# SPACECRAFT SYSTEM-LEVEL INTEGRATION AND TEST DISCREPANCIES: CHARACTERIZING DISTRIBUTIONS AND COSTS

by

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Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aeronautics and Astronautics

at the

Massachusetts Institute of Technology

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## Abstract

The goal of this research is to characterize the distribution and costs of spacecraft discrepancies found at the system level of integration and test, as well as understand the implications of those distributions and costs for the spacecraft enterprise as a whole. If discrepancies can be better understood, they can potentially be reduced or even eliminated. Reducing discrepancies will result in cycle time reduction and cost savings, as well as increased product quality and reliability. All of these potential outcomes are indications of successful progress toward becoming a lean organization.

Data on discrepancies at the system level of integration were gathered from spacecraft vendor databases, while interviews with key program managers and engineers provided perspective and insight into the data. Results are based on 224 spacecraft representing at least 20 different programs or product lines, and encompassing 23,124 discrepancies. The spacecraft date from 1973-1999, and represent different vendors as well as a mix of commercial and government spacecraft.

Spacecraft discrepancies are analyzed in this work on the basis of ten categories: the spacecraft mission, the spacecraft subsystem where the discrepancy occurred, the date of the discrepancy occurrence, the discrepancy report open duration, the immediate action taken to fix the discrepancy (disposition), the root cause of the discrepancy, the long-term corrective action prescribed to prevent the discrepancy from happening again on future spacecraft, the labor time spent on the discrepancy, and the cycle time lost due to the discrepancy. Statistical measures of central tendency, correlation and normality are presented for each category. This statistical analysis forms the basis for research findings at the enterprise level in the areas of quality yield, resource utilization, stakeholder satisfaction and flow time. Recommendations to enterprise stakeholders for increasing the value derived from system-level integration and test follow from the enterprise-level findings.

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## Acknowledgements

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On a personal note, I would like to acknowledge the support of my fellow LAI research assistants. Their camaraderie and friendship have made these past few years a lot of fun, both in and out of the office. I also need to thank my wonderful parents and family, who have provided unwavering encouragement and support of all my life's endeavors. And finally I would like to thank my fiancé, Myles, for both his moral and intellectual support of this work and all the late nights at the office.

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# Chapter 1.

# Introduction

## 1.1. Overview of Thesis

The goal of this thesis is to characterize the distribution and costs of spacecraft discrepancies at the system level of integration and test, and understand the implication of those for the enterprise as a whole. Chapter 1 introduces the issues and gives an overview of the methodology for the research. Chapter 2 explains the research construct for characterizing the discrepancies. Chapter 3 is a statistical analysis of the distributions and central tendencies of various aspects of discrepancies, such as environment, cause and corrective action, among others. Chapter 4 covers the research construct for investigating the costs of discrepancies, and also presents the cost data analysis. Chapter 5 discusses findings of the research at the enterprise level, and is of particular interest to managers and others responsible for creating a lean enterprise. Chapter 6 concludes the thesis by presenting recommendations on how to effectively use integration and test in creating a lean enterprise, and directions for further research in this area.

## 1.2. Background: The Lean Paradigm

This background section summarizes the origins of lean and the Lean Aerospace Initiative. It then discusses the Lean Enterprise Model (LEM) and how this spacecraft system-level integration and test research fits into the LEM.

### 1.2.1. Origins of Lean

Lean began as a manufacturing approach, and was first described in the United States in a book by Womack, Jones and Roos called *The Machine That Changed the World.* This book was born out of research conducted through the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology. IMVP applied the word lean to describe a revolutionary manufacturing approach in contrast to the conventional mass production approach. Lean included the concepts of Total Quality Management, Continuous Improvement, Integrated Product Development, and Just-In-Time inventory control[1].

Several years later, lean was broadened to include the entire product development process in a second book by Womack and Jones called *Lean Thinking.* That book made the case that lean is more than just manufacturing. The essence of lean was a way to specify value in a process or product as seen by the end user, identify and convert waste into value, and perform tasks more and more effectively. Lean is thus a way to "do more and more with less and less" – less human effort, less inventory, less time, and less cost – "while coming closer and closer to providing customers with exactly what they want."[2] Numerous case studies in the book showed the benefits of the lean paradigm applied throughout the entire Enterprise. The lean paradigm continues to develop and evolve, as more and more industries change the way they do business through the use of lean principles. Application of lean to the aerospace business coalesced in the formation of the Lean Aerospace Initiative, a collaborative research consortium.

### 1.2.2. The Lean Aerospace Initiative

The Lean Aerospace Initiative (LAI) is an active research partnership among the U.S. government, labor, the Massachusetts Institute of Technology (MIT), and defense aerospace businesses. Formally launched in 1993, the initial research focused on the aircraft sector. Following very positive results, LAI expanded its research focus to include the space sector in 1998. Work in the research partnership now involves both aircraft and spacecraft sectors. This spacecraft system-level integration and test discrepancy research is the first LAI product to solely address the spacecraft sector.

As a neutral broker, MIT facilitates research across different vendors and fosters an environment of cooperative learning among competitors in the industry. Other research is underway in LAI specifically geared toward the space sector, including work on autonomy in operations, launch range capacity modeling, and launch vehicle upgrade optimization.

### 1.2.3. The Lean Enterprise Model

The Lean Enterprise Model (LEM) is a key original contribution by LAI. The LEM not only applies to aerospace businesses, but to other industries as well. The LEM consists of Meta-principles, Enterprise principles, Enterprise metrics, Overarching practices (OAPs), and Enabling practices. A graphic representation of the LEM[3] structure is shown in Figure 1.1.

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[1] Pomponi, Renata A. Control of Manufacturing Processes with MRP II: Benefits and Barriers in the Defense Aerospace Industry. MIT Master's Thesis (TPP), February 1995. p. 21.

[2] Womack, James P and Daniel T. Jones. *Lean Thinking.* New York: Simon & Schuster, 1996. p. 15.

[3] Lean Aircraft Initiative. "Lean Enterprise Model" (unpublished model and handbook), Massachusetts Institute of Technology, Cambridge, MA. 14 November 1996.

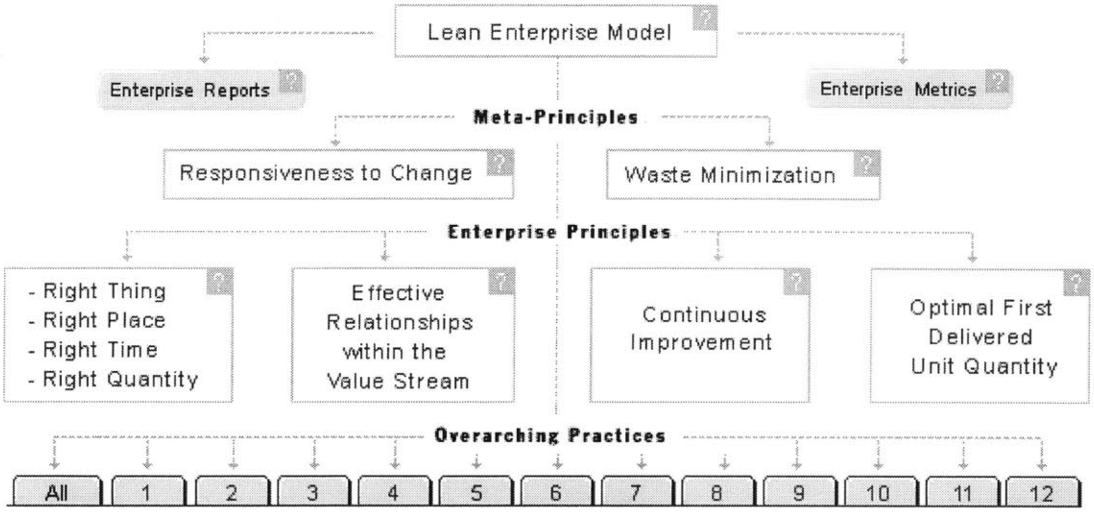

**Figure 1.1: The Lean Enterprise Model structure**

This spacecraft system-level integration and test discrepancy research draws upon several key principles in the LEM:

- Waste Minimization – Waste should be eliminated and value maximized. Discrepancies in integration and test are identified as a form of waste. Understanding waste is the first step towards eliminating it.
- Right Thing – The lean principle of "right thing" as applied to integration and test means that the parts delivered to the integration and test activity should be the right parts, the assembly and test equipment should be the right equipment, and the instructions and procedures should be the right ones. A discrepancy is essentially a "wrong" thing, and not a right thing. Understanding the discrepancies will help to make progress towards achieving the "right thing" principle.
- Continuous Improvement – Continuous improvement means that an organization constantly seeks ways to increase its value and eliminate waste. Active learning from, and correction of, mistakes is one obvious form of continuous improvement. If an organization is not studying its mistakes and making changes based upon those studies, it is not effectively engaging in continuous improvement.

## 1.3. Background: Spacecraft Development Cycle

The spacecraft product development cycle is not dissimilar to other complex product development cycles. A graphical representation is shown in Figure 1.2. It begins with requirements identification in partnership with the customer, and iterates through possible designs to satisfy those requirements. After a suitable design has been chosen, units that will become part of the finished spacecraft are assembled and tested. These units are assembled into subsystems, which are also tested. These subsystems are then assembled onto the payload and bus modules. The payload module performs the mission-specific function of the spacecraft, such as remote sensing, communication, position/navigation, etc. The bus module performs housekeeping functions common to most all spacecraft, including thermal control, attitude control, etc. The payload and bus module are assembled and tested in parallel. When these two modules are mated, the activity of system integration and test begins. After system integration and test, the spacecraft is packed up and shipped from the factory to the launch site. This research focuses exclusively on the final stage of product development conducted in the factory – the system integration and test stage.

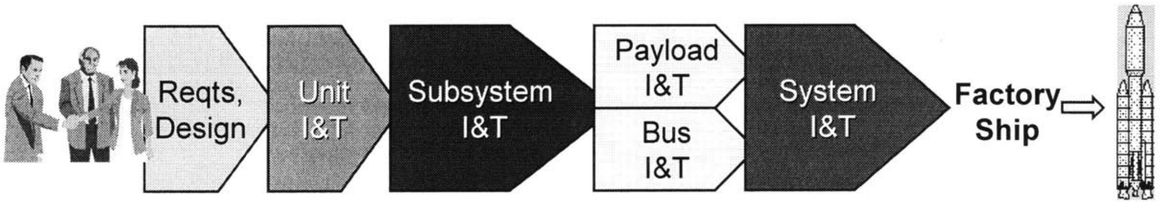

**Figure 1.2: Spacecraft development cycle**

Though spacecraft share many product development similarities to other complex products, there are certain characteristics about spacecraft that make them stand apart from other complex products.

- A typical lot size for spacecraft is 1. Large lots sizes for identical spacecraft are considered to be around 6-8. The largest lot size ever produced was 77 spacecraft for the Iridium constellation.
- Spacecraft are assembled primarily by hand, with extensive touch labor. This large human-in-the-loop factor greatly increases the chances that discrepancies will occur during assembly, integration and test.
- Spacecraft range in cost from about $100M up to $1B and more per spacecraft.
- Typical order to delivery cycle spans 24-36 months for commercial programs, 24-84$^+$ months for a government program.
- As contrasted with aircraft, spacecraft are operated in a "no return" environment. This results in risk-averse customers that usually dictate extensive testing and verification.

## 1.4. Basic Terminology

Several key terms are used throughout this thesis. Their definitions are presented here for clarity. Other definitions will be presented in the thesis where most appropriate.

- Discrepancy – a functional or structural anomaly, which may reveal itself as a deviation from requirements or specifications.
- System Integration and Test – the time from payload and bus module mate until spacecraft ship from the factory.
- Spacecraft – a vehicle designed to operate in space (this research does not include launch vehicles or human-rated vehicles).

## 1.5. Motivation

As discussed above in the section on the Lean Enterprise Model, there are fundamental lean philosophies that motivate this research in general. More specifically, spacecraft vendors are extremely interested in looking at spacecraft system-level integration and test because:

- System-level integration and test takes substantial time and resources, and dealing with discrepancies is perceived as a large percentage of the integration and test activity.
- The cost of fixing discrepancies is believed to increase by an order of magnitude with each higher level of integration. Thus, discrepancies found at the highest level of system integration and test are the most costly to fix.

If discrepancies can be better understood, then perhaps they can be reduced or even eliminated. Reducing discrepancies will result in cycle time and cost savings, as well as increased product quality and reliability. All of these outcomes are greatly desired on the part of vendors and customers alike.

## 1.6. Research Goals and Approach

Responding to the motivation described above, the goals of this research are threefold:

- Characterize the kinds and distribution of spacecraft discrepancies at the system-level of integration across the industry
- Estimate the costs of spacecraft discrepancies at the system-level of integration
- Investigate Enterprise implications of integration and testing

The research approach utilized data gathering from vendor databases to achieve the first goal of characterizing discrepancy distributions. Fortunately, spacecraft vendors are typically required by contractual terms to keep records of all discrepancies that occur during system-level integration and test. This creates a rich record of discrepancies that can be searched now with relative ease, as many vendors have migrated their paper-based discrepancy reporting systems to electronic-based systems.

The research approach utilized expert interviews to achieve the second goal of estimating the costs of discrepancies. Time spent by employees on discrepancies is used as a surrogate for cost in this research. Currently, records are not maintained of the time employees spend on discrepancy discovery and resolution. As a result, expert interviews had to be conducted with people who had extensive experience in discrepancy discovery and resolution. The interviewees provided estimates of the time they spend on discrepancies.

Finally, statistical analysis provided insights into the central tendency behavior and correlation of the characteristics and costs of discrepancies across the spacecraft industry. This analysis lead to findings at the Enterprise level, and ultimately to recommendations for the industry.

# Chapter 2.

# Characterizing I&T Discrepancies: Setting the Stage

## 2.1. Introduction

As detailed in Chapter 1, this research is motivated by several factors. In particular is the idea that problems found at the system level of integration are the most costly to fix. With this idea in mind, Chapter 1 explains the research design for investigating the distribution of system-level integration and test (I&T) discrepancies. Key questions are presented, data needs and data collection are discussed, and potential sources of error are listed. Finally, barriers encountered in the research and ideas for enabling further research in this area are discussed.

## 2.2. Key Questions

Several key questions that succinctly explain the research were formulated to help guide the research process. These are:

- What kinds of discrepancies are being found during spacecraft system-level integration and test?
- What distribution, patterns and correlations exist?

## 2.3. Data Types and Collection

To answer the key questions above, data on system-level integration and test discrepancies were collected from several spacecraft vendors engaged in system-level I&T. A spacecraft customer normally requires a vendor to maintain paper or electronic records of each discrepancy reported during system-level I&T. These records were the basis for obtaining the information on discrepancies that was required for this research.

For each discrepancy reported at the system level of integration for a particular spacecraft, the following information (to the extent it was available) was provided by participating vendors based upon archived discrepancy reports they maintained.

- Spacecraft pseudonym (to protect proprietary concerns, yet enable the ability to distinguish between spacecraft)
- Spacecraft order in production (if the spacecraft was part of a constellation or block build or product line)
- Spacecraft mission area (the primary functional mission area of the spacecraft, such as communications, weather, etc.)
- Discrepancy report open date (year only) and open duration
- Subsystem, or part of the spacecraft testing setup, the discrepancy was written against
- I&T activity taking place at time of discrepancy occurrence
- Description of the discrepant behavior observed
- Root cause of the discrepancy
- Immediate fix action needed to make the current spacecraft functional again (also called disposition)
- Long-term corrective action that was prescribed to prevent the problem from happening again on future spacecraft

To put into context and supplement the information contained in the discrepancy reports, interviews were also conducted with members of spacecraft I&T teams. They were asked to describe the discrepancy lifecycle, from discovery through corrective action, explaining what happens at each step.

## 2.4. Characterization System

Many vendors use their own internal code system to record much of the information about discrepancies. For example, many vendors have a finite code list for causes of discrepancies. So each time a discrepancy is investigated and a root cause determined, the root cause is assigned one of several codes describing the nature of the cause. This coding, or "binning", of the each cause facilitates analysis.

Since each vendor's code was different, it was necessary to create a master code scheme, or characterization system, into which to map the vendor-specific codes. This characterization system is derived from existing vendor codes, DoD military standards documents, and interagency working group products.

Vendors were provided with a description of the characterization system and asked to map their own codes into it. The vendor mapping was then reviewed for potential interpretation issues to ensure the best mapping possible of vendor codes to the characterization system.

The characterization system is divided into six areas: Mission Area Categories, Activity or Test Categories, Subsystem Categories, Disposition Categories, Cause Categories, and Corrective Action Categories. These are each described in detail below, and summarized in Figure 2.1.

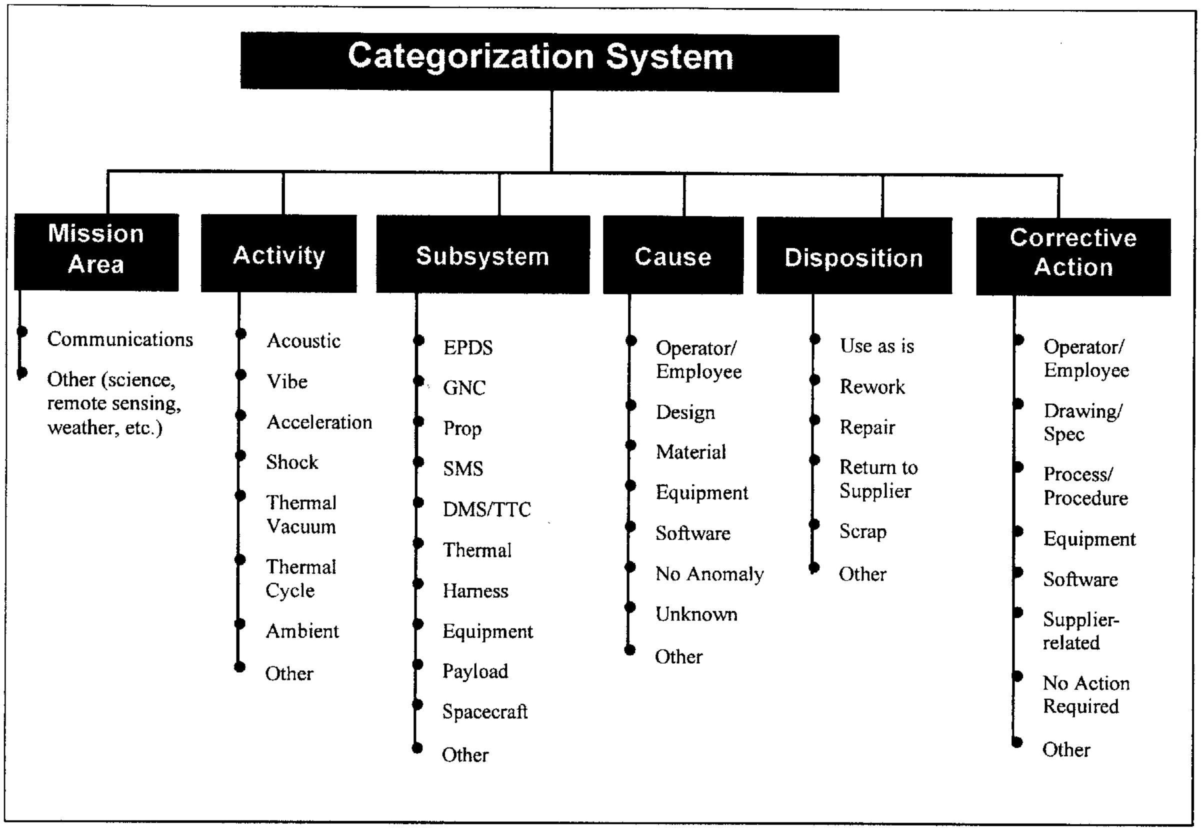

**Figure 2.1: Graphical representation of categorization system of test discrepancy data**

### 2.4.1. Mission Area Categories

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

- **Communications (Comm)** – 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.

### 2.4.2. Activity or Test Categories

These categories describe the spacecraft system I&T activity that was happening at the time the discrepancy occurred.

- **Acoustic Test (Acoustic)** – includes setup and post environment activities, as well as the acoustic test itself and immediate post-environment functional tests.
- **Vibration Test (Vibe)**– includes setup and post environment activities, as well as the vibration test itself and immediate post-environment functional tests.

- **Acceleration Test (Acc)** – includes setup and post environment activities, as well as the acceleration test itself and immediate post-environment functional tests.
- **Shock Test (Shock)** – includes setup and post environment activities, as well as the shock test itself and immediate post-environment functional tests.
- **Thermal Vacuum Test (TV)** – includes setup and post environment activities, as well as the thermal vacuum test itself and immediate post-environment functional tests.
- **Thermal Cycling Test (TC)** – includes setup and post environment activities, as well as the thermal cycling test itself and immediate post-environment functional tests.
- **Ambient Integration and Test Activities (Ambient)** – 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.

### 2.4.3. Subsystem Categories

These categories describe the subsystem or part of the spacecraft that the discrepancy was written against.

- **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. [4]
- **Guidance, Navigation and Control (GNC)** – The GN&C'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). [5]
- **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. [6]
- **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). [7]

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[4] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

[5] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

[6] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

- **Structures and Mechanisms Subsystem (SMS)** – The SMS's primary function provides support structure, booster adaptation, and moving parts. Other names: Structural, Structures and Mechanisms. [8]
- **Combined Data Management Subsystem and Telemetry, Tracking and Command (DMS/TTC)** – The DMS's primary function distributes commands and accumulates, stores, and formats data from the spacecraft and payload. Other names for the DMS: Command and Data Handling (C&DH), Spacecraft Computer System, Spacecraft Processor. [9] 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. [10] [These subsystems were 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). [11]
- **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 fall into this category.

### 2.4.4. Cause Categories

These categories describe the root cause of 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.

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[7] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

[8] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

[9] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

[10] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

[11] Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

- **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.

### 2.4.5. Disposition Categories

These categories describe the disposition of the discrepancy, that is, the immediate action that is required to make the current discrepant spacecraft functional again. Note how this differs from corrective action below.

- **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.

### 2.4.6. Corrective Action Categories

These categories describe the corrective action prescribed. A corrective action is a long-term action that will prevent the discrepancy from occurring again on future spacecraft. Note how this differs from disposition above.

- **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.

## 2.5. Potential Sources of Error

Research is always confounded with potential sources of error. By understanding these potentialities, the research results in the following chapters can be viewed in the proper context.

The discrepancy data used in this research is obtained from vendor-maintained records of discrepancies. These records are accurate to the best of the vendor's knowledge, and were assumed to be accurate. However, the initial discrepancy reports upon which the records are based were created by people, and are thus subject to some inaccuracies and mistakes that are just a fact of life in a fast-paced environment. The data were reviewed for such mistakes, and inaccurate data were discarded before analysis. As an example, several discrepancies were listed as having report close dates happening chronologically before report open dates. Obviously, this is a mistake. For these discrepancies, the open and close date, as well as the open duration, were treated as missing data for the purpose of the analysis.

Another potential source of error arises in mapping the vendor-specific codes to the characterization system described above. This was done with the aid of experts at the vendor who were familiar with the vendor's coding system. Working with the above definition of the characterization system, they mapped their own codes into the characterization system. The mapping was reviewed to minimize interpretation problems and reduce this as a source of error.

## 2.6. Barriers Encountered

Proprietary concerns, lack of standardization, and incomplete data were the chief barriers encountered in this research.

Proprietary concerns by vendors will always be a challenge for researchers. These proprietary concerns are valid ones, and can be addressed by using pseudonyms, normalizing results, and having vendors periodically review the research to identify potential downstream proprietary issues. Though the research may accept a somewhat lower level of fidelity as a result, this is necessary to accomplish any research involving real-world data. An example of this arose in collecting mission area information for spacecraft used in this research. It was originally requested that vendors indicate that the spacecraft fell into one of six mission categories: communications, early warning, navigation, space science, remote sensing, and weather. However vendors felt that this data, combined with an indication of the time period the spacecraft was being produced, would lead to a link between a specific vendor and specific data in the research results. This would compromise the research participant's anonymity and proprietary requirement. A compromise was formulated that broke down mission area into only two categories: communications and other. While this protected the proprietary and anonymity concerns, the coarser categorization prohibited investigating correlation based upon the six original mission area categories desired.

A lack of standardization across vendor discrepancy reporting systems dictated that time needed to be spent learning about and understanding each one. In addition, terminology associated with discrepancy reporting systems is not standardized, resulting in the need to create a "Rosetta Stone" of sorts for discrepancy reporting terminology. This manifested itself in the characterization system described previously.

Finally, incomplete discrepancy records provided a challenge in assembling a comprehensive, cross-vendor set of discrepancy information. For many reasons, ranging from the records no longer existed, to a person forgot to enter certain information, to a vendor was changing over its discrepancy reporting system, incomplete data was provided. This is another reality of real-world data, and was dealt with by not including missing data points in the analysis. For a further discussion of this, see Chapter 1.

## 2.7. Enabling Future Research

Research into characterizing the distribution and patterns of discrepancies can be greatly enabled by the use of a common discrepancy reporting framework and terminology. While many vendors have internal reporting systems that are common throughout their company, these are not common across vendors. A cross-vendor discrepancy analysis is extremely time-consuming without some level of standardization across the industry.

# Chapter 3.

# I&T Discrepancy Characterization: Statistical Analysis

## 3.1. Chapter Introduction

This chapter will discuss the central tendency, correlation, and statistical normality of the data gathered on spacecraft system-level integration and test discrepancies. Understanding these measures of a population helps in making predictions about their future behavior, and is thus a necessary part of the research.

The mean or average usually represents the central tendency of a population. The correlation, or degree of association of two variables, tells how independent the behavior is of two variables. The degree of normality of the population prescribes whether or not the population can be considered normally distributed.

If the data collected fit a specific distribution, then they can be analyzed with tests designed specifically for a certain distribution type. The Normal distribution is the most widely used, and for which many statistical analysis treatments have been developed. Thus, the normality of the data collected is an important attribute to investigate. If certain data follow a statistically normal distribution, then those data can be used in many other analysis activities designed specifically to take advantage of the special characteristics of normal distributions. If the data do not follow a normal distribution, future follow-on work might include testing the data to see if they fit other specific distributions, such as exponential, log linear, or Weibull distributions.

## 3.2. Data Profile and Validity

Over 23,000 discrepancies from over 200 spacecraft representing at least 20 commercial or government programs/product lines were analyzed in this research. The data included a mix of different vendors, and a mix of different mission types as well. The mission type breakdown and the government/commercial program breakdown are shown below in Figure 3.1. The data is ¾ commercial communications missions, and ¼ other type of government missions. Start dates of system integration and test for the data ranged from 1970-1999. A distribution of start dates is shown in Figure 3.2 below. As seen in the figure, the bulk of the data are from 1990-1999.

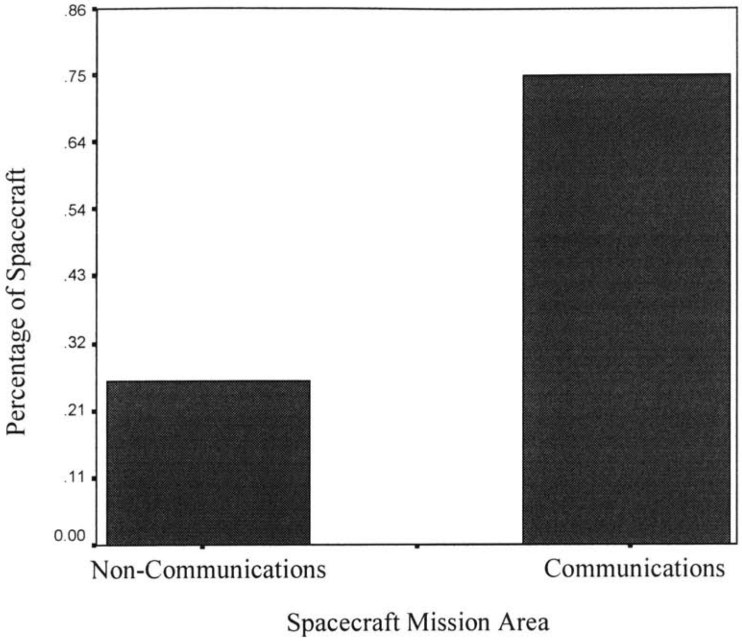


**Figure 3.1: Distribution of spacecraft by mission area**

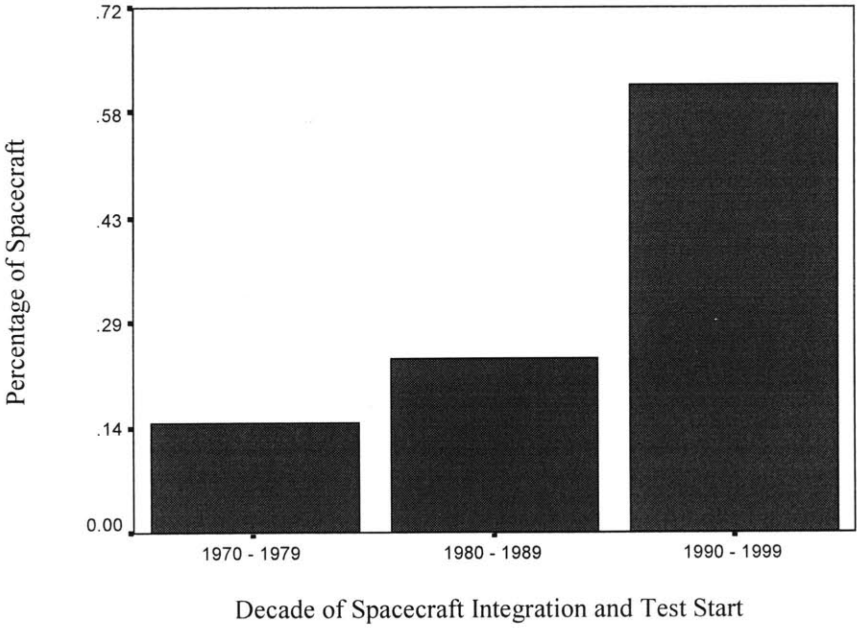


**Figure 3.2: Distribution of spacecraft by decade of integration and test start date**

As discussed in Chapter 1, the following information was sought on each discrepancy that occurred at the system level of integration and test for each spacecraft:

- Spacecraft pseudonym
- Spacecraft order in production
- Spacecraft mission area
- Discrepancy report open date (year only) and open duration
- Subsystem, or part of the spacecraft testing setup, the discrepancy was written against
- I&T activity taking place at time of discrepancy occurrence
- Description of the discrepant behavior observed
- Root cause of the discrepancy
- Immediate fix action needed to make the current spacecraft functional again (also called disposition)
- Long-term corrective action that was prescribed to prevent the problem from happening again on future spacecraft

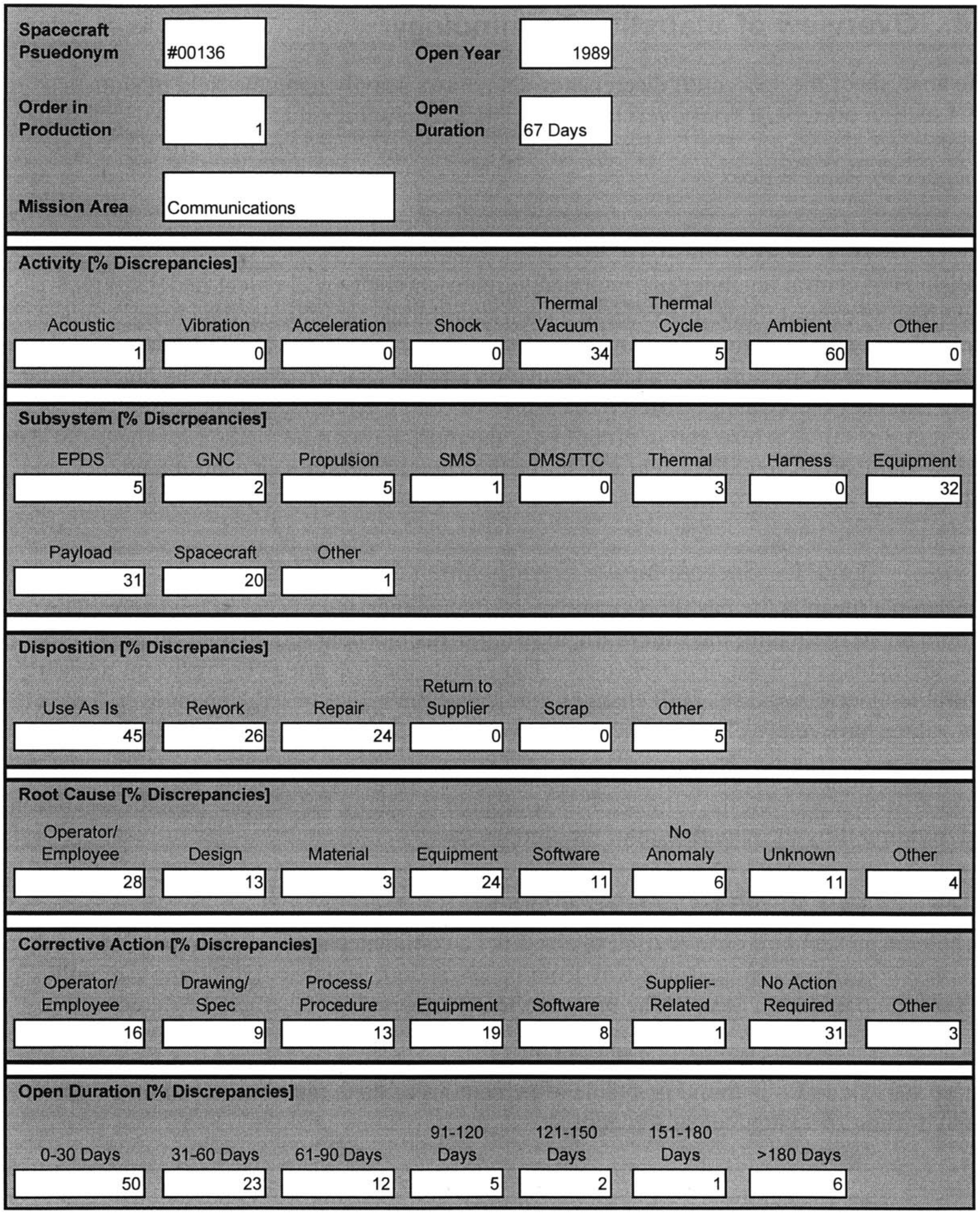
However, the data obtained for some spacecraft was incomplete from the perspective of containing all the above information that was sought. For example, some discrepancies reported did not contain information about the close date, and thus duration information on that discrepancy was unavailable. If a certain category of information (such as duration) was unavailable for more than 50% of the discrepancies reported on a given spacecraft, that category was treated as missing data and not included in the analysis. Each area of analysis will specify the number of spacecraft with valid data for the analysis being conducted. This is referred to as the number of cases in the analysis, and is denoted by N.

In addition, if a vendor provided data for a spacecraft that they speculated was incomplete from the point of view of containing all the discrepancies that were reported during system-level I&T, these spacecraft were not used in the analysis. Several vendors did report that, for instance, they were migrating to a new automated reporting system at particular points in history, and believed that certain spacecraft undergoing system-level I&T around that timeframe were not accurately or completely contained within the records that were provided for this research. Hence, they were not used in the final analysis.

## 3.3. Unit of Analysis

The unit of analysis used in this research is the spacecraft. All data are presented for each subcategory as a percentage of the total discrepancies that occurred in that subcategory on a given spacecraft in a given category. Thus, the numbers are normalized, which protects proprietary concerns. It also effectively evenly weights all spacecraft regardless of the total number of discrepancies reported. This is important, because the reasons behind different numbers of total discrepancies per spacecraft can be considered an artifact of organization and corporate culture. It is important to eliminate this bias from the analysis presented here.

To get a more intuitive idea of using the spacecraft as the unit of analysis, examine Figure 3.3. Figure 3.3 shows a data sheet for a sample spacecraft. The spacecraft pseudonym, order in production, mission area, and discrepancy report dates and duration are listed at the top. Beneath that, the categories of Activity, Subsystem, Disposition (immediate fix action), Root cause, Long-term corrective action, and Open duration are listed. Each of the categories contains a list of the subcategories they contain. Underneath the subcategory name is an entry containing the percentage of discrepancies in the category that occurred in that subcategory. Using percentages in this way, the data is normalized to protect proprietary concerns.



| | | | |
|---|---|---|---|
| **Spacecraft Psuedonym** | #00136 | **Open Year** | 1989 |
| **Order in Production** | 1 | **Open Duration** | 67 Days |
| **Mission Area** | Communications | | |

**Activity [% Discrepancies]**

| Acoustic | Vibration | Acceleration | Shock | Thermal Vacuum | Thermal Cycle | Ambient | Other |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 34 | 5 | 60 | 0 |

**Subsystem [% Discrpeancies]**

| EPDS | GNC | Propulsion | SMS | DMS/TTC | Thermal | Harness | Equipment |
|---|---|---|---|---|---|---|---|
| 5 | 2 | 5 | 1 | 0 | 3 | 0 | 32 |

| Payload | Spacecraft | Other |
|---|---|---|
| 31 | 20 | 1 |

**Disposition [% Discrepancies]**

| Use As Is | Rework | Repair | Return to Supplier | Scrap | Other |
|---|---|---|---|---|---|
| 45 | 26 | 24 | 0 | 0 | 5 |

**Root Cause [% Discrepancies]**

| Operator/ Employee | Design | Material | Equipment | Software | No Anomaly | Unknown | Other |
|---|---|---|---|---|---|---|---|
| 28 | 13 | 3 | 24 | 11 | 6 | 11 | 4 |

**Corrective Action [% Discrepancies]**

| Operator/ Employee | Drawing/ Spec | Process/ Procedure | Equipment | Software | Supplier-Related | No Action Required | Other |
|---|---|---|---|---|---|---|---|
| 16 | 9 | 13 | 19 | 8 | 1 | 31 | 3 |

**Open Duration [% Discrepancies]**

| 0-30 Days | 31-60 Days | 61-90 Days | 91-120 Days | 121-150 Days | 151-180 Days | >180 Days |
|---|---|---|---|---|---|---|
| 50 | 23 | 12 | 5 | 2 | 1 | 6 |

**Figure 3.3: Example data sheet for a notional spacecraft**

Future analyses could certainly be performed focusing on the discrepancy as the unit of analysis. This would of course provide different insights, and could be performed to compare the insights gained using the discrepancy vice the spacecraft as the unit of analysis.

## 3.4. Overview of Statistics Terminology

The analysis of the spacecraft discrepancy data draws heavily upon the field of statistics. This section presents a brief overview of statistics terminology that will be used in this chapter and elsewhere. For further information on statistics, see *Statistics for the Social Sciences* by Rand Wilcox.

### 3.4.1. Measures of Central Tendency

Measures of central tendency are intended to represent the typical object under study. Specifically, central tendency refers to a central or middle point in the data being studied. Choosing an appropriate measure of central tendency is a complex issue, and depends on the characteristics of the data set under examination and the characteristics of the object under study, among others. Thus, different measures of central tendency will be applied to different parts of this research in order to use the most appropriate method for the set of data being examined. The entries below describe the various measures of central tendency that will be used.

### *3.4.1.1. Sample Mean, Sample Mean Standard Error*

The sample mean is the best-known and most-studied measure of central tendency. The sample mean is equal to the sum of the measurements in a data set, divided by the number of measurements contained in that data set. The sample mean is not a very resistant measure of central tendency, because small changes in many of the values or large changes in only a few values have relatively big effects on its value.[12]

The sample mean standard error is used to assess the precision with which the population mean is estimated from the sample. It is computed by taking the sample standard deviation and dividing it by the square root of the sample size.[13]

### *3.4.1.2. 95% Confidence Interval*

Sample mean standard error is used to construct a confidence interval such that 95% of the intervals constructed in the same way from many random samples of the same size will include the population mean. The 95% confidence interval is constructed by computing

$$\text{Mean} \pm t_{0.975}(df) \times \text{Standard Error}$$

where the value of $t$ is found in a table of percentiles of the $t$ distribution, and the table is entered using $(n-1)$ degrees of freedom.[14]

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[12] Entire paragraph drawn from Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 15.

[13] *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 24.

[14] *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 28.

#### 3.4.1.3. Sample Median

The sample median is the middle number when all of the data in a set are put in order and the number of data is odd. The sample median is the average of the two middle numbers when all of the data in a set are put in order and the number of data is even. The sample median is a very resistant measure of central tendency, meaning that small changes in many of the data or large changes in only a few data have a relatively small effect on its value. It is often applied as a measure of central tendency when the data set has a large number of outlier, or extreme, values that would significantly influence the sample mean. [15]

#### 3.4.1.4. 5% Trimmed Mean

The 5% trimmed mean represents a compromise between the two extremes of sample mean and sample median. It is computed by ordering the values within a data set from smallest to largest, trimming 5% of the values from the top and 5% of the values from the bottom of the data set, and then computing the usual sample mean as described above for the data that remain. This prevents unusual outlier and extreme values in the tails of the distribution from affecting the size of the sample mean, and makes the trimmed mean measurement more resistant than the sample mean measurement. While it still is not as resistant as the sample median measurement, the benefit of the trimmed mean measurement is that it is based on more values than the sample median measurement while effectively dealing with outliers and extreme values. [16]

### 3.4.2. Measures of Dispersion

Measures of dispersion are numerical quantities intended to indicate how spread out the values in a data set happen to be.[17] There are many measures of dispersion, and like the measures of central tendency, some are very resistant to changes in the data set while others are less resistant. Those used in this research are described in the following subsections, preceded by a discussion of the normal distribution.

#### 3.4.2.1. Normal Distribution

The normal distribution is the most widely used probability density function in statistics. All normal distributions are unimodal, symmetric and continuous probability density functions that have the distinctive bell shape. The mean and standard deviation of a normal distribution are such that:

- Approximately 68% of the area under the normal curve falls between +/- 1 standard deviation from the mean

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[15] Entire paragraph drawn from Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 14-15.

[16] Entire paragraph drawn from Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 15-16.

[17] Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 17.

- Approximately 95% of the area under the normal curve falls between +/- 2 standard deviations from the mean
- Approximately 100% of the probability under the normal curve falls between +/- 3 standard deviations from the mean[18]

#### 3.4.2.2. Maximum, Minimum and Range

The maximum value is the largest value in the data set, and the minimum value is the smallest value in the data set. The range is the difference between the smallest and largest values in a data set. The range is not a very resistant measure of dispersion, and while the measure of range is useful, its utility is limited.[19]

#### 3.4.2.3. Sample Variance

The sample variance is intended to measures the "typical" distance of the values in a data set from the sample mean. The sample variance is equal to the sum of the squared distances of the data set values ($X_i$) from the sample mean ($\overline{X}$) divided by $(n-1)$. The sample variance, $s^2$, is shown in equation form as

$$s^2 = \frac{\sum (X_i - \overline{X})^2}{n-1}$$

The sample variance is not a resistant measure, yet is plays an important role in applied statistical analysis. [20]

#### 3.4.2.4. Sample Standard Deviation

The sample standard deviation is the positive square root of $s^2$, the sample variance. Like the sample variance, it is not a resistant measure, yet it plays an important role in analyzing data.[21]

#### 3.4.2.5. Percentiles

Percentiles are values above and below which a specified percentage of data points fall. As an example, the 25th percentile is the value below which 25% of the data points fall and above which 75% of the data points fall.[22]

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[18] Section 3.4.2.1. drawn from Becker, William E. and Donald L. Harnett. *Business and Economic Statistics.* Massachusetts: Addison-Wesley Publishing, 1987. p. 235.

