

- **Electrical Power and Distribution Subsystem (EPDS)** – EPDS’s primary function includes the generation, regulation, storage and distribution of electrical/electronic power throughout the vehicle. Other names: Electrical Power System (EPS), Power Subsystems, Power.
- **Guidance, Navigation and Control (GNC)** – The GNC’s primary function provides determination and control of orbit and attitude, plus pointing of
spacecraft and appendages. Other names: Attitude Control Subsystem (ACS), Attitude Determination and Control Subsystem (ADCS).

- **Payload** – The Payload subsystem's primary function provides mission specific capabilities to the space vehicles' functionality. Payloads have various capabilities such as communication, navigation, science, imaging, radar, and others.

- **Propulsion (Prop)** – The Propulsion subsystem's primary function provides thrust to adjust orbit and attitude, and to manage angular momentum. Other names: Reaction Control Subsystem (RCS).

- **Structures and Mechanisms Subsystem (SMS)** – The SMS's primary function provides support structure, booster adaptation, and moving parts. Other names: Structural, Structures and Mechanisms.

- **Combined Data Management Subsystem (DMS) and Telemetry, Tracking and Command (TTC)** – The DMS's primary function distributes commands and accumulates, stores, and formats data from the spacecraft and payload. Other names: Command and Data Handling (C&DH), Spacecraft Computer System, Spacecraft Processor. The TT&C's primary function provides communications with ground and other spacecraft. A basic subsystem consists of receivers, transmitters, and wide-angle antennas. Uplink data consists of commands and ranging tones while downlink data consists of status telemetry, ranging tones, and may include payload data. Other names: Communication subsystem. [These subsystems are combined because not all vendor data made a distinction between the two.]

- **Thermal** – The Thermal Control subsystem maintains equipment within allowed temperature range. Other names: TCS, Environmental Control Subsystem (ECS).

- **Wiring and Cabling (Harness)** – Wiring (harness) and cabling that is not considered part of a particular subsystem called out above.

- **Equipment** – Test equipment or ground support equipment of any type.

- **Other** – Discrepancies that are traceable down to a subsystem level, but the subsystem does not fall into one of the above categories.

- **Spacecraft** – Discrepancies that cannot be traced down to a particular subsystem called out above, or were chosen not to be traced down to a particular subsystem, fall into this category.

**Disposition Categories Description**

These categories describe the disposition, or immediate fix action taken on the discrepancy.

- **Use as is** – discrepancies which are dispositioned to use the anomalous item in its present state, not requiring any changes.

- **Rework** – discrepancies which are dispositioned as rework to the original blueprint.

- **Repair** – discrepancies which are dispositioned as repair, either standard or unique. Repair leaves the spacecraft different from the original print.

- **Return to Supplier** – discrepancies which are dispositioned to return the anomalous part to the supplier.

- **Scrap** – discrepancies which are dispositioned as scrap, meaning the anomalous items will be thrown away because they can no longer serve their designed purpose.

- **Other** – discrepancies which don’t fit into the above 4 categories for disposition.

**Root Cause Categories Description**

These categories describe the root cause that was determined for the discrepancy.

- **Employee/Operator** – discrepancies caused by a person incorrectly executing a procedure, bumping an object, etc. For example handling errors, manufacturing errors, operator error, workmanship, etc.

- **Design** – discrepancies caused by incorrect design of spacecraft or procedures; includes bonding/encapsulation, drawing/layout and design characteristics. Also a planned procedure executed as planned and determined to be planned incorrectly, etc.

- **Material** – discrepancies caused by defective material, parts, etc. ON the spacecraft

- **Equipment** – discrepancies caused by defective test equipment, GSE, etc. that is NOT on the spacecraft

- **Software** – discrepancies caused by software, either on the spacecraft or on the ground equipment

- **No Anomaly** – discrepancies written up in error, or determined later to not be anomalies, etc.

- **Unknown** – discrepancies whose cause is unknown or unable to be determined, etc.

- **Other** – discrepancies which don’t fit into the above 7 categories.

**Corrective Action Categories Description**

These categories describe the long-term corrective action that was prescribed to prevent the discrepancy from occurring again in the organization.

- **Operator/Employee** – a corrective action involving an operator or employee; e.g. training, counseling, notifying supervisor.
- **Drawing or Spec** – corrective action involving drawings or specifications that need to be changed, corrected, modified, etc.
- **Process/Procedure** – Corrective action involving processes or procedures that need a change, certification, recertification, etc.
- **Software Change** – Corrective action involving software (either on the spacecraft or on ground support equipment) changes, corrections, modifications, etc.
- **Equipment** – corrective action involving testing, manufacturing, assembly, etc. equipment that needs to be repaired, replaced, recalibrated, corrected, etc.
- **Supplier-related** – corrective action involving a supplier or vendor.
- **No Action Required** – it is determined that no corrective action is needed, for whatever reason.
- **Other** – corrective actions which don’t fit into the above 7 categories.

