747 Data Management System Development and Implementation

Scott Muske
David Salisbury
Boeing Commercial Airplane Group

Robert Salerno, Ph.D.
Joseph Calkins
New River Kinematics

Copyright © 1999 The Boeing Co.

ABSTRACT

In 1994, Boeing and one of its prime suppliers undertook a trilogy of programs to upgrade and update the engineering and manufacturing process of the 747. The 747 Fuselage Assembly Improvement Team (FAIT) is the third phase of this effort. FAIT resulted in a requirement for an integrated large-scale metrology system to support data acquisition and analysis. Real-time information is required to ensure conformance to product design and aid in identifying process improvements within manufacturing. The resulting system must gather the measurement data, analyze per engineering definition, and store all critical information in a secure database. Additionally, the system must be able to perform 3D analysis and create Statistical Process Control/Hardware Variability Control (SPC/HVC) charts of archived data. These functionalities had to be developed at low cost and within a six-month time frame. All of the above requirements have been met and/or exceeded by the implementation of the 747 Data Management System (DMS). This paper describes the development and implementation of DMS for the 747 FAIT program.

Background

Boeing has been building the 747 for over thirty years. During that time there have been numerous enhancements to the aircraft design and materiel specifications, but the assembly methods for the fuselage have changed little since the conception of the 747. The assembly method made use of large assembly tools that were developed from a physical master model. These assembly tools required periodic certification and proof that they met a specified tolerance relative to the master model. Since the plane was built using the certified tools conformance to engineering design was ensured. With the development of CAD, computer models have replaced the physical master models but the overall build process remained the same.

The 747 program has implemented a new method for assembling the 747 fuselage. This assembly method is known as Determinant Assembly (DA). DA is a method of self-indexing of the detail parts to each other to create an assembly. By utilizing DA parts can be assembled with a minimum number of tools. The advantage to this method is that it drastically reduces the cost of tooling and has been shown to produce a more repeatable product. Figure 1 depicts in color the sections of the airplane where DA is currently being implemented.

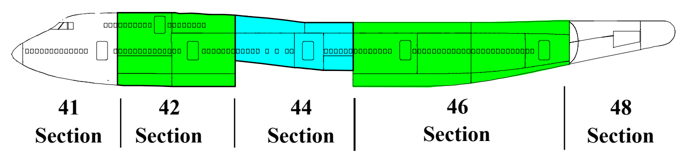


Figure 1 Application of DA on the 747

One of the biggest challenges of using DA on the 747 was showing conformance to type design without the use of traditional final assembly tools. The 747 program required a metrology system that would enable the shop floor mechanics to measure the sections of the 747 and instantaneously show product conformance.

DMS Functional Requirements

A cross-functional team was developed to meet the challenge of developing a 747 Data Management System. This team was lead by Quality Engineering Technology and consisted of Manufacturing Research & Development (MR&D), Manufacturing Engineering (ME), Quality Assurance (QA), Tooling Quality Assurance (TQA), Tooling, and Manufacturing. The team began by first developing the functional requirements for the system. There were eight key elements that would be required for the system to be deemed a success. First, the system had to be capable of interfacing with a laser tracker. Laser trackers had been selected as the means to collect the required 3D measurements on the airplane sections. The program had purchased four Leica laser trackers for this purpose. Second, the system had to be capable of handling manually collected data. Since many of the measurements taken were simple gap measurements the system would have to allow the operator to manually input the values. Third, the system had to be capable of analyzing the measurements with reference to an engineered CAD master model, thus proving product. Fourth, the entire analysis process had to be accomplished within a five-minute time frame upon completion of the measurements. One of the critical factors in successfully integrating a measurement system into a production line is to insure that the additional costs due to lost production time while measurements are taken plus time to complete analysis and provide useful information does not exceed the expected benefits. Fifth, the system would be required to report all the data in a conformance report that would be used to buyoff the airplane. Sixth, the system would have to store all the measurements in a secure database. Because these measurements are used to accept product, the data that is collected once sent to the database, cannot be altered or deleted unless done so by an authorized individual entrusted with the task. Seventh, the system would be capable of producing a set number of SPC charts. The actual SPC charts created by DMS are show in Figure 2. The measurements being gathered play a vital role in process improvement. By using the measurements to produce SPC charts decisions can be made on how to make future improvements. Eighth and most importantly, the system would have to be developed within a six-month time frame to meet the needs of manufacturing.