[19] Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 17.

[20] Section 3.4.2.3. drawn from Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 18.

[21] Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 18.

[22] *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 24.

#### 3.4.2.6. Skewness, Skewness Standard Error

Skewness measures the symmetry of a given distribution. A large positive value for skewness indicates a long right tail on the distribution as compared to the normal distribution, while a large negative number indicates a long left tail. The value for skewness divided by the standard error for skewness yields a measurement for a test of normality for a given data set. If the ratio of these two numbers is less than –2 or greater than +2, then normality can be rejected. [23]

#### 3.4.2.7. Kurtosis, Kurtosis Standard Error

Kurtosis is defined as the sharpness of a peak on a curve[24]. A large positive value for kurtosis indicates that the tails of the given distribution are longer than the tails of a normal distribution, while a large negative value for kurtosis indicates that the tails are shorter and becoming more like those of a box-shaped uniform distribution.[25] The value for kurtosis divided by the standard error for kurtosis yields a measurement of normality for a given data set. If the ratio of these two numbers is less than –2 or greater than +2, then normality can be rejected.[26]

#### 3.4.2.8. Box plot

The box plot display is useful for graphically examining the dispersion of the data set. It was designed by John Tukey, and is a graphical display that indicates range, quartiles, interquartile range, median and outliers of a data set. An annotated sketch of a box plot is shown in Figure 3.4. The bold horizontal line in the middle of the box indicates the sample median. The edges of each box, called hinges, mark the 25th and 75th percentiles, so that the central 50% of the data values fall within the range of the box. The length of the box is called the hspread and corresponds to the interquartile range. The whiskers, or the vertical lines extending up and down from each box, show the range of values that fall within 1.5 hspreads of the hinges. Data points that have values between 1.5 and 3 hspreads outside the hinges are marked by an open circle and are called outliers. Data points more than 3 hspreads below the lower hinge or above the upper hinge are marked by an asterisk and are called extreme values. [27]

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[23] Entire paragraph drawn from *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 27-28.

[24] Porkess, Roger. *The HarperCollins Dictionary of Statistics.* New York: HarperPerennial, 1991. p.121.

[25] *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 28.

[26] *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 28.

[27] Entire paragraph drawn from *SPSS Base 10.0 Applications Guide.* Chicago: SPSS Inc, 1999. p. 40-41.

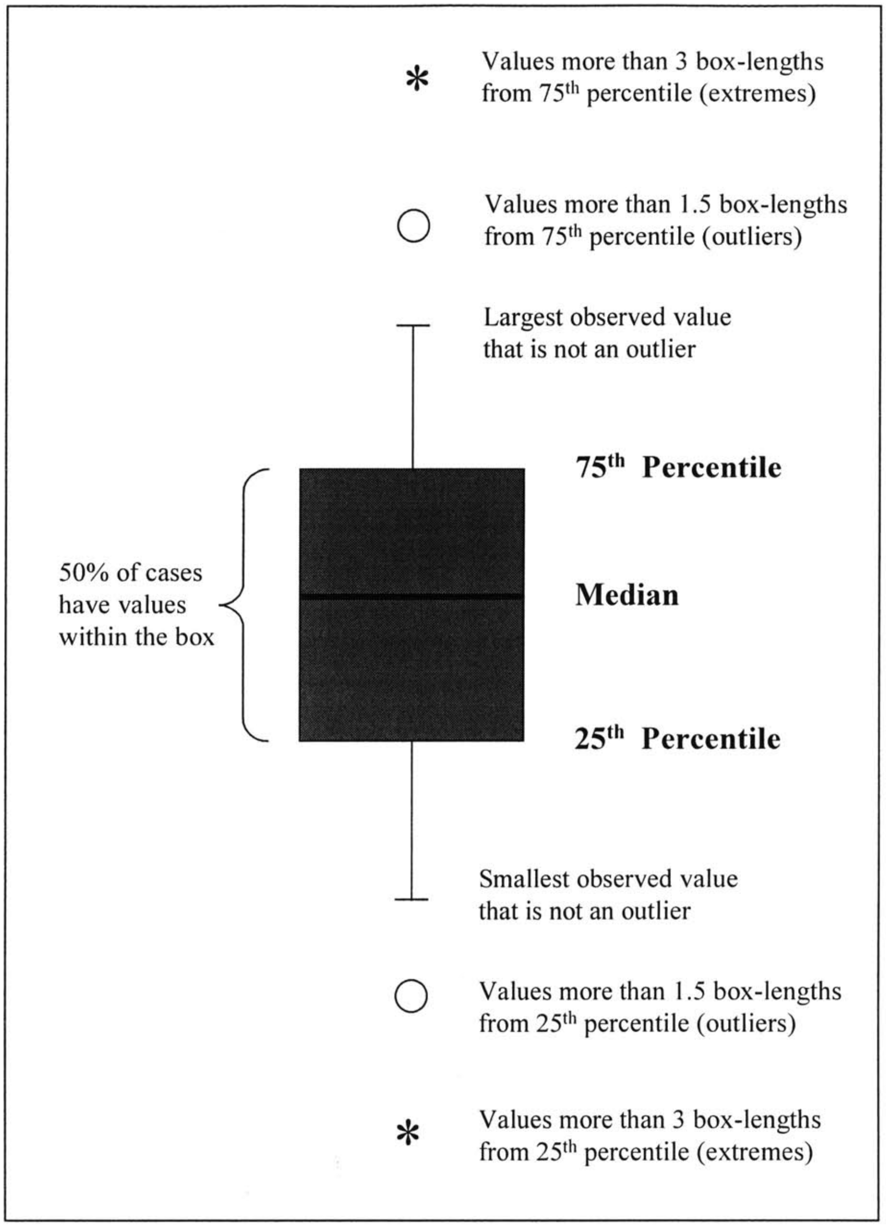

**Figure 3.4: Annotated sketch of a box plot**

### 3.4.3. Measures of Correlation

Correlation is defined as the degree of relative correspondence between two sets of data. The correlation between variables X and Y, for example, can be interpreted as the ability to predict or explain the behavior of variable X based upon variable Y's behavior. Correlation indicates a relationship between variables, but does not indicate a direction of causality of that relationship.

#### 3.4.3.1. Spearman's Rho

Spearman's Rho is one measure of association based on ranks, useful for examining correlation between variables that do not follow a normal distribution. Since the data gathered on spacecraft discrepancies do not follow a normal distribution, Spearman's Rho will be used as the measure of correlation. Other measures of association commonly used are Kendall's Tau-B and Pearson's Gamma. These are more commonly applied to variables that are normally distributed, and hence will not be used in this analysis.

Spearman's Rho measures the extent to which two variables have a monotonic relationship. Two random variables, X and Y, are said to have a monotonic relationship if Y has a strictly increasing or strictly decreasing relationship with X.[28]

Associated with the Spearman's Rho statistical test are two important measures of correlation. One is the correlation coefficient, and the other is the two-tailed significance of that coefficient.

#### 3.4.3.2. Correlation Coefficient

A correlation coefficient is defined as a measure of concomitant variation in two variables.[29] The correlation coefficient ranges from zero to one. A higher correlation coefficient indicates a greater strength of relationship between the two variables.

#### 3.4.3.3. Two-tailed Significance

The smaller the two-tailed significance, the less likely that the correlation would have happened by chance. For large data sets, such as the one used in this analysis of spacecraft discrepancies, two-tailed significance of less than 0.01 is the preferred level of significance.

For this research, a two-tailed significance less than 0.01 was used. All correlation indicated in these analyses will have a significance less than 0.01 unless otherwise noted.

## 3.5. Activity Statistical Analysis

This section analyzes the Activity data for spacecraft discrepancies. These data describe the activity or test that was taking place when the discrepancy was discovered, and are categorized into seven bins. For a detailed description of each of these bins, please see Chapter 1. The seven bins, or subcategories, with their short names in parentheses, are:

- Acoustic Test (Acoustic)
- Vibration Test (Vibe)
- Acceleration Test (Acc)

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[28] Wilcox, Rand R. *Statistics for the Social Sciences.* San Diego: Academic Press, 1996. p. 382.

[29] Morris, William (Ed.) The American Heritage Dictionary of the English :Language. Boston: Houghton-Mifflin, 1969. p. 295.

- Shock Test (Shock)
- Thermal Cycling Test (TC)
- Thermal Vacuum Test (TV)
- Ambient Integration and Test Activities (Ambient)

A presentation of the subcategory percentile statistics first introduces the general nature of the distribution of the activity data. Box plots and a summary of means follows. Finally, descriptive statistics and correlation for each subcategory are explored. The total number of spacecraft used in the activity analysis is 130.

### 3.5.1. Activity Category Percentiles

All data in the seven subcategories of activity do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics to better visualize how the data are distributed. These are shown in Table 3.1.

Acceleration and shock have all their non-zero values above the 90th percentile. Acoustic has its non-zero values above the 75th percentile. Vibration and thermal cycling have all their non-zero values above the 25th percentile. Finally, thermal vacuum and ambient follow a relatively more normal distribution by comparison, but as shown in following sections, do not pass accepted tests of normality.

**Table 3.1: Activity category percentile statistics**

| *Activity Subcategory* | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| **Acceleration** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Shock** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| **Acoustic** | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 2.90 | 4.00 |
| **Vibe** | 0.00 | 0.00 | 0.00 | 1.00 | 2.00 | 4.00 | 8.00 |
| **Thermal Cycling** | 0.00 | 0.00 | 0.00 | 1.00 | 4.00 | 11.00 | 15.00 |
| **Thermal Vacuum** | 0.00 | 6.20 | 16.00 | 24.00 | 43.00 | 62.90 | 70.00 |
| **Ambient** | 25.55 | 29.20 | 53.75 | 65.50 | 77.00 | 87.00 | 94.00 |

### 3.5.2. Activity Category Box Plots

The box plots below in Figure 3.5 show another portrayal of the dispersion of the activity data. This graphically displays that the medians and spreads of the seven subcategories tend to appear in two general shapes. The first and third box plots on the right show somewhat normal distributions, while the remaining five show highly non-normal distributions, evidenced by the large number of outliers and extreme values.

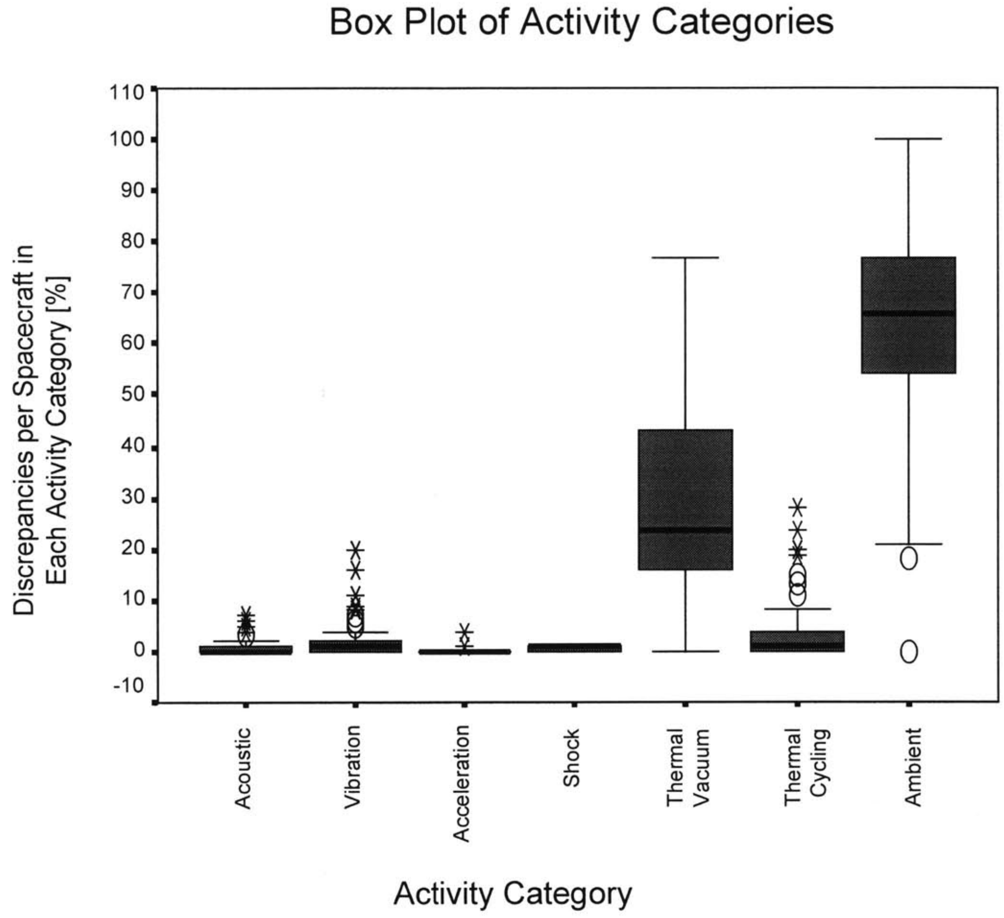


**Figure 3.5: Box plot of activity categories**

### 3.5.3. Overview of Activity Means and Confidence Intervals

Figure 3.6 shows a summary of the means of the seven activity subcategories, along with the 95% confidence interval upper and lower bounds on those means, and the medians. The vast majority of discrepancies found in environment exposures are occurring during the thermal vacuum activity. The ambient activity category accounts for nearly 2/3 of all discrepancies reported at the system level of integration and test. Proportionally, ambient activities account for more time than environment activities during system-level I&T, which may help to explain the preponderance of discrepancies discovered during ambient activities.

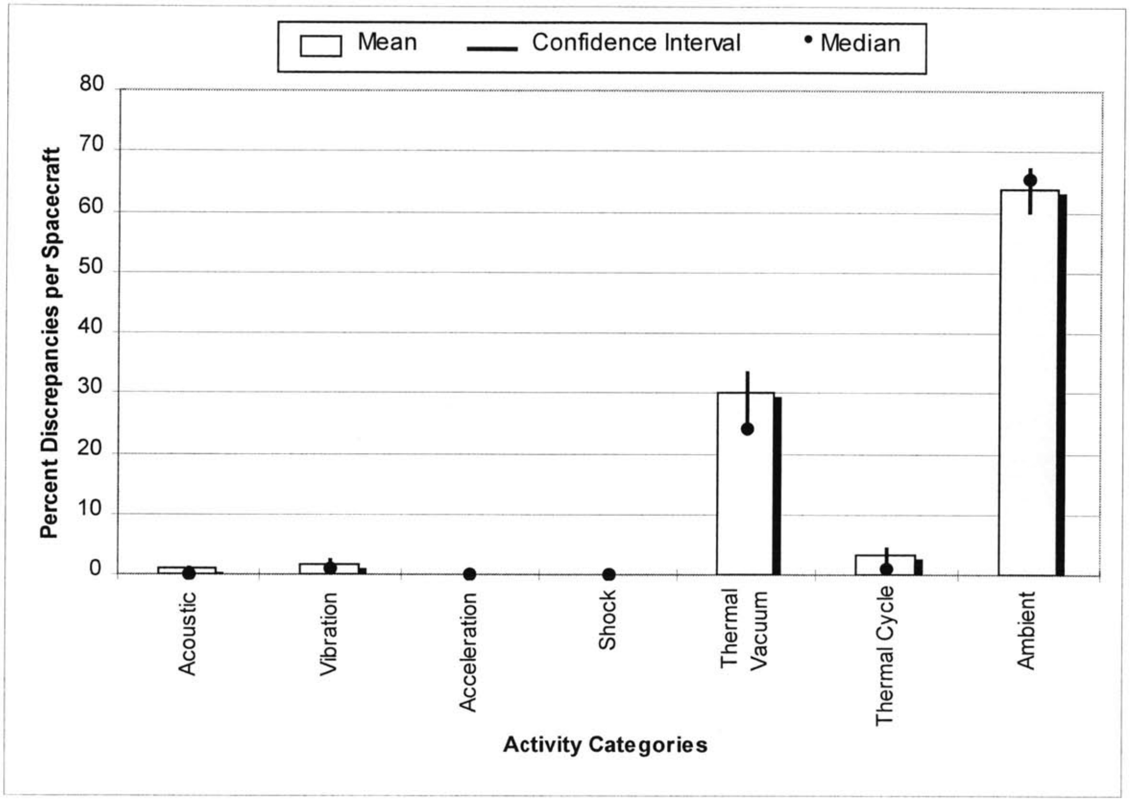


**Figure 3.6: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each activity category.**

### 3.5.4. Acoustic Activity

Descriptive statistics for the acoustics subcategory are shown in Table 3.2. The mean, 5% trimmed mean, and median for the acoustic subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 11.63, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 14.81, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the acoustic data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the acoustics subcategory in Figure 3.7.

**Table 3.2: Acoustic subcategory descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 0.85 | 0.13 |
| **95% Confidence Interval for Mean: Lower Bound** | 0.58 | |
| **95% Confidence Interval for Mean: Upper Bound** | 1.11 | |
| **5% Trimmed Mean** | 0.62 | |
| **Median** | 0.00 | |
| **Variance** | 2.286 | |
| **Standard Deviation** | 1.51 | |
| **Minimum** | 0 | |
| **Maximum** | 7 | |
| **Skewness** | 2.466 | 0.212 |
| **Kurtosis** | 6.249 | 0.422 |

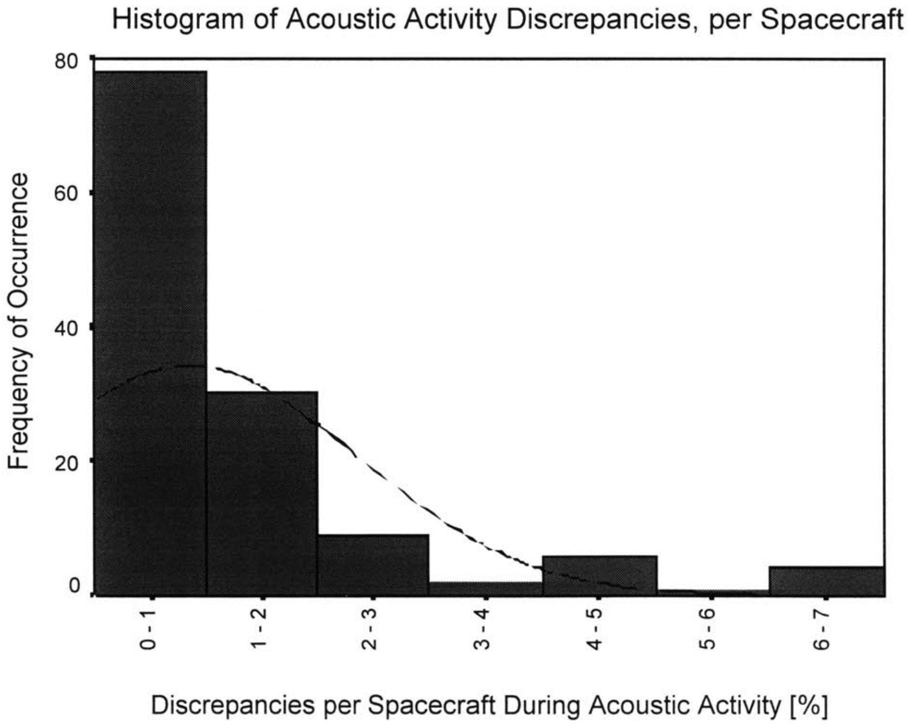


**Figure 3.7: Histogram for acoustic subcategory**

### 3.5.5. Vibration Activity

Descriptive statistics for the vibration subcategory are shown in Table 3.3. The mean, 5% trimmed mean, and median for the vibration subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 16.01, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 35.88, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the vibration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the vibration subcategory in Figure 3.8.

**Table 3.3: Vibration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 1.78 | 0.26 |
| **95% Confidence Interval for Mean: Lower Bound** | 1.27 | |
| **95% Confidence Interval for Mean: Upper Bound** | 2.29 | |
| **5% Trimmed Mean** | 1.32 | |
| **Median** | 1.00 | |
| **Variance** | 8.671 | |
| **Standard Deviation** | 2.94 | |
| **Minimum** | 0 | |
| **Maximum** | 20 | |
| **Skewness** | 3.395 | 0.212 |
| **Kurtosis** | 15.140 | 0.422 |

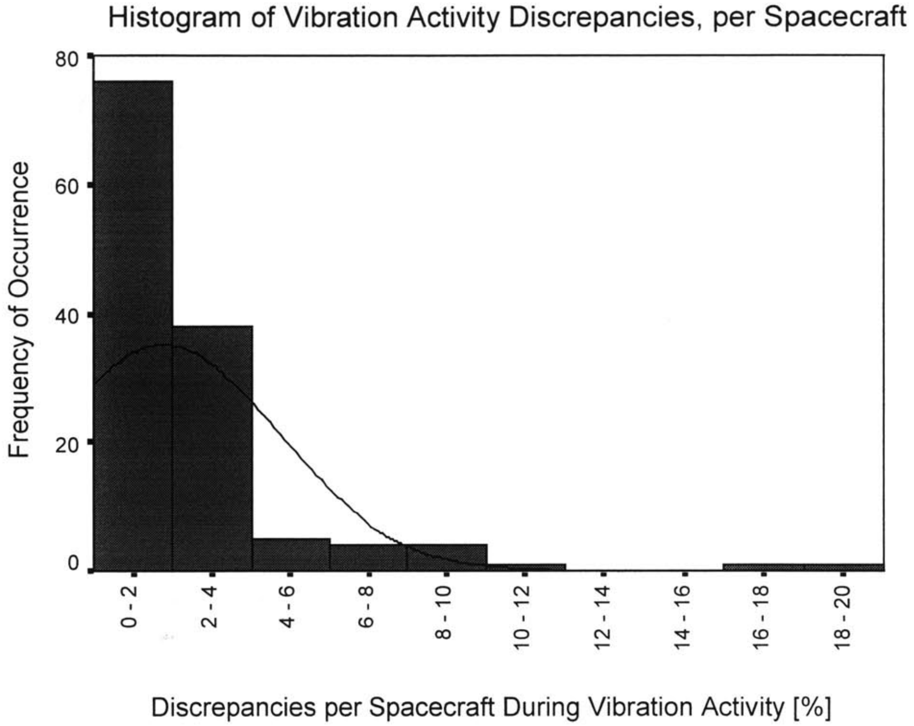


**Figure 3.8: Histogram for vibration subcategory**

### 3.5.6. Acceleration Activity

Descriptive statistics for the acceleration subcategory are shown in Table 3.4. The mean, 5% trimmed mean, and median for the acceleration subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 46.33, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 243.57, indicates that the distribution has much longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the vibration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the vibration subcategory in Figure 3.9.

**Table 3.4: Acceleration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 0.0462 | 0.0325 |
| **95% Confidence Interval for Mean: Lower Bound** | -0.0182 | |
| **95% Confidence Interval for Mean: Upper Bound** | 0.11 | |
| **5% Trimmed Mean** | 0.00 | |
| **Median** | 0.00 | |
| **Variance** | 0.1371 | |
| **Standard Deviation** | 0.37 | |
| **Minimum** | 0 | |
| **Maximum** | 4 | |
| **Skewness** | 9.822 | 0.212 |
| **Kurtosis** | 102.787 | 0.422 |

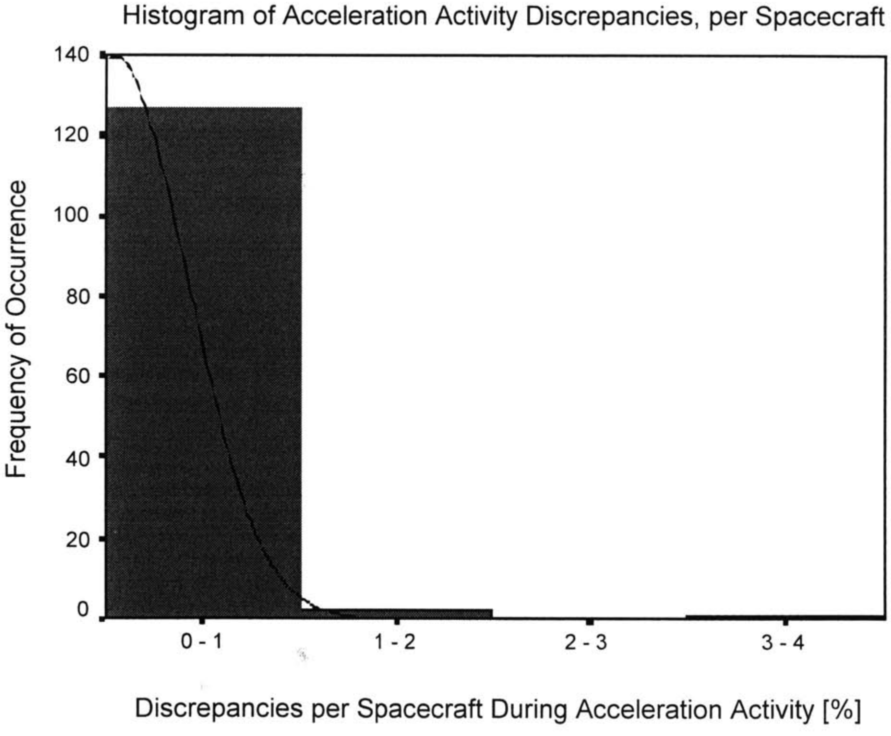


**Figure 3.9: Histogram for acceleration subcategory**

### 3.5.7. Shock Activity

Descriptive statistics for the shock subcategory are shown in Table 3.5. The mean, 5% trimmed mean, and median for the shock subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 47.07, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 252.97, indicates that the distribution has much longer tails than a normal distribution. The skewness and kurtosis for the thermal cycling data are very similar to those for the shock data. Because the absolute value of at least one of the ratios is greater than 2, normality for the shock data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the shock subcategory in Figure 3.10.

**Table 3.5: Shock subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 0.16 | 0.0963 |
| **95% Confidence Interval for Mean: Lower Bound** | -0.029 | |
| **95% Confidence Interval for Mean: Upper Bound** | 0.35 | |
| **5% Trimmed Mean** | 0.00427 | |
| **Median** | 0.00 | |
| **Variance** | 1.206 | |
| **Standard Deviation** | 1.10 | |
| **Minimum** | 0 | |
| **Maximum** | 12 | |
| **Skewness** | 9.978 | 0.212 |
| **Kurtosis** | 106.754 | 0.422 |

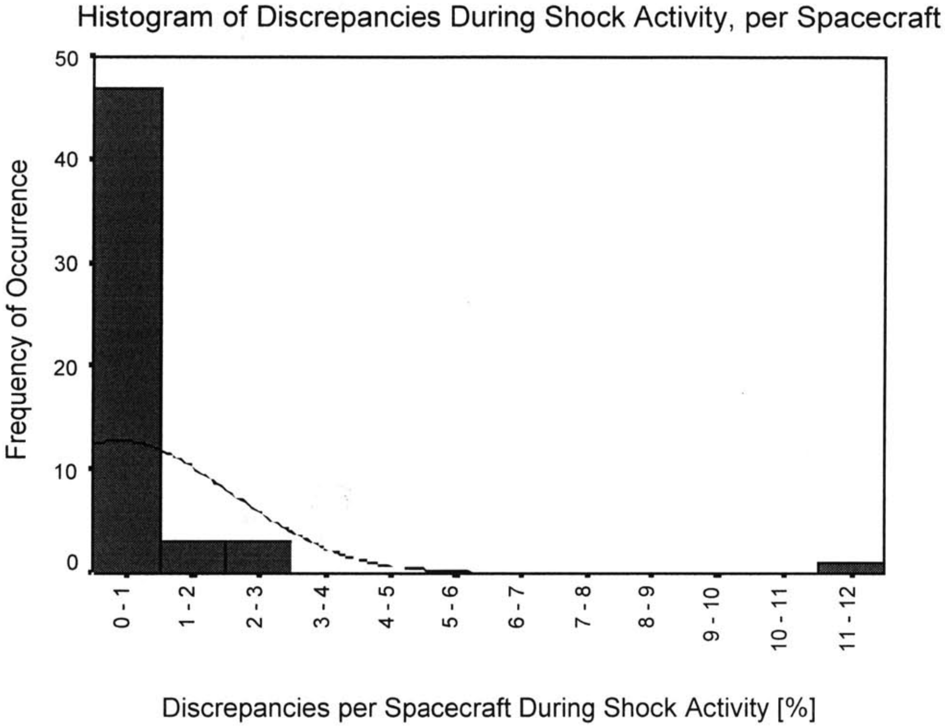


**Figure 3.10: Histogram for shock subcategory**

### 3.5.8. Thermal Cycling Activity

Descriptive statistics for the thermal cycling subcategory are shown in Table 3.6. The mean, 5% trimmed mean, and median for the thermal cycling subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 46.33, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 243.57, indicates that the distribution has much longer tails than a normal distribution. The skewness and kurtosis for the thermal cycling data are very similar to those for the shock data. Because the absolute value of at least one of the ratios is greater than 2, normality for the vibration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the thermal cycling subcategory in Figure 3.11.

**Table 3.6: Thermal cycling subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 3.26 | 0.47 |
| **95% Confidence Interval for Mean: Lower Bound** | 2.32 | |
| **95% Confidence Interval for Mean: Upper Bound** | 4.20 | |
| **5% Trimmed Mean** | 2.48 | |
| **Median** | 1.00 | |
| **Variance** | 29.171 | |
| **Standard Deviation** | 5.40 | |
| **Minimum** | 0 | |
| **Maximum** | 28 | |
| **Skewness** | 2.258 | 0.212 |
| **Kurtosis** | 5.294 | 0.422 |

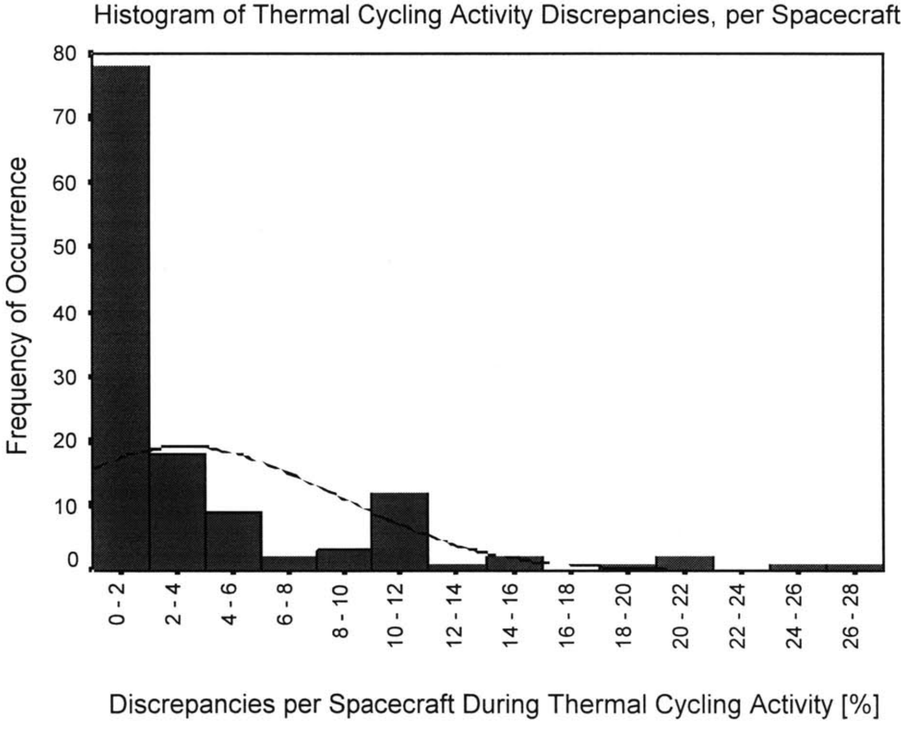


**Figure 3.11: Histogram for thermal cycling subcategory**

### 3.5.9. Thermal Vacuum Activity

Descriptive statistics for the thermal vacuum subcategory are shown in Table 3.7. The mean, 5% trimmed mean, and median for the thermal vacuum subcategory are somewhat different, indicating that the data might not be quite normally distributed. By examining the skewness and kurtosis, the degree of normality can be understood better.

The ratio of kurtosis to its standard error, -0.75, indicates that the distribution has a center peak and tails like a normal distribution. However, the ratio of skewness to its standard error, 3.11, indicates that the distribution is very slightly right-skewed compared to a normal distribution. Since the absolute value of the ratio is greater than 2, normality has to be rejected based upon the skewness measure. The skewness and kurtosis indications are confirmed by examining the histogram of the thermal vacuum subcategory in Figure 3.12.

**Table 3.7: Thermal vacuum subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 30.05 | 1.73 |
| **95% Confidence Interval for Mean: Lower Bound** | 26.64 | |
| **95% Confidence Interval for Mean: Upper Bound** | 33.47 | |
| **5% Trimmed Mean** | 29.32 | |
| **Median** | 24.00 | |
| **Variance** | 386.951 | |
| **Standard Deviation** | 19.67 | |
| **Minimum** | 0 | |
| **Maximum** | 77 | |
| **Skewness** | 0.660 | 0.212 |
| **Kurtosis** | -0.317 | 0.422 |

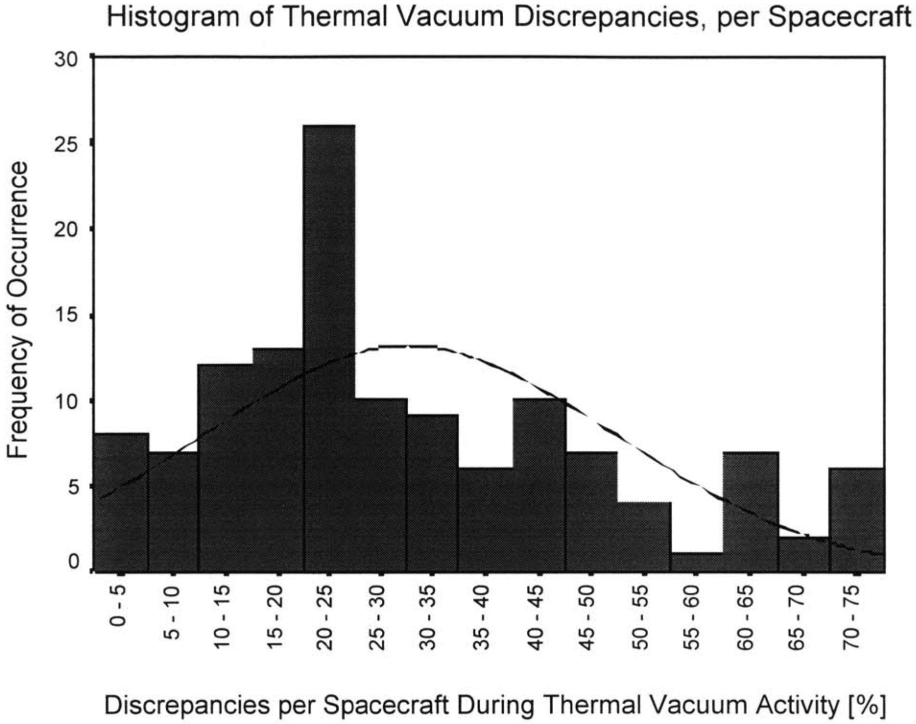


**Figure 3.12: Histogram for thermal vacuum subcategory**

### *3.5.9.1. Thermal Vacuum Activity Correlation*

Correlation appeared between the thermal vacuum activity and other parameters collected about spacecraft system-level I&T discrepancies.

- The thermal vacuum activity category and the DMS/TTC subsystem category have a negative correlation of 0.618 (N=122) at the 0.01 level of significance. This means that as the occurrences of thermal vacuum discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrences of DMS/TTC discrepancies.
- The thermal vacuum activity category and the Use as is disposition category have a positive correlation of 0.602 (N=49) at the 0.01 level of significance. This means that as the occurrences of thermal vacuum discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrences of Use as is dispositions.
- The thermal vacuum activity category and the ambient activity category have a negative correlation of 0.927 (N=130) at the 0.01 level of significance. This means that as the occurrences of thermal vacuum discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrences of ambient discrepancies.

### 3.5.10. Ambient I&T Activity

Descriptive statistics for the ambient subcategory are shown in Table 3.8. The mean, 5% trimmed mean, and median for the ambient subcategory are fairly similar, indicating that the data might be normally distributed. By examining the skewness and kurtosis, the degree of normality can be understood better.

The ratio of kurtosis to its standard error, 0.36, indicates that the distribution has a center peak and tails like a normal distribution. However, the ratio of skewness to its standard error, -2.84, indicates that the distribution is very slightly left-skewed compared to a normal distribution. Since this ratio is greater than |2|, normality has to be rejected based upon the skewness measure. The skewness and kurtosis indications are confirmed by examining the histogram of the ambient subcategory in Figure 3.13.

**Table 3.8: Ambient subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 63.78 | 1.76 |
| **95% Confidence Interval for Mean: Lower Bound** | 60.30 | |
| **95% Confidence Interval for Mean: Upper Bound** | 67.27 | |
| **5% Trimmed Mean** | 64.35 | |
| **Median** | 65.50 | |
| **Variance** | 402.294 | |
| **Standard Deviation** | 20.06 | |
| **Minimum** | 0 | |
| **Maximum** | 100 | |
| **Skewness** | -0.603 | 0.212 |
| **Kurtosis** | 0.152 | 0.422 |

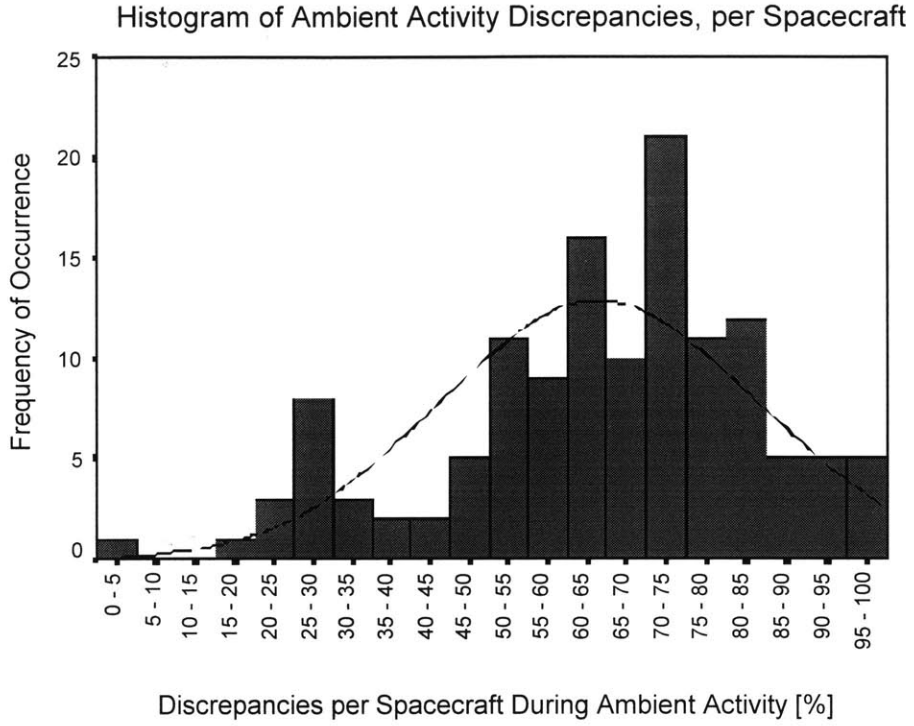


**Figure 3.13: Histogram for ambient subcategory**

#### 3.5.10.1. *Ambient Correlation*

Correlation appeared between the ambient activity and other parameters collected about spacecraft system-level I&T discrepancies.

- The ambient activity category and the DMS/TTC subsystem category have a positive correlation of 0.609 (N=122) at the 0.01 level of significance. This means that as the occurrences of ambient discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrences of DMS/TTC discrepancies.
- The ambient activity category and the Use as is disposition category have a negative correlation of 0.632 (N=49) at the 0.01 level of significance. This means that as the occurrences of ambient discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrences of Use as is dispositions.
- The ambient activity category and the thermal vacuum activity category have a negative correlation of 0.927 (N=130) at the 0.01 level of significance. This means that as the occurrences of ambient discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrences of thermal vacuum discrepancies.

## 3.6. Subsystem Statistical Analysis

This section analyzes the "Subsystem" data for spacecraft discrepancies. This data describes the subsystem or part of the spacecraft or related equipment that the discrepancy was written against. This data is categorized into eleven bins. For a detailed description of each of these bins, please see Chapter 1. The eleven bins, or subcategories, with their short names in parentheses, are:

- Electrical Power and Distribution Subsystem (EPDS)
- Guidance, Navigation and Control (GNC)
- Payload
- Propulsion (Prop)
- Structures and Mechanisms Subsystem (SMS)
- Telemetry, Tracking and Command (TTC) / Data Management Subsystem (DMS)
- Thermal
- Wiring and Cabling (Harness)
- Equipment
- Spacecraft
- Other

A presentation of the subcategory percentile statistics first introduces the general nature of the distribution of the subsystem data. Box plots and a summary of means follows. Finally, descriptive statistics and correlation for each subcategory are explored. The total number of spacecraft used in the subsystem analysis is 129.

### 3.6.1. Subsystem Category Percentiles

Most of the data in the eleven subcategories of subsystem do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics to better visualize how the data are distributed. These are shown in Table 3.9.

The thermal, harness and SMS subsystems all have their non-zero values above the 50th percentile, indicating that there is a large concentration of zero values in the population. The equipment and spacecraft subcategories appear to be more normally distributed, with non-zero values appearing at the lower end of the range of values.

**Table 3.9: Subsystem category percentile statistics**

| *Subsystem Subcategory* | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| EPDS | 0.00 | 0.00 | 1.00 | 6.00 | 12.00 | 26.00 | 31.00 |
| GNC | 0.00 | 0.00 | 1.00 | 4.00 | 9.00 | 16.00 | 21.50 |
| Payload | 0.00 | 0.00 | 5.00 | 15.00 | 27.00 | 39.00 | 43.00 |
| Prop | 0.00 | 0.00 | 0.00 | 2.00 | 5.00 | 11.00 | 20.50 |
| SMS | 0.00 | 0.00 | 0.00 | 0.00 | 2.50 | 4.00 | 20.50 |
| TTC / DMS | 0.00 | 0.00 | 0.00 | 7.00 | 15.00 | 20.00 | 25.00 |
| Thermal | 0.00 | 0.00 | 53.75 | 65.50 | 77.00 | 87.00 | 94.00 |
| Harness | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 6.00 | 8.00 |
| Equipment | 0.00 | 1.00 | 5.00 | 31.00 | 47.00 | 60.00 | 69.00 |
| Spacecraft | 0.00 | 0.00 | 4.00 | 9.00 | 30.00 | 47.00 | 55.00 |
| Other | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.00 | 5.50 |

### 3.6.2. Subsystem Category Box Plots

The box plots below in Figure 3.14 show another portrayal of the dispersion of the subsystem data. Most of the subsystems have a large number of outlier and extreme values, as shown by the marks above the top whisker. This indicates that they are most likely non-normal distributions. The subsystems that do no have many outlying values are payload, equipment and spacecraft. These could potentially fit a normal distribution, and this is investigated in the following sections.