**Research Findings**

Five major findings from the research are presented in this paper in the areas of Subsystem, Activity, Root Cause, Corrective Action and Flow Time.

**Subsystem Findings**

The prevailing philosophy for spacecraft test is to drive the testing to the lowest possible level of integration that is able to find a specific problem. This is based upon the notion that the cost of fixing discrepancies grows by an order of magnitude with each increasing level of integration. This translates to a desire to find unit problems at the unit integration and test level, find subsystem problems at the subsystem integration and test, and find system problems at system integration and test level.

Figure 1 shows a graph of the distribution of discrepancies on an average spacecraft at the system level of integration, broken down by the part of the spacecraft that the discrepancy was written against. As shown in the graph, 36% of the discrepancies found at system level test are written against subsystems, and 29% of the discrepancies are written against test or support equipment. The remaining 35% of the discrepancies are written against system level problems.

If the goal is to drive testing to the lowest level possible to find a problem, then only system level problems are the type of problems that ideally should be discovered at the system level of integration and test. It can be argued that finding subsystem problems at the system level of integration may in fact be the most cost-effective method (though no cost-benefit analysis has presented itself). However, it is difficult to argue that finding equipment problems at system-level integration and test is not waste in the process that should be eliminated. Since a suite of test equipment, particularly for commercial satellites, will be reused over and over again on numerous satellites, there is a potentially large return on investment for addressing and remediying discrepancies associated with test equipment.

![Figure 1: Distribution of discrepancies on an average spacecraft at the system level of integration, by area the discrepancy was written against.](image-url)
Activity Findings

Environmental test chambers are very large and expensive resources for a spacecraft manufacturer to maintain. Thus, there is great interest among spacecraft producers to use these resources in an effective manner. Figure 2 shows a graph of the percentage of discrepancies on an average spacecraft that were found during system-level integration and test in each of the traditional environmental exposures.

As shown in the graph below, the thermal vacuum environment finds 36% of all the discrepancies discovered at system-level I&T. The thermal cycling environment finds about 3% of all discrepancies discovered at the system level, and the "shake" environments of acoustic, vibration, acceleration and shock together find about 3% of all discrepancies discovered at the system level. This is consistent with previous studies that have suggested that the thermal vacuum environment catches substantially more discrepancies than the other environments. As the thermal cycling and "shake" environments account for a small percentage of discrepancy discoveries, they would be logical targets for further tradeoff studies. These tradeoff studies would examine the costs and benefits of continuing the thermal cycle and shake environmental exposures vice eliminating those exposures in lieu of other countermeasures for discovering, or otherwise eliminating, the discrepancies currently found in those environments.

Root Cause Findings

An analysis of the root cause of problems can be quite insightful for an organization. It can indicate where to spend resources to increase quality or performance.

As demonstrated in Figure 3 human error and design-related problems are reported as the leading causes of discrepancies at the system level of integration. An example of human error would be a procedure that was not carried out as written, or a component that was installed not according to specifications. Design problems include the design of both hardware and processes.

![Distribution of Discrepancies on an Average Spacecraft at the System Level of Integration, by System Test Environment that Precipitated the Discrepancy](image)

Figure 2: Distribution of discrepancies on an average spacecraft at the system level of integration, by system test environment that precipitated the discrepancy
Figure 3: Distribution of discrepancies on an average spacecraft at the system level of integration, by root cause of the discrepancy

As human error and design-related problems are reported as the leading causes of discrepancies, effective corrective action aligned to address these two areas would potentially yield the largest reduction in discrepancy occurrences. The same workforce, as well as the same test support equipment, is in used over and over again in the production of spacecraft. Fixing discrepancies that are caused by these things will thus yield benefits that scale with the production rate.

It is interesting to note that the percentage of human error-caused discrepancies per spacecraft has remained more stable over the past thirty years than percentages of the other root cause categories, based on observations of the data used in this research. It is also perhaps interesting to observe that less than half of the discrepancies were related to things typically associated with the challenges of building sophisticated spacecraft, such as design and software.

**Corrective Action**

Toyota production philosophies say that mistakes are more valuable than gold, because they are opportunities for learning and improvement. Without mistakes, it is hard to improve. Thus, each discrepancy, or problem, points out opportunities for improvement. A measure of how well an organization is capitalizing on these opportunities is a measure of how an organization is learning and improving itself.

Figure 4 shows a graph of long-term corrective action reported for an average spacecraft, broken down by categories. There is a fairly even spread of actions involving equipment, procedure changes, specification changes, more training, and so on. However, the largest category of corrective action reported is "No Action Required" which totals about 24% on an average spacecraft. This appears to indicate that organizations are passing up opportunities to capitalize on problems they have spent significant time and money on finding. Moreover, interview data suggests that follow-through on prescribed long-term corrective actions gets overcome by more urgent and immediate needs.
In addition, it was found that the supplier was involved in long-term corrective action only 1 out of 3 times per discrepancy whose root cause was traced to a supplied component. This disconnect will need to be addressed in the future. As spacecraft vendors increase their reliance on suppliers and out-sourced parts, a close relationship with suppliers will become even more necessary and mutually beneficial.