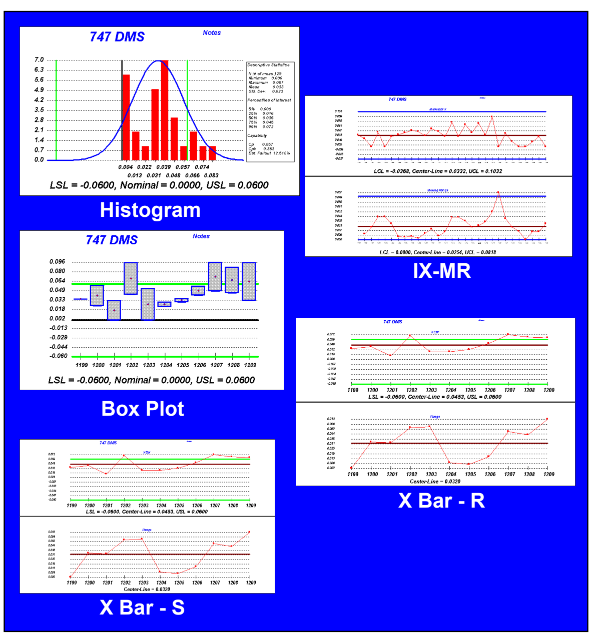


Figure 2 DMS SPC charts

Large-scale Metrology Challenges

There are several metrology challenges in measuring a 747 section. These include part indexing, datum transfers, temperature, measurement point visibility, part/tool stability, and system accuracy. In the early stages of the project, the development team attempted to understand these challenges and develop requirements that would meet the technical needs, cost and schedule of the program. The following are a summary of some of the challenges the team addressed.

Each body section of the 747 utilizes a mixture of manufacturing processes and tools as it is built up. One of the first challenges addressed was part indexing. Engineering provided assembly drawings for each section. Geometric Dimensioning and Tolerancing (GD&T) was utilized to express the datuming and tolerancing requirements for each of the sections. The two datum schemes developed utilized either specific features of the parts or hard tooling points to control the part setup. The laser tracker was required to tie-in to these engineering reference systems. The concept was developed by engineering to eliminate the use of “best fitting” and instead to use specific features of the part (fixed tie-in) from which to define the datuming system. Best fitting refers to the practice of measuring a series of points and fitting those points to another set of points with equal weight. By creating a fixed tie-in method the variation caused by best fitting would be eliminated. It was not presumed that all variation due to tie-ins would not exist, but the cause of the variation is isolated so it can be better controlled. One example of a fixed tie-in is section 44 station 1000 shown in figure 3. The three A points lie on a Station (X) plane, the two B points lie on an (averaged) Buttline (Y) plane and the two C points line on a Waterline (Z) plane. All the indexes were physically on the part and could be reached by either a sphere fitting routine or a hidden point bar adapter (Adapters will be discussed later).

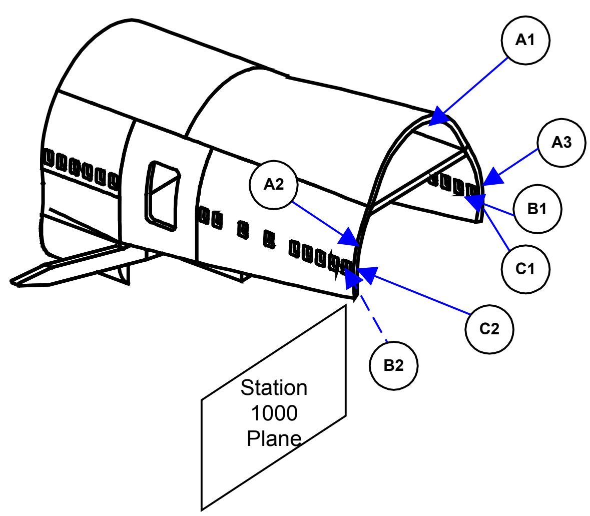
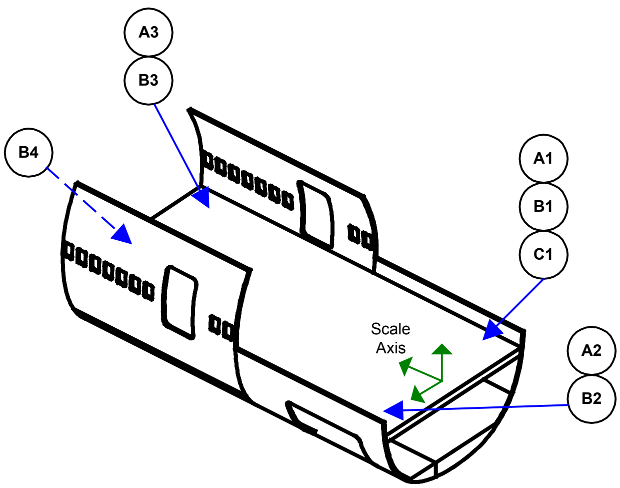