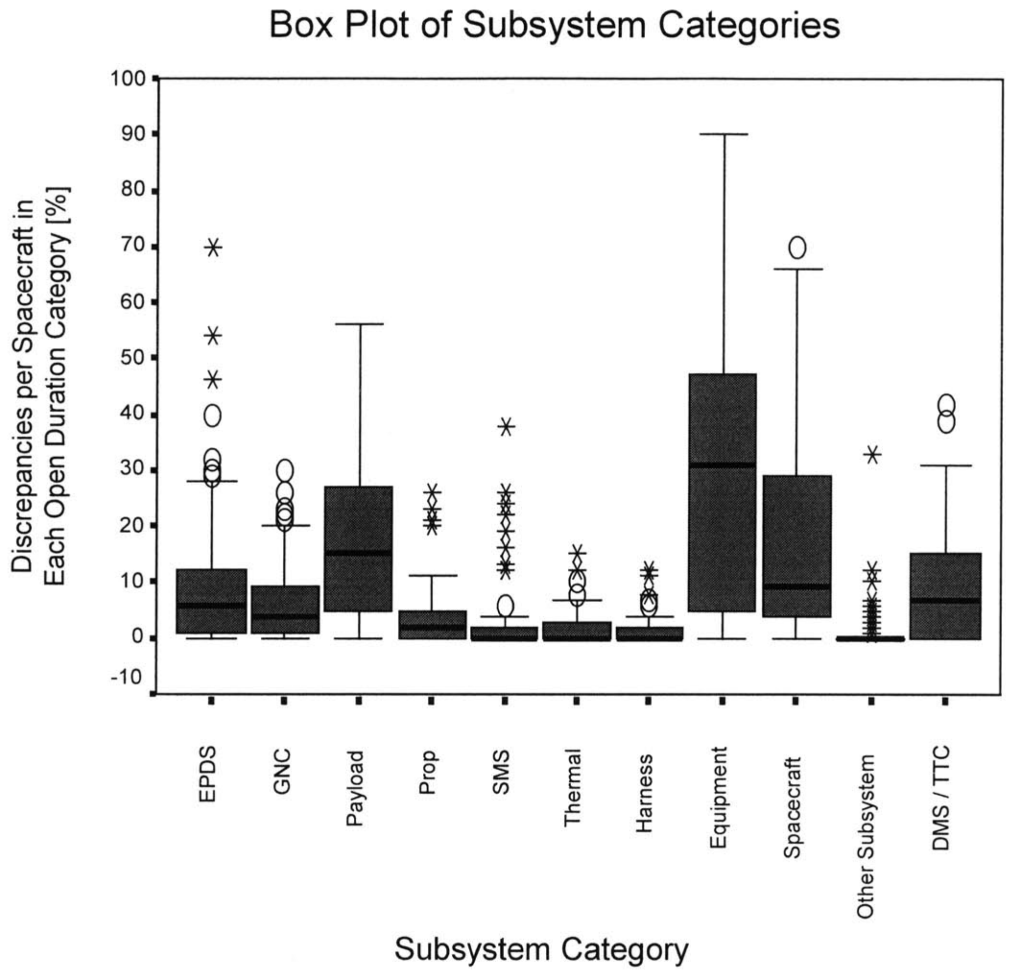


**Figure 3.14: Box plot of subsystem categories**

## 3.6.3. Overview of Subsystem Means and Confidence Intervals

Figure 3.15 shows a summary of the means of the eleven subsystem subcategories, along with the 95% confidence interval upper and lower bounds on those means, and the medians. Equipment accounts for the largest percentage of discrepancies written against a particular subsystem on an average spacecraft, with a mean of 30%. The payload subsystem and the spacecraft are the next largest percentages of discrepancies, at 17% each. The remaining 36% of discrepancies are distributed between the remaining traditional subsystems of the spacecraft, with no single subsystem accounting for more than 9% of the total discrepancies.

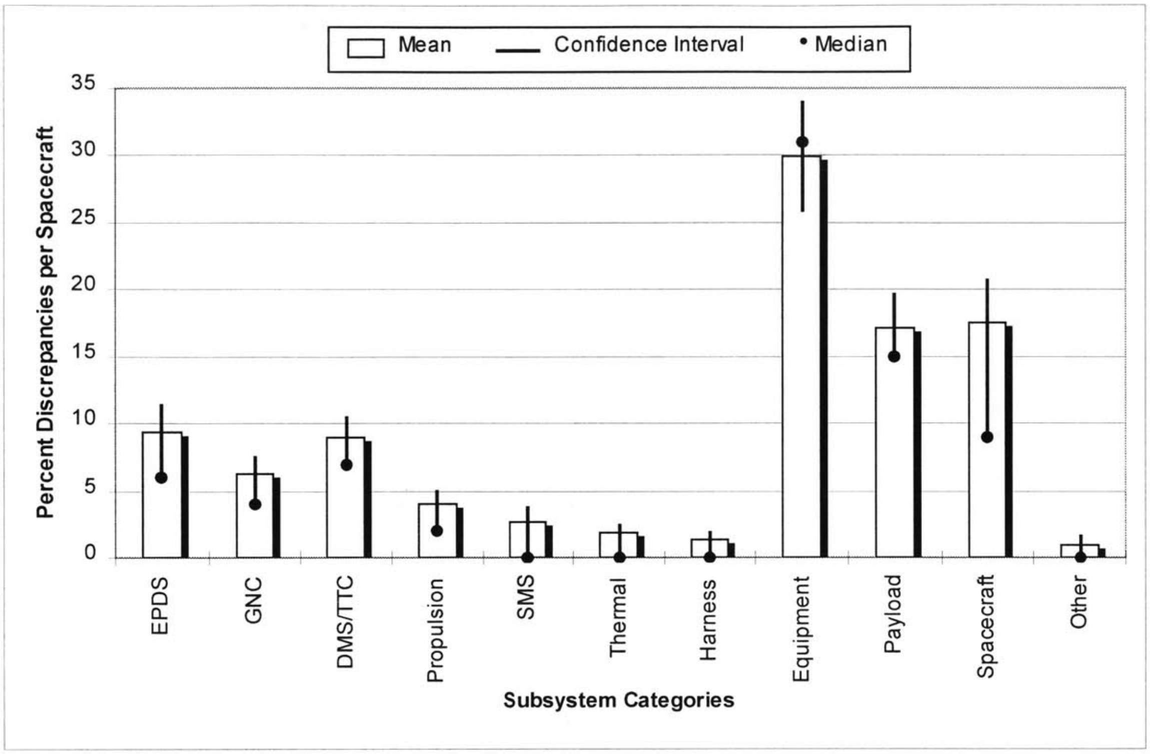


**Figure 3.15: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each subsystem category**

### 3.6.4. Electrical Power and Distribution Subsystem (EPDS)

Descriptive statistics for the EPDS subcategory are shown in Table 3.10. The mean, 5% trimmed mean, and median for the EPDS subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 11.27, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 17.95, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the EPDS data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the EPDS subcategory in Figure 3.16.

**Table 3.10: EPDS subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 9.29 | 1.01 |
| **95% Confidence Interval for Mean: Lower Bound** | 7.29 | |
| **95% Confidence Interval for Mean: Upper Bound** | 77.29 | |
| **5% Trimmed Mean** | 7.77 | |
| **Median** | 6.00 | |
| **Variance** | 132.034 | |
| **Standard Deviation** | 11.49 | |
| **Minimum** | 0 | |
| **Maximum** | 70 | |
| **Skewness** | 2.402 | 0.213 |
| **Kurtosis** | 7.597 | 0.423 |

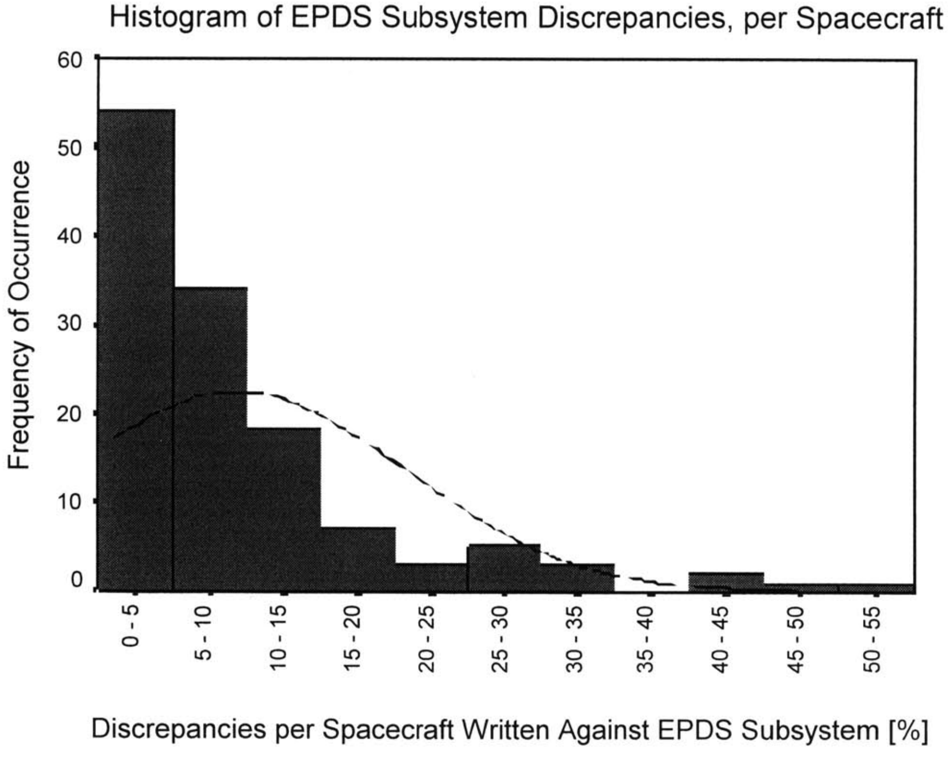


**Figure 3.16: Histogram of EPDS subsystem discrepancies, per spacecraft**

#### 3.6.4.1. EPDS Subsystem Correlation

Correlation appeared between the EPDS subsystem category and other parameters collected about spacecraft system-level I&T discrepancies.

- The EPDS subsystem subcategory and the Equipment subsystem subcategory have a negative correlation of 0.747 (N=129) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies.
- The EPDS subsystem subcategory and the Spacecraft subsystem subcategory have a negative correlation of 0.698 (N=129) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of spacecraft subsystem discrepancies.
- The EPDS subsystem subcategory and the Other subsystem subcategory have a positive correlation of 0.614 (N=129) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of other subsystem discrepancies.
- The EPDS subsystem subcategory and the DMS/TTC subsystem subcategory have a positive correlation of 0.643 (N=129) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of DMS/TTC subsystem discrepancies.
- The EPDS subsystem subcategory and the No Anomaly cause subcategory have a negative correlation of 0.608 (N=105) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of No Anomaly causes for discrepancies.
- The EPDS subsystem subcategory and the Other cause subcategory have a positive correlation of 0.689 (N=105) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Other causes for discrepancies.
- The EPDS subsystem subcategory and the Drawing/Spec corrective action subcategory have a positive correlation of 0.720 (N=100) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Drawing/Spec corrective actions for discrepancies.
- The EPDS subsystem subcategory and the Equipment corrective action subcategory have a negative correlation of 0.619 (N=100) at the 0.01 level of significance. This means that as the occurrence of EPDS subsystem discrepancies on a given spacecraft

went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment corrective actions for discrepancies.

### 3.6.5. Guidance, Navigation and Control (GNC) Subsystem

Descriptive statistics for the GNC subcategory are shown in Table 3.11. The mean, 5% trimmed mean, and median for the GNC subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 6.3, indicates that the distribution is slightly right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 3.48, indicates that the distribution has slightly longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the GNC data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the GNC subcategory in Figure 3.17.

**Table 3.11: GNC subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 6.32 | 0.58 |
| **95% Confidence Interval for Mean: Lower Bound** | 5.16 | |
| **95% Confidence Interval for Mean: Upper Bound** | 7.47 | |
| **5% Trimmed Mean** | 5.66 | |
| **Median** | 4.00 | |
| **Variance** | 43.875 | |
| **Standard Deviation** | 6.62 | |
| **Minimum** | 0 | |
| **Maximum** | 30 | |
| **Skewness** | 1.342 | 0.213 |
| **Kurtosis** | 1.475 | 0.423 |

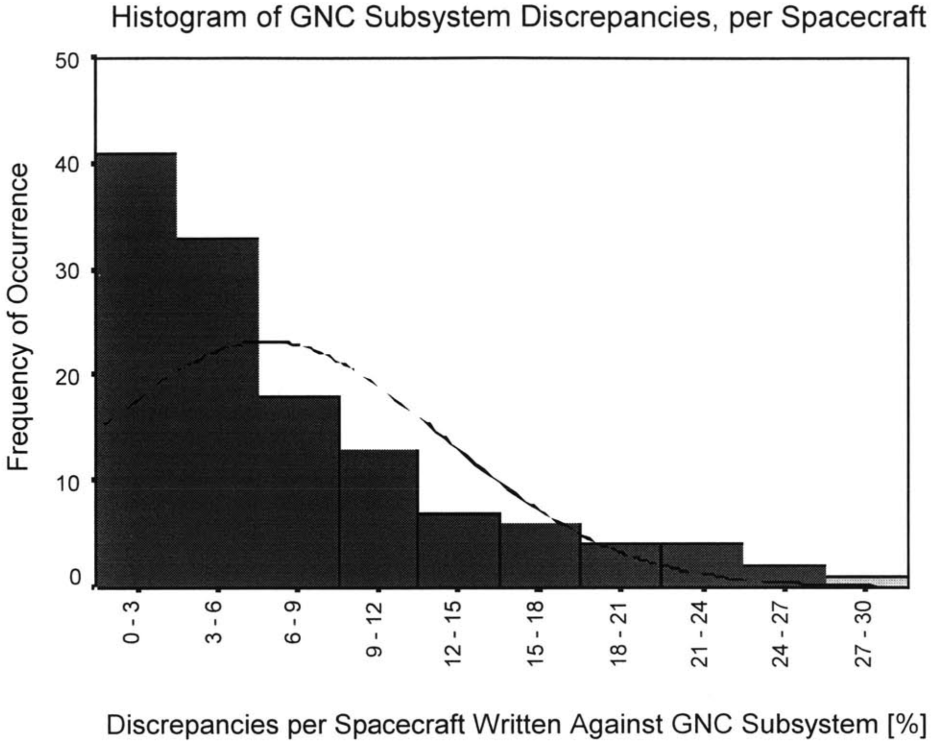


**Figure 3.17: Histogram of GNC subsystem discrepancies, per spacecraft**

### 3.6.6. Payload Subsystem

Descriptive statistics for the payload subcategory are shown in Table 3.12. The mean, 5% trimmed mean, and median for the payload subcategory are somewhat different. This indicates that the data are likely not normally distributed. The ratio of skewness to its standard error, 3.06, indicates that the distribution is just slightly right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -1.2, indicates that the distribution has a peak and tail lengths similar to a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the payload data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the payload subcategory in Figure 3.18.

**Table 3.12: Payload subsystem descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 17.16 | 1.24 |
| **95% Confidence Interval for Mean: Lower Bound** | 14.72 | |
| **95% Confidence Interval for Mean: Upper Bound** | 19.61 | |
| **5% Trimmed Mean** | 16.44 | |
| **Median** | 15.00 | |
| **Variance** | 197.215 | |
| **Standard Deviation** | 14.04 | |
| **Minimum** | 0 | |
| **Maximum** | 56 | |
| **Skewness** | 0.653 | 0.213 |
| **Kurtosis** | -0.511 | 0.423 |

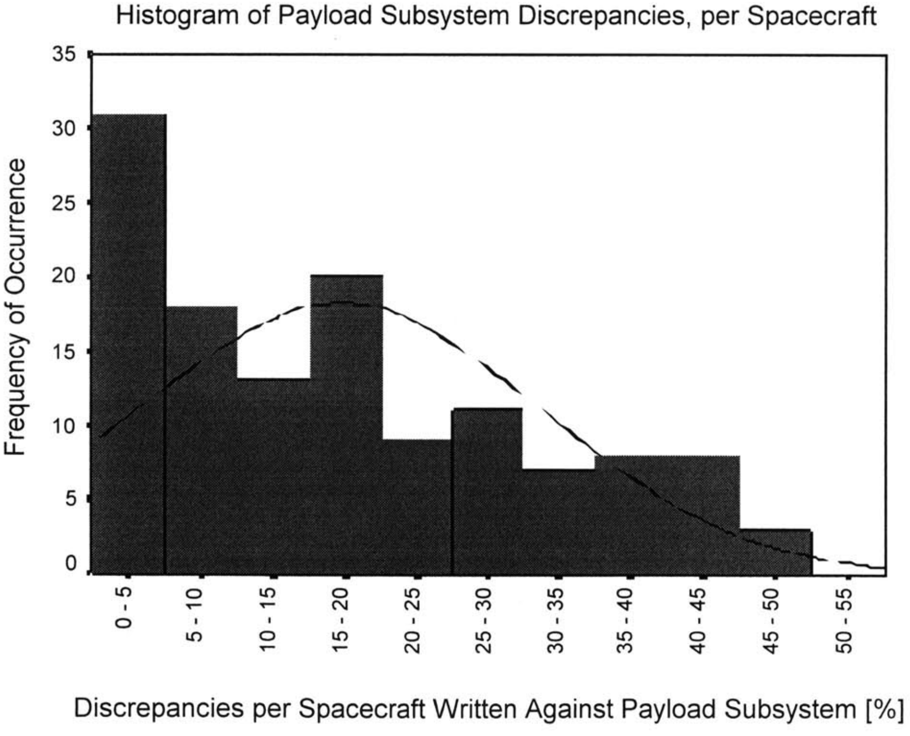


**Figure 3.18: Histogram of payload subsystem discrepancies, per spacecraft.**

### 3.6.7. Propulsion Subsystem

Descriptive statistics for the propulsion subcategory are shown in Table 3.13. The mean, 5% trimmed mean, and median for the propulsion subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 10.94, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 13.53, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the propulsion data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the propulsion subcategory in Figure 3.19.

**Table 3.13: Propulsion subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 4.00 | .49 |
| **95% Confidence Interval for Mean: Lower Bound** | 3.04 | |
| **95% Confidence Interval for Mean: Upper Bound** | 4.96 | |
| **5% Trimmed Mean** | 3.16 | |
| **Median** | 2.00 | |
| **Variance** | 30.406 | |
| **Standard Deviation** | 5.51 | |
| **Minimum** | 0 | |
| **Maximum** | 26 | |
| **Skewness** | 2.332 | 0.213 |
| **Kurtosis** | 5.722 | 0.423 |

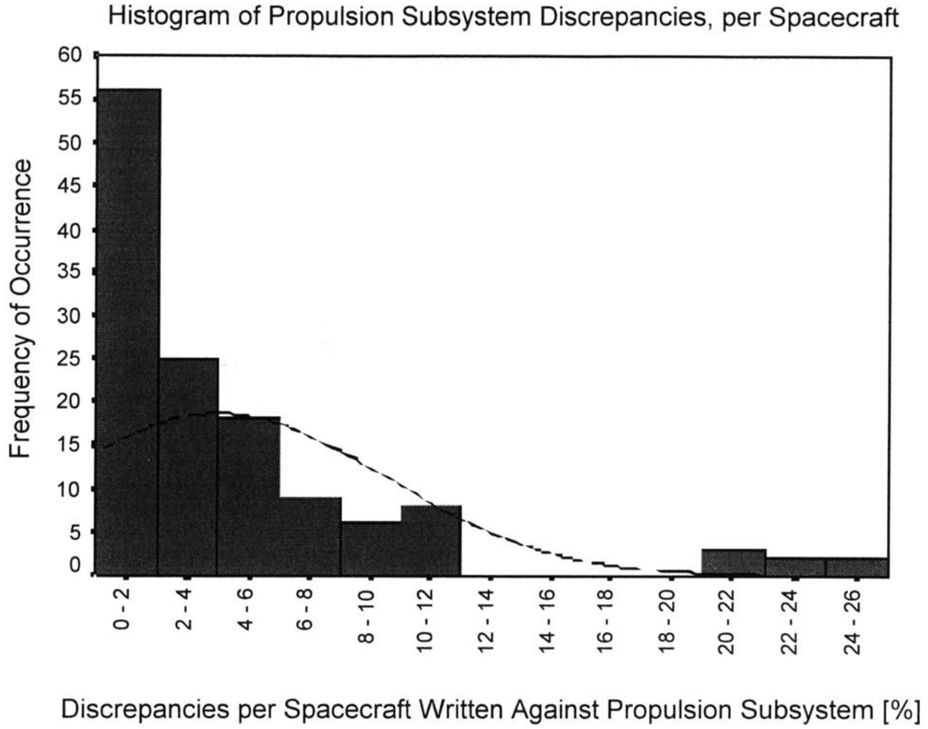


**Figure 3.19: Histogram of propulsion subsystem discrepancies, per spacecraft**

### 3.6.8. Structures and Mechanisms Subsystem (SMS)

Descriptive statistics for the SMS subcategory are shown in Table 3.14. The mean, 5% trimmed mean, and median for the SMS subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 16.18, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 30.12, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the SMS data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the SMS subcategory in Figure 3.20.

**Table 3.14: SMS subsystem subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 2.62 | 0.54 |
| **95% Confidence Interval for Mean: Lower Bound** | 1.55 | |
| **95% Confidence Interval for Mean: Upper Bound** | 3.69 | |
| **5% Trimmed Mean** | 1.49 | |
| **Median** | 0.00 | |
| **Variance** | 37.394 | |
| **Standard Deviation** | 6.12 | |
| **Minimum** | 0 | |
| **Maximum** | 38 | |
| **Skewness** | 3.448 | 0.213 |
| **Kurtosis** | 12.742 | 0.423 |

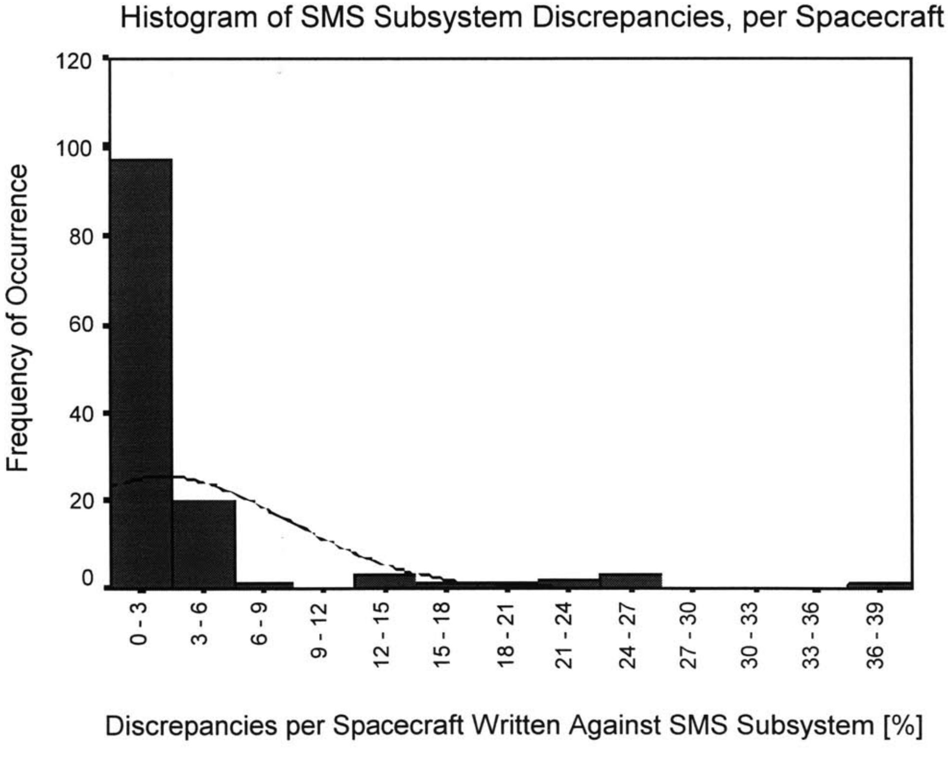


**Figure 3.20: Histogram of SMS subsystem discrepancies, per spacecraft.**

#### *3.6.8.1. SMS Subsystem Correlation*

Correlation appeared between the SMS subsystem category and other parameters collected about spacecraft system-level I&T discrepancies.

- The SMS subsystem subcategory and the Return to Supplier disposition subcategory have a positive correlation of 0.620 (N=48) at the 0.01 level of significance. This means that as the occurrence of SMS subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Return to Supplier dispositions of discrepancies.
- The SMS subsystem subcategory and the Supplier-Related corrective action subcategory have a positive correlation of 0.690 (N=100) at the 0.01 level of significance. This means that as the occurrence of SMS subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Supplier-Related corrective action for discrepancies.

### 3.6.9. Telemetry, Tracking and Command (TTC) / Data Management Subsystem (DMS)

Descriptive statistics for the TTC/DMS subcategory are shown in Table 3.15. The mean, 5% trimmed mean, and median for the TTC/DMS subcategory are somewhat different. This indicates that the data are not likely normally distributed. The ratio of skewness to its standard error, 4.55, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 2.00, indicates that the distribution has about the same peak height and tail length as a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the TTC/DMS data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the TTC/DMS subcategory in Figure 3.21.

**Table 3.15: DMS / TTC subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 8.89 | 0.79 |
| **95% Confidence Interval for Mean: Lower Bound** | 7.32 | |
| **95% Confidence Interval for Mean: Upper Bound** | 10.46 | |
| **5% Trimmed Mean** | 8.15 | |
| **Median** | 7.00 | |
| **Variance** | 80.863 | |
| **Standard Deviation** | 8.99 | |
| **Minimum** | 0 | |
| **Maximum** | 42 | |
| **Skewness** | 0.970 | 0.213 |
| **Kurtosis** | 0.850 | 0.423 |

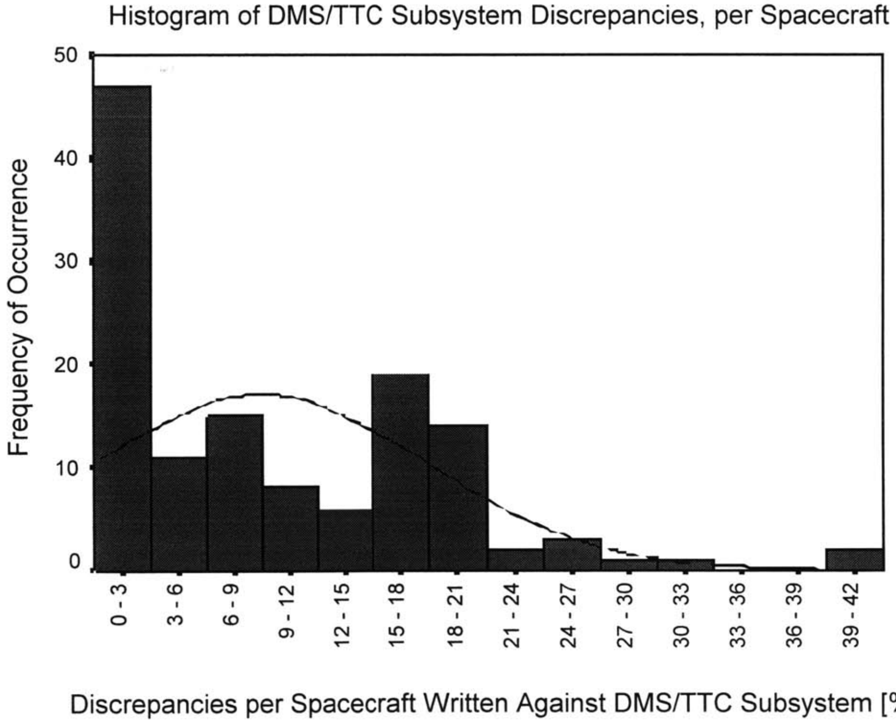


**Figure 3.21: Histogram of DMS/TTC subsystem discrepancies, per spacecraft**

#### 3.6.9.1. DMS/TTC Subsystem Correlation

Correlation appeared between the DMS/TTC subsystem category and other parameters collected about spacecraft system-level I&T discrepancies.

- The DMS/TTC subsystem subcategory and the EPDS subsystem subcategory have a positive correlation of 0.643 (N=129) at the 0.01 level of significance. This means that as the occurrence of DMS/TTC subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The DMS/TTC subsystem subcategory and the spacecraft subsystem subcategory have a negative correlation of 0.631 (N=129) at the 0.01 level of significance. This means that as the occurrence of DMS/TTC subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of spacecraft subsystem discrepancies.
- The DMS/TTC subsystem subcategory and the Thermal Vacuum activity subcategory have a negative correlation of 0.618 (N=122) at the 0.01 level of significance. This means that as the occurrence of DMS/TTC subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Thermal Vacuum activity discrepancies.
- The DMS/TTC subsystem subcategory and the Equipment cause subcategory have a negative correlation of 0.606 (N=105) at the 0.01 level of significance. This means that as the occurrence of DMS/TTC subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment causes of discrepancies.
- The DMS/TTC subsystem subcategory and the Other cause subcategory have a positive correlation of 0.713 (N=105) at the 0.01 level of significance. This means that as the occurrence of DMS/TTC discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Other causes of discrepancies.
- The DMS/TTC subsystem subcategory and the Drawing /Spec corrective action subcategory have a positive correlation of 0.684 (N=100) at the 0.01 level of significance. This means that as the occurrence of DMS/TTC subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Drawing/Spec corrective actions for discrepancies.

### 3.6.10. Thermal Subsystem

Descriptive statistics for the thermal subcategory are shown in Table 3.16. The mean, 5% trimmed mean, and median for the thermal subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 8.70, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 8.30, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the thermal data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the thermal subcategory in Figure 3.22.

**Table 3.16: Thermal subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 1.93 | 0.26 |
| **95% Confidence Interval for Mean: Lower Bound** | 1.41 | |
| **95% Confidence Interval for Mean: Upper Bound** | 2.45 | |
| **5% Trimmed Mean** | 1.55 | |
| **Median** | 0.00 | |
| **Variance** | 8.987 | |
| **Standard Deviation** | 3.00 | |
| **Minimum** | 0 | |
| **Maximum** | 15 | |
| **Skewness** | 1.853 | 0.213 |
| **Kurtosis** | 3.513 | 0.423 |

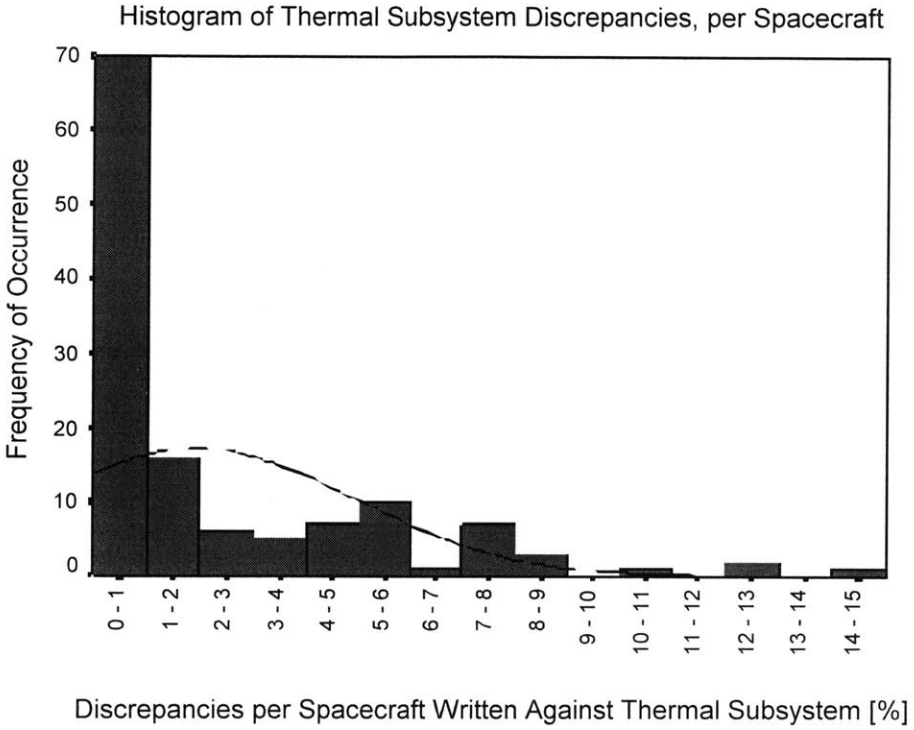


**Figure 3.22: Histogram of thermal subsystem discrepancies, per spacecraft**

### 3.6.10.1. Thermal Subsystem Correlation

Correlation appeared between the Thermal subsystem category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Thermal subsystem subcategory and the Mission category have a correlation of 0.713 (N=129) at the 0.01 level of significance. This means that the number of thermal discrepancies occurring on a given spacecraft tended to be higher for non-communications missions, and lower for communications missions.
- The Thermal subsystem subcategory and the Other cause subcategory have a positive correlation of 0.631 (N=105) at the 0.01 level of significance. This means that as the occurrence of Thermal subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Other causes of discrepancies.
- The Thermal subsystem subcategory and the Supplier-Related corrective action subcategory have a positive correlation of 0.645 (N=100) at the 0.01 level of significance. This means that as the occurrence of Thermal subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Supplier-Related corrective actions for discrepancies.

### 3.6.11. Wiring and Cabling (Harness) Subsystem

Descriptive statistics for the harness subcategory are shown in Table 3.17. The mean, 5% trimmed mean, and median for the harness subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 10.19, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 10.16, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the harness data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the harness subcategory in Figure 3.23.

**Table 3.17: Harness subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 1.38 | 0.22 |
| **95% Confidence Interval for Mean: Lower Bound** | 0.94 | |
| **95% Confidence Interval for Mean: Upper Bound** | 1.82 | |
| **5% Trimmed Mean** | 1.03 | |
| **Median** | 0.00 | |
| **Variance** | 6.487 | |
| **Standard Deviation** | 2.55 | |
| **Minimum** | 0 | |
| **Maximum** | 12 | |
| **Skewness** | 2.171 | 0.213 |
| **Kurtosis** | 4.269 | 0.423 |

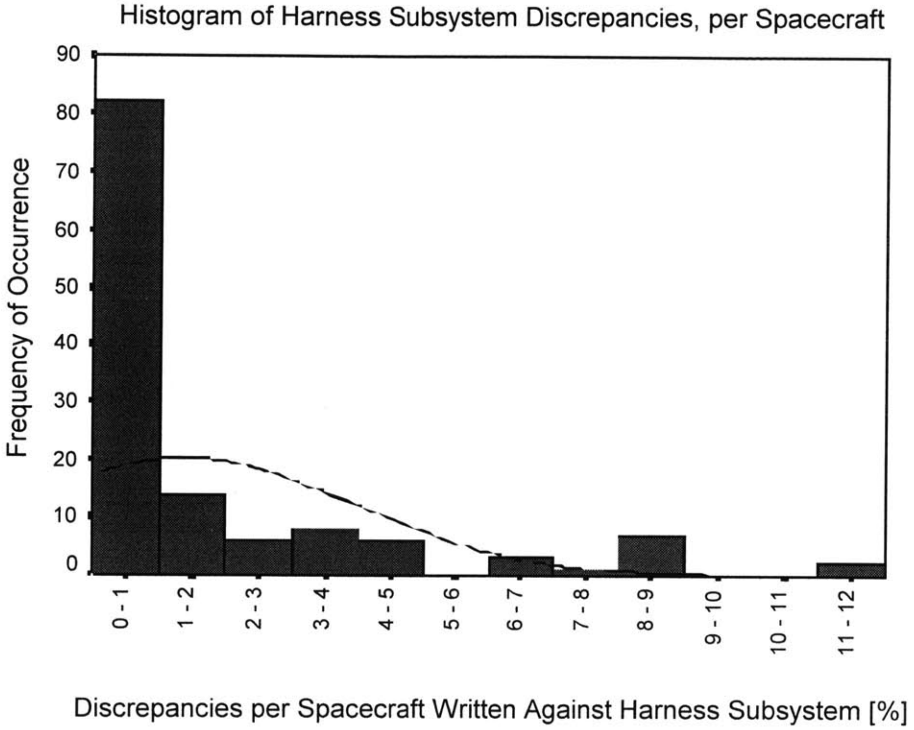


**Figure 3.23: Histogram of harness subsystem discrepancies, per spacecraft**

### 3.6.12. Test Equipment Subsystem

Descriptive statistics for the test equipment subsystem subcategory are shown in Table 3.18. The mean, 5% trimmed mean, and median for the test equipment subsystem subcategory are somewhat different, yet the measures of skewness and kurtosis show that the distribution of the equipment data follows a normal distribution. The ratio of skewness to its standard error, 1.53, indicates that the distribution is not skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -1.71, indicates that the distribution has a similar peak height and tail length as a normal distribution. Because the absolute value of both of these ratios is less than 2, normality for the test equipment subsystem data cannot be rejected. Thus, the test equipment subsystem data follow an approximate normal distribution. The histogram of the equipment subcategory is shown in Figure 3.24.

**Table 3.18: Test equipment subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 29.93 | 2.05 |
| **95% Confidence Interval for Mean: Lower Bound** | 25.88 | |
| **95% Confidence Interval for Mean: Upper Bound** | 33.98 | |
| **5% Trimmed Mean** | 28.82 | |
| **Median** | 31.00 | |
| **Variance** | 541.378 | |
| **Standard Deviation** | 23.27 | |
| **Minimum** | 0 | |
| **Maximum** | 90 | |
| **Skewness** | 0.327 | 0.213 |
| **Kurtosis** | -0.724 | 0.423 |

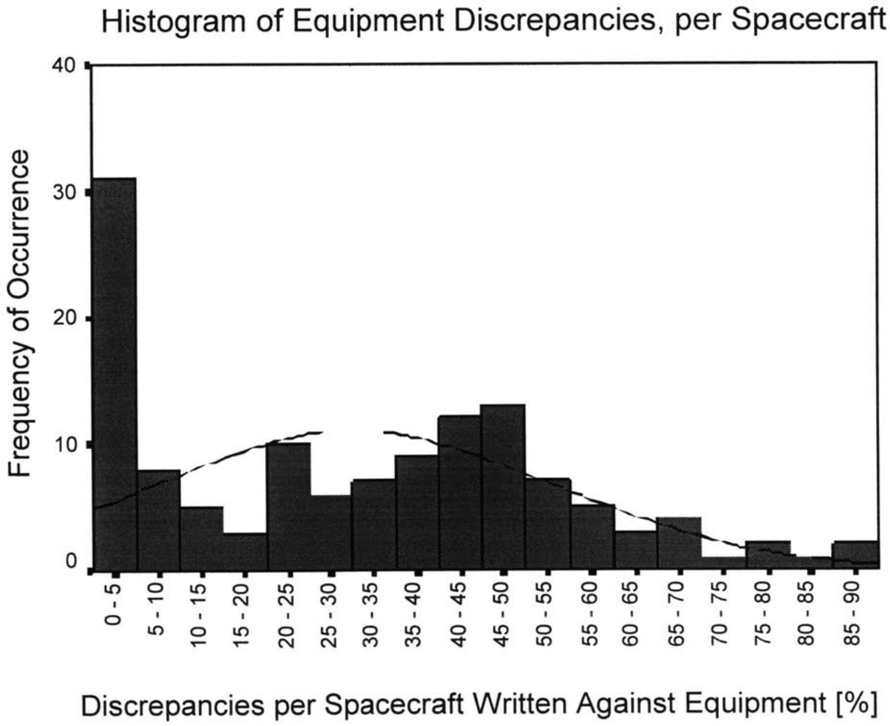


**Figure 3.24: Histogram of test equipment subsystem discrepancies, per spacecraft**

### *3.6.12.1. Test Equipment Subsystem Correlation*

Correlation appeared between the Test Equipment subsystem category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Equipment subsystem subcategory and the EPDS subsystem subcategory have a negative correlation of 0.747 (N=129) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The Equipment subsystem subcategory and the No Anomaly cause subcategory have a positive correlation of 0.604 (N=105) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of No Anomaly causes of discrepancies.
- The Equipment subsystem subcategory and the Other cause subcategory have a negative correlation of 0.611 (N=105) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Other causes of discrepancies.
- The Equipment subsystem subcategory and the Repair disposition subcategory have a positive correlation of 0.661(N=48) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Repair dispositions of discrepancies.
- The Equipment subsystem subcategory and the Rework disposition subcategory have a negative correlation of 0.707 (N=48) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Rework dispositions of discrepancies.
- The Equipment subsystem subcategory and the Drawing/Spec corrective action subcategory have a negative correlation of 0.696 (N=100) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Drawing/Spec corrective actions for discrepancies.
- The Equipment subsystem subcategory and the Equipment corrective action subcategory have a positive correlation of 0.625 (N=100) at the 0.01 level of significance. This means that as the occurrence of Equipment subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Equipment corrective actions for discrepancies.

### 3.6.13. Spacecraft Subsystem

Descriptive statistics for the spacecraft subsystem subcategory are shown in Table 3.19. The mean, 5% trimmed mean, and median for the spacecraft subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 5.35, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 0.46, indicates that the distribution has a similar peak height and tail length as a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the spacecraft data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the spacecraft subcategory in Figure 3.25.

**Table 3.19: Spacecraft subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 17.47 | 1.61 |
| **95% Confidence Interval for Mean: Lower Bound** | 14.28 | |
| **95% Confidence Interval for Mean: Upper Bound** | 20.65 | |
| **5% Trimmed Mean** | 15.91 | |
| **Median** | 9.00 | |
| **Variance** | 333.610 | |
| **Standard Deviation** | 18.26 | |
| **Minimum** | 0 | |
| **Maximum** | 70 | |
| **Skewness** | 1.139 | 0.213 |
| **Kurtosis** | 0.193 | 0.423 |

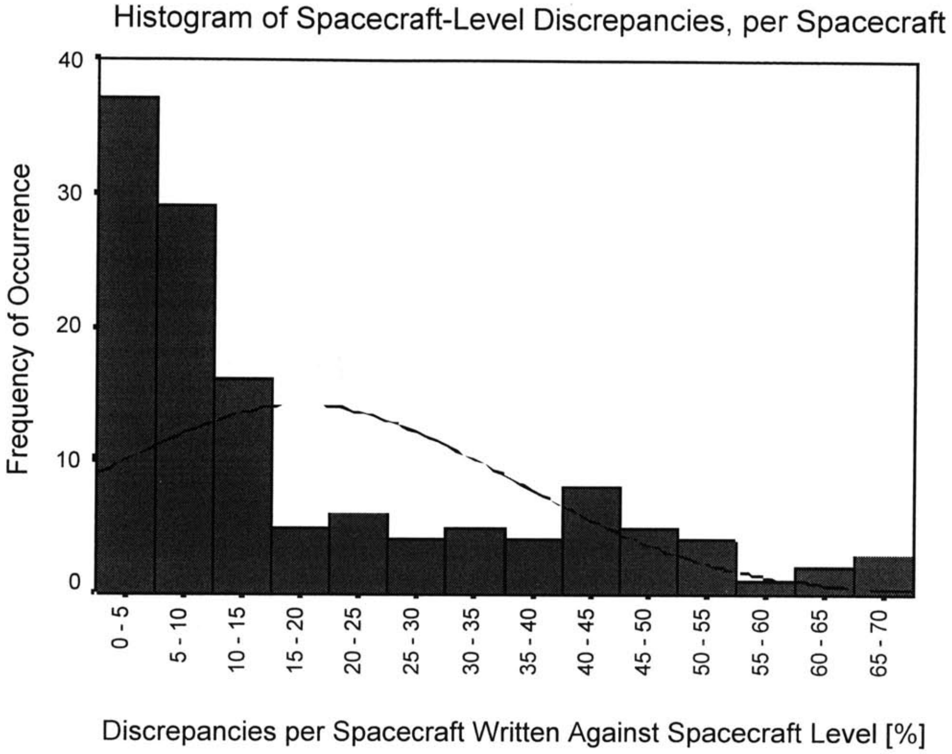


**Figure 3.25: Histogram of spacecraft subsystem discrepancies, per spacecraft**

### *3.6.13.1. Spacecraft Subsystem Correlation*

Correlation appeared between the Spacecraft subsystem category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Spacecraft subsystem subcategory and the DMS/TTC subsystem subcategory have a negative correlation of 0.631 (N=129) at the 0.01 level of significance. This means that as the occurrence of Spacecraft subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of DMS/TTC subsystem discrepancies.
- The Spacecraft subsystem subcategory and the EPDS subsystem subcategory have a negative correlation of 0.698 (N=129) at the 0.01 level of significance. This means that as the occurrence of Spacecraft subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The Spacecraft subsystem subcategory and the Other cause subcategory have a negative correlation of 0.684 (N=105) at the 0.01 level of significance. This means that as the occurrence of Spacecraft subsystem discrepancies on a given spacecraft

went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Other causes of discrepancies.