**Flow Time Findings**

Flow time findings are discussed in two categories: Labor time and Cycle time. Labor time refers strictly to hours that personnel spend on certain tasks. Cycle time refers to the serial calendar time required to deliver the product. Time is important because it is a surrogate for cost. A picture of discrepancies at the system level of integration, as has been sketched out above, is of questionable value to a decision-maker without an idea of the costs involved with those discrepancies.

**Labor Time**

Through interviews, rough order of magnitude estimates were developed of commercial spacecraft discrepancy cost and schedule losses per spacecraft at the system level of integration. For an average commercial satellite, the total labor time spent on discrepancies per satellite is about 12 to 13 person-years. This figure includes anyone in the organization who could reasonably be determined to play a part in the discrepancy discovery and resolution life cycle - from finding the discrepancy, through investigation, root cause determination, making repairs, and prescribing a long-term corrective action. This included program managers, system, subsystem and unit engineers, I&T personnel, and quality assurance. This estimate does not include the time of other people waiting that might be owed to a discrepancy occurrence. It also does not include facility time such as might be incurred by needing to rerun a test. Feedback from industry stakeholders indicates that these discounted areas might be large contributors to cost in and of themselves.
To translate the total labor time into a rough idea of cost, the labor time in person-years is multiplied by a full burdened cost estimate of a person-year in the aerospace industry. Using a figure of $160,000 per person year in $FY00 [3] that equates to roughly $2M per satellite for discrepancy costs at the system level of integration. This does not include the cost of capital due to the associated cycle time delay (cycle time delay is discussed in the following section), which may be large.

To put the $2M cost of discrepancies figure into perspective, it can be compared it to an estimate of profit made on an average commercial communications satellite. Taking a number from a widely used textbook on spacecraft design, the average communications satellite costs about $130M [3]. If a profit margin per satellite of 15% is assumed, then the profit per satellite is approximately $20M. If discrepancies were eliminated at the system level, and all resulting cost savings were put towards that bottom line and not passed on to the customer, the profit margin per satellite would be increased by 10%.

**Cycle Time**

In addition to examining labor time of spacecraft discrepancies at the system level, cycle time was also investigated. On average, a commercial spacecraft would experience nearly two months of serial time delays due to discrepancies at the system level of integration. If the industry standard for commercial spacecraft cycles times have been 24-36 months in the 1990’s, and the goal is to bring that down to 12-18 months in the coming decade, then this apparent cycle time delay will have to be addressed.

Figure 5 presents a summary of flow time findings. About 10% of the product development cycle time and 10% of the profit per product are spent fixing discrepancies at the system level of integration. The labor time and cycle time impacts appear large, but currently spacecraft vendors are not tracking these metrics. Further work is warranted in this area, with the potential for large benefits.

### Conclusion

If discrepancies could be reduced or eliminated, cost and cycle time reductions would follow, as well as quality and reliability improvements in the spacecraft product. Several important recommendations emerge out of this research that will help organizations increase the value-added contribution of test to their entire Enterprise.

#### Collect Data

While some data is currently being tracked for discrepancies, increased data collection on several aspects of discrepancies would be very beneficial to an organization. In particular, data on costs and cycle time delays associated with discrepancies should be...
collected. This data then forms the basis for evaluating a host of cost-benefit trades on reducing waste – discrepancies – from the integration and test process by improving the upstream product development processes.

Continuous Improvement

Continuous improvement should be established, valued and maintained as part of the corporate culture. Improvement also involves a commitment to find the true root cause of discrepancies or problems, and implement an enterprise-wide corrective action solution to prevent them from reoccurring in the long term. Finally, improvements need to be measured and evaluated for their effectiveness.

Align Incentives

It is critical to align incentives, in the broadest sense and at all levels, with fixing problems for the long term. Interview data suggest that the current incentive structure in organizations may not be entirely consistent with this, and needs some examination in that regard. In particular, organizations appear to be structuring incentives that result in a sub-optimization of performance and profit at the program level. Incentives should instead be structured to optimize performance at the Enterprise level.

Use Test to Improve the Enterprise

Product testing can become more than measuring the performance of the current product to its specifications. Testing can also provide feedback on the organization’s product development system, its manufacturing system, its testing system, its supply chain, and so on. This is shown conceptually in Figure 6. To illustrate this point, take the finding that, on average, 29% of problems reported during system-level integration and test are related to test equipment. This provides feedback on how well the organization’s testing system is functioning, and it shows that there is currently opportunity for improvement in this area.

Future Work

Additional data analysis will examine correlation between various aspects of discrepancies, as well as significant differences in discrepancy attributes between communication spacecraft and spacecraft performing other primary missions. In addition, a monograph of this research and results will be produced. Please contact the authors for details.

References

[1] Percentages provided by The Aerospace Corporation for commercial communication satellites and The Boeing Corporation for Global Positioning System satellites.