Figure 3 Section 44 Station 1000 Tie-in

In the 42 section lower lobe of the aircraft, there is no easy access to the physical datum features specified in the engineering. This was due to the design of the tool fixtures required to support the structure. Features of the hard tool were used to orient the laser tracker into the correct reference frame. This is referred to as a datum transfer. A large tool was built to hold and index the lower lobe. An Enhanced Reference System (ERS) was established on the tool that could be viewed by the laser tracker to tie-in to the part.

With large structures this practice is common, but in this case there was the issue of differential growth. The tool was made of steel and the assembly was made of aluminum. The tie-ins were carefully selected to reduce the effect of differential growth to insignificance. The exact tie-ins are shown in figure 4. By establishing the Buttline (Y) origin mid way between the two Buttline indexes, the differential growth between the two structures can be nullified.



Transform Weighting

	X	Y	Z
A1	0	0	1
A2	0	0	1
A3	0	0	1
B1	0	1	0
B2	0	1	0
B3	0	1	0
B4	0	1	0
C1	1	0	0

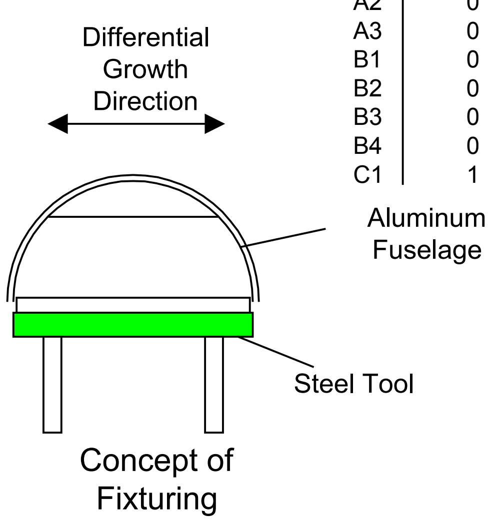


Figure 4 Section 42 Lower Lobe Tie-in

Differential growth is only one-aspect temperature variation considerations. Temperature causes many more problems in the measurements of large structures. The Everett factory does not have a temperature-controlled environment. The thermal environment can fluctuate as much as 15 degrees over four hours. Since all engineering drawings are defined at a temperature of 68 degrees all measurements must be scaled. The 747-fuselage is made of aluminum and can be scaled to 68 degrees by using the coefficient of expansion for aluminum. Scaling the part was straightforward, but determining what temperature to use was not, due to the fact that the temperature varies with elevation. Figure 5 shows a chart of the temperature gradients between the bottom and top of the aircraft. This variation can be as much as 4 degrees.

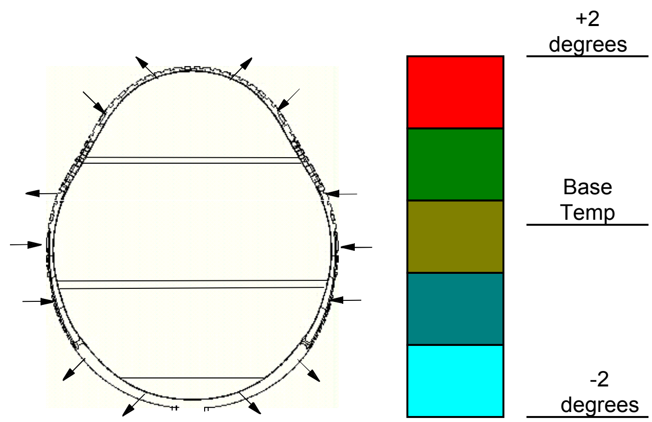


Figure 5 Temperature Gradient

The physical size of the Everett facilities made it impractical to control the temperature within the desired 2-degree temperature range. The recourse was to devise a method to minimize the impact of temperature variation. Temperature probes are placed on both sides of the aircraft at the mid-point of the structure. The two temperature readings are taken, averaged, and utilized as the part temperature. If the beginning and ending temperature of the survey vary more than 4 degrees then the survey was considered void and has to be repeated. If the difference was less then 4 degrees, then the average is used to scale the part. Temperature also causes problems with laser tracker wavelength compensation. The air temperature and pressure are taken at the beginning of the survey and used to calculate the wavelength compensation for the laser tracker. This is fixed throughout the survey since the accuracy lost due to the wavelength compensation factor is an order of magnitude smaller than the required tolerance over the envelope of the survey.[1]