- The Spacecraft subsystem subcategory and the Use As Is disposition subcategory have a positive correlation of 0.719 (N=48) at the 0.01 level of significance. This means that as the occurrence of Spacecraft subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Use As Is dispositions of discrepancies.

### 3.6.14. Other Subsystems

Descriptive statistics for the Other subsystems subcategory are shown in Table 3.20. The mean, 5% trimmed mean, and median for the Other susbsystems subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 33.24, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 145.62, indicates that the distribution has much longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the other subsystems data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the other subsystems subcategory in Figure 3.26.

**Table 3.20: Other subsystem descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 0.98 | 0.30 |
| **95% Confidence Interval for Mean: Lower Bound** | 0.39 | |
| **95% Confidence Interval for Mean: Upper Bound** | 1.58 | |
| **5% Trimmed Mean** | 0.43 | |
| **Median** | 0.00 | |
| **Variance** | 11.672 | |
| **Standard Deviation** | 3.42 | |
| **Minimum** | 0 | |
| **Maximum** | 33 | |
| **Skewness** | 7.081 | 0.213 |
| **Kurtosis** | 61.601 | 0.423 |

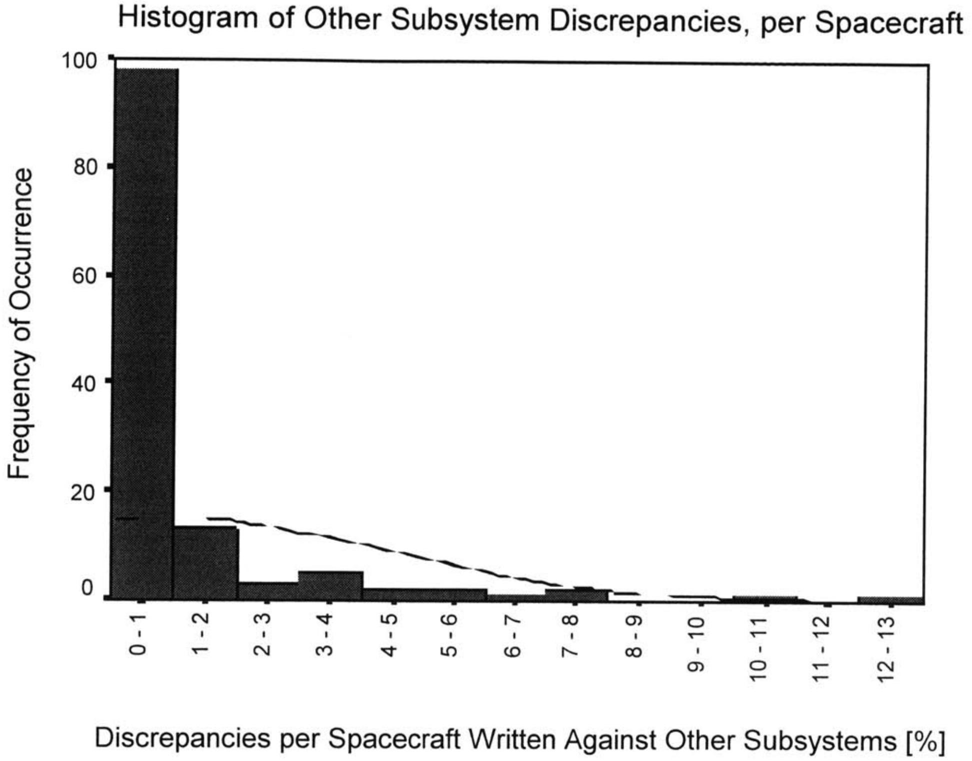


**Figure 3.26: Histogram of other subsystem discrepancies, per spacecraft**

### 3.6.14.1. Other Subsystem Correlation

Correlation appeared between the Other subsystem subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The Other subsystem subcategory and the EPDS subsystem subcategory have a positive correlation of 0.614 (N=129) at the 0.01 level of significance. This means that as the occurrence of Other subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The Other subsystem subcategory and the Use As Is disposition subcategory have a negative correlation of 0.651 (N=48) at the 0.01 level of significance. This means that as the occurrence of Other subsystem discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Use As Is dispositions of discrepancies.
- The Other subsystem subcategory and the Drawing/Spec corrective action subcategory have a positive correlation of 0.651 (N=100) at the 0.01 level of significance. This means that as the occurrence of Other subsystem discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Drawing/Spec corrective actions for discrepancies.

## 3.7. Disposition Statistical Analysis

This section analyzes the disposition data for spacecraft discrepancies. These data describe the immediate fix action that was performed on a spacecraft due to a discrepancy. These data are categorized into six bins. For a detailed description of each of these bins, please see Chapter 1. The six bins, or subcategories, are:

- Use as is
- Rework
- Repair
- Return to Supplier
- Scrap
- Other

A presentation of the subcategory percentile statistics first introduces the general nature of the distribution of the disposition data. Box plots and a summary of means follows. Finally, descriptive statistics and correlation for each subcategory are explored. The total number of spacecraft used in the disposition analysis is 56.

### 3.7.1. Disposition Category Percentiles

Most of the data in the six subcategories of disposition do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics to better visualize how the data are distributed.

Table 3.21 shows the percentiles for the disposition category. The return-to-supplier and scrap disposition subcategories have non-zero values at or above the 25th percentile, indicating that there is a concentration of zero values in the population. The use-as-is, rework and repair subcategories appear to be more normally distributed, with non-zero values appearing at the 5th percentile.

**Table 3.21: Disposition category percentile statistics**

| *Disposition Subcategory* | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| Use as is | 7.00 | 9.70 | 30.00 | 41.00 | 52.00 | 58.80 | 68.00 |
| Rework | 6.55 | 9.00 | 11.25 | 15.50 | 31.00 | 41.00 | 59.20 |
| Repair | 3.40 | 14.70 | 20.00 | 25.50 | 33.50 | 41.00 | 43.15 |
| Return to Supplier | 0.00 | 0.00 | 0.00 | 1.00 | 3.00 | 10.00 | 13.00 |
| Scrap | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 3.00 | 4.15 |
| Other | 0.00 | 1.40 | 4.00 | 7.50 | 11.75 | 19.30 | 21.00 |

### 3.7.2. Disposition Category Box Plots

The box plots below in Figure 3.27 show another portrayal of the dispersion of the disposition data. The use as is subcategory box plot shows a symmetric distribution by the equal box areas above and below the median line as well as by the equal whisker lengths above and below the box. Subsequent tests of normality will show that normality cannot be rejected for the use as is data.

The box plot also shows that the return to supplier and scrap subcategories have several outliers and extreme values, as shown by the marks above the top whisker. This indicates that they are most likely non-normal distributions.

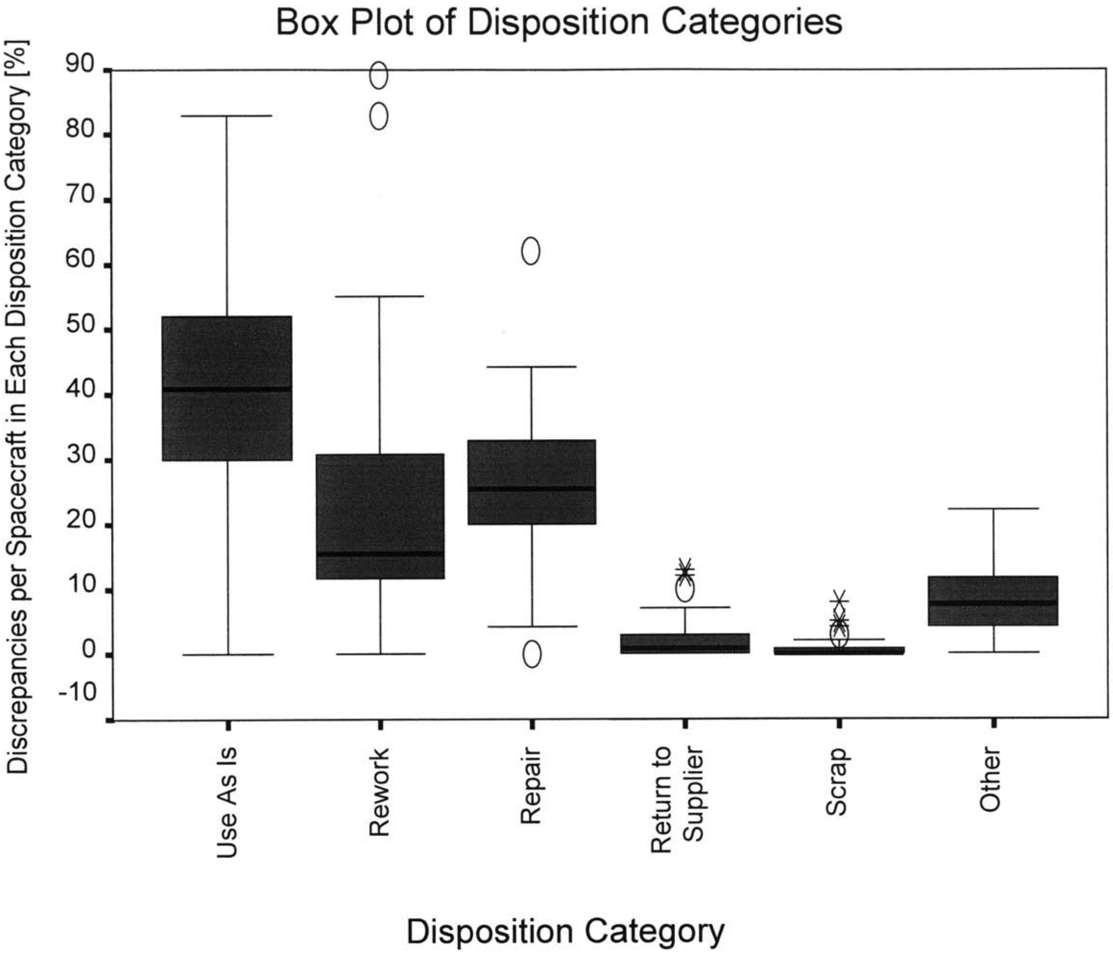


**Figure 3.27: Box plot of disposition categories**

### 3.7.3. Overview of Disposition Means and Confidence Intervals

Figure 3.28 shows a summary of the means of the six disposition subcategories, along with the 95% confidence interval upper and lower bounds on those means, and the medians. Use As Is accounts for the largest percentage of dispositions of discrepancies on an average spacecraft, with a mean of 39%. The Repair and Rework dispositions are the next largest percentages of discrepancy dispositions, at 26% and 23%, respectively. The Scrap disposition accounts for less than 1% of the discrepancy dispositions, as was expected for a product such as a spacecraft with expensive components with long procurement lead times.

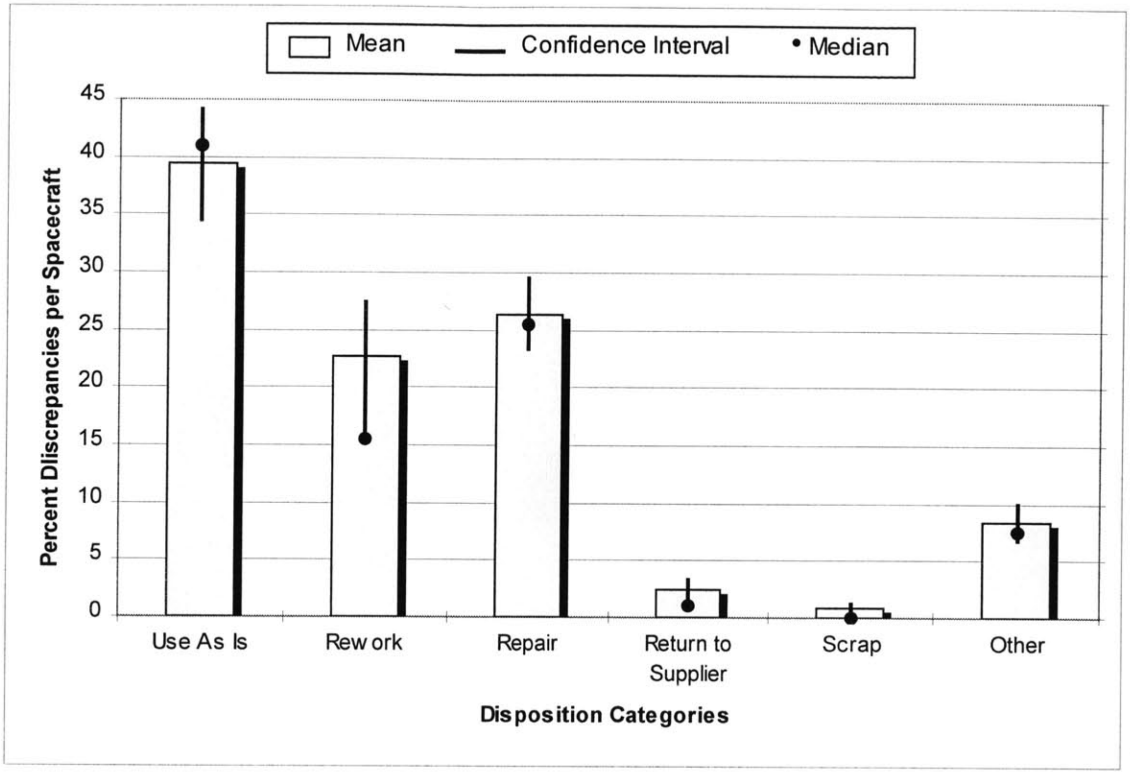


**Figure 3.28: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each disposition category**

### 3.7.4. Use As Is Disposition

Descriptive statistics for the Use As Is disposition subcategory are shown in Table 3.22. The mean and 5% trimmed mean of the Use As Is disposition subcategory are very similar, but the median is different. Despite this, the measures of skewness and kurtosis show that the distribution of the Use As Is data follows a normal distribution. The ratio of skewness to its standard error, -0.89, indicates that the distribution is not skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -0.36, indicates that the distribution has a similar peak height and tail length as a normal distribution. Because the absolute value of both of these ratios is less than 2, normality for the Use As Is data cannot be rejected. Thus, the Use As Is data follow an approximate normal distribution. The histogram of the Use As Is subcategory is shown in Figure 3.29.

**Table 3.22: Use as is subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 39.34 | 2.42 |
| **95% Confidence Interval for Mean: Lower Bound** | 34.48 | |
| **95% Confidence Interval for Mean: Upper Bound** | 44.20 | |
| **5% Trimmed Mean** | 39.38 | |
| **Median** | 41.00 | |
| **Variance** | 329.065 | |
| **Standard Deviation** | 18.14 | |
| **Minimum** | 0 | |
| **Maximum** | 83 | |
| **Skewness** | -0.283 | 0.319 |
| **Kurtosis** | -0.227 | 0.628 |

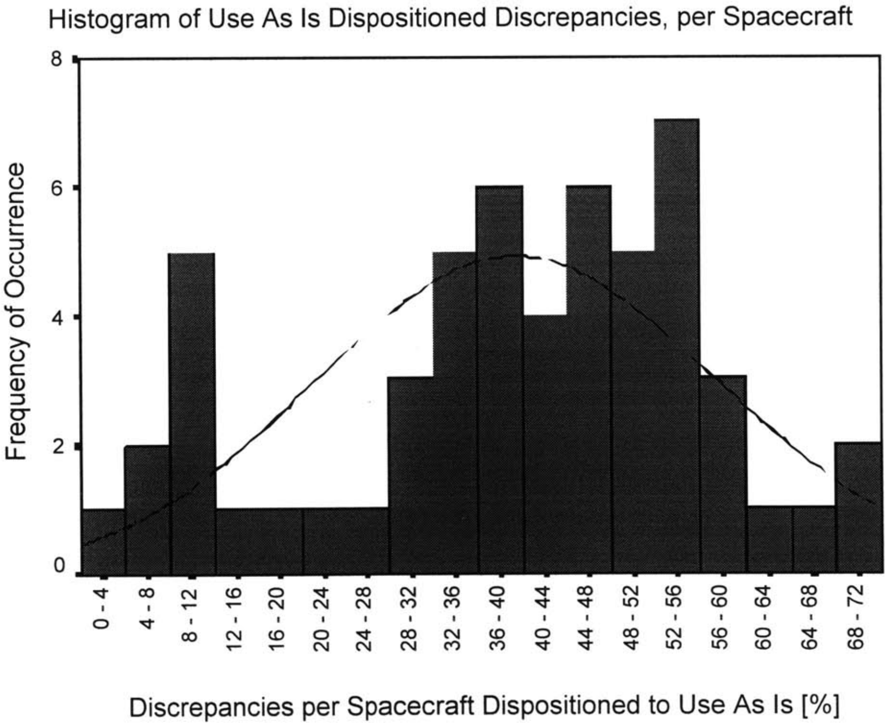


**Figure 3.29: Histogram of use as is dispositioned discrepancies, per spacecraft**

#### 3.7.4.1. Use As Is Disposition Correlation

Correlation appeared between the Use As Is disposition category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Use As Is disposition subcategory and the Mission category have a correlation of 0.612 (N=56) at the 0.01 level of significance. This means that the number of Use As Is dispositions occurring on a given spacecraft tended to be higher for communications missions, and lower for non-communications missions.
- The Use As Is disposition subcategory and the Spacecraft subsystem subcategory have a positive correlation of 0.719 (N=48) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Spacecraft subsystem discrepancies.
- The Use As Is disposition subcategory and the Other subsystem subcategory have a negative correlation of 0.651 (N=48) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Other subsystem discrepancies.
- The Use As Is disposition subcategory and the Thermal Vacuum activity subcategory have a positive correlation of 0.602 (N=49) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Thermal Vacuum activity discrepancies.
- The Use As Is disposition subcategory and the Ambient activity subcategory have a negative correlation of 0.633 (N=49) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Ambient activity discrepancies.
- The Use As Is disposition subcategory and the Other cause subcategory have a negative correlation of 0.674 (N=56) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Other causes of discrepancies.
- The Use As Is disposition subcategory and the Rework disposition subcategory have a negative correlation of 0.652 (N=56) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Rework dispositioned discrepancies.
- The Use As Is disposition subcategory and the Supplier-Related corrective action subcategory have a negative correlation of 0.686 (N=53) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed

on that given spacecraft in the occurrence of Supplier-Related corrective actions for discrepancies.

- The Use As Is disposition subcategory and the No Action Required corrective action subcategory have a positive correlation of 0.604 (N=53) at the 0.01 level of significance. This means that as the occurrence of Use As Is dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of No Action Required corrective actions for discrepancies.

### 3.7.5. Rework Disposition

Descriptive statistics for the Rework disposition subcategory are shown in Table 3.23. The mean, 5% trimmed mean, and median for the Rework disposition subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 6.05, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 7.63, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Rework disposition data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Rework disposition subcategory in Figure 3.30.

**Table 3.23: Rework disposition subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 22.66 | 2.32 |
| **95% Confidence Interval for Mean: Lower Bound** | 18.02 | |
| **95% Confidence Interval for Mean: Upper Bound** | 27.31 | |
| **5% Trimmed Mean** | 20.70 | |
| **Median** | 15.50 | |
| **Variance** | 300.883 | |
| **Standard Deviation** | 17.35 | |
| **Minimum** | 0 | |
| **Maximum** | 89 | |
| **Skewness** | 1.931 | 0.319 |
| **Kurtosis** | 4.793 | 0.628 |

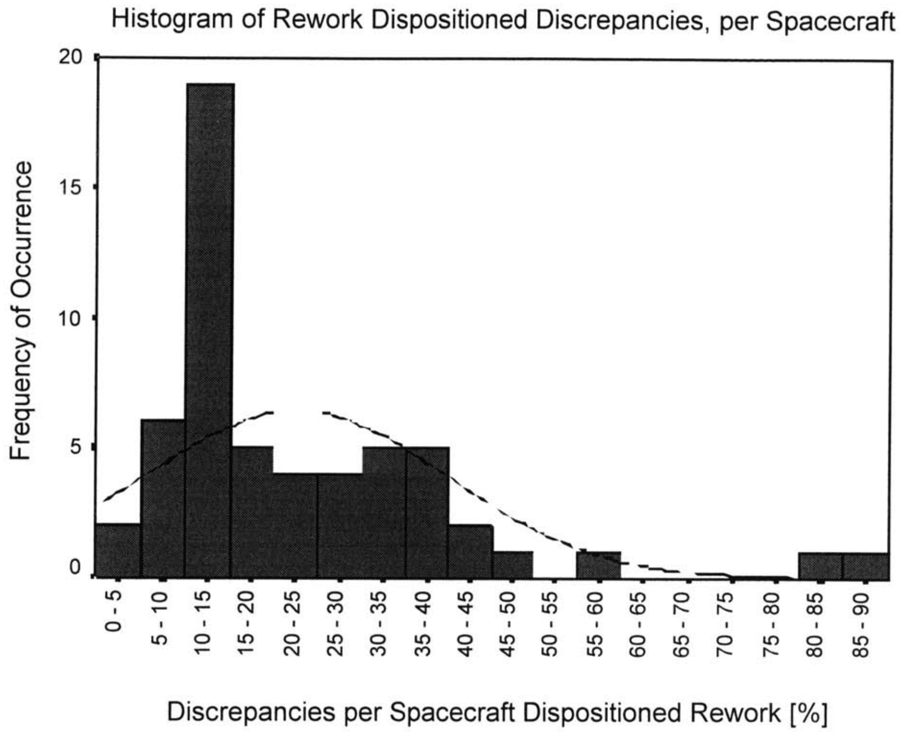


**Figure 3.30: Histogram of rework dispositioned discrepancies, per spacecraft**

### *3.7.5.1. Rework Disposition Correlation*

Correlation appeared between the Rework disposition category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Rework disposition subcategory and the Equipment subsystem subcategory have a negative correlation of 0.707 (N=48) at the 0.01 level of significance. This means that as the occurrence of Rework dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies.
- The Rework disposition subcategory and the Use As Is disposition subcategory have a negative correlation of 0.652 (N=56) at the 0.01 level of significance. This means that as the occurrence of Rework dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Use As Is dispositioned discrepancies.
- The Rework disposition subcategory and the Other cause subcategory have a positive correlation of 0.755 (N=56) at the 0.01 level of significance. This means that as the occurrence of Rework dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Other causes of discrepancies.

- The Rework disposition subcategory and the Equipment cause subcategory have a negative correlation of 0.630 (N=56) at the 0.01 level of significance. This means that as the occurrence of Rework dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment causes of discrepancies.
- The Rework disposition subcategory and the No Action Required corrective action subcategory have a negative correlation of 0.737 (N=53) at the 0.01 level of significance. This means that as the occurrence of Rework dispositioned discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of No Action Required corrective actions for discrepancies.
- The Rework disposition subcategory and the Supplier-related corrective action subcategory have a positive correlation of 0.778 (N=53) at the 0.01 level of significance. This means that as the occurrence of Rework dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Supplier-related corrective actions for discrepancies.

### 3.7.6. Repair Disposition

Descriptive statistics for the Repair disposition subcategory are shown in Table 3.24. The mean, 5% trimmed mean, and median for the Repair disposition subcategory are somewhat different. This indicates that the data are likely not normally distributed. The ratio of skewness to its standard error, 0.52, indicates that the distribution is not skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 2.19, indicates that the distribution has slightly longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Repair disposition data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Repair disposition subcategory in Figure 3.31.

**Table 3.24: Repair disposition subcategory descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 26.41 | 1.49 |
| **95% Confidence Interval for Mean: Lower Bound** | 23.43 | |
| **95% Confidence Interval for Mean: Upper Bound** | 29.39 | |
| **5% Trimmed Mean** | 26.50 | |
| **Median** | 25.50 | |
| **Variance** | 123.956 | |
| **Standard Deviation** | 11.13 | |
| **Minimum** | 0 | |
| **Maximum** | 62 | |
| **Skewness** | 0.165 | 0.319 |
| **Kurtosis** | 1.377 | 0.628 |

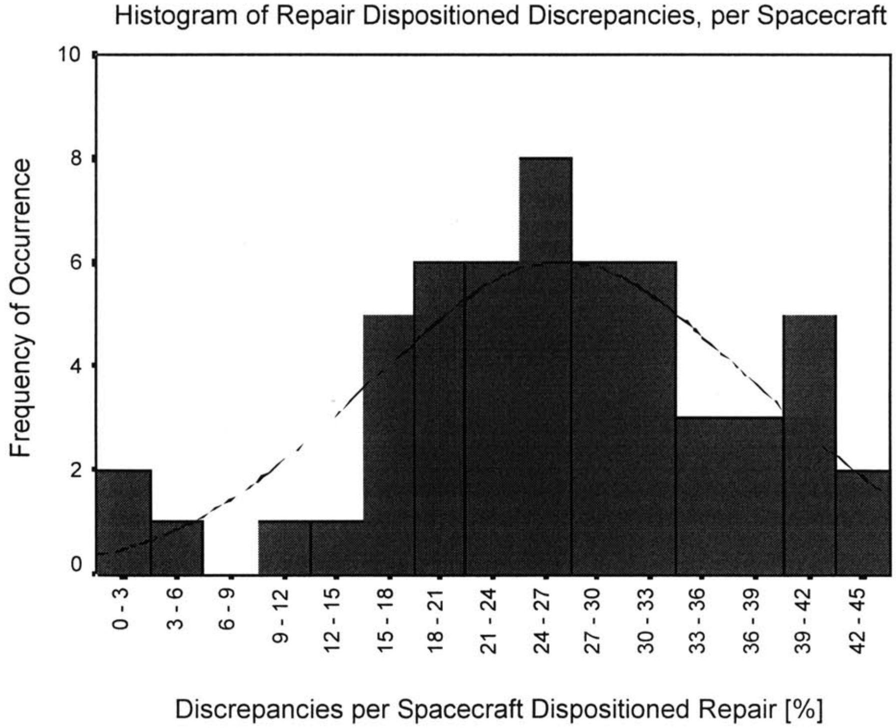


**Figure 3.31: Histogram of repair dispositioned discrepancies, per spacecraft**

#### 3.7.6.1. Repair Disposition Correlation

Correlation appeared between the Repair disposition category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Repair disposition subcategory and the Equipment subsystem subcategory have a positive correlation of 0.661 (N=48) at the 0.01 level of significance. This means that as the occurrence of Repair dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies.

### 3.7.7. Return to Supplier Disposition

Descriptive statistics for the Return to Supplier disposition subcategory are shown in Table 3.25. The mean, 5% trimmed mean, and median for the Return to Supplier disposition subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 5.94, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 4.21, indicates that the distribution has somewhat longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Return to Supplier disposition data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Return to Supplier disposition subcategory in Figure 3.32.

**Table 3.25: Return to supplier disposition subcategory descriptive statistics.**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 2.41 | 0.50 |
| **95% Confidence Interval for Mean: Lower Bound** | 1.42 | |
| **95% Confidence Interval for Mean: Upper Bound** | 3.40 | |
| **5% Trimmed Mean** | 1.96 | |
| **Median** | 1.00 | |
| **Variance** | 13.774 | |
| **Standard Deviation** | 3.71 | |
| **Minimum** | 0 | |
| **Maximum** | 13 | |
| **Skewness** | 1.896 | 0.319 |
| **Kurtosis** | 2.641 | 0.628 |

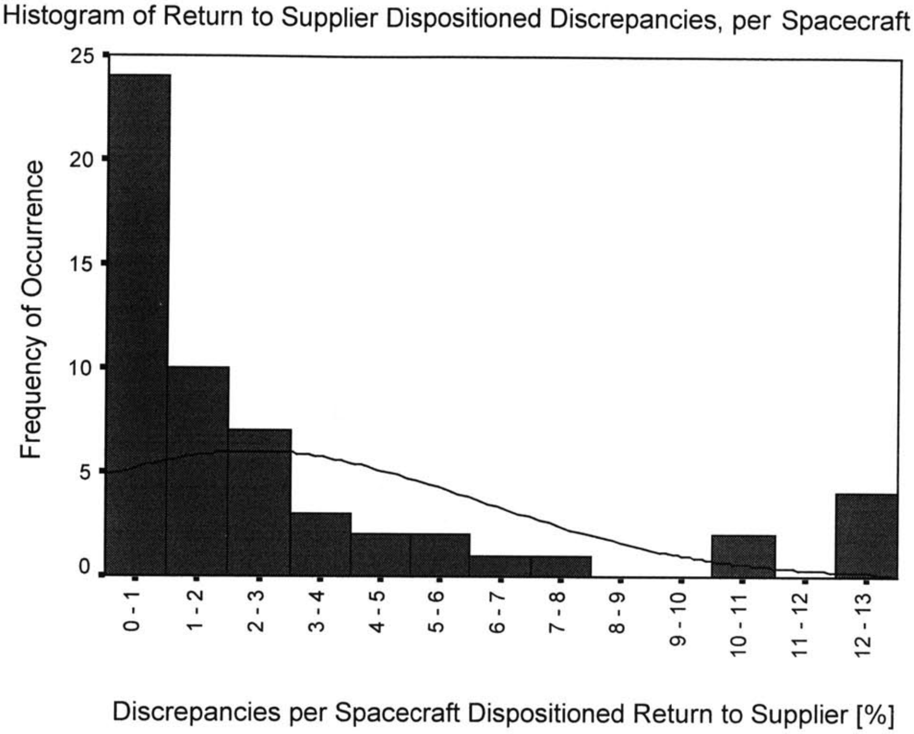


**Figure 3.32: Histogram of Return to Supplier dispositioned discrepancies, per spacecraft**

### 3.7.7.1. *Return to Supplier Disposition Correlation*

Correlation appeared between the Return to Supplier disposition category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Return to Supplier disposition subcategory and the SMS subsystem subcategory have a positive correlation of 0.626 (N=48) at the 0.01 level of significance. This means that as the occurrence of Return to Supplier dispositioned discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of SMS subsystem discrepancies.

## 3.7.8. Scrap Disposition

Descriptive statistics for the Scrap disposition subcategory are shown in Table 3.26. The mean, 5% trimmed mean, and median for the Scrap disposition subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 7.67, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 11.38, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Scrap disposition data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Scrap disposition subcategory in Figure 3.33.

**Table 3.26: Scrap disposition subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 0.84 | 0.21 |
| **95% Confidence Interval for Mean: Lower Bound** | 0.42 | |
| **95% Confidence Interval for Mean: Upper Bound** | 1.26 | |
| **5% Trimmed Mean** | 0.61 | |
| **Median** | 0.00 | |
| **Variance** | 2.501 | |
| **Standard Deviation** | 1.58 | |
| **Minimum** | 0 | |
| **Maximum** | 8 | |
| **Skewness** | 2.448 | 0.319 |
| **Kurtosis** | 7.151 | 0.628 |

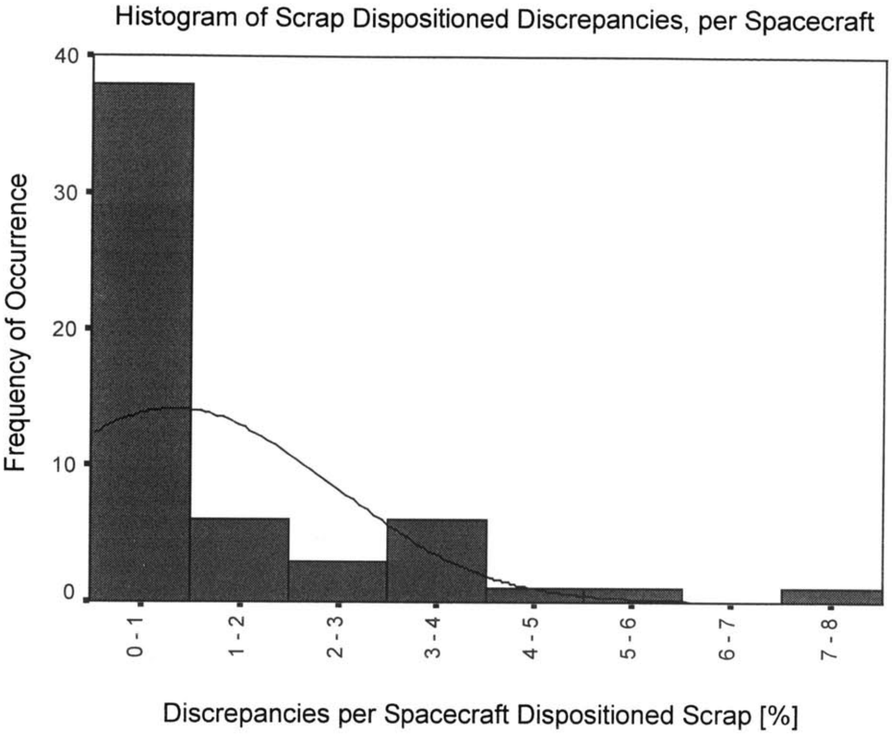


**Figure 3.33: Histogram of scrap dispositioned discrepancies, per spacecraft**

### 3.7.9. Other Disposition

Descriptive statistics for the Other disposition subcategory are shown in Table 3.27. The mean, 5% trimmed mean, and median for the Other disposition subcategory are somewhat different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 33.66, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 0.23, indicates that the distribution has approximately the same tail length and peak height as a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Other disposition data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Other disposition subcategory in Figure 3.34.

**Table 3.27: Other dispositions subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 8.34 | 0.77 |
| **95% Confidence Interval for Mean: Lower Bound** | 6.79 | |
| **95% Confidence Interval for Mean: Upper Bound** | 9.89 | |
| **5% Trimmed Mean** | 8.08 | |
| **Median** | 7.50 | |
| **Variance** | 33.501 | |
| **Standard Deviation** | 5.79 | |
| **Minimum** | 0 | |
| **Maximum** | 22 | |
| **Skewness** | 10.739 | 0.319 |
| **Kurtosis** | 0.143 | 0.628 |

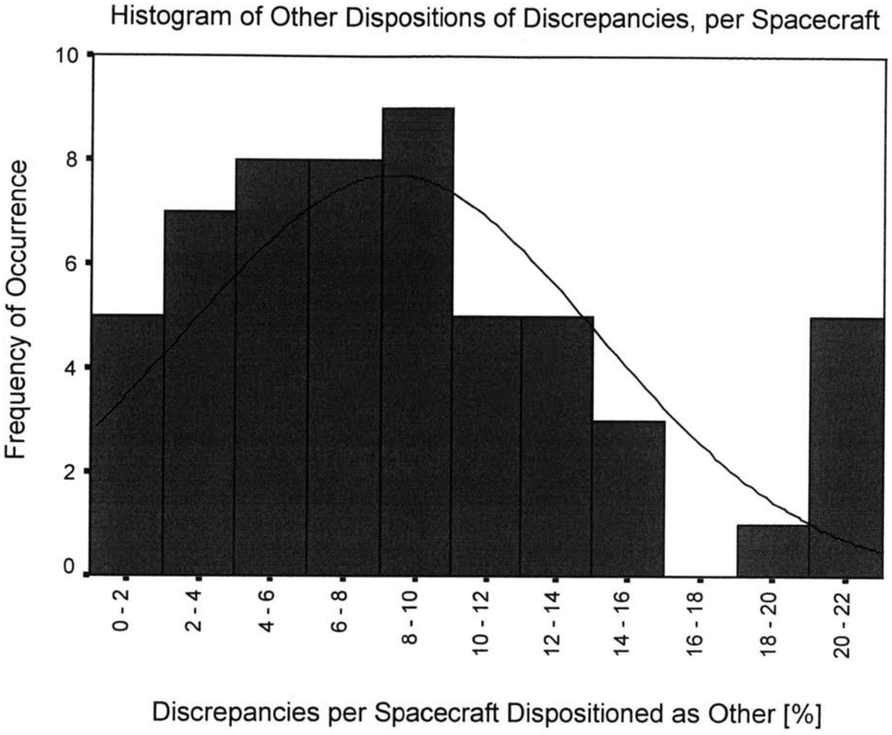


**Figure 3.34: Histogram of Other Dispositioned discrepancies, per spacecraft**

## 3.8. Root Cause Statistical Analysis

This section analyzes the root cause data for spacecraft discrepancies. These data describe the underlying reason for occurrence of a discrepancy. These data are categorized into eight bins. For a detailed description of each of these bins, please see Chapter 1. The eight bins, or subcategories, are:

- Employee/Operator
- Design
- Material
- Equipment
- Software
- No Anomaly
- Unknown
- Other

A presentation of the subcategory percentile statistics first introduces the general nature of the distribution of the root cause data. Box plots and a summary of means follows. Finally, descriptive statistics and correlation for each subcategory are explored. The total number of spacecraft used in the root cause analysis is 113.

### 3.8.1. Root Cause Category Percentiles

Most of the data in the eight subcategories of root cause do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics to better visualize how the data are distributed. These are presented in Table 3.28.

Material, Software, No Anomaly, Unknown and Other causes all have zero values below the 25th percentile, indicating a concentration at the left end of those distributions. Employee/Operator, Design and Equipment do not appear to have a concentration of values in any of their percentile categories, indicating that those data are more spread out and potentially candidates to be normally distributed.

**Table 3.28: Root cause category percentile statistics**

| *Root Cause Subcategory* | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| Employee/ Operator | 15.00 | 15.40 | 21.00 | 26.00 | 32.00 | 41.00 | 43.00 |
| Design | 5.00 | 11.00 | 18.00 | 23.00 | 33.00 | 39.00 | 41.30 |
| Material | 0.00 | 0.00 | 0.00 | 1.00 | 3.00 | 7.00 | 8.30 |
| Equipment | 0.00 | 2.00 | 9.00 | 13.00 | 24.50 | 36.00 | 39.60 |
| Software | 0.00 | 0.00 | 3.00 | 11.00 | 17.00 | 22.60 | 25.00 |
| No Anomaly | 0.00 | 0.00 | 2.00 | 5.00 | 8.00 | 15.00 | 17.00 |
| Unknown | 0.00 | 0.00 | 0.00 | 0.00 | 6.00 | 10.00 | 12.00 |
| Other | 0.00 | 0.00 | 0.00 | 7.00 | 14.00 | 22.00 | 27.00 |

### 3.8.2. Root Cause Category Box Plots

The box plots below in Figure 3.35 show another portrayal of the dispersion of the root cause data. The Employee/Operator, Design and Equipment subcategory box plots all show a fairly even distribution around their median lines, indicating good candidates for normal distributions. Subsequent tests of normality will show that normality cannot be rejected for the design data.

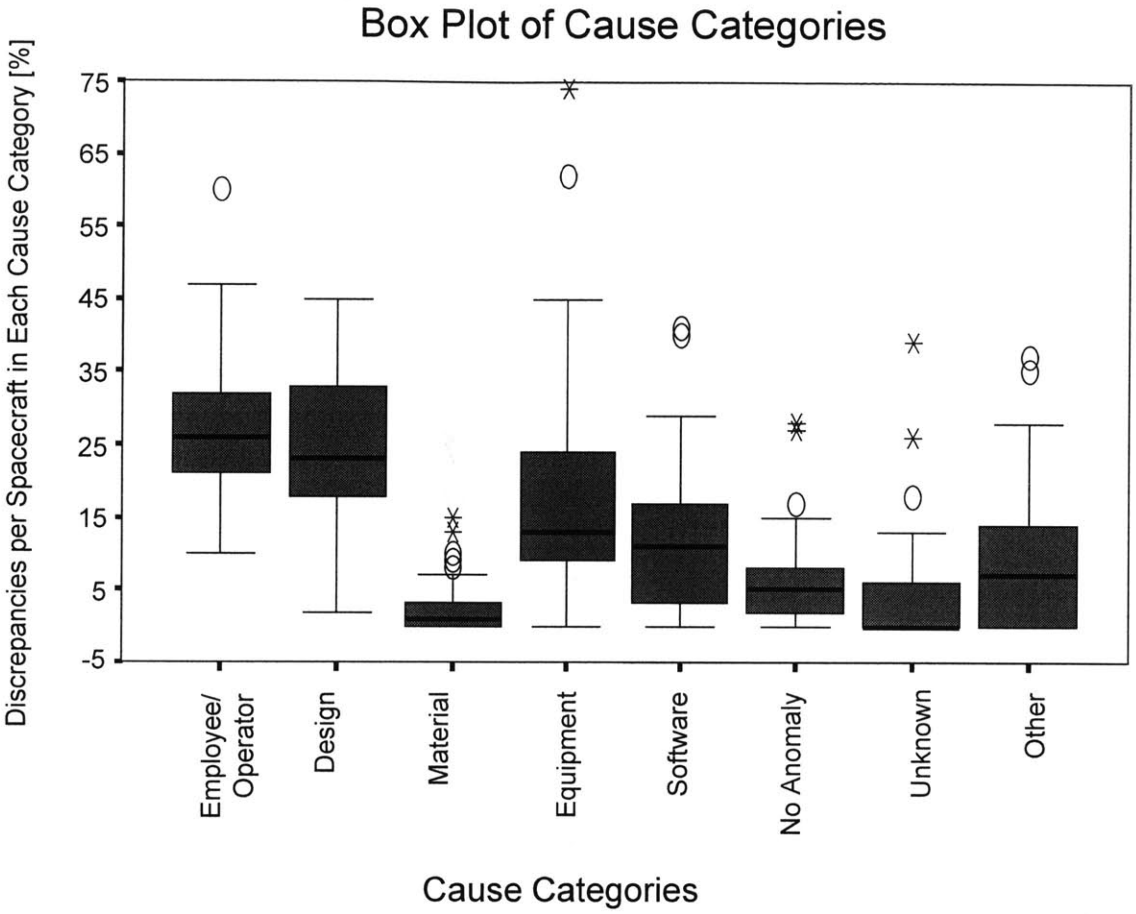


**Figure 3.35: Box plot of root cause categories**

### 3.8.3. Overview of Root Cause Means and Confidence Intervals

Figure 3.36 shows a summary of the means of the eight root cause subcategories, along with the 95% confidence interval upper and lower bounds on those means, and the medians. The Operator/Employee and Design subcategories account for the largest percentages of cause of discrepancies on an average spacecraft, with means of 27% and 25%, respectively. Equipment is also a significant contributor to the cause of discrepancies, with a mean of 17%.

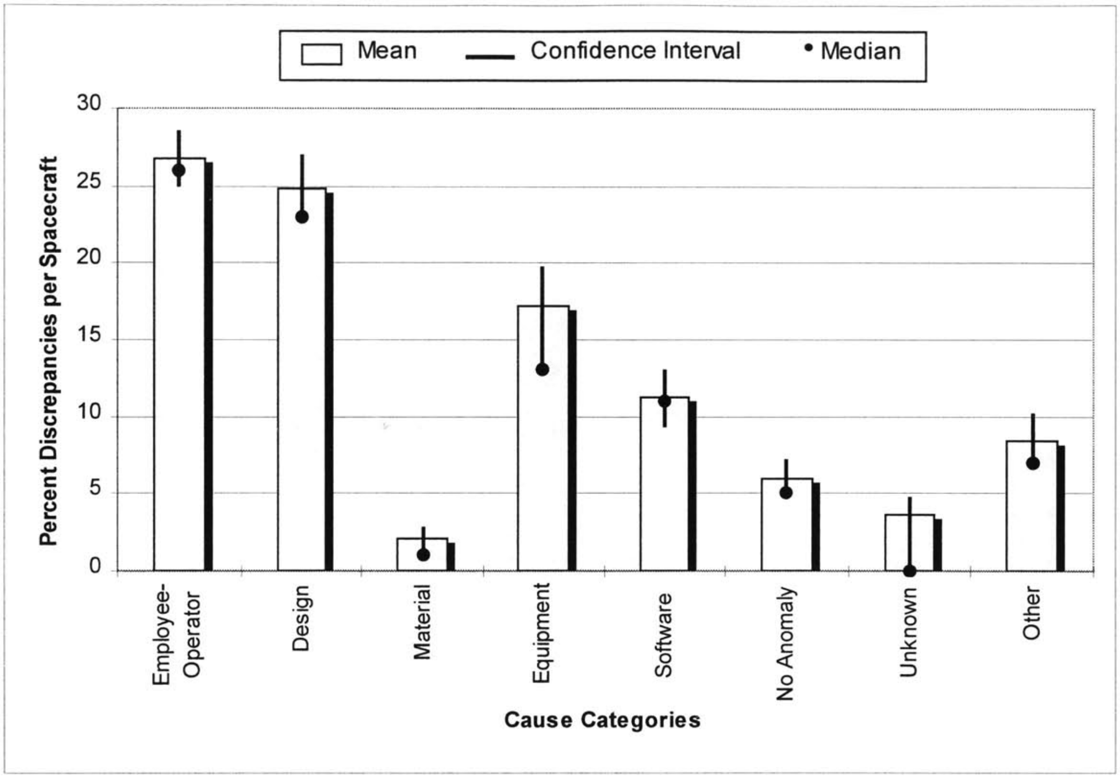


**Figure 3.36: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each cause category**

### 3.8.4. Employee/Operator Root Cause

Descriptive statistics for the Employee/Operator root cause subcategory are shown in Table 3.29. The mean, 5% trimmed mean, and median for the Employee/Operator root cause subcategory are somewhat similar, indicating that the data might be normally distributed. However, the ratio of skewness to its standard error, 3.28, indicates that the distribution is slightly right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 1.50, indicates that the distribution has tail lengths and peak height similar to a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Employee/Operator root cause data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Employee/Operator root cause subcategory in Figure 3.37.

**Table 3.29: Employee/operator root cause subcategory descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 26.82 | 0.84 |
| **95% Confidence Interval for Mean: Lower Bound** | 25.15 | |
| **95% Confidence Interval for Mean: Upper Bound** | 28.49 | |
| **5% Trimmed Mean** | 26.44 | |
| **Median** | 26.00 | |
| **Variance** | 80.254 | |
| **Standard Deviation** | 8.96 | |
| **Minimum** | 10 | |
| **Maximum** | 60 | |
| **Skewness** | 0.746 | 0.227 |
| **Kurtosis** | 0.677 | 0.451 |

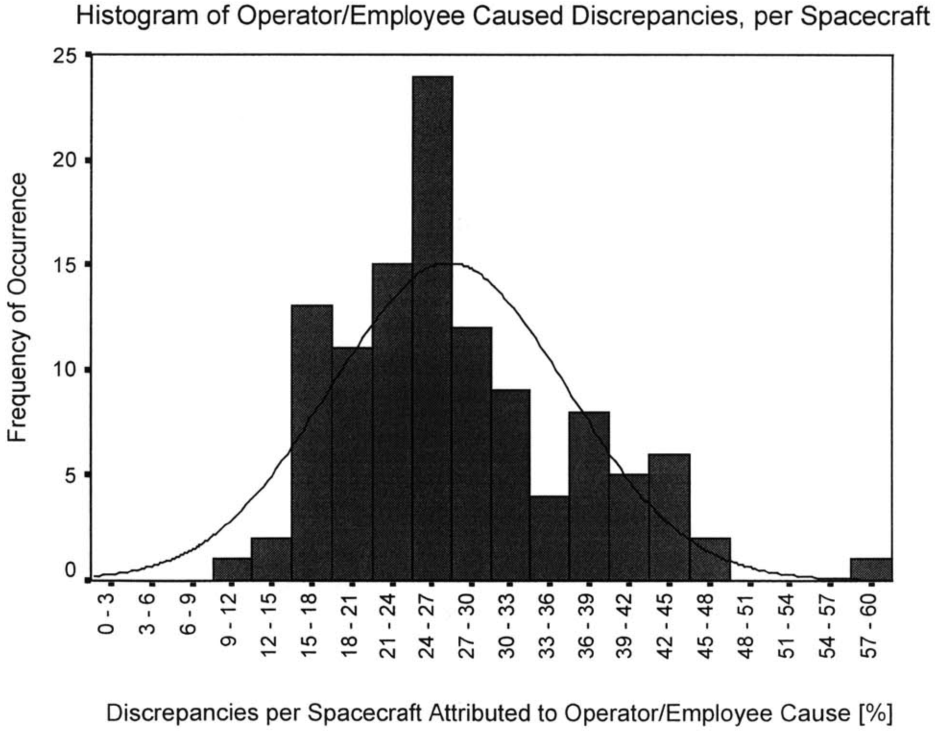


**Figure 3.37: Histogram of operator/employee caused discrepancies, per spacecraft**

### 3.8.5. Design Root Cause

Descriptive statistics for the Design root cause subcategory are shown in Table 3.30. The mean, 5% trimmed mean, and median for the Design root cause subcategory are somewhat similar, indicating that the data might be normally distributed. The ratio of skewness to its standard error, -0.60, indicates that the distribution is not skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -1.62, indicates that the distribution has tail lengths and a peak height similar to a normal distribution. Because the absolute value of both of the ratios is less than 2, normality for the Design root cause data cannot be rejected. Thus, the Design root cause data are normally distributed. The skewness and kurtosis measures are confirmed by examining the histogram of the Design root cause subcategory in Figure 3.38.

**Table 3.30: Design root cause subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 24.89 | 0.98 |
| **95% Confidence Interval for Mean: Lower Bound** | 22.95 | |
| **95% Confidence Interval for Mean: Upper Bound** | 26.84 | |
| **5% Trimmed Mean** | 25.07 | |
| **Median** | 23.00 | |
| **Variance** | 108.560 | |
| **Standard Deviation** | 10.42 | |
| **Minimum** | 2 | |
| **Maximum** | 45 | |
| **Skewness** | -0.166 | 0.227 |
| **Kurtosis** | -0.732 | 0.451 |

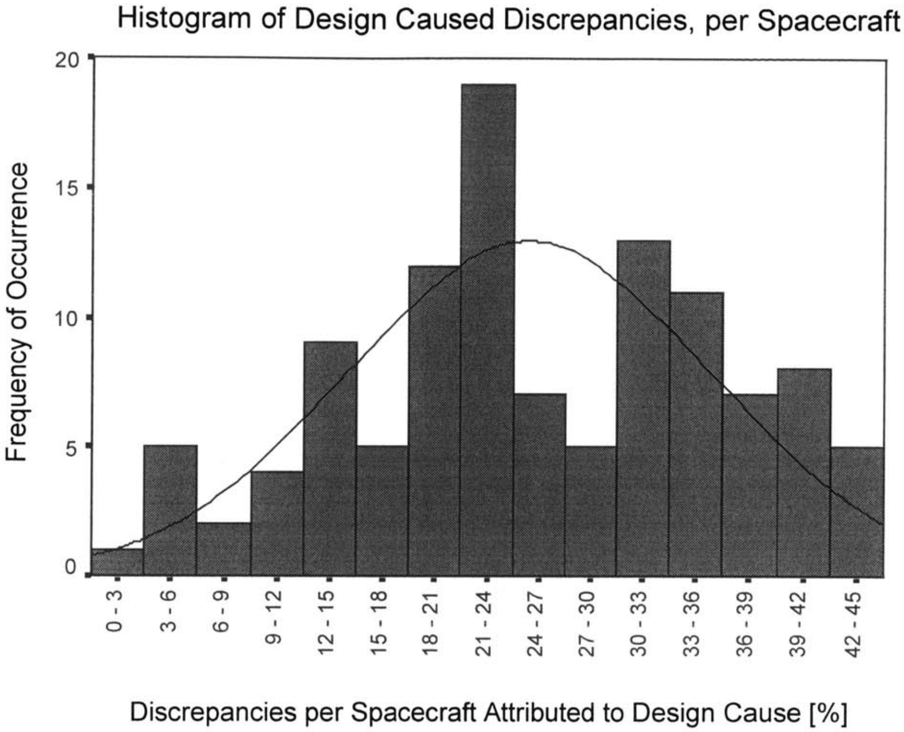


**Figure 3.38: Histogram of design caused discrepancies, per spacecraft**

### 3.8.5.1. Design Cause Correlation

Correlation appeared between the Design cause category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Design cause subcategory and the Drawing/Spec corrective action subcategory have a positive correlation of 0.724 (N=107) at the 0.01 level of significance. This means that as the occurrence of Design cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Drawing/Spec corrective action for discrepancies.

## 3.8.6. Material Root Cause

Descriptive statistics for the Material root cause subcategory are shown in Table 3.31. The mean, 5% trimmed mean, and median for the Material root cause subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 8.21, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 8.04, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Material root cause by examining the histogram of the Material root cause subcategory in Figure 3.39.

**Table 3.31: Material root cause subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 2.13 | 0.29 |
| **95% Confidence Interval for Mean: Lower Bound** | 1.57 | |
| **95% Confidence Interval for Mean: Upper Bound** | 2.70 | |
| **5% Trimmed Mean** | 1.76 | |
| **Median** | 1.00 | |
| **Variance** | 9.188 | |
| **Standard Deviation** | 3.03 | |
| **Minimum** | 0 | |
| **Maximum** | 15 | |
| **Skewness** | 1.863 | 0.227 |
| **Kurtosis** | 3.626 | 0.451 |

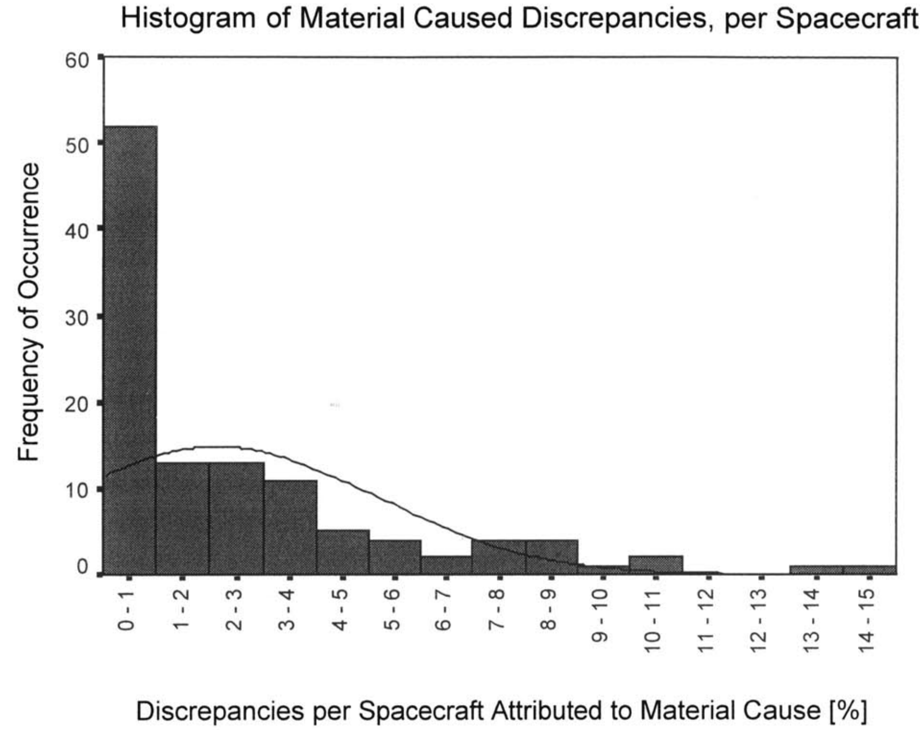


**Figure 3.39: Histogram of material caused discrepancies, per spacecraft**

### 3.8.7. Test Equipment Root Cause

Descriptive statistics for the Test Equipment root cause subcategory are shown in Table 3.32. The mean, 5% trimmed mean, and median for the Test Equipment root cause subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 5.97, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 5.91, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Test Equipment root cause data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Test Equipment root cause subcategory in Figure 3.40.

**Table 3.32: Test equipment root cause subcategory descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 17.14 | 1.25 |
| **95% Confidence Interval for Mean: Lower Bound** | 14.67 | |
| **95% Confidence Interval for Mean: Upper Bound** | 19.62 | |
| **5% Trimmed Mean** | 16.20 | |
| **Median** | 13.00 | |
| **Variance** | 176.533 | |
| **Standard Deviation** | 13.29 | |
| **Minimum** | 0 | |
| **Maximum** | 74 | |
| **Skewness** | 1.356 | 0.227 |
| **Kurtosis** | 2.664 | 0.451 |

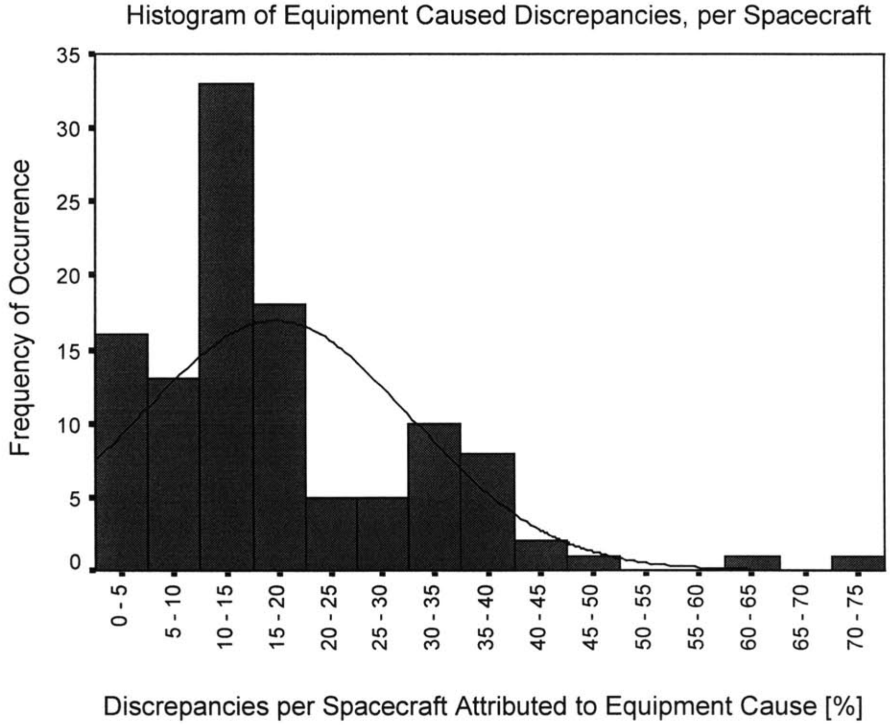


**Figure 3.40: Histogram of test equipment caused discrepancies, per spacecraft**

#### *3.8.7.1. Test Equipment Cause Correlation*

Correlation appeared between the Equipment cause category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Equipment cause subcategory and the DMS/TTC subsystem subcategory have a negative correlation of 0.606 (N=105) at the 0.01 level of significance. This means that as the occurrence of Equipment cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of DMS/TTC subsystem discrepancies.
- The Equipment cause subcategory and the Other cause subcategory have a negative correlation of 0.606 (N=113) at the 0.01 level of significance. This means that as the occurrence of Equipment cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Other causes of discrepancies.
- The Equipment cause subcategory and the Rework disposition subcategory have a negative correlation of 0.630 (N=56) at the 0.01 level of significance. This means that as the occurrence of Equipment cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Rework dispositioned discrepancies.
- The Equipment cause subcategory and the Drawing/Spec corrective action subcategory have a negative correlation of 0.698 (N=107) at the 0.01 level of significance. This means that as the occurrence of Equipment cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Drawing/Spec corrective actions for discrepancies.
- The Equipment cause subcategory and the Equipment corrective action subcategory have a positive correlation of 0.806 (N=107) at the 0.01 level of significance. This means that as the occurrence of Equipment cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Equipment corrective actions for discrepancies.

### 3.8.8. Software Root Cause

Descriptive statistics for the Software root cause subcategory are shown in Table 3.33. The mean, 5% trimmed mean, and median for the Software root cause subcategory are somewhat different. This indicates that the data are likely not normally distributed. The ratio of skewness to its standard error, 3.65, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 2.03, indicates that the distribution has nearly the same length tails as a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Software root cause data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Software root cause subcategory in Figure 3.41.

**Table 3.33: Software root cause subcategory descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 11.19 | 0.87 |
| **95% Confidence Interval for Mean: Lower Bound** | 9.47 | |
| **95% Confidence Interval for Mean: Upper Bound** | 12.92 | |
| **5% Trimmed Mean** | 10.55 | |
| **Median** | 11.00 | |
| **Variance** | 85.212 | |
| **Standard Deviation** | 9.23 | |
| **Minimum** | 0 | |
| **Maximum** | 41 | |
| **Skewness** | 0.839 | 0.227 |
| **Kurtosis** | 0.914 | 0.451 |

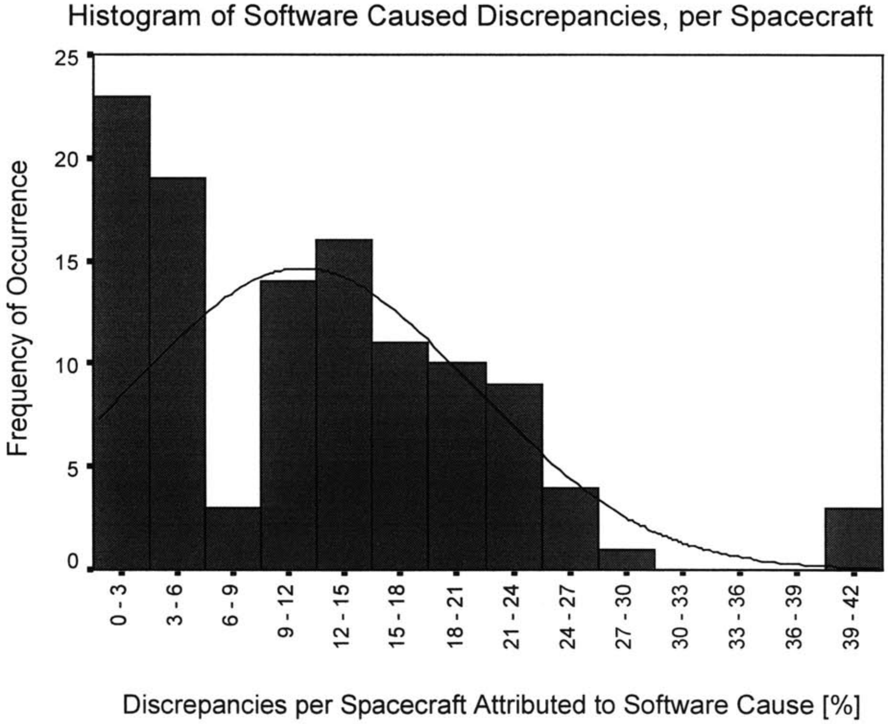


**Figure 3.41: Histogram of software caused discrepancies, per spacecraft**

#### 3.8.8.1. Software Cause Correlation

Correlation appeared between the Software cause category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Software cause subcategory and the Software corrective action subcategory have a positive correlation of 0.864 (N=107) at the 0.01 level of significance. This means that as the occurrence of Software cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Software corrective actions for discrepancies.

### 3.8.9. No Anomaly Root Cause

Descriptive statistics for the No Anomaly root cause subcategory are shown in Table 3.34. The mean, 5% trimmed mean, and median for the No Anomaly root cause subcategory are somewhat different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 7.72, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 8.54, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the No Anomaly root cause data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the No Anomaly root cause subcategory in Figure 3.42.

**Table 3.34: No anomaly root cause subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 5.99 | 0.54 |
| **95% Confidence Interval for Mean: Lower Bound** | 4.93 | |
| **95% Confidence Interval for Mean: Upper Bound** | 7.06 | |
| **5% Trimmed Mean** | 5.40 | |
| **Median** | 5.00 | |
| **Variance** | 32.687 | |
| **Standard Deviation** | 5.72 | |
| **Minimum** | 0 | |
| **Maximum** | 28 | |
| **Skewness** | 1.753 | 0.227 |
| **Kurtosis** | 3.853 | 0.451 |

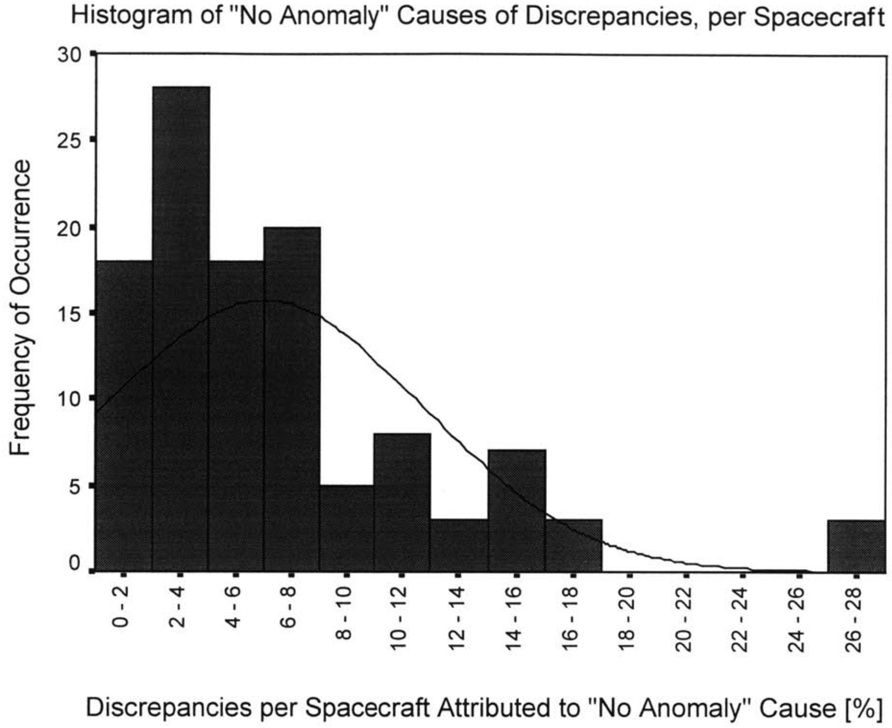


**Figure 3.42: Histogram of "no anomaly" causes of discrepancies, per spacecraft**

### *3.8.9.1. No Anomaly Cause Correlation*

Correlation appeared between the No Anomaly cause category and other parameters collected about spacecraft system-level I&T discrepancies.

- The No Anomaly cause subcategory and the EPDS subsystem subcategory have a negative correlation of 0.608 (N=105) at the 0.01 level of significance. This means that as the occurrence of No Anomaly cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The No Anomaly cause subcategory and the Equipment subsystem subcategory have a positive correlation of 0.604 (N=105) at the 0.01 level of significance. This means that as the occurrence of No Anomaly cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies

### 3.8.10. Unknown Root Cause

Descriptive statistics for the Unknown root cause subcategory are shown in Table 3.35. The mean, 5% trimmed mean, and median for the Unknown root cause subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 13.45, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 31.54, indicates that the distribution has much longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Unknown root cause data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Unknown root cause subcategory in Figure 3.43.

**Table 3.35: Unknown root cause subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 3.58 | 0.53 |
| **95% Confidence Interval for Mean: Lower Bound** | 2.52 | |
| **95% Confidence Interval for Mean: Upper Bound** | 4.64 | |
| **5% Trimmed Mean** | 2.84 | |
| **Median** | 0.00 | |
| **Variance** | 32.334 | |
| **Standard Deviation** | 5.69 | |
| **Minimum** | 0 | |
| **Maximum** | 39 | |
| **Skewness** | 3.053 | 0.227 |
| **Kurtosis** | 14.224 | 0.451 |

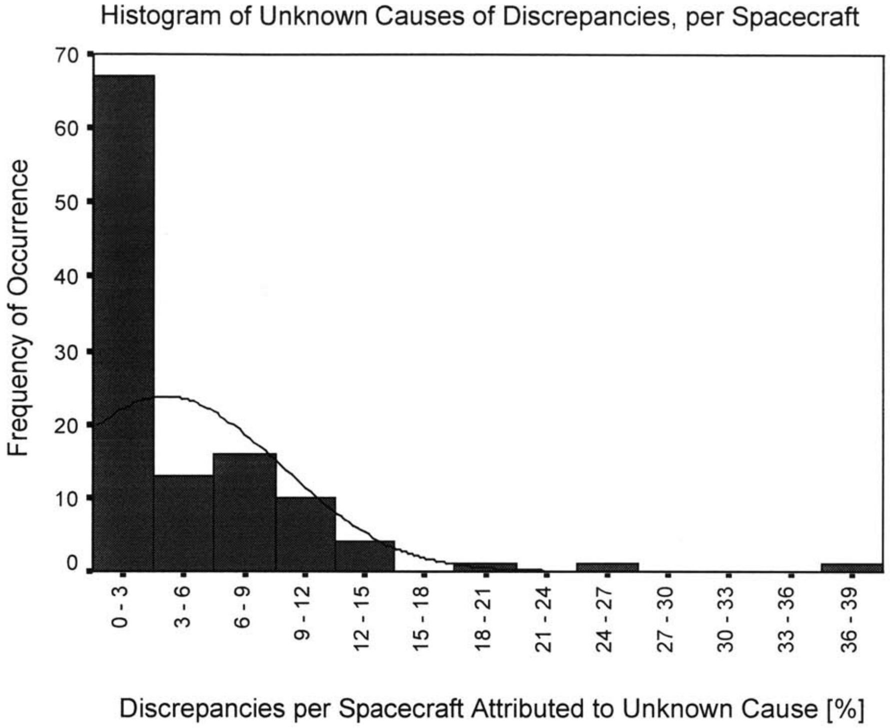


**Figure 3.43: Histogram of unknown causes of discrepancies, per spacecraft**

### *3.8.10.1. Unknown Cause Correlation*

Correlation appeared between the Unknown cause category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Unknown cause subcategory and the 0-30 Days open duration subcategory have a positive correlation of 0.601 (N=113) at the 0.01 level of significance. This means that as the occurrence of Unknown cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of discrepancies open 0-30 Days.
- The Unknown cause subcategory and the Employee/Operator corrective action subcategory have a positive correlation of 0.734 (N=107) at the 0.01 level of significance. This means that as the occurrence of Unknown Cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Employee/Operator corrective actions for discrepancies.

### 3.8.11. Other Root Cause

Descriptive statistics for the Other root cause subcategory are shown in Table 3.36. The mean, 5% trimmed mean, and median for the Other root cause subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 4.50, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 0.77, indicates that the distribution has tail lengths and peak height similar to a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Other root cause data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Other root cause subcategory in Figure 3.44.

**Table 3.36: Other root cause subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 8.36 | 0.85 |
| **95% Confidence Interval for Mean: Lower Bound** | 6.68 | |
| **95% Confidence Interval for Mean: Upper Bound** | 10.04 | |
| **5% Trimmed Mean** | 7.61 | |
| **Median** | 7.00 | |
| **Variance** | 81.340 | |
| **Standard Deviation** | 9.02 | |
| **Minimum** | 0 | |
| **Maximum** | 37 | |
| **Skewness** | 1.021 | 0.227 |
| **Kurtosis** | 0.346 | 0.451 |

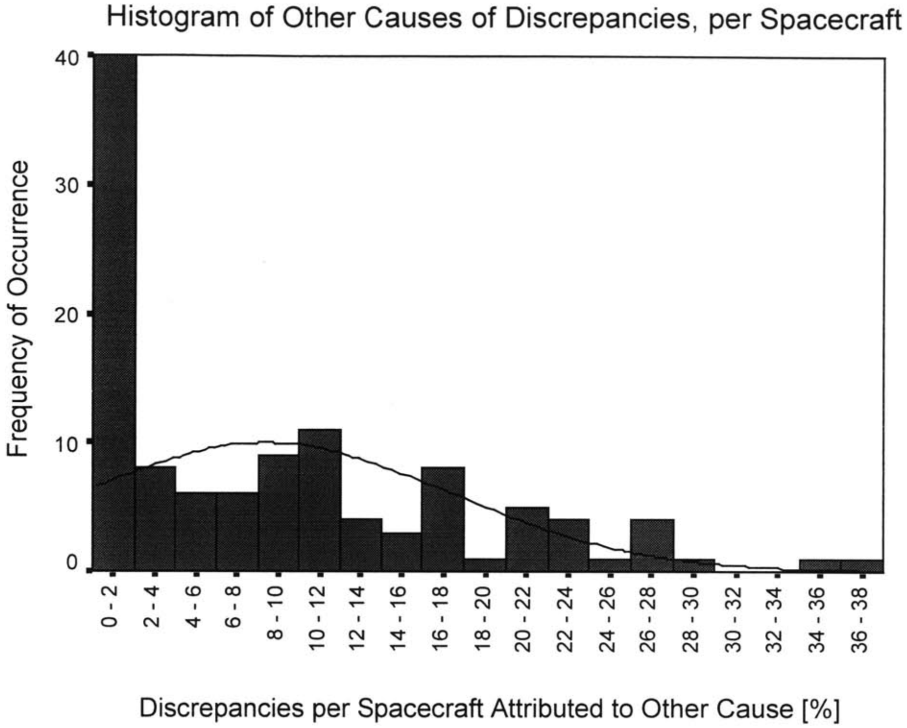


**Figure 3.44: Histogram of other causes of discrepancies, per spacecraft.**

### *3.8.11.1. Other Cause Correlation*

Correlation appeared between the Unknown cause category and other parameters collected about spacecraft system-level I&T discrepancies.

- The Other cause subcategory and the Mission category have a correlation of 0.617 (N=113) at the 0.01 level of significance. This means that the number of Other causes occurring on a given spacecraft tended to be lower for communications missions, and higher for non-communications missions.
- The Other cause subcategory and the Thermal subsystem subcategory have a positive correlation of 0.631 (N=105) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Thermal subsystem discrepancies.
- The Other cause subcategory and the EPDS subsystem subcategory have a positive correlation of 0.689 (N=105) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.

- The Other cause subcategory and the Equipment subsystem subcategory have a negative correlation of 0.611 (N=105) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies.
- The Other cause subcategory and the Spacecraft subsystem subcategory have a negative correlation of 0.684 (N=105) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Spacecraft subsystem discrepancies.
- The Other cause subcategory and the DMS/TTC subsystem subcategory have a positive correlation of 0.713 (N=105) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of DMS/TTC subsystem discrepancies.
- The Other cause subcategory and the Use As Is disposition subcategory have a negative correlation of 0.674 (N=56) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Use As Is dispositioned discrepancies.
- The Other cause subcategory and the Rework dispositioned subcategory have a positive correlation of 0.755 (N=56) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Rework dispositioned discrepancies.
- The Other cause subcategory and the Drawing/Spec corrective action subcategory have a positive correlation of 0.671 (N=107) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Drawing/Spec corrective action for discrepancies.
- The Other cause subcategory and the Equipment corrective action subcategory have a negative correlation of 0.695 (N=107) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment corrective action for discrepancies.
- The Other cause subcategory and the Equipment cause subcategory have a negative correlation of 0.606 (N=113) at the 0.01 level of significance. This means that as the occurrence of Other cause discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment cause for discrepancies.

## 3.9. Corrective Action Statistical Analysis

This section analyzes the corrective action data for spacecraft discrepancies. These data describe the long-term corrective action that was prescribed to prevent the discrepancy from occurring on future spacecraft. These data are categorized into eight bins. For a detailed description of each of these bins, please see Chapter 1. The eight bins, or subcategories, are:

- Operator/Employee
- Drawing/Spec
- Process/Procedure
- Software Change
- Equipment
- Supplier-related
- No Action Required
- Other Corrective Action

A presentation of the subcategory percentile statistics first introduces the general nature of the distribution of the corrective action data. Box plots and a summary of means follows. Finally, descriptive statistics and correlation for each subcategory are explored. The total number of spacecraft used in the corrective action analysis is 108.

### 3.9.1. Corrective Action Category Percentiles

Most of the data in the eight subcategories of corrective action do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics to better visualize how the data are distributed. These are shown in Table 3.37.

Drawing/Spec, Software Change, Supplier-Related and Other corrective action subcategories all have zero values at or below the 25th percentile, indicating a concentration at the left end of those distributions. Employee/Operator and Process/Procedure do not appear to have a concentration of values in any of their percentile categories, indicating that those data are more spread out and potentially candidates to be normally distributed.

**Table 3.37: Corrective action category percentile statistics**

| *Corrective Action Subcategory* | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| Operator/ Employee | 0.00 | 3.00 | 6.00 | 9.50 | 23.00 | 32.00 | 34.55 |
| Drawing/Spec | 0.00 | 0.00 | 5.00 | 10.50 | 24.00 | 34.10 | 40.55 |
| Process/ Procedure | 1.00 | 4.00 | 9.00 | 15.00 | 22.00 | 34.00 | 38.85 |
| Software Change | 0.0 | 0.00 | 1.00 | 9.00 | 16.00 | 28.20 | 34.55 |
| Equipment | 0.00 | 1.80 | 6.00 | 10.00 | 24.75 | 35.00 | 41.65 |
| Supplier-related | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 6.00 | 11.00 |
| No Action Required | 7.00 | 9.90 | 17.00 | 22.00 | 28.00 | 33.00 | 44.55 |
| Other Corrective Action | 0.00 | 0.00 | 0.00 | 1.00 | 5.00 | 11.10 | 14.00 |

### 3.9.2. Corrective Action Box Plots

The box plots below in Figure 3.45 show another portrayal of the dispersion of the corrective action data. The box plots show an unsymmetrical distribution in most variables, indicated by the unequal box areas above and below the median line as well as by the unequal whisker lengths above and below the box. In addition, the Supplier-Related, No Action Required, and Other corrective action subcategories have several outliers and extreme values, as shown by the marks above the top whisker. Subsequent tests of normality will show that normality can be rejected for these corrective action data.

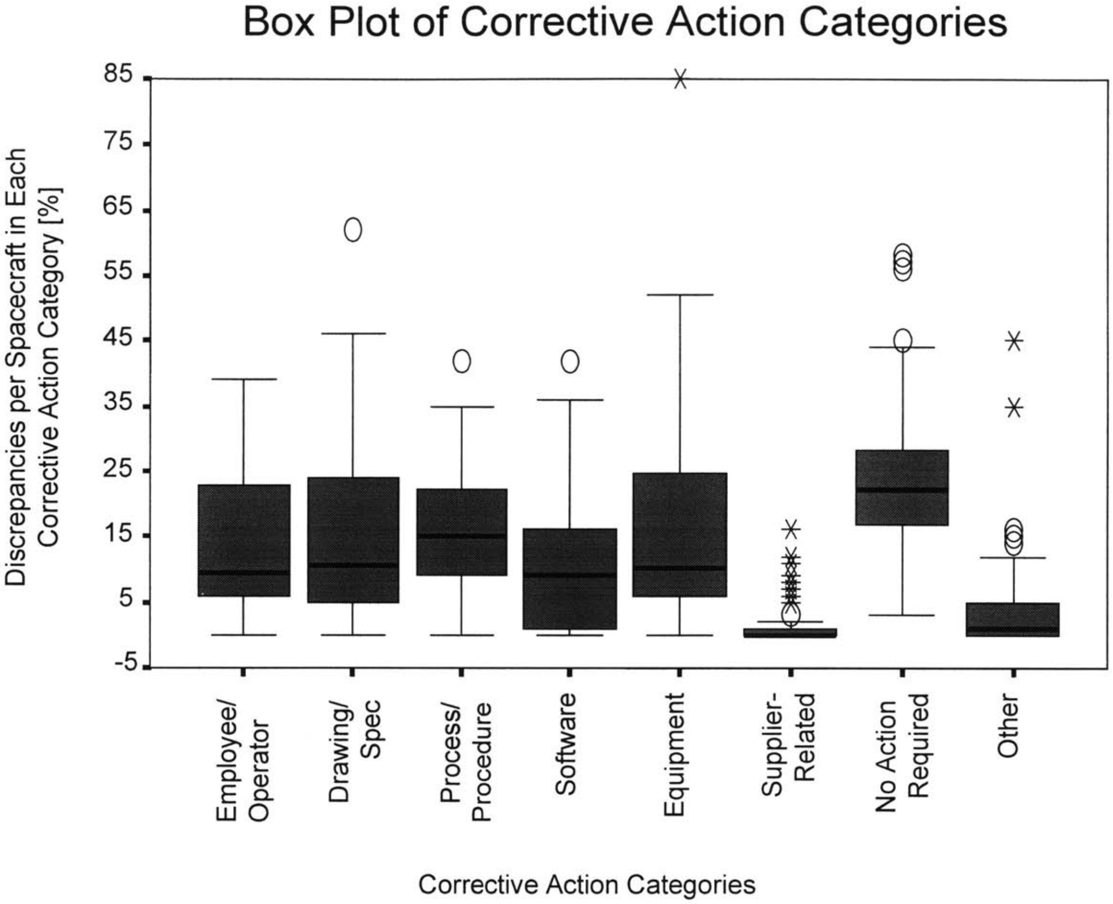


**Figure 3.45: Box plot of corrective action categories**

### 3.9.3. Overview of Corrective Action Means and Confidence Intervals

Figure 3.46 shows a summary of the means of the corrective action subcategories, along with the 95% confidence interval upper and lower bounds on those means, and the medians. The No Action Required subcategory, with a mean of 23%, accounts for the largest percentage of corrective action for discrepancies on an average spacecraft. Employee/Operator, Drawing/Spec, Process/Procedure, Software and Equipment each account for between 11% and 17% of corrective action for discrepancies on an average spacecraft. Supplier-Related and Other corrective action each account for only a few percent of corrective actions for discrepancies on an average spacecraft.

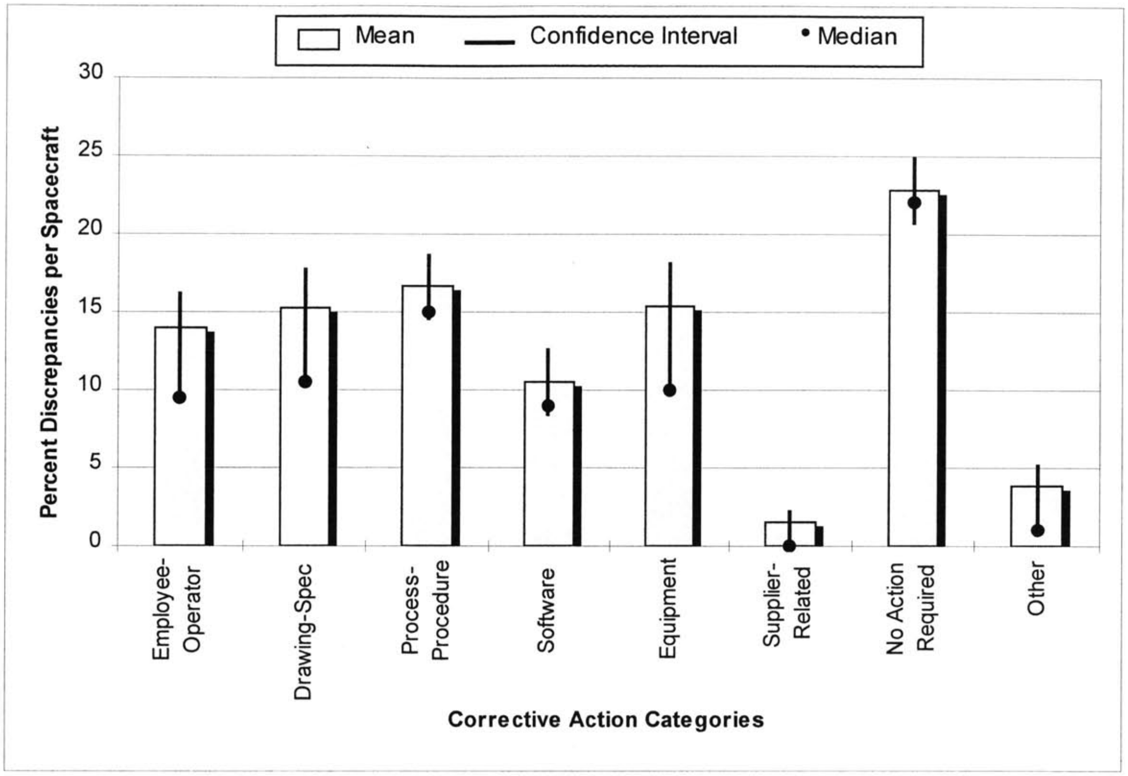


**Figure 3.46: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each corrective action category**

### 3.9.4. Operator/Employee Corrective Action

Descriptive statistics for the Operator/Employee corrective action subcategory are shown in Table 3.38. The mean, 5% trimmed mean, and median for the Operator/Employee corrective action subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 2.81, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -1.84, indicates that the distribution has tail lengths and a peak height similar to that of a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Operator/Employee corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Operator/Employee corrective action subcategory in Figure 3.47.