The relative proximity of the tracker head to the airplane structure, along with the obtrusiveness of the jigs, provided challenges for visibility. The laser tracker

[1] Uncertainty of the measurements was not addressed for the initial implementation. A Measurement System Analysis (MSA) is currently being conducted.

requires clear visibility of the SMR (laser target). Some areas provide less than three feet of clearance between the plane and tools. In order to gain visibility, all the laser tracker surveys were taken from the inside of the aircraft, shown in figure 6.

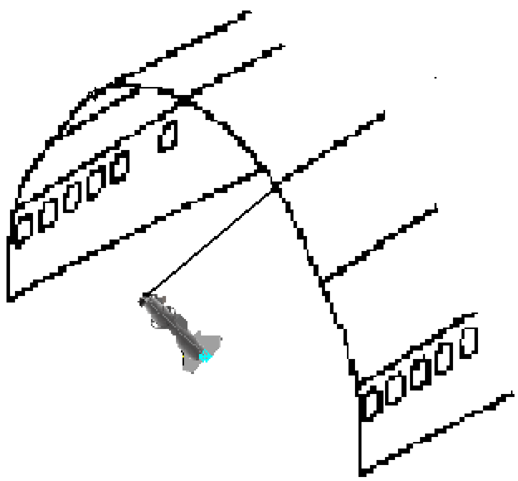


Figure 6 Picture of laser tracker setup

Some of the features that are being measured are located on the outside skin surface or are otherwise not visible on a line of sight to the tracker. Special adapters were created for these instances. For example, the outside contour of a section bulkhead was one of the required measurements. To allow access to this type of hidden feature, a special two-point adapter was created that could be indexed and clamped to the desired part and viewed from inside of the structure. In another case, the primary datum for the part was hidden from view and a three-point adapter was required.

Because DA takes advantage of minimum tooling to hold the airplane in the proper configuration, stability became another challenge to the project. A significant factor in collecting valid measurements is to minimize the movement of the tracker relative to the part. This proved to be a difficult obstacle to resolve. Vibration of the jig decks during the laser shoot moved the tracker head significantly enough to reject the jobs that were being collected. The tracker was then moved onto the airplane itself so that the tracker now moves with the part. To ensure that the tracker movement is within acceptable limits, drift points are taken at the beginning and end of the survey. The relationship between the drift points and the tracker is not allowed to exceed +/- .010 at 40 feet from the tracker.

Finally, the accuracy of the system is paramount in the measurement of the section. Engineering has established aggressive tolerances. The measurement system would have to meet, at a minimum, one fourth of the engineering tolerance and do so on a repeatable basis. This includes the natural inherent precision of the laser tracker and the adapters.

System Development

SpatialAnalyzer ®, a 3D-analysis product developed by New River Kinematics, was chosen to act as the foundation for what would become DMS. New River Kinematics had developed SpatialAnalyzer with an architecture that could communicate with numerous measurement devices with the capability to generate relational databases.

Boeing and New River Kinematics worked closely together to develop a laser tracker and a database interface that would be simple and easy to use for the shop floor mechanics. One of the challenges laid out in the design phase was that the database interface would not require more then three key strokes before the user would be able to input manual data. Once all the requirements were gathered detail tasks were laid out for both Boeing and New River Kinematics. The development team created data flow diagrams and a data scheme based on these functional requirements. New River Kinematics began a very intensive development effort to meet the required implementation date and Boeing began developing all the testing, processes and procedures to implement the product into production. Initial delivery of the alpha system framework took place 45 days after commencement of the project. Followed by a functional beta delivery at 75 days and a final fully functional delivery in 90 days.

As an aid to the development process an acceptance database was developed and utilized to gather and track all change requests and testing for the product. Test scripts were developed and inputted into the acceptance database during the software development. The testers ran the test scripts as the software became available and created change requests if the function either did not pass or had a variance based on the expected results. This method of development, testing and tracking was one of the keys to the success of the project. This process allowed a very small group of individuals to test the system, communicate with the vendor, and maintain a very aggressive project schedule.