**Table 3.38: Operator/employee corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 14.03 | 1.06 |
| **95% Confidence Interval for Mean: Lower Bound** | 11.94 | |
| **95% Confidence Interval for Mean: Upper Bound** | 16.12 | |
| **5% Trimmed Mean** | 13.54 | |
| **Median** | 9.50 | |
| **Variance** | 120.233 | |
| **Standard Deviation** | 10.97 | |
| **Minimum** | 0 | |
| **Maximum** | 39 | |
| **Skewness** | 0.653 | 0.233 |
| **Kurtosis** | -0.848 | 0.461 |

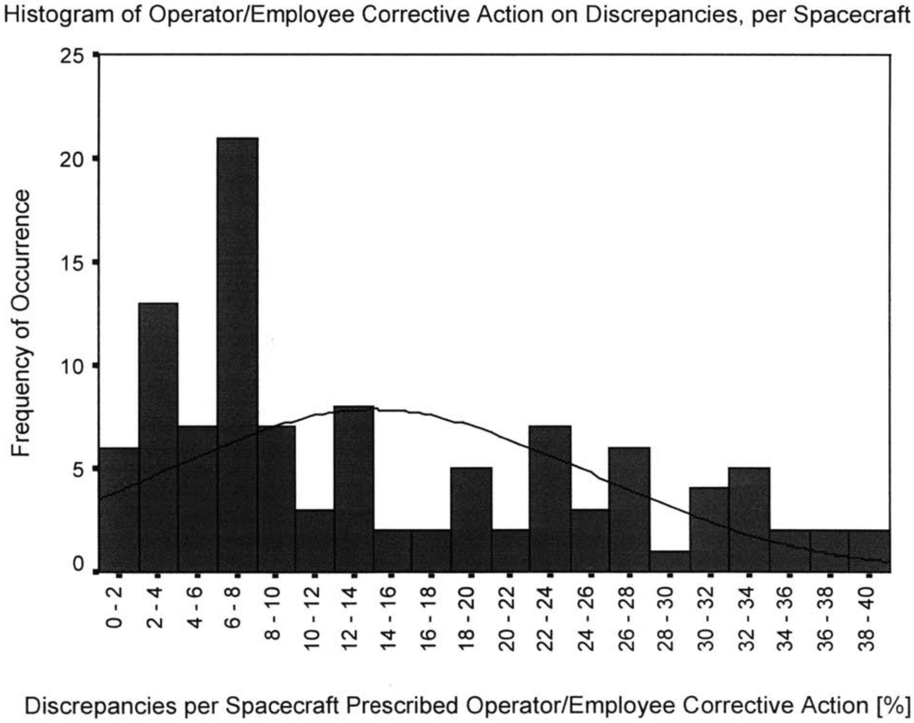


**Figure 3.47: Histogram of operator/employee corrective action on discrepancies, per spacecraft**

#### 3.9.4.1. Operator/Employee Corrective Action Correlation

Correlation appeared between the Operator/Employee corrective action subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The Operator/Employee corrective action subcategory and the Unknown cause subcategory have a positive correlation of 0.734 (N=107) at the 0.01 level of significance. This means that as the occurrence of Operator/Employee corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Unknown cause discrepancies.

### 3.9.5. Drawing/Specification Corrective Action

Descriptive statistics for the Drawing/Specification (Drawing/Spec) corrective action subcategory are shown in Table 3.39. The mean, 5% trimmed mean, and median for the Drawing/Spec corrective action subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 4.04, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 1.20, indicates that the distribution has tail lengths and a peak height similar to that of a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Drawing/Spec corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Drawing/Spec corrective action subcategory in Figure 3.48.

**Table 3.39: Drawing/specification corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 15.20 | 1.25 |
| **95% Confidence Interval for Mean: Lower Bound** | 12.73 | |
| **95% Confidence Interval for Mean: Upper Bound** | 17.68 | |
| **5% Trimmed Mean** | 14.29 | |
| **Median** | 10.50 | |
| **Variance** | 168.052 | |
| **Standard Deviation** | 12.96 | |
| **Minimum** | 0 | |
| **Maximum** | 62 | |
| **Skewness** | 0.943 | 0.233 |
| **Kurtosis** | 0.553 | 0.461 |

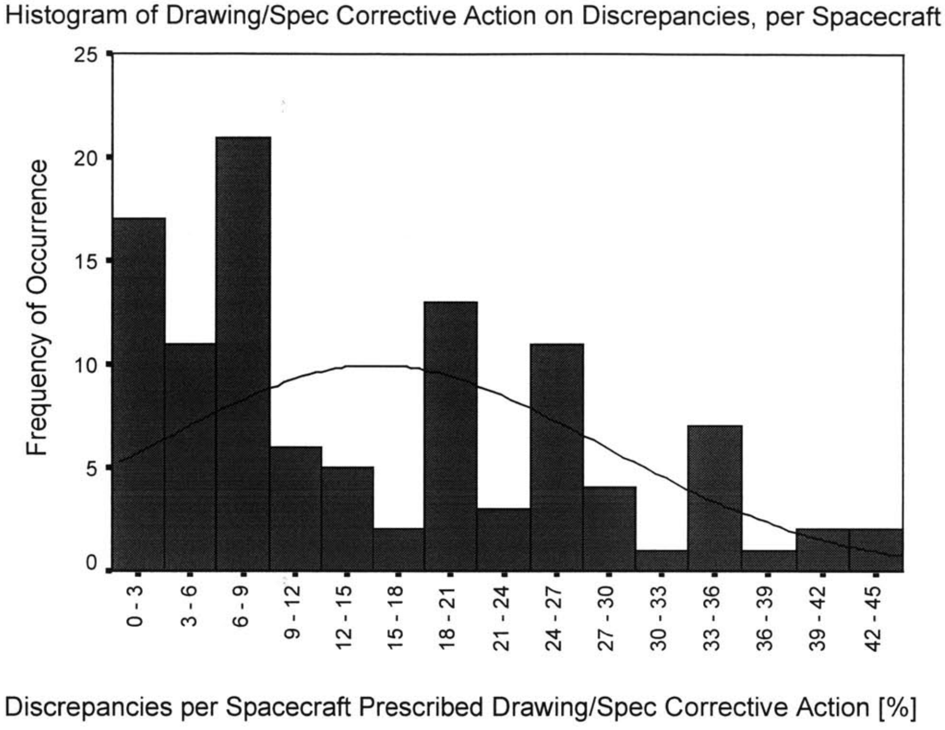


**Figure 3.48: Histogram of drawing/spec corrective action on discrepancies, per spacecraft**

### *3.9.5.1. Drawing/Spec Corrective Action Correlation*

Correlation appeared between the Drawing/Spec corrective action subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The Drawing/Spec corrective action subcategory and the EPDS subsystem subcategory have a positive correlation of 0.720 (N=100) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The Drawing/Spec corrective action subcategory and the Equipment subsystem subcategory have a negative correlation of 0.696 (N=100) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies.
- The Drawing/Spec corrective action subcategory and the Other subsystem subcategory have a positive correlation of 0.651 (N=100) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action

discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Other subsystem discrepancies.

- The Drawing/Spec corrective action subcategory and the DMS/TTC subsystem subcategory have a positive correlation of 0.684 (N=100) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of DMS/TTC subsystem discrepancies.
- The Drawing/Spec corrective action subcategory and the Design cause subcategory have a positive correlation of 0.724 (N=107) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Design cause of discrepancies.
- The Drawing/Spec corrective action subcategory and the Equipment cause subcategory have a negative correlation of 0.698 (N=107) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment cause of discrepancies.
- The Drawing/Spec corrective action subcategory and the Other cause subcategory have a positive correlation of 0.671 (N=107) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Other cause of discrepancies.
- The Drawing/Spec corrective action subcategory and the Equipment corrective action subcategory have a negative correlation of 0.750 (N=108) at the 0.01 level of significance. This means that as the occurrence of Drawing/Spec corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Equipment corrective action for discrepancies.

### 3.9.6. Process/Procedure Corrective Action

Descriptive statistics for the Process/Procedure corrective action subcategory are shown in Table 3.40. The mean, 5% trimmed mean, and median for the Process/Procedure corrective action subcategory are different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 2.76, indicates that the distribution is slightly right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -0.10, indicates that the distribution has tail lengths and a peak height very similar to that of a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Process/Procedure corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Process/Procedure corrective action subcategory in Figure 3.49.

**Table 3.40: Process/procedure corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 16.66 | 1.01 |
| **95% Confidence Interval for Mean: Lower Bound** | 14.66 | |
| **95% Confidence Interval for Mean: Upper Bound** | 18.65 | |
| **5% Trimmed Mean** | 16.19 | |
| **Median** | 15.00 | |
| **Variance** | 109.573 | |
| **Standard Deviation** | 10.47 | |
| **Minimum** | 0 | |
| **Maximum** | 42 | |
| **Skewness** | 0.643 | 0.233 |
| **Kurtosis** | -0.048 | 0.461 |

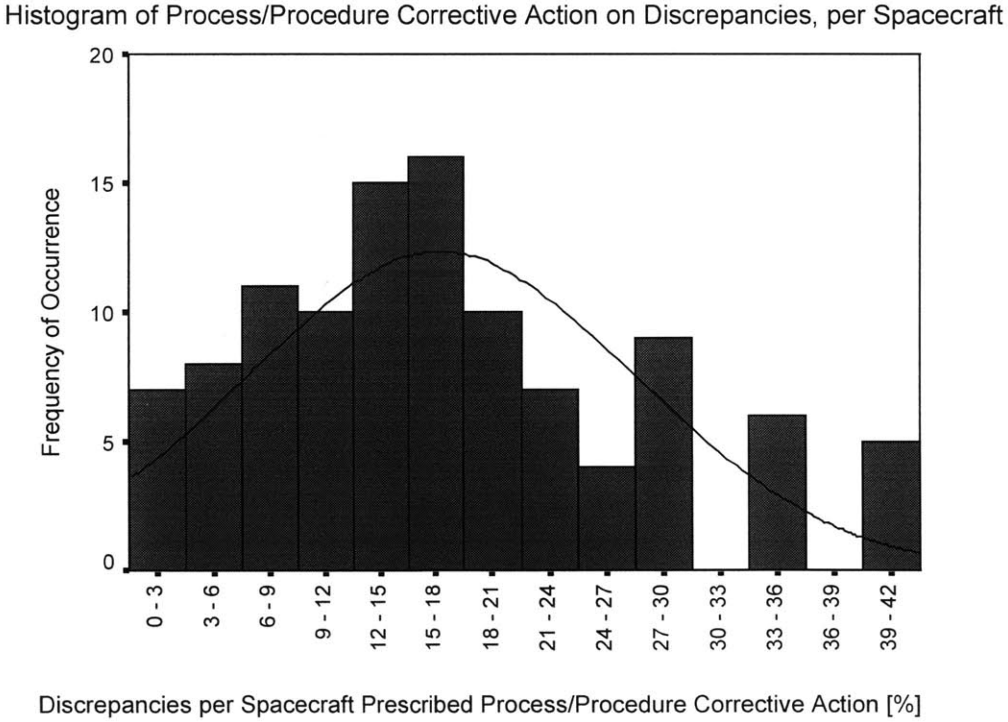


**Figure 3.49: Histogram of process/procedure corrective action on discrepancies, per spacecraft**

### 3.9.7. Software Corrective Action

Descriptive statistics for the Software corrective action subcategory are shown in Table 3.41. The mean, 5% trimmed mean, and median for the Software corrective action subcategory are somewhat different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 4.72, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 1.34, indicates that the distribution has tail lengths and a peak height similar to that of a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Software corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Software corrective action subcategory in Figure 3.50.

**Table 3.41: Software corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 10.47 | 1.03 |
| **95% Confidence Interval for Mean: Lower Bound** | 8.44 | |
| **95% Confidence Interval for Mean: Upper Bound** | 12.51 | |
| **5% Trimmed Mean** | 9.53 | |
| **Median** | 9.00 | |
| **Variance** | 113.896 | |
| **Standard Deviation** | 10.67 | |
| **Minimum** | 0 | |
| **Maximum** | 42 | |
| **Skewness** | 1.100 | 0.233 |
| **Kurtosis** | 0.617 | 0.461 |

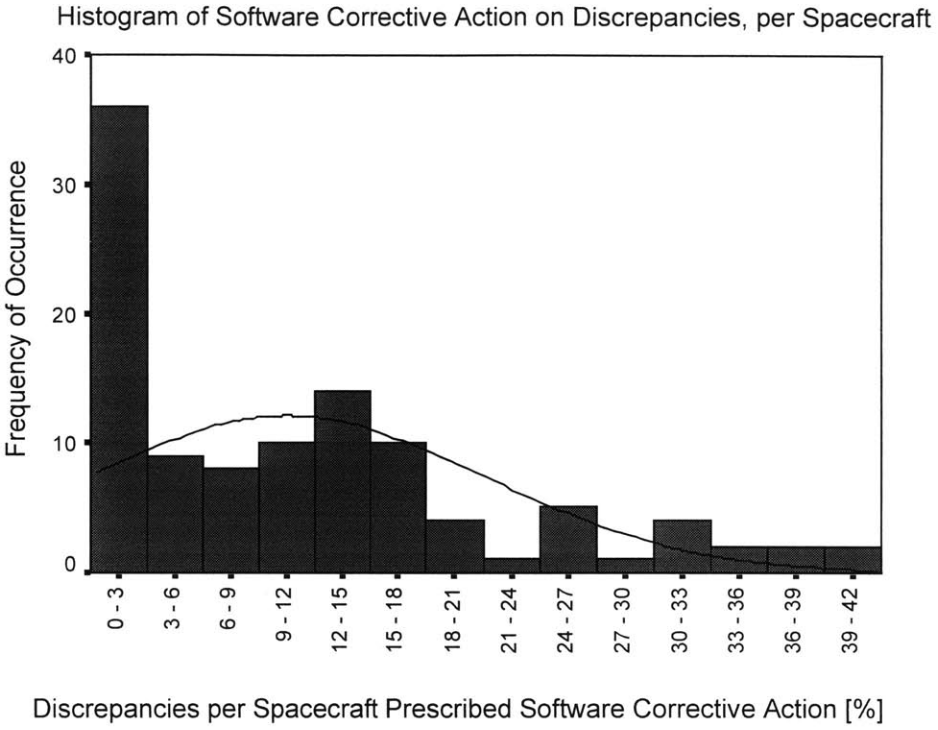


**Figure 3.50: Histogram of software corrective action on discrepancies, per spacecraft**

### 3.9.7.1. Software Corrective Action Correlation

Correlation appeared between the Software corrective action subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The Software corrective action subcategory and the Software cause subcategory have a positive correlation of 0.864 (N=107) at the 0.01 level of significance. This means that as the occurrence of Software corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Software causes of discrepancies.

## 3.9.8. Test Equipment Corrective Action

Descriptive statistics for the Test Equipment corrective action subcategory are shown in Table 3.42. The mean, 5% trimmed mean, and median for the Test Equipment corrective action subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 7.23, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 9.38, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Test Equipment corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Test Equipment corrective action subcategory in Figure 3.51.

**Table 3.42: Test equipment corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 15.40 | 1.38 |
| **95% Confidence Interval for Mean: Lower Bound** | 12.67 | |
| **95% Confidence Interval for Mean: Upper Bound** | 18.12 | |
| **5% Trimmed Mean** | 14.10 | |
| **Median** | 10.00 | |
| **Variance** | 204.242 | |
| **Standard Deviation** | 14.29 | |
| **Minimum** | 0 | |
| **Maximum** | 85 | |
| **Skewness** | 1.685 | 0.233 |
| **Kurtosis** | 4.322 | 0.461 |

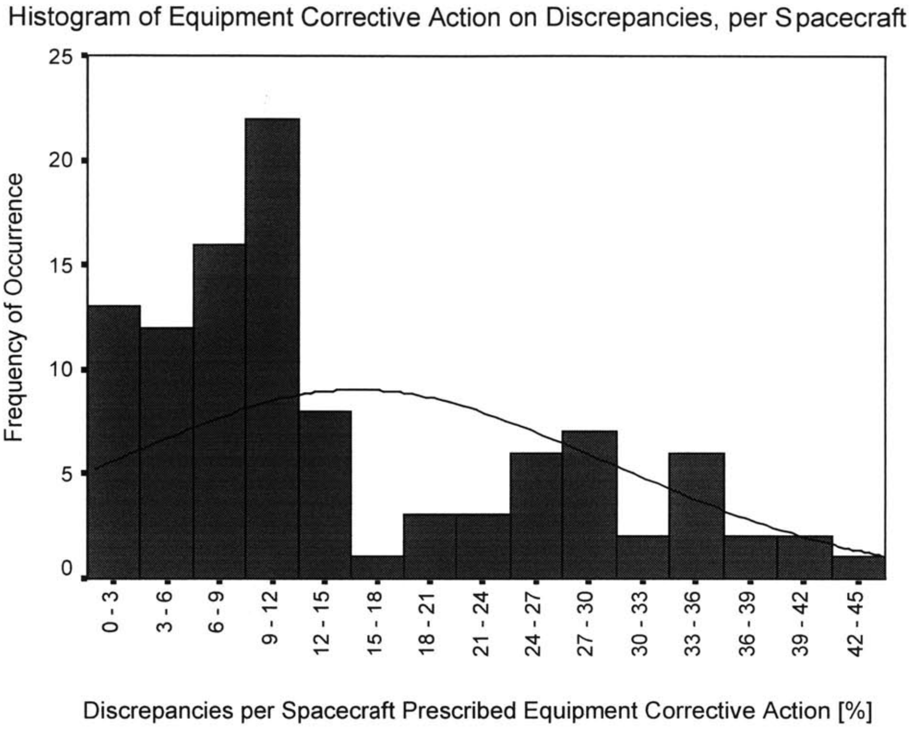


**Figure 3.51: Histogram of test equipment corrective action on discrepancies, per spacecraft**

#### 3.9.8.1. Test Equipment Corrective Action Correlation

Correlation appeared between the Equipment corrective action subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The Equipment corrective action subcategory and the EPDS subsystem subcategory have a negative correlation of 0.619 (N=100) at the 0.01 level of significance. This means that as the occurrence of Equipment corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of EPDS subsystem discrepancies.
- The Equipment corrective action subcategory and the Equipment subsystem subcategory have a positive correlation of 0.625 (N=100) at the 0.01 level of significance. This means that as the occurrence of Equipment corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Equipment subsystem discrepancies.
- The Equipment corrective action subcategory and the Equipment cause subcategory have a positive correlation of 0.806 (N=107) at the 0.01 level of significance. This means that as the occurrence of Equipment corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Equipment causes of discrepancies.

- The Equipment corrective action subcategory and the Other cause subcategory have a negative correlation of 0.695 (N=107) at the 0.01 level of significance. This means that as the occurrence of Equipment corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Other causes of discrepancies.
- The Equipment corrective action subcategory and the Drawing/Spec corrective action subcategory have a negative correlation of 0.750 (N=108) at the 0.01 level of significance. This means that as the occurrence of Equipment corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Drawing/Spec corrective action for discrepancies.

### 3.9.9. Supplier-related Corrective Action

Descriptive statistics for the Supplier-Related corrective action subcategory are shown in Table 3.43. The mean, 5% trimmed mean, and median for the Supplier-Related corrective action subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 11.72, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 15.51, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Supplier-Related corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Supplier-Related corrective action subcategory in Figure 3.52.

**Table 3.43: Supplier-related corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 1.50 | 0.33 |
| **95% Confidence Interval for Mean: Lower Bound** | 0.85 | |
| **95% Confidence Interval for Mean: Upper Bound** | 2.15 | |
| **5% Trimmed Mean** | 0.93 | |
| **Median** | 0.00 | |
| **Variance** | 11.505 | |
| **Standard Deviation** | 3.39 | |
| **Minimum** | 0 | |
| **Maximum** | 16 | |
| **Skewness** | 2.731 | 0.233 |
| **Kurtosis** | 7.152 | 0.461 |

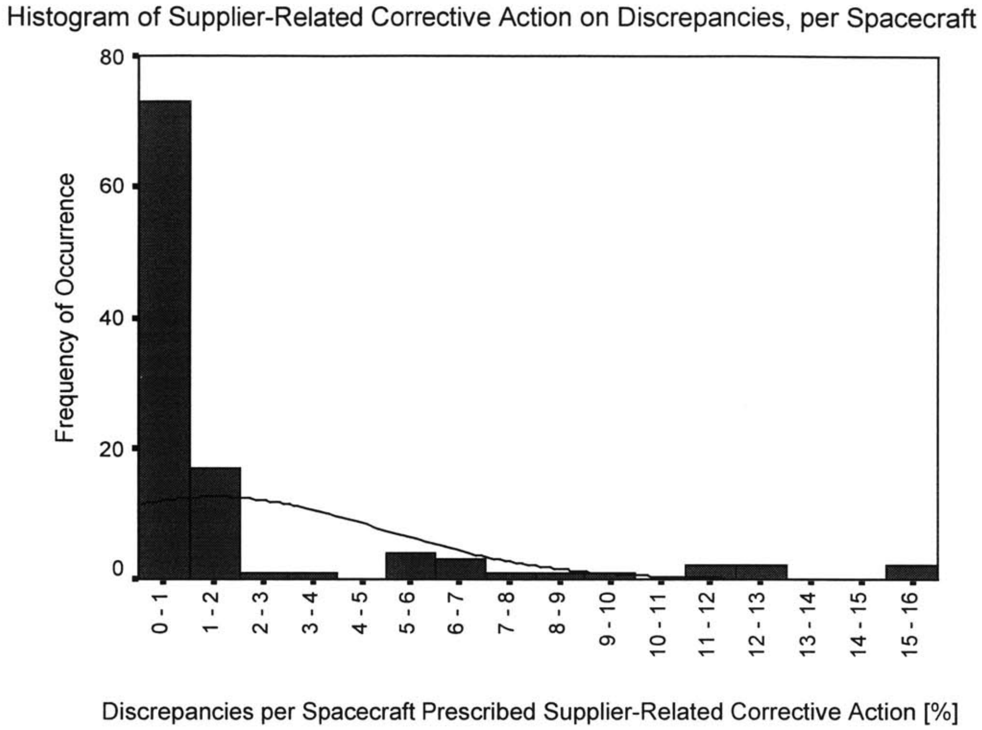


**Figure 3.52: Histogram of supplier-related corrective action on discrepancies, per spacecraft**

### *3.9.9.1. Supplier-Related Corrective Action Correlation*

Correlation appeared between the Supplier-Related corrective action subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The Supplier-Related corrective action subcategory and the SMS subsystem subcategory have a positive correlation of 0.690 (N=100) at the 0.01 level of significance. This means that as the occurrence of Supplier-Related corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of SMS subsystem discrepancies.
- The Supplier-Related corrective action subcategory and the Thermal subsystem subcategory have a positive correlation of 0.645 (N=100) at the 0.01 level of significance. This means that as the occurrence of Supplier-Related corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Thermal subsystem discrepancies.
- The Supplier-Related corrective action subcategory and the Use As Is disposition subcategory have a negative correlation of 0.686 (N=53) at the 0.01 level of significance. This means that as the occurrence of Supplier-Related corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Use As Is dispositioned discrepancies.

- The Supplier-Related corrective action subcategory and the Rework disposition subcategory have a positive correlation of 0.778 (N=53) at the 0.01 level of significance. This means that as the occurrence of Supplier-Related corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Rework dispositioned discrepancies.

### 3.9.10. No Action Required Corrective Action

Descriptive statistics for the Operator/Employee corrective action subcategory are shown in Table 3.44. The mean, 5% trimmed mean, and median for the Operator/Employee corrective action subcategory are somewhat similar. This indicates that the data might be normally distributed. However, the ratio of skewness to its standard error, 3.88, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 4.07, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Operator/Employee corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Operator/Employee corrective action subcategory in Figure 3.53.

**Table 3.44: No action required corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 22.81 | 1.01 |
| **95% Confidence Interval for Mean: Lower Bound** | 20.82 | |
| **95% Confidence Interval for Mean: Upper Bound** | 24.81 | |
| **5% Trimmed Mean** | 22.18 | |
| **Median** | 22.00 | |
| **Variance** | 109.199 | |
| **Standard Deviation** | 10.45 | |
| **Minimum** | 3 | |
| **Maximum** | 58 | |
| **Skewness** | 0.904 | 0.233 |
| **Kurtosis** | 1.878 | 0.461 |

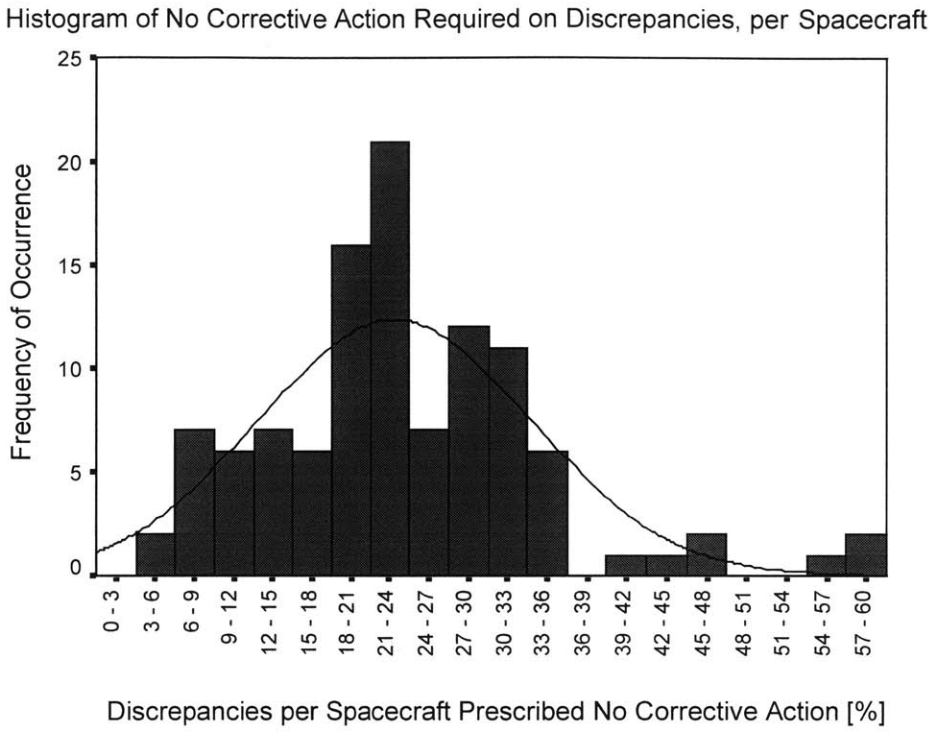


**Figure 3.53: Histogram of no corrective action required on discrepancies, per spacecraft**

### *3.9.10.1. No Action Required Corrective Action Correlation*

Correlation appeared between the No Action Required corrective action subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The No Action Required corrective action subcategory and the Use As Is disposition subcategory have a positive correlation of 0.604 (N=53) at the 0.01 level of significance. This means that as the occurrence of No Action Required corrective action discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Use As Is dispositioned discrepancies.
- The No Action Required corrective action subcategory and the Rework disposition subcategory have a negative correlation of 0.737 (N=53) at the 0.01 level of significance. This means that as the occurrence of No Action Required corrective action discrepancies on a given spacecraft went up, a corresponding decrease was observed on that given spacecraft in the occurrence of Rework dispositioned discrepancies.

### 3.9.11. Other Corrective Action

Descriptive statistics for the Other corrective action subcategory are shown in Table 3.45. The mean, 5% trimmed mean, and median for the Other corrective action subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 15.12, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 36.89, indicates that the distribution has much longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the Other corrective action data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the Other corrective action subcategory in Figure 3.54.

**Table 3.45: Other corrective action subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 3.83 | 0.64 |
| **95% Confidence Interval for Mean: Lower Bound** | 2.57 | |
| **95% Confidence Interval for Mean: Upper Bound** | 5.10 | |
| **5% Trimmed Mean** | 2.92 | |
| **Median** | 1.00 | |
| **Variance** | 43.972 | |
| **Standard Deviation** | 6.63 | |
| **Minimum** | 0 | |
| **Maximum** | 45 | |
| **Skewness** | 3.523 | 0.233 |
| **Kurtosis** | 17.005 | 0.461 |

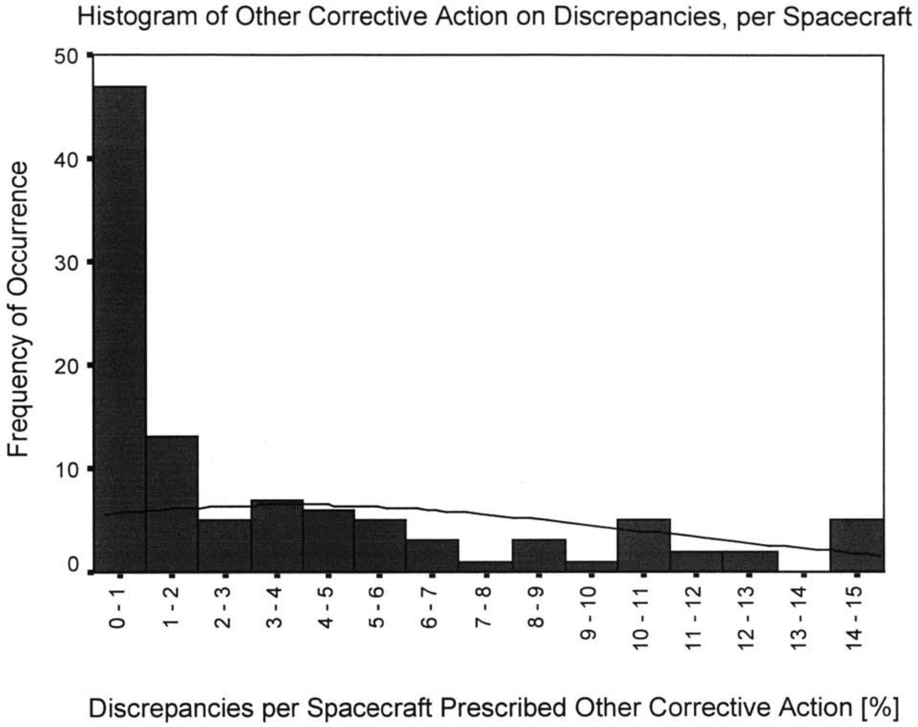


**Figure 3.54: Histogram of other corrective action on discrepancies, per spacecraft**

## 3.10. Open Duration Statistical Analysis

This section analyzes the open duration data for spacecraft discrepancies. These data describe how long a discrepancy remained open, or under investigation, on a spacecraft. This is not, however, an indication of the total labor hours that are spent on discrepancies. These data are categorized into eight bins. The seven bins, or subcategories, roughly correspond to months:

- 0-30 Days
- 31-60 Days
- 61-90 Days
- 91-120 Days
- 121-150 Days
- 151-180 Days

- Greater than 180 Days

A presentation of the subcategory percentile statistics first introduces the general nature of the distribution of the open duration data. Box plots and a summary of means follows. Finally, descriptive statistics and correlation for each subcategory are explored. The total number of spacecraft used in the open duration analysis is 139.

### 3.10.1. Open Duration Category Percentiles

Most of the data in the eight subcategories of open duration do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics to better visualize how the data are distributed. These are shown in Table 3.46.

121-150 Days and 151-180 Days open duration subcategories all have zero values at or below the 10th percentile, indicating a slight concentration at the left end of those distributions. The open duration subcategories of 0-30 Days and 31-60 Days do not appear to have a concentration of values in any of their percentile categories, indicating that those data are more spread out and potentially candidates to be normally distributed.

**Table 3.46: Open duration category percentile statistics**

| *Open Duration Subcategory* | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| 0-30 Days | 13.00 | 18.00 | 24.00 | 45.00 | 56.00 | 67.00 | 78.00 |
| 31-60 Days | 6.00 | 9.00 | 12.00 | 18.00 | 23.00 | 29.00 | 32.00 |
| 61-90 Days | 0.00 | 4.00 | 7.00 | 11.00 | 15.00 | 17.00 | 21.00 |
| 91-120 Days | 0.00 | 2.00 | 3.00 | 6.00 | 10.00 | 12.00 | 14.00 |
| 121-150 Days | 0.00 | 0.00 | 2.00 | 5.00 | 7.00 | 10.00 | 13.00 |
| 151-180 Days | 0.00 | 0.00 | 1.00 | 3.00 | 4.00 | 7.00 | 9.00 |
| >180 Days | 0.00 | 2.00 | 5.00 | 8.00 | 16.00 | 27.00 | 31.00 |

### 3.10.2. Open Duration Box Plots

The box plots below in Figure 3.55 show another portrayal of the dispersion of the open duration data. The three open duration subcategories that are less than 90 days all show a fairly even distribution around their median lines, indicating good candidates for normal distributions.

The box plots for open duration greater than 120 days show an unsymmetrical distribution, indicated by the unequal box areas above and below the median line as well as by the unequal whisker lengths above and below the box. In addition, they have several outliers and extreme values, as shown by the marks above the top whisker.

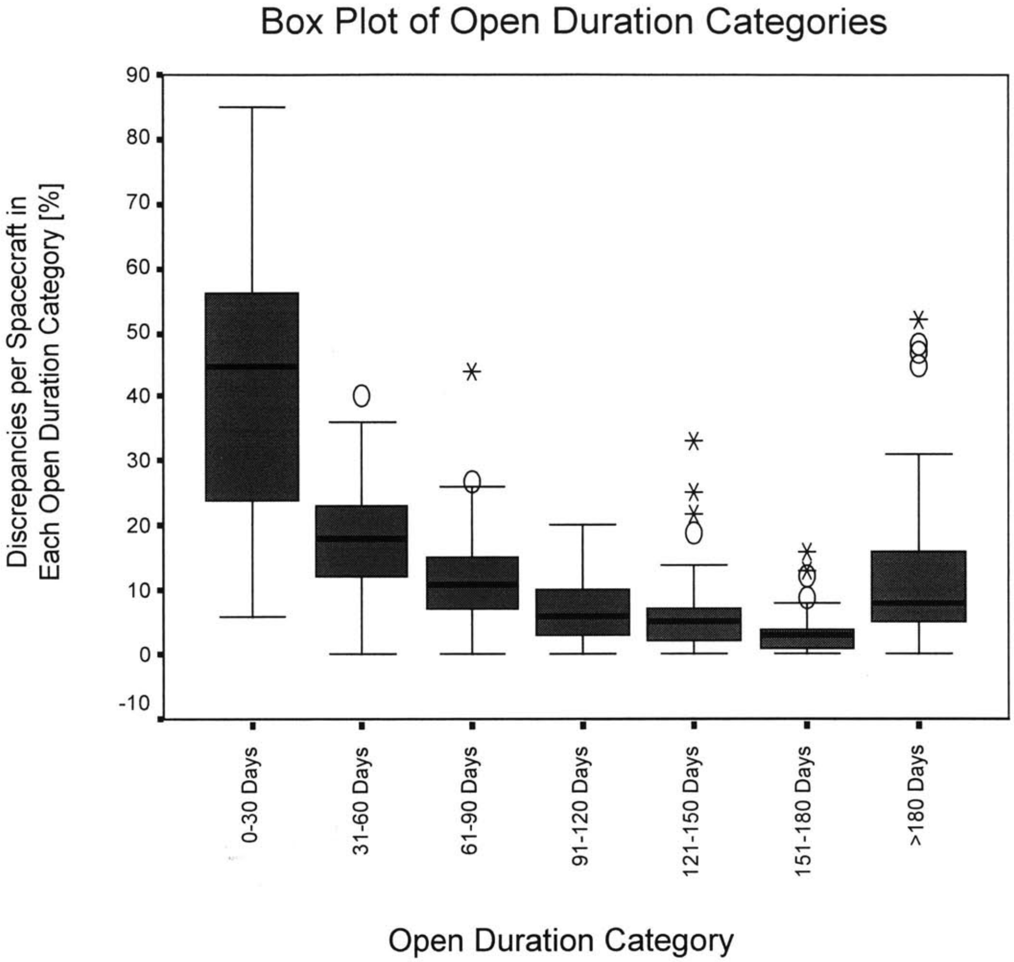


**Figure 3.55: Box plot of open duration of discrepancies, per spacecraft**

### 3.10.3. Overview of Open Duration Means and Confidence Intervals

Figure 3.56 shows a summary of the means of the open duration subcategories, along with the 95% confidence interval upper and lower bounds on those means, and the medians. The 0-30 days subcategory, with a mean of 43%, accounts for the largest percentage of open durations for discrepancies on an average spacecraft. Discrepancies open for greater than 180 days account for 12% of discrepancies at the system level of integration on an average spacecraft.

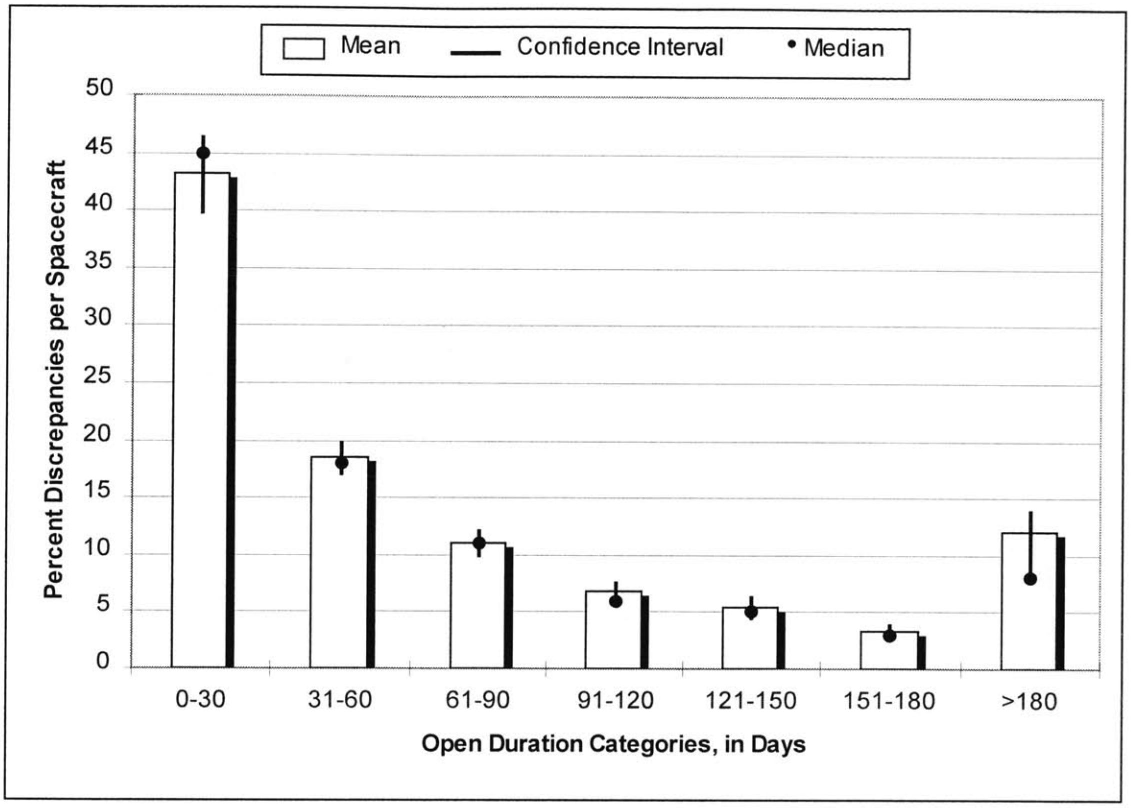


**Figure 3.56: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each open duration category**

### 3.10.4. 0-30 Days Open Duration

Descriptive statistics for the 0-30 Days open duration subcategory are shown in Table 3.47. The mean, 5% trimmed mean, and median for the 0-30 Days open duration subcategory are somewhat different. This indicates that the data might not be normally distributed. However, the ratio of skewness to its standard error, 0.37, indicates that the distribution is not skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -1.76, indicates that the distribution has tail lengths and a peak height very similar to a normal distribution. Because the absolute value of at least one of the ratios is not greater than 2, normality for the 0-30 Days open duration data can be accepted. Thus, the data follow an approximate normal distribution. The skewness and kurtosis measures are confirmed by examining the histogram of the 0-30 Days open duration subcategory in Figure 3.57.

**Table 3.47: 0-30 days open duration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 43.12 | 1.61 |
| **95% Confidence Interval for Mean: Lower Bound** | 39.93 | |
| **95% Confidence Interval for Mean: Upper Bound** | 46.30 | |
| **5% Trimmed Mean** | 42.77 | |
| **Median** | 45.00 | |
| **Variance** | 359.813 | |
| **Standard Deviation** | 18.97 | |
| **Minimum** | 6 | |
| **Maximum** | 85 | |
| **Skewness** | 0.077 | 0.206 |
| **Kurtosis** | -0.721 | 0.408 |

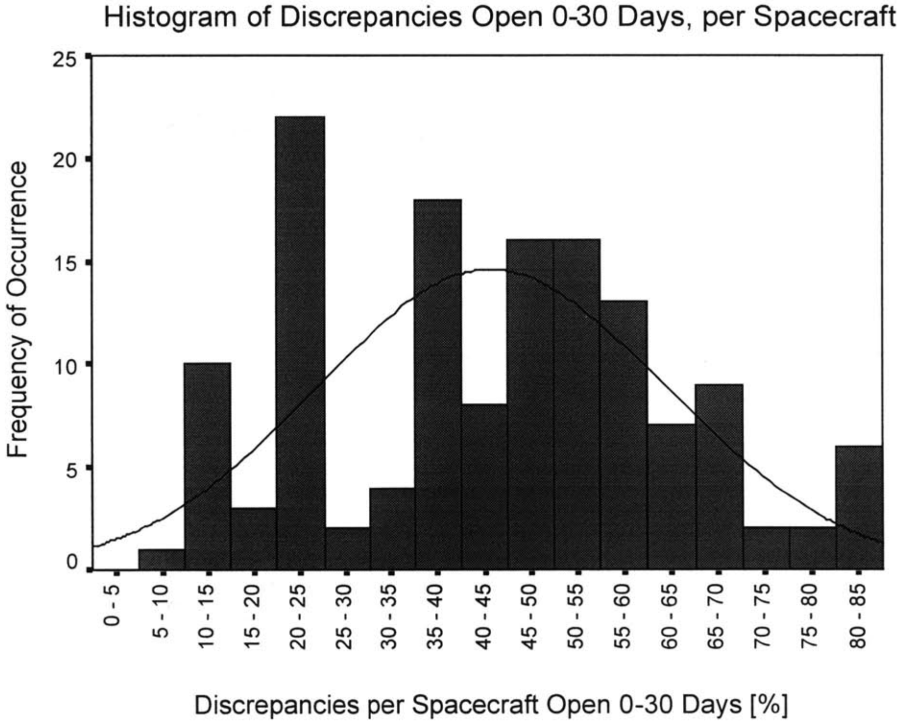


**Figure 3.57: Histogram of discrepancies open 0-30 days, per spacecraft**

#### 3.10.4.1. 0-30 Day Open Duration Correlation

Correlation appeared between the 0-30 Days open duration subcategory and other parameters collected about spacecraft system-level I&T discrepancies.

- The 0-30 Days open duration subcategory and the Unknown cause subcategory have a positive correlation of 0.601 (N=113) at the 0.01 level of significance. This means that as the occurrence of 0-30 Days open duration discrepancies on a given spacecraft went up, a corresponding increase was observed on that given spacecraft in the occurrence of Unknown causes of discrepancies.

### 3.10.5. 31-60 Days Open Duration

Descriptive statistics for the 31-60 Days open duration subcategory are shown in Table 3.48. The mean, 5% trimmed mean, and median for the 31-60 Days open duration subcategory are somewhat similar. This indicates that the data might be normally distributed. The ratio of skewness to its standard error, 1.04, indicates that the distribution is not skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -0.87, indicates that the distribution has tail lengths and a peak height very similar to a normal distribution. Because the absolute value of at least one of the ratios is not greater than 2, normality for the 31-60 Days open duration data can be accepted. Thus, the data follow an approximate normal distribution. The skewness and kurtosis measures are confirmed by examining the histogram of the 31-60 Days open duration subcategory in Figure 3.58.

**Table 3.48: 31-60 days open duration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 18.45 | 0.67 |
| **95% Confidence Interval for Mean: Lower Bound** | 17.13 | |
| **95% Confidence Interval for Mean: Upper Bound** | 19.78 | |
| **5% Trimmed Mean** | 18.28 | |
| **Median** | 18.00 | |
| **Variance** | 62.626 | |
| **Standard Deviation** | 7.91 | |
| **Minimum** | 0 | |
| **Maximum** | 40 | |
| **Skewness** | 0.215 | 0.206 |
| **Kurtosis** | -0.355 | 0.408 |

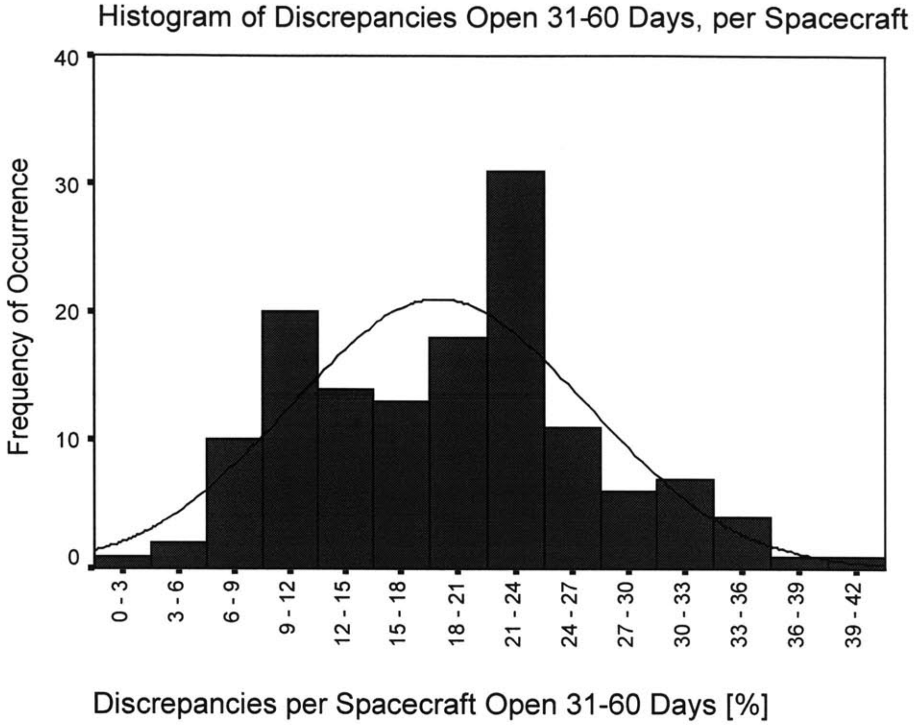


**Figure 3.58: Histogram of discrepancies open 31-60 days, per spacecraft**

### 3.10.6. 61-90 Days Open Duration

Descriptive statistics for the 61-90 Days open duration subcategory are shown in Table 3.49. The mean, 5% trimmed mean, and median for the 61-90 Days open duration subcategory are somewhat similar. This indicates that the data might be normally distributed. However, the ratio of skewness to its standard error, 5.56, indicates that the distribution is just slightly right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -10.75, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the 61-90 Days open duration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the 61-90 Days open duration subcategory in Figure 3.59.

**Table 3.49: 61-90 days open duration subcategory descriptive statistic.**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 10.96 | 0.54 |
| **95% Confidence Interval for Mean: Lower Bound** | 9.89 | |
| **95% Confidence Interval for Mean: Upper Bound** | 12.03 | |
| **5% Trimmed Mean** | 10.66 | |
| **Median** | 11.00 | |
| **Variance** | 40.673 | |
| **Standard Deviation** | 6.38 | |
| **Minimum** | 0 | |
| **Maximum** | 44 | |
| **Skewness** | 1.145 | 0.206 |
| **Kurtosis** | 4.388 | 0.408 |

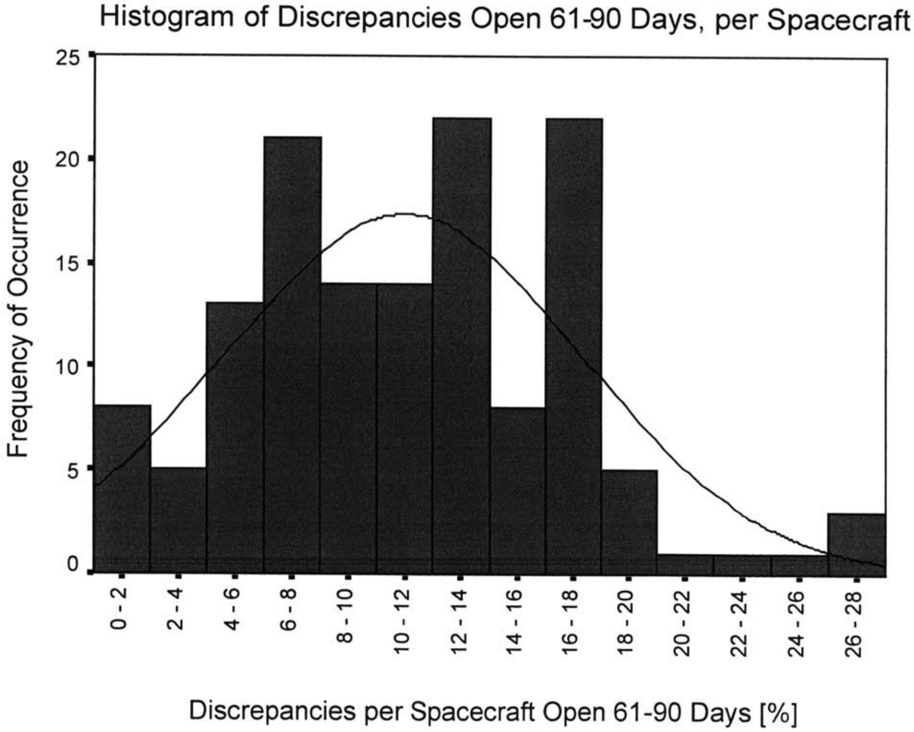


**Figure 3.59: Histogram of discrepancies open 61-90 days, per spacecraft**

### 3.10.7. 91-120 Days Open Duration

Descriptive statistics for the 91-120 Days open duration subcategory are shown in Table 3.50. The mean, 5% trimmed mean, and median for the 91-120 Days open duration subcategory are somewhat similar. This indicates that the data might be normally distributed. However, the ratio of skewness to its standard error, 2.12, indicates that the distribution is just slightly right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, -0.436, indicates that the distribution has tail lengths and a peak height very similar to a normal distribution. But because the absolute value of at least one of the ratios is greater than 2, normality for the 91-120 Days open duration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the 91-120 Days open duration subcategory in Figure 3.60.

**Table 3.50: 91-120 days open duration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---:|---|---|
| **Mean** | 6.75 | 0.35 |
| **95% Confidence Interval for Mean: Lower Bound** | 6.05 | |
| **95% Confidence Interval for Mean: Upper Bound** | 7.45 | |
| **5% Trimmed Mean** | 6.60 | |
| **Median** | 6.00 | |
| **Variance** | 17.480 | |
| **Standard Deviation** | 4.18 | |
| **Minimum** | 0 | |
| **Maximum** | 20 | |
| **Skewness** | 0.438 | 0.206 |
| **Kurtosis** | -0.178 | 0.408 |

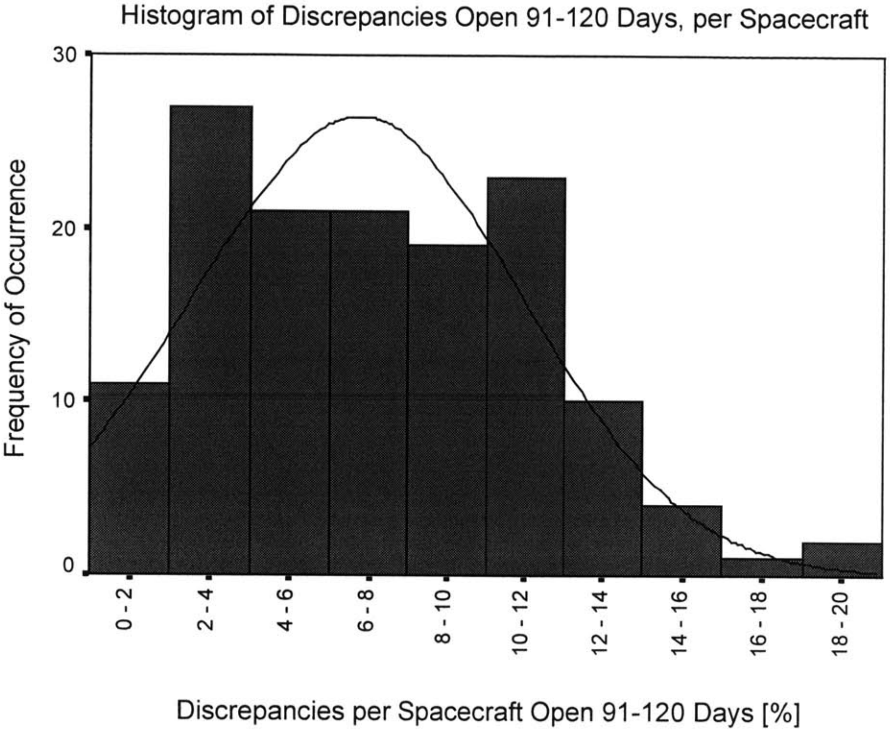


**Figure 3.60: Histogram of discrepancies open 91-120 days, per spacecraft**

### 3.10.8. 121-150 Days Open Duration

Descriptive statistics for the 121-150 Days open duration subcategory are shown in Table 3.51. The mean, 5% trimmed mean, and median for the 121-150 Days open duration subcategory are somewhat similar. This indicates that the data might be normally distributed. However, the ratio of skewness to its standard error, 11.46, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 23.44, indicates that the distribution has much longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the 121-150 Days open duration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the 121-150 Days open duration subcategory in Figure 3.61.

**Table 3.51: 121-150 days open duration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 5.42 | 0.41 |
| **95% Confidence Interval for Mean: Lower Bound** | 4.61 | |
| **95% Confidence Interval for Mean: Upper Bound** | 6.22 | |
| **5% Trimmed Mean** | 4.91 | |
| **Median** | 5.00 | |
| **Variance** | 22.955 | |
| **Standard Deviation** | 4.79 | |
| **Minimum** | 0 | |
| **Maximum** | 33 | |
| **Skewness** | 2.361 | 0.206 |
| **Kurtosis** | 9.564 | 0.408 |

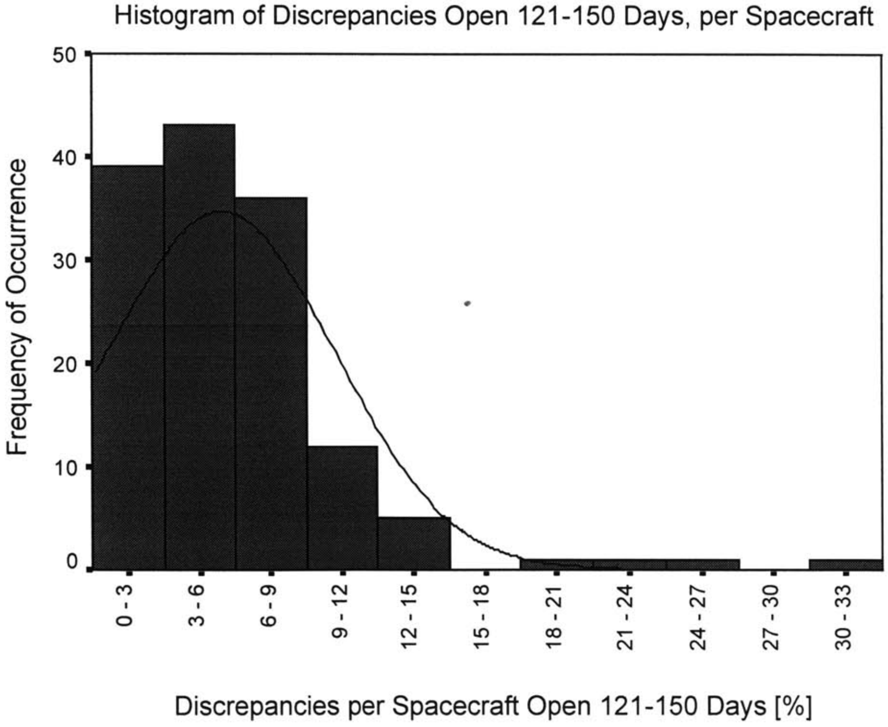


**Figure 3.61: Histogram of discrepancies open 121-150 days, per spacecraft**

### 3.10.9. 151-180 Days Open Duration

Descriptive statistics for the 151-180 Days open duration subcategory are shown in Table 3.52. The mean, 5% trimmed mean, and median for the 151-180 Days open duration subcategory are somewhat different. This indicates that the data are likely not normally distributed. The ratio of skewness to its standard error, 7.30, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 7.78, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the 151-180 Days open duration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the 151-180 Days open duration subcategory in Figure 3.62.

**Table 3.52: 151-180 days open duration subcategory descriptive statistics**

| *Statistic Name* | *Value* | *Standard Error* |
|---|---|---|
| **Mean** | 3.28 | 0.26 |
| **95% Confidence Interval for Mean: Lower Bound** | 2.78 | |
| **95% Confidence Interval for Mean: Upper Bound** | 3.79 | |
| **5% Trimmed Mean** | 2.97 | |
| **Median** | 3.00 | |
| **Variance** | 9.087 | |
| **Standard Deviation** | 3.01 | |
| **Minimum** | 0 | |
| **Maximum** | 16 | |
| **Skewness** | 1.503 | 0.206 |
| **Kurtosis** | 3.173 | 0.408 |

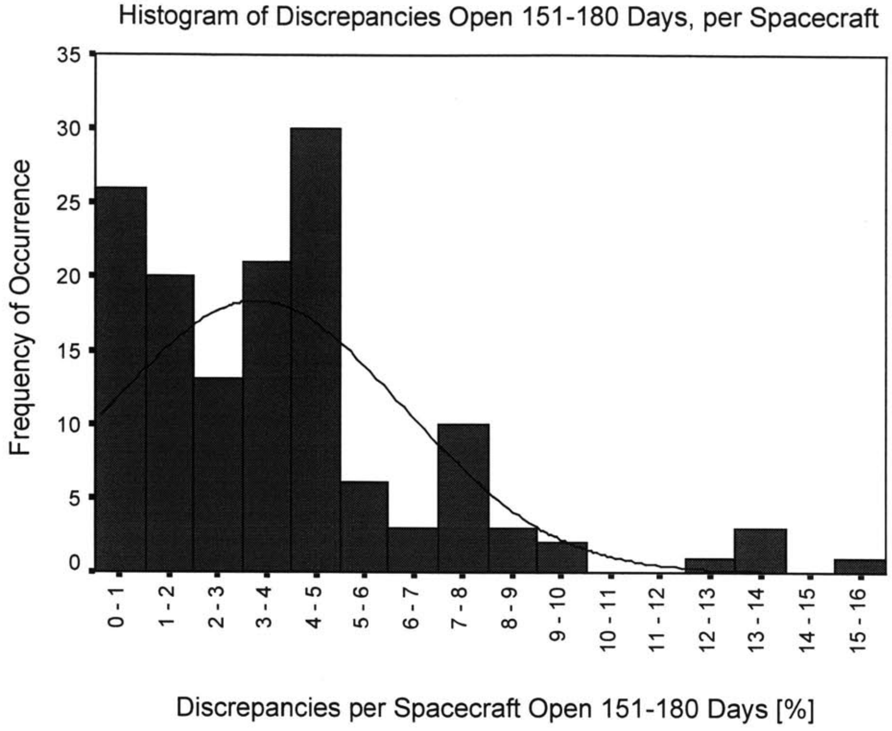


**Figure 3.62: Histogram of discrepancies open 151-180 days, per spacecraft**

### 3.10.10. Greater Than 180 Days Open Duration

Descriptive statistics for the >180 Days open duration subcategory are shown in Table 3.53. The mean, 5% trimmed mean, and median for the >180 Days open duration subcategory are very different. This indicates that the data are not normally distributed. The ratio of skewness to its standard error, 8.00, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 7.13, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the >180 Days open duration data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the >180 Days open duration subcategory in Figure 3.63.

**Table 3.53: Greater than 180 days open duration subcategory descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 12.01 | 0.93 |
| **95% Confidence Interval for Mean: Lower Bound** | 10.18 | |
| **95% Confidence Interval for Mean: Upper Bound** | 13.84 | |
| **5% Trimmed Mean** | 10.03 | |
| **Median** | 8.00 | |
| **Variance** | 119.087 | |
| **Standard Deviation** | 10.91 | |
| **Minimum** | 0 | |
| **Maximum** | 52 | |
| **Skewness** | 1.649 | 0.206 |
| **Kurtosis** | 2.909 | 0.408 |

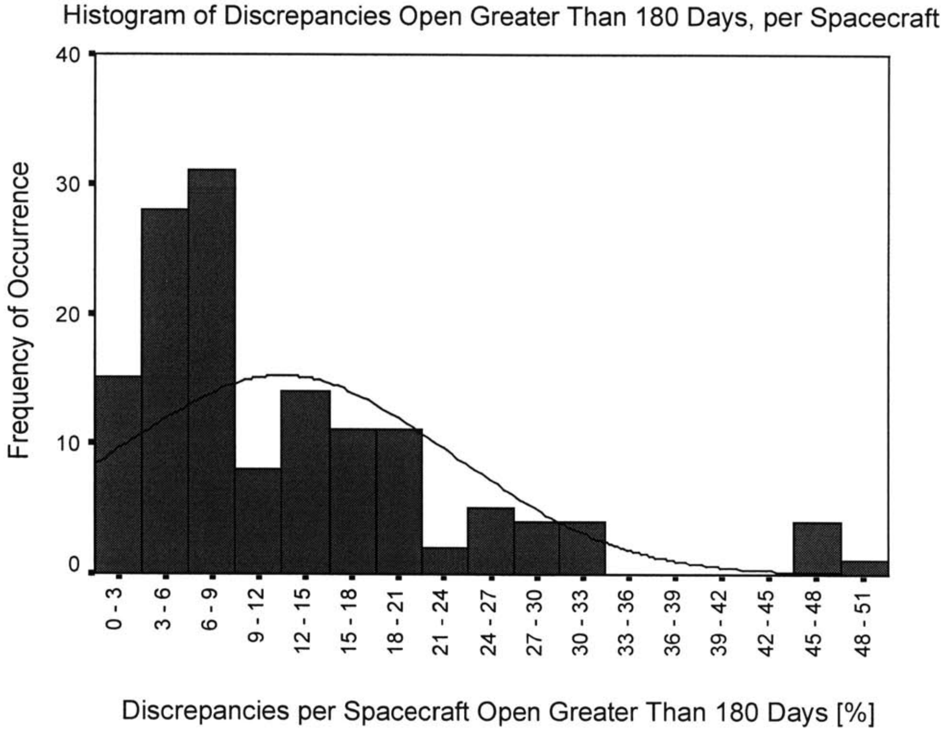


**Figure 3.63: Histogram of discrepancies open greater than 180 days, per spacecraft**

## 3.11. Conclusion on Statistical Analysis

This chapter discussed the central tendency, correlation, and statistical normality of the data gathered on spacecraft system-level integration and test discrepancies. Understanding these measures of a population helps in making predictions about their future behavior, and is thus an important part of the research. The mean or average usually represents the central tendency of a population. The correlation, or degree of association of two variables, tells how independent the behavior is of two variables. The degree of normality of the population prescribes whether or not the population can be considered normally distributed.

### 3.11.1. Summary of Means

The means of the data were presented in this chapter under the "Overview of Activity Means and Confidence Intervals" section headings. The largest means in each category observed for an average spacecraft during system-level integration and test were:

- **Activity**: 30% of discrepancies occurred in the thermal vacuum environment.
- **Subsystem**: 30% of discrepancies were written against test equipment.
- **Disposition**: 39% of discrepancies were given the disposition "Use As Is."
- **Root Cause**: 27% and 25% of discrepancies were attributed to the causes of Employee/Operator and Design, respectively.
- **Corrective Action**: 23% of discrepancies were prescribed no corrective action.
- **Open Duration**: 43% of discrepancies were closed in 0-30 days.

### 3.11.2. Summary of Correlation

The statistical analysis showed some correlation in the data, indicating that these system-level integration and test data are not entirely independent. Several summary tables of correlation are presented below in Table 3.54 through Table 3.60. All of the correlation is significant at the 0.01 level. It is important to remember that correlation is indicates a relationship between variables, but does not indicate a direction of causality of that relationship. It is also important to note that the correlation coefficients used in this analysis represent a relative degree of dependence, and not an absolute measure.

**Table 3.54: Summary of correlation for mission area**

| | *Communications Mission* | *Non-Communications Missions* |
|---|---|---|
| **Thermal Subsystem** | -0.713<br>N=129 | 0.713<br>N=129 |
| **Use As Is Disposition** | 0.612<br>N=56 | -0.612<br>N=56 |
| **Other Cause** | -0.617<br>N=113 | 0.617<br>N=113 |

**Table 3.55: Summary of correlation for activity category**

| | *Thermal Vacuum Activity* | *Ambient Activity* |
|---|---|---|
| **DMS/TTC** | -0.618<br>N=122 | 0.609<br>N=122 |
| **Use As Is Disposition** | 0.602<br>N=49 | -0.632<br>N=49 |
| **Ambient Activity** | -0.927<br>N=130 | * |
| **Thermal Vacuum Activity** | * | -0.927<br>N=130 |

* = perfect self-correlation, or correlation below 0.6

**Table 3.56: Summary of correlation for subsystem category**

| | *EPDS* | *SMS* | *Thermal* | *DMS/ TTC* | *Test Equip* | *Space-craft* | *Other* |
|---|---|---|---|---|---|---|---|
| **Communications Missions** | * | * | -0.713<br>N=129 | * | * | * | * |
| **Other Missions** | * | * | 0.713<br>N=129 | * | * | * | * |
| **Test Equipment Subsystem** | -0.747<br>N=129 | * | * | * | * | * | * |
| **EPDS Subsystem** | * | * | * | 0.643<br>N=129 | -0.747<br>N=129 | -0.698<br>N=129 | 0.614<br>N=129 |
| **Spacecraft Subsystem** | -0.698<br>N=129 | * | * | -0.631<br>N=129 | * | * | * |
| **DMS/TTC Subsystem** | 0.643<br>N=129 | * | * | * | * | -0.631<br>N=129 | * |
| **Other Subsystem** | 0.614<br>N=129 | * | * | * | * | * | * |
| **Thermal Vacuum Activity** | * | * | * | -0.618<br>N=122 | * | * | * |
| **Use As Is Disposition** | * | * | * | * | * | 0.719<br>N=48 | -0.651<br>N=48 |
| **Rework Disposition** | * | * | * | * | -0.707<br>N=48 | * | * |
| **Repair Disposition** | * | * | * | * | 0.661<br>N=48 | * | * |
| **Return to Supplier Disposition** | * | 0.620<br>N=48 | * | * | * | * | * |
| **Test Equipment Cause** | * | * | * | -0.606<br>N=105 | * | * | * |
| **No Anomaly Cause** | -0.608<br>N=105 | * | * | * | 0.604<br>N=105 | * | * |
| **Other Cause** | 0.689<br>N=105 | * | 0.631<br>N=105 | 0.713<br>N=105 | -0.611<br>N=105 | -0.684<br>N=105 | * |
| **Drawing/Spec Corrective Action** | 0.720<br>N=100 | * | * | 0.684<br>N=100 | -0.696<br>N=100 | * | 0.651<br>N=100 |
| **Test Equip. Corrective Action** | -0.619<br>N=100 | * | * | * | 0.625<br>N=100 | * | * |
| **Supplier-Related Corrective Action** | * | 0.690<br>N=100 | 0.645<br>N=100 | * | * | * | * |

* = perfect self-correlation, or correlation below 0.6

**Table 3.57: Summary of correlation for disposition category**

| | *Use As Is* | *Rework* | *Repair* | *Return to Supplier* |
|---|---|---|---|---|
| **Communications Missions** | 0.612<br>N=56 | * | * | * |
| **Other Missions** | -0.612<br>N=56 | * | * | * |
| **Test Equipment Subsystem** | * | -0.707<br>N=48 | 0.661<br>N=48 | * |
| **SMS Subsystem** | * | * | * | 0.626<br>N=48 |
| **Spacecraft Subsystem** | 0.719<br>N=48 | * | * | * |
| **Other Subsystem** | -0.651<br>N=48 | * | * | * |
| **Thermal Vacuum Activity** | 0.602<br>N=49 | * | * | * |
| **Ambient Activity** | -0.633<br>N=49 | * | * | * |
| **Use As Is Disposition** | * | -0.652<br>N=56 | * | * |
| **Rework Disposition** | -0.652<br>N=56 | * | * | * |
| **Test Equipment Cause** | * | -0.630<br>N=56 | * | * |
| **Other Cause** | -0.674<br>N=56 | 0.755<br>N=56 | * | * |
| **Supplier-Related Corrective Action** | -0.686<br>N=53 | 0.778<br>N=53 | * | * |
| **No Action Required Corrective Action** | 0.604<br>N=53 | -0.737<br>N=53 | * | * |

* = perfect self-correlation, or correlation below 0.6

**Table 3.58: Summary of correlation for cause category**

| | Test Equip | Design | Software | No Anomaly | Unknown | Other |
|---|---|---|---|---|---|---|
| **Communications Missions** | * | * | * | * | * | -0.617<br>N=113 |
| **Other Missions** | * | * | * | * | * | 0.617<br>N=113 |
| **0-30 Days open Duration** | * | * | * | * | 0.601<br>N=113 | * |
| **Thermal Subsystem** | * | * | * | * | * | 0.631<br>N=105 |
| **Test Equipment Subsystem** | * | * | * | 0.604<br>N=105 | * | -0.611<br>N=105 |
| **EPDS Subsystem** | * | * | * | -0.608<br>N=105 | * | 0.689<br>N=105 |
| **Spacecraft Subsystem** | * | * | * | * | * | -0.684<br>N=105 |
| **DMS/TTC Subsystem** | -0.606<br>N=105 | * | * | * | * | 0.713<br>N=105 |
| **Use As Is Disposition** | * | * | * | * | * | -0.674<br>N=56 |
| **Rework Disposition** | -0.630<br>N=56 | * | * | * | * | 0.755<br>N=56 |
| **Repair Disposition** | -0.698<br>N=107 | * | * | * | * | * |
| **Test Equipment Cause** | * | * | * | * | * | -0.606<br>N=113 |
| **Other Cause** | -0.606<br>N=113 | * | * | * | * | * |
| **Drawing/Spec Corrective Action** | * | 0.724<br>N=107 | * | * | * | 0.671<br>N=107 |
| **Test Equipment Corrective Action** | 0.806<br>N=107 | * | * | * | * | -0.695<br>N=107 |
| **Software Corrective Action** | * | * | 0.864<br>N=107 | * | * | * |
| **Employee/ Operator Corrective Action** | * | * | * | * | 0.734<br>N=107 | * |

* = perfect self-correlation, or correlation below 0.6

**Table 3.59: Summary of correlation for corrective action category**

| | *Employee /Operator* | *Drawing /Spec* | *Supplier -Related* | *Software* | *Test Equip* | *No Action Required* |
|---|---|---|---|---|---|---|
| **SMS Subsystem** | * | * | 0.690<br>N=100 | * | * | * |
| **Thermal Subsystem** | * | * | 0.645<br>N=100 | * | * | * |
| **Test Equipment Subsystem** | * | -0.696<br>N=100 | * | * | 0.625<br>N=100 | * |
| **EPDS Subsystem** | * | 0.720<br>N=100 | * | * | -0.619<br>N=100 | * |
| **DMS/TTC Subsystem** | * | 0.684<br>N=100 | * | * | * | * |
| **Other Subsystem** | * | 0.651<br>N=100 | * | * | * | * |
| **Use As Is Disposition** | * | * | -0.686<br>N=53 | * | * | 0.604<br>N=53 |
| **Rework Disposition** | * | * | 0.778<br>N=53 | * | * | -0.737<br>N=53 |
| **Design Cause** | * | 0.724<br>N=107 | * | * | * | * |
| **Software Cause** | * | * | * | 0.864<br>N=107 | * | * |
| **Test Equipment Cause** | * | -0.698<br>N=107 | * | * | 0.806<br>N=107 | * |
| **Unknown Cause** | 0.734<br>N=107 | * | * | * | * | * |
| **Other Cause** | * | 0.671<br>N=107 | * | * | -0.695<br>N=107 | * |
| **Drawing/Spec Corrective Action** | * | * | * | * | -0.750<br>N=108 | * |
| **Test Equipment Corrective Action** | * | -0.750<br>N=108 | * | * | * | * |

* = perfect self-correlation, or correlation below 0.6

**Table 3.60: Summary of correlation for open duration category**

| | *0-30 Days* |
|---|---|
| **Unknown Cause** | 0.601<br>N=113 |

### 3.11.3. Summary of Normality

As was seen in this statistical analysis chapter, most of the data are not normally distributed. Follow-on activities to this research should investigate the data to see if they fit other specific distributions, such as exponential, log linear, or Weibull distributions. If the data are found to fit known distributions, those data can be used in other statistical tests to gain further insight into the behavior of the data.

# Chapter 4.

# The Cost of Discrepancies: Research and Findings

## 4.1. Chapter Introduction

Discrepancies in system-level integration and test are considered to be the most costly to fix, in general, with respect to all other levels of integration. Yet little published information exists on more precise costs of discrepancies at this level. Further, vendors currently are not tracking this information. It is difficult to evaluate the cost-benefit trades of fixing problems for the long-term if the cost information is unknown. For the purposes of this research, time (labor hours, facility hours, etc.) will be used as a surrogate for cost.

Chapter 1 describes the research design and methodology for investigating the cost of spacecraft system-level integration and test (I&T) discrepancies and presents results of the research. Key questions are presented, the research methodology is introduced, and the interview questions and resulting data products are explained. The results of the research are then summarized. Finally, potential sources of error are listed, as well as barriers encountered in the research and ideas for enabling further research in this area.

## 4.2. Key Questions

Several key questions that succinctly explain the research were formulated to help guide the research process. These are:

- How much labor time do discrepancies take?
- How much serial flow time do discrepancies take?
- How significant is that time?
- Is further research into discrepancy time warranted?

## 4.3. Research Methodology

Recorded data from vendors on the costs of discrepancies were initially sought, but this information was not available in current cost accounting structures. This indicated that an alternative means of obtaining the data had to be used.

A survey instrument and a structured interview instrument for gathering this data were evaluated. A structured interview setting provided the best opportunity for obtaining complete and thorough data. It permitted asking for clarifications, explaining questions to respondents in more detail than possible on paper, and being confident of a high response rate.

Quality of information, not quantity, was stressed in the data gathering. Thus, an expert interview approach was chosen over a large sample size approach because there were few people in any organization who had enough insight on the time spent on discrepancies to provide a reasonable and credible answer to the interview questions.

Initial, unstructured interviews were set up at vendor sites to see facilities, gather information on which product lines might be available for inclusion in the research and discuss which personnel would be needed for the structured interviews. Two spacecraft vendors agreed to make commercial spacecraft product lines available for this research.

On return visits to those two vendor sites, 1- to 1.5-hour structured interviews were conducted with over 50 experts, including program managers, systems engineers, subsystem engineers, unit engineers, I&T engineers, and quality assurance engineers. The range of expert experience was chosen to include everyone who played in role in the discrepancy lifecycle, with a particular emphasis on non-factory floor personnel and non-program office personnel, such as the typically cross-program matrixed organization functions of system, subsystem and unit engineering. These experts were asked to give their best estimate of the probability distribution of labor hours they and their associated staffs would spend on different types of system-level I&T discrepancies throughout the entire discrepancy lifecycle. They were also asked to give a probability distribution of the serial flow time that gets spent on discrepancies at the system level of integration.

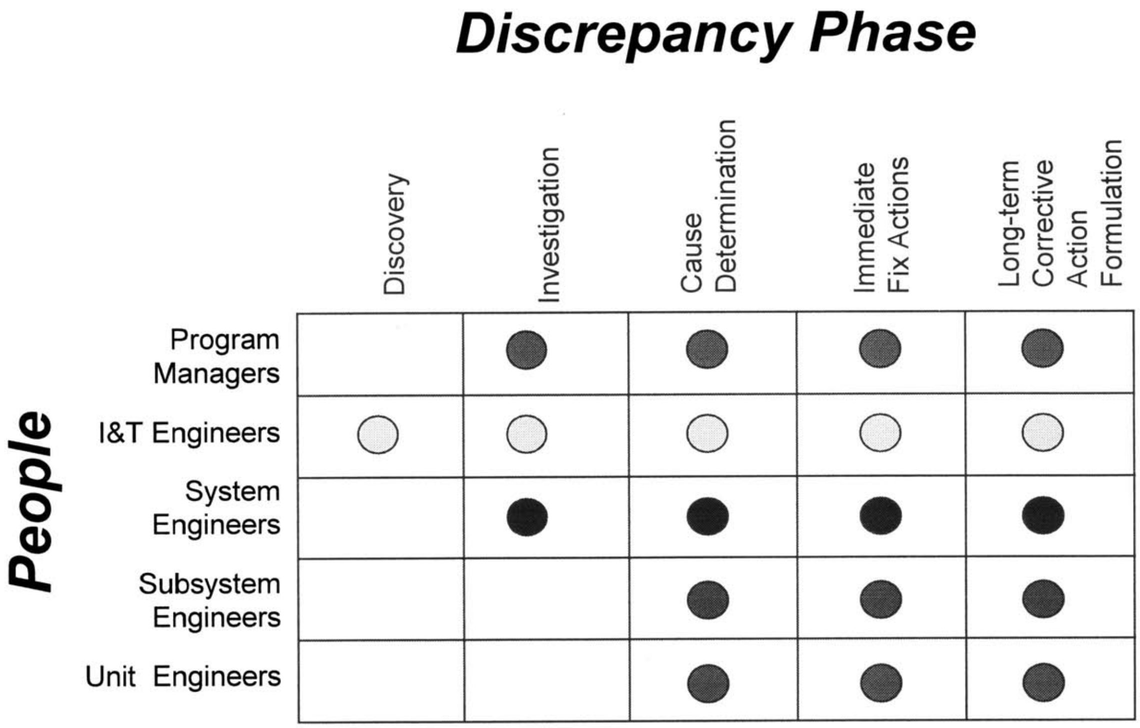
The probability distributions produced from the interview questions were used to generate expected values for the time required for different types of discrepancies. The different types of discrepancies had traceability to a particular feature in the discrepancy reports that were used in investigating the distributions discussed in Chapter 1. Thus, an expected time value could be matched up to each discrepancy that had actually occurred on a program, and a total discrepancy time was calculated for each system-level I&T discrepancy on each spacecraft.

## 4.4. Interview Questions and Products

The three types of interviews conducted and the products drawn from them are listed below.

### 4.4.1. Initial Interviews and Products

These interviews were loosely structured and their main purpose was qualitative data gathering and familiarization. They were designed to elicit descriptions of the vendor's organizational structure, their I&T structure and philosophy, and how personnel participated in system I&T and the discrepancy lifecycle. A graphic showing the various stages of the discrepancy lifecycle and the personnel involved in each stage is shown in Figure 4.1.



| | Discovery | Investigation | Cause Determination | Immediate Fix Actions | Long-term Corrective Action Formulation |
|---|---|---|---|---|---|
| Program Managers | | ● | ● | ● | ● |
| I&T Engineers | ○ | ○ | ○ | ○ | ○ |
| System Engineers | | ● | ● | ● | ● |
| Subsystem Engineers | | | ● | ● | ● |
| Unit Engineers | | | ● | ● | ● |

**Figure 4.1: Matrix of discrepancy phases and employee involvement**

### 4.4.2. Structured Interviews on Labor Hours

These interviews were designed to elicit specific responses about the probability distributions of labor hours spent on discrepancies. Interviewees were told to consider all their associated staff, all the meetings, all the paperwork and all the analysis that goes on during the entire lifecycle of a discrepancy. They were then asked to answer a question such as "What is the distribution of labor hours you and your staff spend on mechanical discrepancies over the whole lifecycle of the discrepancy?"

### 4.4.3. Structured Interviews on Serial Flow Time Hours

These interviews were designed to elicit specific responses about the probability distributions of serial flow time hours spent on discrepancies. Interviewees were asked to think about the total production line downtime that is associated with different kinds of discrepancies, considering only the true downtime of the production line that prohibits the accomplishing of other tasks on the program. They were then asked to answer a question such as "What is the distribution of serial flow time hours for mechanical discrepancies?"

### 4.4.4. Structured Interview Products

These two types of structured interviews resulted in specific probability mass distributions for each type of discrepancy, reflecting the fact that there is variability in the time each discrepancy takes within a category. In equation form, the function $p_x(x_o)$ is known as the probability mass function (PMF) for discrete random variable $x$, defined by[30]

$$p_x(x_o) = \text{probabilitythat the experimental value of random variable } x \text{ obtained on a performance of the experient is equal to } x_o$$

The PMF is often presented graphically. Figure 4.2 shows a sample probability mass function that resulted from the structured interviews.

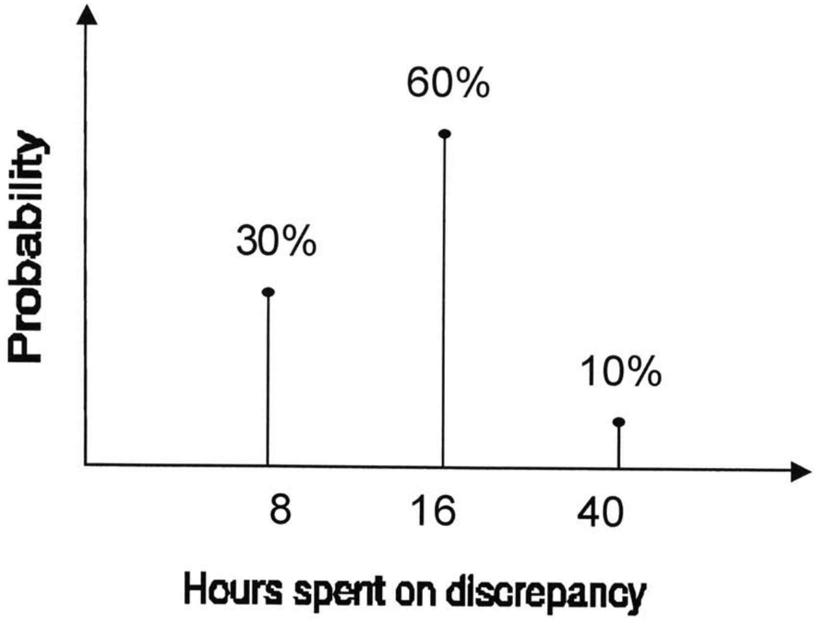


**Figure 4.2: Graphical representation of sample probability mass function derived from interview data**

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[30] Drake, Alvin W. Fundamentals of Applied Probability Theory. New York: McGraw-Hill, 1988. p. 45.

## 4.5. Deriving Data from Interviews

Using an expected value calculation, the expected time for a discrepancy type can be derived from its PMF as follows:

Let x be a random variable, and let *g(x)* be a single-valued function of its argument. Then *g(x)* is a function of a random variable and is itself a random variable. *E[g(x)]* is defined as the expectation, or expected value, of this function of random variable *x*, to be[31]

$$E[g(x)] \equiv \sum_{x_o} g(x_o) p_x(x_o) \equiv \overline{g(x)}$$

An example will help illustrate this. Using the PMF displayed in Figure 4.2, for a certain discrepancy type, the calculation for the expected value of that discrepancy type yields

$$\text{Expectation} = (8\text{ hrs}) \times 0.3 + (16\text{ hrs}) \times 0.6 + (40\text{ hrs}) \times 0.1 = 15.7\text{ hours}$$

After calculating the expected time for each discrepancy type as just demonstrated, the expected time for both labor hours and serial flow hours was summed for all discrepancies occurring on each spacecraft used in this cost part of the research. This produced two measures:

- Total labor time spent on system I&T discrepancies per spacecraft
- Total serial flow time spent on system I&T discrepancies per spacecraft

## 4.6. Results of Labor Time Statistical Analysis

A presentation of the percentile statistics first introduces the general nature of the distribution of the labor time data. A box plot, descriptive statistics and a histogram follow. Finally, correlation with other characteristics of the data is explored. The total number of spacecraft used in the labor time analysis is 68.

### 4.6.1. Percentiles

The labor time data do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics, presented in Table 4.1, to better visualize how the data are distributed. Since the 50th percentile is in the lower half of the range of values computed for labor time, this indicates that the distribution is heavily weighted on the lower end of the range. In addition, the difference between the 50th percentile and the 95th percentile is four

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[31] Entire paragraph drawn from Drake, Alvin W. Fundamentals of Applied Probability Theory. New York: McGraw-Hill, 1988. p. 53.

times as large as the difference between the 50th percentile and the 5th percentile, indicating a spread out upper range.

**Table 4.1: Labor hours percentile statistics**

| | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| Labor Hours | 2142 | 3,837.6 | 9,048 | 14,615 | 36,775 | 59,677 | 75,689 |

### 4.6.2. Box Plot

The box plot in Figure 4.3 shows another portrayal of the dispersion of the labor time data. This graphically displays that the middle 50% of the data tends to fall between approximately 8,000 and 42,000 hours. By the relatively longer upper whisker, it also confirms the observation made from the percentile table of a spread-out upper range. In addition, it indicates an outlier and extreme value in the upper half of the range.

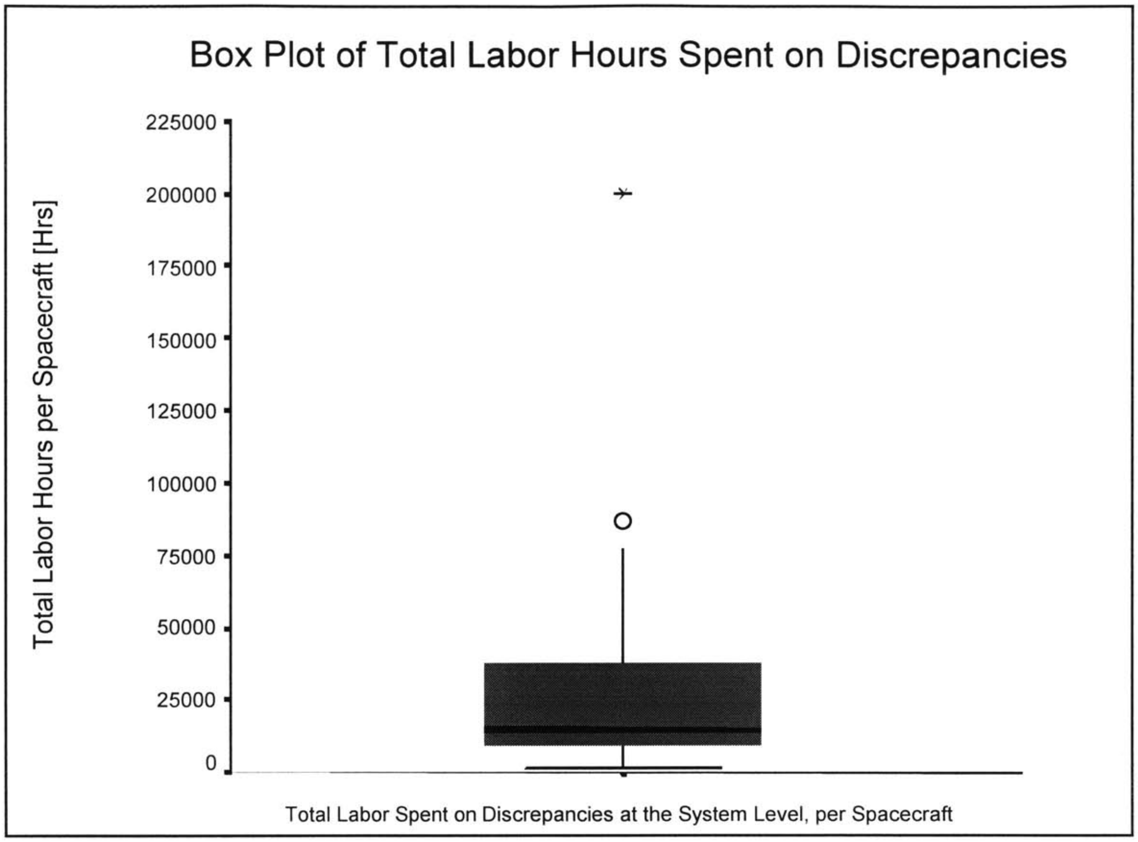

**Figure 4.3: Box plot of total labor hours spent on discrepancies per spacecraft**

### 4.6.3. Descriptive Statistics and Histogram

Descriptive statistics for the labor time data are shown in Table 4.2. The mean, 5% trimmed mean, and median are 26,344 hours, 22,735 hours, and 14,615 hours respectively. They are very different, indicating that the data are not normally distributed. The ratio of skewness to its standard error, 11.98, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 31.27, indicates that the distribution has much longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the labor time data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the labor time data in Figure 4.4.