Software Components

There are essentially three main functional tasks of the 747 DMS system. These main tasks can be classified as data acquisition, data analysis, and data storage/retrieval. As depicted in Figure 7, the three software components of this project, SpatialAnalyzer, the DMS software, and the Leica tracker interface (LTrack), share responsibilities to accomplish the stated tasks.

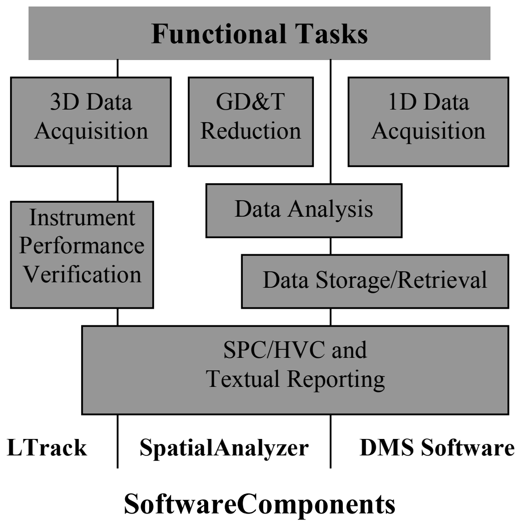


Figure 7 – Software Components and Tasks

Three-dimensional data acquisition is principally handled by the LTrack interface. The 3D data acquisition relies on SpatialAnalyzer for automatically locating the instrument with respect to the established reference coordinate system (auto-buck). All communication between the LTrack module and SpatialAnalyzer is done with TCP/IP sockets (the same protocol used for the Internet). The LTrack interface also performs instrument operational verification checks and prepares survey information for final reporting.

SpatialAnalyzer handles the data analysis tasks. These include items such as system auto-buck, GD&T data analysis (excluding form), CAD model import, and report generation. To most effectively acquire the coordinate measurement data, a new general-purpose instrument interface module was developed for the Leica line of laser trackers. In keeping with the general architecture philosophy of SpatialAnalyzer, the measurement device selected for a given task is a matter of user preference; other types of instruments may be substituted at will. In fact, the overall DMS design is structured so that new metrologic technologies may be incorporated with minimal changes to the system.

The core of the database management system is the DMS application, written specifically for this task. The DMS module is responsible for general database management, including database initialization (stamping), and all write and read operations from the database. All database operations follow strict rollback type error checking to avoid possible contamination of the central database. One dimensional measurement data is directly deposited in the database through a user interface specifically developed for novice computer users. The DMS package also contains the SPC/HVC charting engine used to generate required production charts and standard conformance reports.

By starting the design process with an array of extremely flexible and general tools, all design tasks were accomplished in a remarkably short time period. Total development time for the three components of the DMS system was six months.

System Integration with Production

Integrating a new system into production is always a challenge and DMS was no exception. The 747 program has never before used the laser tracker exclusively to collect and directly show conformance to type designs. In the past, hard tooling was the means by which configuration was ensured. With the implementation of FAIT, the traditional hard tools were replaced with the new FAIT tools. Acceptance of product has also changed from the traditional Quality Assurance roles, in which the use of laser trackers in a production environment was reserved for highly trained specialist, to now include manufacturing personnel in the collection of the acceptance data. To achieve this end, there have been many obstacles that had to be overcome. One of the issues was the use of adapters to allow visibility of features of the part. The adapters had to be tested on the actual airplane structure (sometimes over several iterations) to insure that they would work. Boeing utilized the experience of the Coordinate Measurement Lab to develop the adapters and other measurement techniques. Figure 8 shows a concept sketch of a two-point adapter.

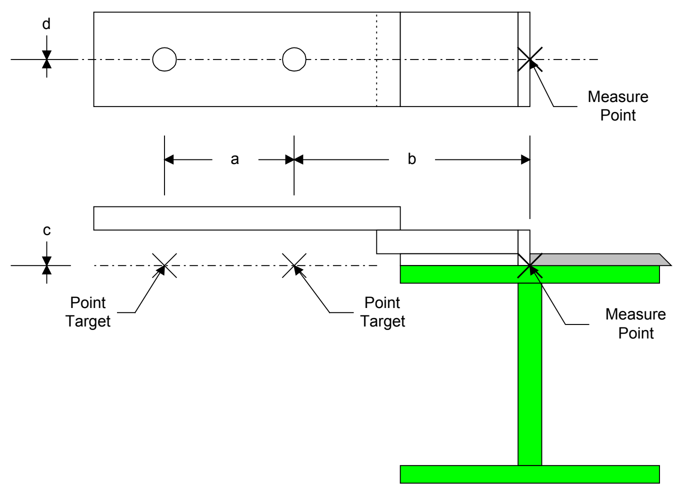


Figure 8 Two Point Adapter

A method was developed for deriving the hidden measurement point from the offset target points on the adapter. Adapters are created in a table within the DMS database. A reference axis is defined on the adapter, originating at the measurement point, and the coordinates of the offset target points are defined in this axis system. When the offset target points are measured with the tracker the hidden point can then be created. The idea was to decouple the measurement process from engineering, in that offset target point definitions need not be included in the engineering CAD model. By decoupling the process, any changes to the adapter would not effect the engineering model. The actual adapter calculations would be handled by DMS.[2]

Another important part of the integration was training. Training was separated into two categories: DMS training, and Laser tracker training. Manufacturing Engineering spearheaded the DMS activity. Due the simplicity of the database interface the required time for the training course was only two hours. The challenging part is that over one hundred individuals would have to be trained. The Brunson Instruments provided the initial laser tracker training classes. Each class went through the basics of tracker usage and the use of the DMS interface. Additional laser tracker training was provided by the Tooling organization for the first ten airplanes. Providing the mechanics with early hands on experience allowed us to identify change requests to improve the system prior to final delivery.

New River Kinematics developed the laser tracker interface from scratch to meet the needs expressed by the Coordinate Measurement Lab and Tooling. The interface was designed to be simple but still meet the needs of laser tracker operation. Tooling was responsible for all the shots prior to hand off to manufacturing. They acted as the guinea pigs and provided invaluable feedback on what functionality and changes were required to the interface.

Key to meeting the schedule implementation date was the ability to accredit and certify the system. MR&D and Coordinate Measurement Lab worked closely together to develop comprehensive tests that would prove SpatialAnalyzer capable of gathering data in an accurate and repeatable manner. Procedures were developed with the help of the Calibration and Certification Lab to certify the product utilizing the Leica Laser tracker. Although this seems mundane in retrospect, the process of certification has caused as much as a year delay in the implementation of other measurement devices and systems. The accreditation process is the methodology followed to ensure that the software and documentation are developed, tested, and delivered as defined and as purchased. All software that is used in the acceptance of airplane product must adhere to this process. The methodology used with DMS is Productivity Plus. This system was tested, accredited, and certified in less than two months.

Conclusions

747 DMS was delivered in time, within budget, and exceeded the functional requirements. The customer has deemed the system a success and future enhancements and applications are now under consideration.

This project was made possible by follow a structured approach for product development and teaming early with a supplier. It is important to understand that this type of effort requires an immense amount of coordination and communication. The development team, New River Kinematics, and Brunson Instruments made great efforts to overcome the technical hurdles to make this project possible.

Some of the lessons learned from this effort include the following:

- Up front manufacturing involvement was critical. The measurement method that was being replaced required only the knowledge of utilizing a pencil. When implementing a system the user interface will determine the success of the system. In the case of DMS the laser tracker interface required several iterations to develop an interface that was deemed acceptable.
- Utilize Subject Mater Experts (SME) in the development process. Although this seems obvious, more often then not systems are installed without the collaboration of SMEs. DMS would not have been possible without the support of the Coordinate Measurement Lab, MR&D, and Cal/Cert.
- Detailed process documentation for system utilization and maintenance. Documenting the process is a critical aspect of system integration when dealing with a large group of people. This requires customer involvement to determine the format and detail of documentation to best communicate the intent.

Acknowledgments

This paper would not have been possible without the hard work of each and every member of the 747 Data Management System team. Some of the main contributors are as follows:

- Craig McKelvey, Quality Engineering Technology, Coordinate Measurement Lab, Boeing Commercial Airplane Group
- Michael Rounds, Manufacturing Engineering, Boeing Commercial Airplane Group
- Terry Wilhelmsen, Tooling Quality Assurance, Boeing Commercial Airplane Group
- Mike Kalahar, Information Systems Support, Boeing Commercial Airplane Group
- Rick Carrillo, Manufacturing Engineering, Boeing Commercial Airplane Group
- Eddie Salahshoor, Quality Engineering Technology, Coordinate Measurement Lab, Boeing Commercial Airplane Group
- Rick Cole, Brunson Instrument Company
- Mark Wilmoth, Brunson Instrument Company
- Matt Settle, Brunson Instrument Company

[2] The axes in the CAD model are only necessary for ADM to find the targets. If hand held measurements are used, the hidden point is calculated solely from the adapter definition in DMS.