**Table 4.2: Labor hours descriptive statistics**

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 26,344.54 | 3,547.80 |
| **95% Confidence Interval for Mean: Lower Bound** | 19,263.10 | |
| **95% Confidence Interval for Mean: Upper Bound** | 33,425.99 | |
| **5% Trimmed Mean** | 22,735.18 | |
| **Median** | 14,615.00 | |
| **Variance** | 8.56E+08 | |
| **Standard Deviation** | 29,255.93 | |
| **Minimum** | 1240 | |
| **Maximum** | 200,030 | |
| **Skewness** | 3.487 | 0.291 |
| **Kurtosis** | 17.953 | 0.574 |

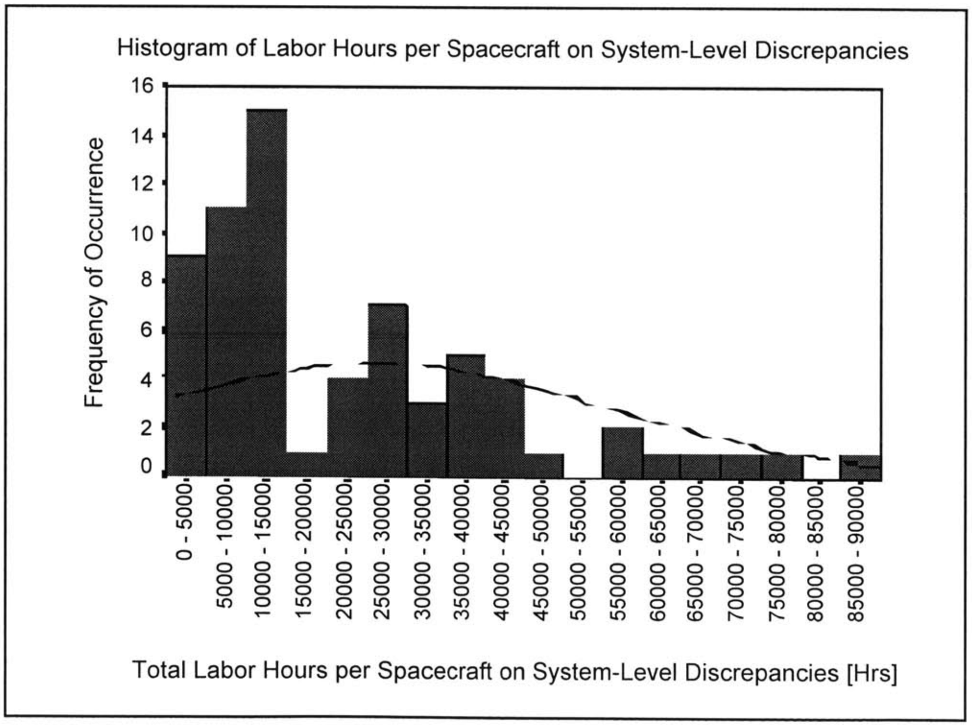

**Figure 4.4: Histogram of labor hours spent on discrepancies per spacecraft**

### 4.6.4. Correlation

No significant correlation of strength greater than 0.6 was found between labor time and other characteristics of the discrepancy data using the Spearman's Rho measure of association.

## 4.7. Results of Flow Time Statistical Analysis

A presentation of the percentile statistics first introduces the general nature of the distribution of the flow time data. A box plot, descriptive statistics and a histogram follow. Finally, correlation with other characteristics of the data is explored. The total number of spacecraft used in the flow time analysis is 68.

### 4.7.1. Percentiles

The flow time data do not follow a normal distribution. Hence, it is appropriate to first examine their percentile statistics, presented in Table 4.3, to better visualize how the data are distributed. Since the 50th percentile is in the lower half of the range of values computed for flow time, this indicates that the distribution is weighted on the lower end of the range. In addition, the difference between the 50th percentile and the 95th percentile is almost three times as large as the difference between the 50th percentile and the 5th percentile, indicating a somewhat larger spread in the upper range than the lower range.

**Table 4.3: Flow hours percentile statistics**

| | *Percentile* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *5* | *10* | *25* | *20* | *75* | *90* | *95* |
| Flow Hours | 270.4 | 367.7 | 622.5 | 978.0 | 1867.7 | 2382.4 | 2915.7 |

### 4.7.2. Box Plot

The box plot in Figure 4.5 shows another portrayal of the dispersion of the labor time data. This graphically displays that the middle 50% of the data tends to fall between approximately 8500 and 1900 hours. By the relatively longer upper whisker, it also confirms the observation made from the percentile table of a spread-out upper range. In addition, it indicates an outlier and extreme value in the upper half of the range.

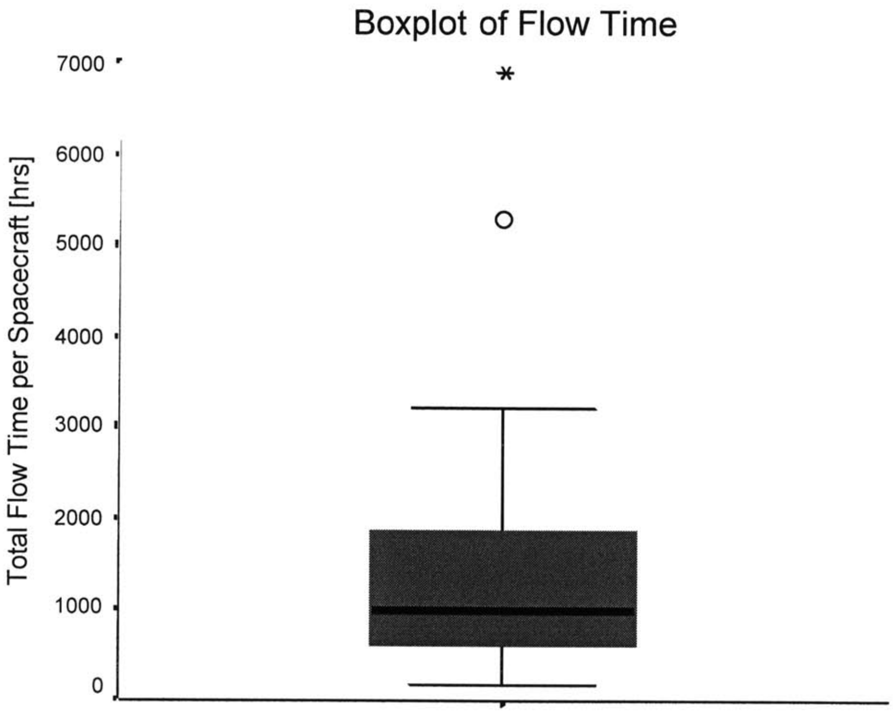

**Figure 4.5: Box plot of total flow time spent on discrepancies, per spacecraft**

### 4.7.3. Descriptive Statistics and Histogram

Descriptive statistics for the flow time data are shown in Table 4.2. The mean, 5% trimmed mean, and median are 1349 hours, 1217 hours, and 978 hours respectively. These are very different, indicating that the data are not normally distributed. The ratio of skewness to its standard error, 9.07, indicates that the distribution is right-skewed compared to a normal distribution. The ratio of kurtosis to its standard error, 17.93, indicates that the distribution has longer tails than a normal distribution. Because the absolute value of at least one of the ratios is greater than 2, normality for the labor time data must be rejected. The skewness and kurtosis measures are confirmed by examining the histogram of the flow time data in Figure 4.4.

Table 4.4: Flow hours descriptive statistics

| Statistic Name | Value | Standard Error |
|---|---|---|
| **Mean** | 1349.16 | 134.55 |
| **95% Confidence Interval for Mean: Lower Bound** | 1080.60 | |
| **95% Confidence Interval for Mean: Upper Bound** | 1617.73 | |
| **5% Trimmed Mean** | 1217.08 | |
| **Median** | 978.00 | |
| **Variance** | 1.23E+06 | |
| **Standard Deviation** | 1109.54 | |
| **Minimum** | 180 | |
| **Maximum** | 6923 | |
| **Skewness** | 2.640 | 0.291 |
| **Kurtosis** | 10.292 | 0.574 |

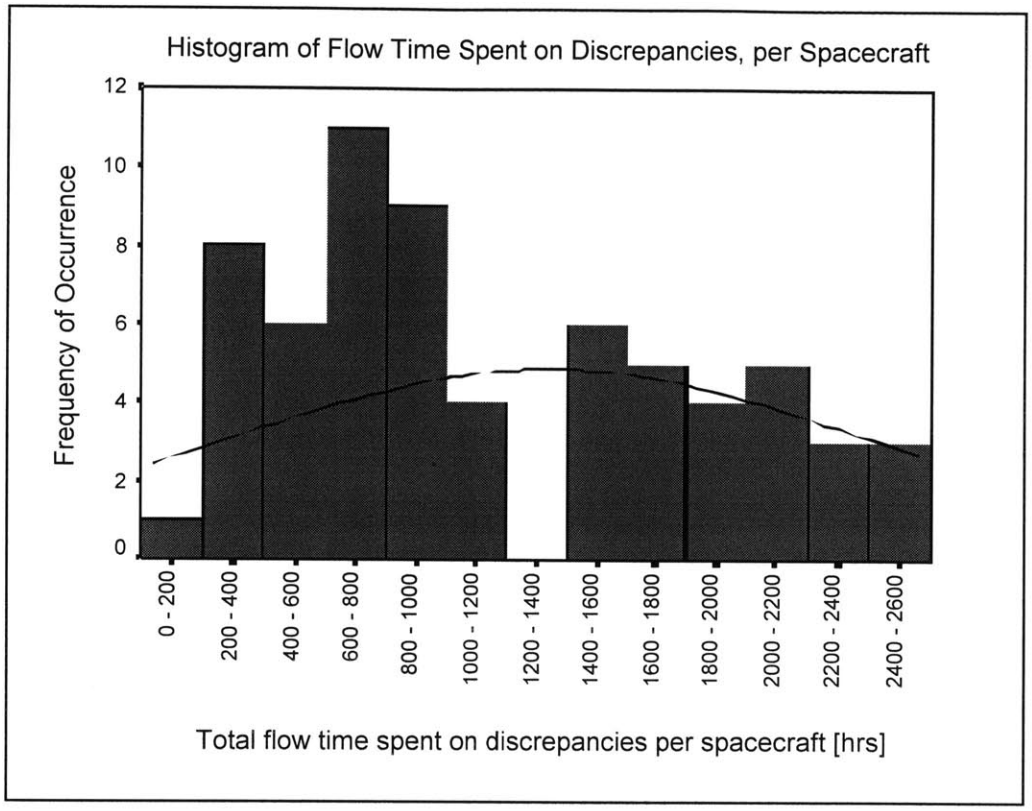

**Figure 4.6: Histogram of flow time spent on discrepancies at the system level of integration, per spacecraft**

### 4.7.4. Correlation

No significant correlation of strength greater than 0.6 was found between labor time and other characteristics of the discrepancy data using the Spearman's Rho measure of association.

## 4.8. Potential Sources of Error

Since the labor and flow time data were obtained through interviews, they are subject to the errors inherent in interview data, namely the ability of interview subjects to accurately answer the questions being posed. Clarity of the questions and the ability of the interviewer to communicate the correct question also come into play.

The underreporting of socially undesirable behavior has been documented in other interview- and survey-based social science research efforts.[32] Fixing a problem is

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[32] See Maisto, S.A et al. "Self-Report Issues in Substance Abuse – State of the Art and Future Directions" *Behavioral Assessment*, Vol. 12, No. 1. 1990. p. 117-134. And also, Hays, R.D et al. "Impact of Response

considered a somewhat socially undesirable behavior for the purposes of this research. This is actually beneficial for the cost research on discrepancies, for it means that the results presented here on the labor and flow time can be viewed as a kind of lower bound on the actual numbers. The actual time is likely much larger than the time reported through interviews.

Lastly, the cost research is based on an expert interview approach instead of a large sample size approach because there were few people in any organization who had enough insight on the time spent on discrepancies to provide a reasonable and credible answer to the interview questions. As such, the results of the research are dependent on the quality of the information provided by those experts.

## 4.9. Barriers Encountered

Two barriers that were encountered in the course of the cost of discrepancies research were proprietary concerns by research participants and lack of standardization of systems across vendors.

Proprietary concerns by vendors were a similar barrier to the cost research as it was to the distribution research described in Chapter 1. Proprietary concerns limited the detail level and granularity of information that could be exchanged, and this in turn limited the ability of the interviewer and interviewees to communicate in an efficient manner.

A lack of standardization across vendor discrepancy reporting systems dictated that the interview questions had to be unique for each vendor participating in the cost of discrepancies research. This is because the cost interview questions need to be linked back to the discrepancy reporting systems. Because of the uniqueness of the questions to the different vendors, direct comparisons between the vendors at lower levels were very limited, and only a comparison in the aggregate would be possible.

## 4.10. Enabling Future Research

Research into the cost of discrepancies can be greatly enabled by the use of a higher fidelity cost accounting system. Such a system would track the people, materials, facilities and resources involved in the discrepancy lifecycle and keep a record of activities performed and time spent. In addition, such a cost accounting system should be integrated with the discrepancy reporting and tracking system, to enable real-time analysis of both jointly. The coupling of these two data sources can provide a powerful enabling tool for performing cost-benefit trades on repairs, corrective action, and implementing product development process improvements.

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Options and Feedback About Response: Inconsistencies on Frequency of Alcohol Use Self-Reports by Microcomputer" *Journal of Alcohol and Drug Education*, Vol. 42, No. 2. 1997. p. 1-18.

# Chapter 5.

# Enterprise Findings

## 5.1. Chapter Introduction

The previous chapter discussed a statistical treatment of the spacecraft system-level test discrepancy data. This chapter evaluates the research data and present it in the form of findings on Enterprise level metrics as stated in the Lean Enterprise Model. This chapter will be of particular interest to managers and Enterprise leadership who want to increase quality yield, resource utilization, and stakeholder satisfaction while decreasing flow time. In summary, testing can play an instrumental role in creating value for the entire enterprise.

## 5.2. Lean Enterprise Model

The Lean Enterprise Model (LEM) was formulated as part of the Lean Aerospace Initiative in 1996. Based upon LAI research conducted over several years, the LEM contains six guiding Principles, four enterprise level metrics, twelve overarching practices, and many supporting practices. Figure 5.1 below shows a diagram of the structure of the LEM[33].

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[33] Lean Aircraft Initiative. "Lean Enterprise Model" (unpublished model and handbook), Massachusetts Institute of Technology, Cambridge, MA. 14 November 1996.

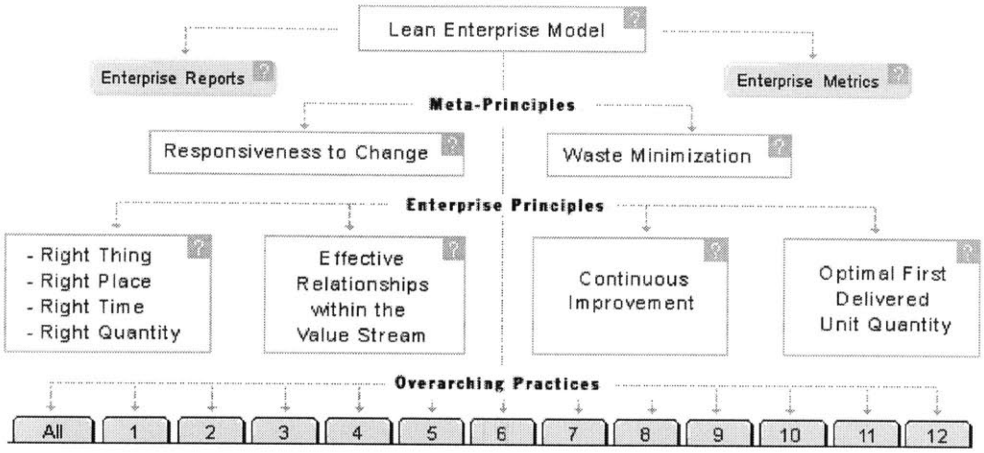

**Figure 5.1: Lean enterprise model structure**

As discussed in Chapter 1, this spacecraft integration and test research draws upon several key principles in the LEM, including waste minimization, "right thing", and continuous improvement. These principles, as well as the others outlined in the LEM, can be measured through Enterprise level metrics. This chapter discusses research findings grouped into the four Enterprise level metrics of the LEM. These are:

- Quality yield
- Resource utilization
- Stakeholder satisfaction
- And flow time

## 5.3. Quality Yield 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 directive 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 5.2 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.

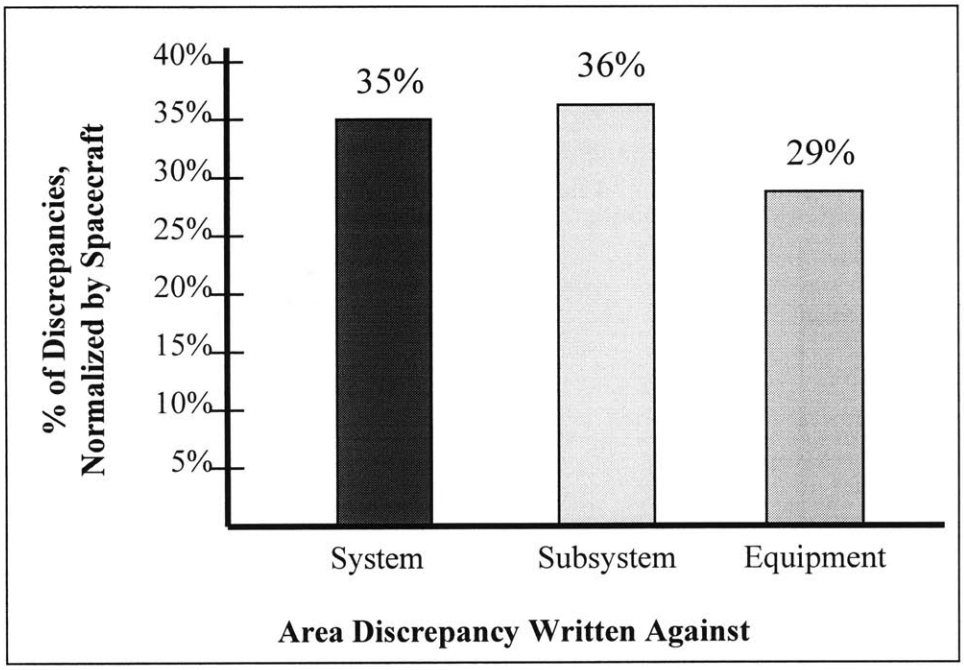

**Figure 5.2: Distribution of discrepancies on an average spacecraft at the system level of integration, by area the discrepancy was written against**

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. Currently, subsystem and equipment problems account for nearly two thirds of the discrepancies found during system level I&T. This provides an enterprise metric for measuring progress towards the goal of driving testing to the lowest level possible.

## 5.4. Resource Utilization Findings

Resource utilization findings for three resources will be discussed: Environmental chamber facilities, root cause analysis, and corrective action.

### 5.4.1. Environment Utilization

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 5.3 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.

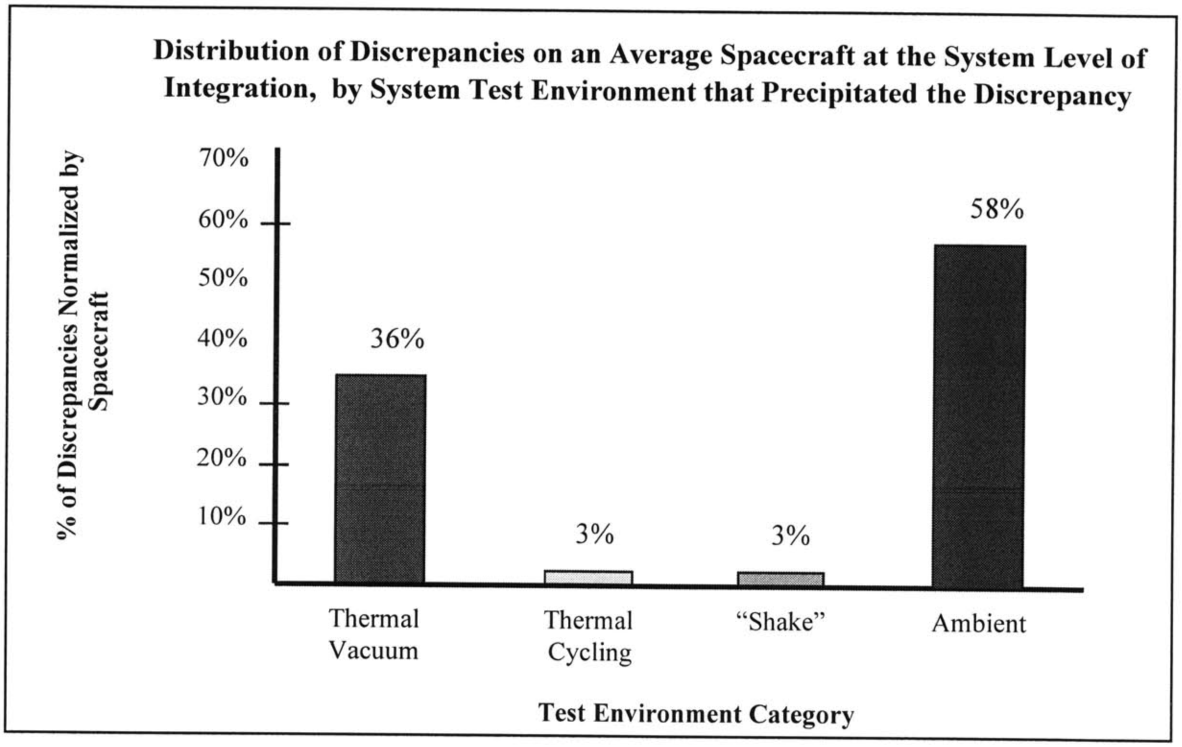

**Figure 5.3: Distribution of discrepancies on an average spacecraft at the system level of integration, by system test environment that precipitated the discrepancy**

As shown in the graph above, 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. For more detail on the activities contained within each of these environment categories, please see Chapter 4.

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.

### 5.4.2. Root Cause

An analysis of the root cause of problems can be quite insightful for the enterprise. It can tell you where you might want to spend your resources to increase quality or performance, and in this way provides insights into resource utilization.

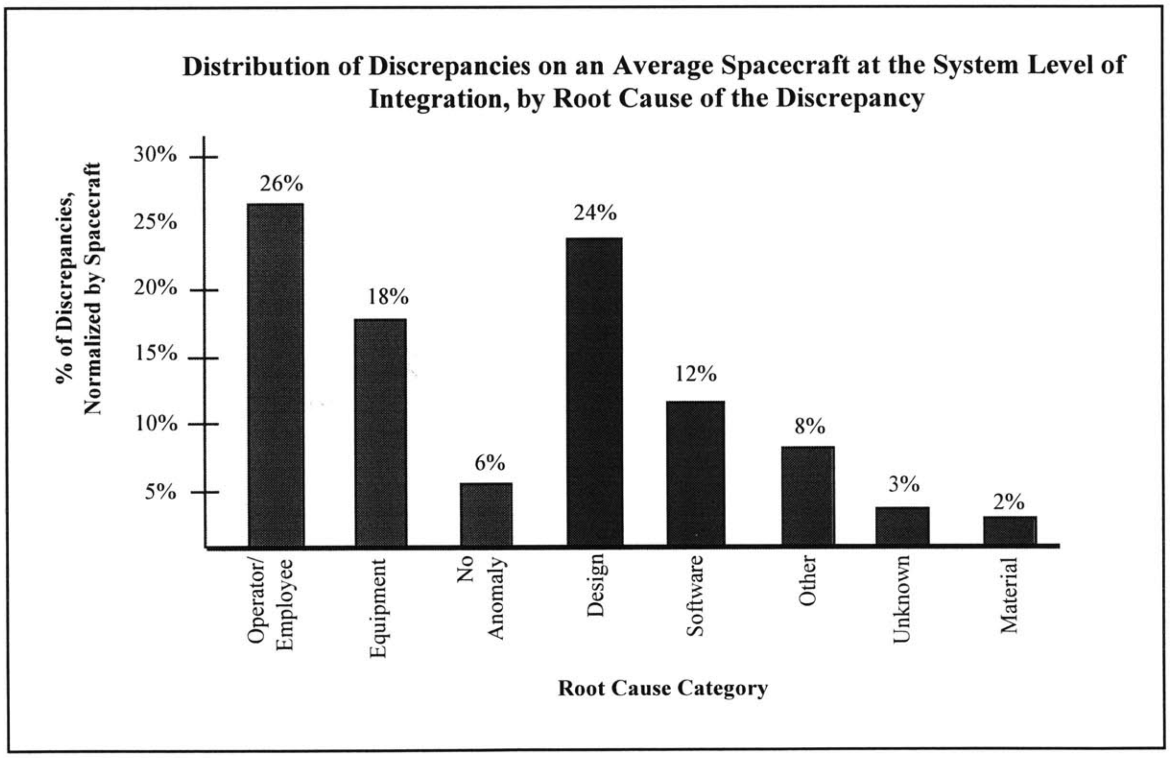

**Figure 5.4: Distribution of discrepancies on an average spacecraft at the system level of integration, by root cause of the discrepancy**

As demonstrated in Figure 5.4, 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. For more details on what is contained in each of the root cause categories shown in Figure 5.4, please see Chapter 4.

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. 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, software and material problems.

### 5.4.3. Corrective Action

Long-term corrective action, defined as an action taken to prevent a specific discrepancy from occurring on future spacecraft, is a resource utilization issue when the discrepancies themselves are considered as the resource. 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, is a resource that points out opportunities for improvement. If all these opportunities are not capitalized upon, then resources are not being utilized to the fullest.

Figure 5.5 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 missed opportunities for improvement.

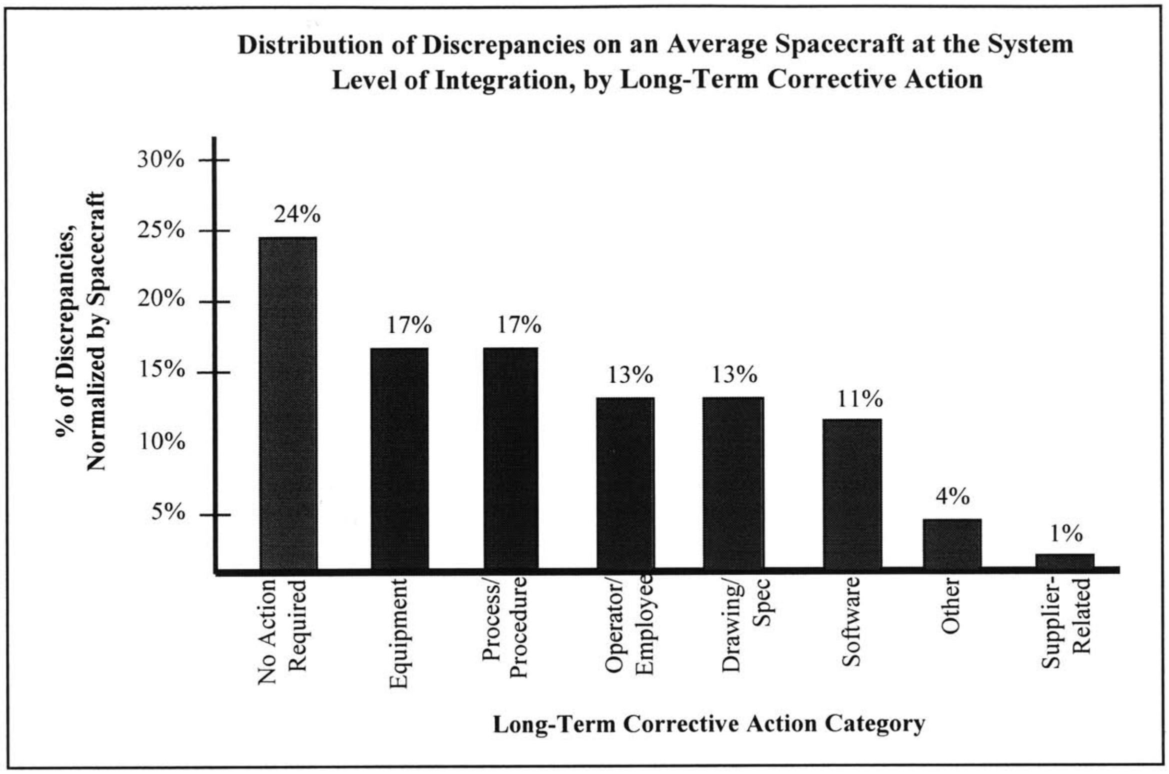

**Figure 5.5: Distribution of discrepancies on an average spacecraft at the system level of integration, by long-term corrective action**

## 5.5. Stakeholder Satisfaction Findings

Stakeholders are defined broadly to include customers, suppliers, subcontractors, and all that are involved in creating the product and bringing it into operation. Thus, metrics that might involve suppliers or customers are typically found in this category. The observations below illustrate that components of this particular enterprise level metric can sometimes be measured and understood clearly, but oftentimes it can be difficult to measure certain components, and even then, those measures have unclear interpretations.

### 5.5.1. Suppliers

In examining long-term corrective action and root cause, 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 does not appear to be fully in line with the Lean philosophy to establish stable and ongoing cooperative relationships with all players in the value stream. In addition, 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.

### 5.5.2. Customers

In examining the duration that a discrepancy remains open at the system level of integration, it is found that there is a difference between the distribution of open duration for commercial vice government spacecraft programs. This is illustrated below in Figure 5.6, which shows that roughly 50% more discrepancies at the system level of integration are closed in one month's time for commercial programs than for government programs.

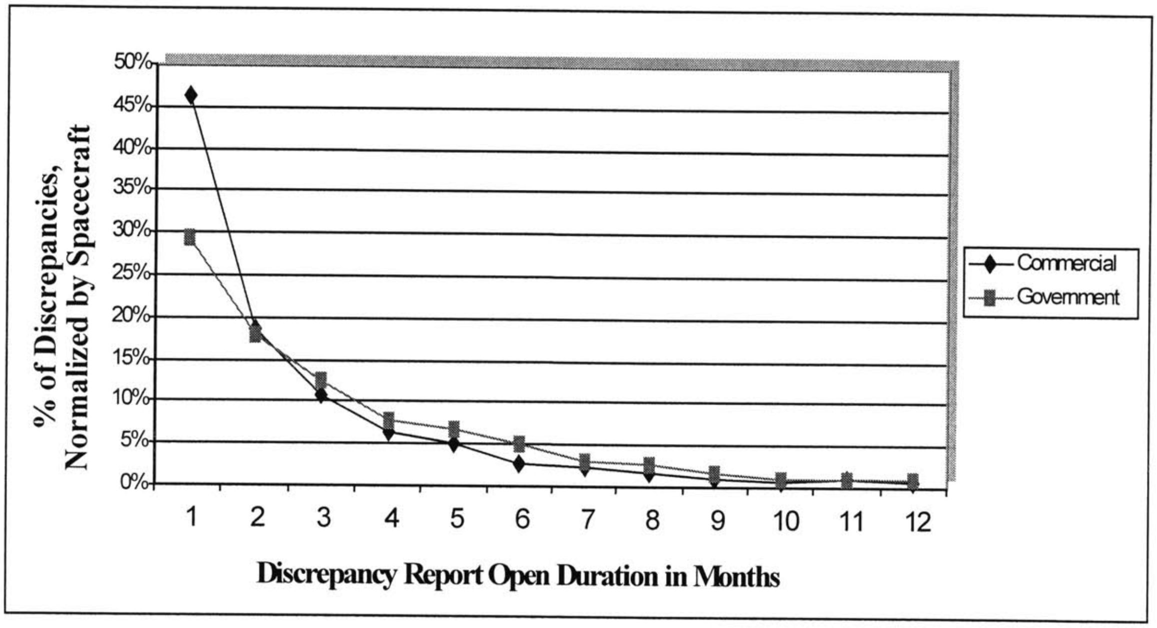

**Figure 5.6: Histogram of discrepancy report open duration on an average spacecraft, broken out by sector**

While this is an interesting dynamic, the dynamic by itself has unclear implications. However, if the actual open duration could be compared with the duration that the discrepancy would have to remain open in order to start causing a cycle time delay in production, then a more useful metric with clearer implications could be created. But that data is not currently collected, and thus the comparison of open duration among the sectors is less meaningful.

## 5.6. 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. So far, this chapter has examined an enterprise-level picture of discrepancies at the system level of integration, but without an idea of the costs involved with those discrepancies, that picture is of questionable value to a decision-maker.

### 5.6.1. Labor Time

As discussed in detail in Chapter 1, 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 process – 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[34], 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[35]. 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%.

### 5.6.2. 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

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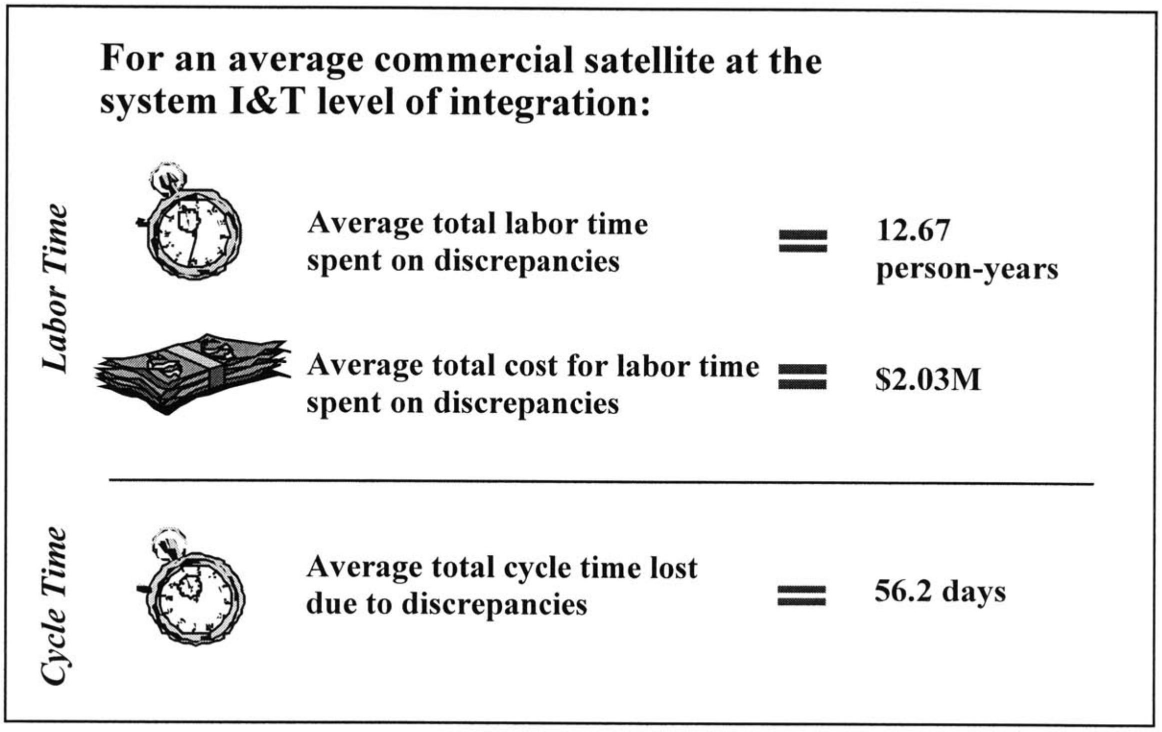
[34] Wertz, James R. and Wiley J. Larson. Space Mission Analysis and Design. Third Edition. California: Microcosm Press, 1999. p. 801.

[35] Wertz, James R. and Wiley J. Larson. Space Mission Analysis and Design. Third Edition. California: Microcosm Press, 1999. p. 808.

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 5.7 presents a summary of flow time findings. 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.



**For an average commercial satellite at the system I&T level of integration:**

*Labor Time*

**Average total labor time spent on discrepancies = 12.67 person-years**

**Average total cost for labor time spent on discrepancies = $2.03M**

*Cycle Time*

**Average total cycle time lost due to discrepancies = 56.2 days**

**Figure 5.7: Graphic of Labor and Cycle Time Spent on Discrepancies at the System Level of Integration, per Spacecraft**

# Chapter 6.

# Conclusion

## 6.1. Summary

This thesis began by introducing some background on the origins of lean practices, the Lean Enterprise Model (LEM), and the spacecraft development process. Motivated by the LEM principles of waste minimization and continuous improvement, this research investigated spacecraft system-level integration and test discrepancies, which are considered waste in the process. If this waste could be removed, cost and cycle time reductions would follow, as well as quality and reliability improvements in the product. An examination of the distribution and costs of spacecraft discrepancies at system-level integration and test yielded several key findings for the Enterprise:

- *System-level test is finding significant portions of non-system-level problems.* Test equipment problems account for 29% of all discrepancies found at the system-level of integration, and subsystem discrepancies account for 36%. It can potentially 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.

- *Half of the system-level problems were caused by "non-spacecraft" things, such as human error and test support equipment.* 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.

- *Cycle time and labor time impacts of system-level discrepancies appear large, but currently these metrics are untracked.* 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.

- *Organizations are passing up opportunities to capitalize on problems they have spent significant time and money on finding.* Testing is an expensive part of any spacecraft development program. The high percentage of discrepancies for which no long-term corrective action is prescribed serves to enhance the point of missed opportunities. In addition, interview data suggests that follow-through on prescribed long-term corrective actions gets overcome by more urgent and immediate needs.

## 6.2. Recommendations

Significant opportunities exist to increase the value-added contribution of test across the entire Enterprise. Several important recommendations emerge out of this research that will help organizations to make progress towards that end.

### 6.2.1. 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.

### 6.2.2. Continuous Improvement

Continuous improvement should be established, valued and maintained as part of the corporate culture. Through an attitude of continuous improvement, waste minimization and a lean environment can be achieved. Improvement also involves a commitment to find the true root cause of discrepancies or problems, and implement an enterprise-wide solution to prevent them from reoccurring. Finally, improvements need to be measured and evaluated for their effectiveness.

### 6.2.3. 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.

### 6.2.4. Use Test to Improve the Enterprise

Product testing can become more than measuring the performance of the present product to its specifications. As demonstrated in the findings of this research, 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 6.1. To illustrate this point, take the finding from Chapter 1 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.

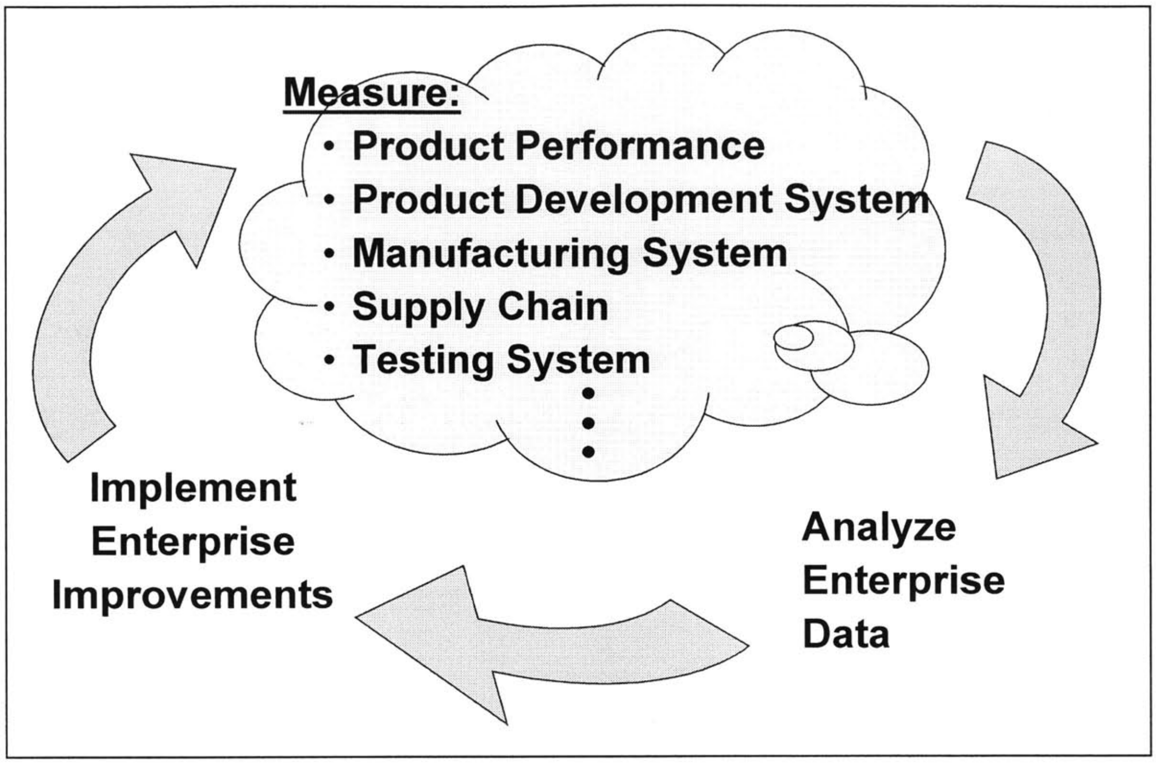


**Figure 6.1: The enterprise testing value stream**

## 6.3. For Further Research

The subject area of this thesis provides many opportunities for additional research. Follow-on activities should focus on addressing the following questions:

- How does organizational structure influence the frequency and distribution of discrepancies in the spacecraft industry? The degree of vertical integration within an organization, the types of relationships with suppliers, and the use of integrated teams should be investigated for their specific correlation with types and frequencies of discrepancies.
- What are the relationships between the amount of non-recurring engineering on a program and the type, frequency and time associated with discrepancies on a non-recurring engineering program? Also, what are the relationships between product complexity and the type, frequency and time associated with discrepancies?
- How does the degree of subsystem testing at lower levels of integration influence the types and frequency of discrepancies found at the system level of integration?