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Title: Shell Inspection History and Current CMM Inspection Efforts

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Shell Inspection History
and
Current CMM Inspection Efforts

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Abstract

The following report provides a review of past and current CMM Shell Inspection efforts. Calibration of the Sheffield rotary contour gauge has expired and the primary inspector, Matthew Naranjo, has retired. Efforts within the Inspection team are transitioning from maintaining and training new inspectors on Sheffield to off-the-shelf CMM technology. Although inspection of a shell has many requirements, the scope of the data presented in this report focuses on the inner contour, outer contour, radial wall thickness and mass comparisons.

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1.0 Introduction

The Coordinate Measuring Machine (CMM) Shell Inspection project was conducted as a possible alternative to the current shell inspection process. The current process utilizes unique rotary contour machines which are obsolete, difficult to maintain, difficult to calibrate, and require highly skilled and trained inspectors. CMMs are off-the-shelf machinery, and sold by numerous vendors, with a large user base. CMMs are easier to calibrate, maintain, use, and have steadily become more accurate with technological developments. In addition, they can measure an assortment of parts unlike the rotary contour machines designed only for shells.

The goals of the CMM Shell Inspection Project are:

- Meet 4:1 ratio as specified by drawing specifications to equipment accuracy (*"General Requirements (U)"*, 9900000 [1]) for contour and wall tolerances
- Meet 4:1 or Sheffield to CMM comparisons within 25% of drawing tolerance for contour and wall tolerances
- Mass comparison (estimated volume X density versus balance) within specified quality limits
- Internal goal: Outperform Phase III Qualification Results

2.0 Previous Work

2.1 CMM Requirements and Acceptance

Early efforts began with first looking at parts of interest. This included a detailed investigation of the features to be inspected and the geometric dimension and tolerances (GD&T) associated with them. This review was documented in *"Pit Manufacturing Project Coordinate Measuring Machine Inspection Development Inspection Requirements Document"* [2].

Next came a comprehensive look at which CMM technologies would provide the best solution for the inspection of Los Alamos National Laboratory's (LANL) parts. Key machine characteristics like machine accuracy and maintainability were taken into account and documented in *"Pit Manufacturing Project Coordinate Measuring Machine Inspection Development CMM Acceptance Document"* [3].

2.2 Point-to-Point, Parameter Optimization, and Scanning Mode

After the requirements were set and a CMM was chosen, the next logical step in the CMM Shell Inspection development process was to test some of the CMM parameters that would affect the measurement. Parameters such as probe force and scan speed were varied while different data gathering techniques such as point-to-point versus scanning were also tested and documented in *"CMM Point-to-Point Mode Inspection of a 126 Stainless Steel Hemi-Shell (U)"* [4], *"CMM Inspection of a 126 Stainless Hemi-Shell;*

Scanning Parameter Optimization Study (U)" [5], and *"CMM Scanning Mode Inspection of a 126 Stainless Steel Hemi-Shell"* [6].

2.3 Low Density

The Non-nuclear Component Development (NCD) portion of the Pit Manufacturing Project (PMP) funded the development and qualification of a CMM shell inspection process. A process qualification plan was written *"308942/308943 CMM Contour Inspection"* [7], a work instruction was created to execute the work *"308942/308943 CMM Contour Inspection"* [8], and a Process Qualification Plan (PQR) documented the results *"308942/308943 CMM Contour Inspection"* [9]. The process was never qualified because the customer was unwilling to accept the significantly lower data density as compared to the Sheffield rotary contour gauge.

2.4 High Data Density, Phase I – Proof of Concept

The Inspection Team attempted to achieve a similar data density as rotary contour gauges using a different measurement strategy. All previous scanning efforts at LANL had been done through the use of undefined path scanning or closed loop scanning. This type of scanning uses the force feedback from the CMM probe head to drive the machine. In the new strategy, the use of defined path or open loop scanning was tested. The benefit is that defined path scanning is much faster allowing for more data density. This proof of concept was documented in *"High Point-density Shell Measurement on CMM Proof of Concept"* [10].

2.5 High Data Density, Phase II – Process Improvement

After proving that the CMM was capable of capturing the data density in an eight hour shift, the process was further enhanced. LANL worked directly with the CMM manufacturer to streamline the process and enhance the accuracy of the measurement. The end result produced a document *"High Point-density Shell Measurement on CMM Data Correlation Study, Program Tuning (Phase II)"* [11] and program suitable to the Phase III effort.

2.6 CMM Shell Inspection Phase III Process Prove In

In the first part of the Phase III effort or Process Prove In, *"CMM Shell Inspection"*, LA-UR-11-02659 [12] analyzed data from a stainless steel monitor part 157Y701317 serial number 0001. This part was inspected on multiple machines including Sheffield 1, Shell Measuring Machine (SMM), Sheffield 2, and the Hot CMM. Data was collected in accordance with process qualification plan *"CMM Shell Inspections (U)"*, PM-PQP-178 [13] while working under the following work instructions: *"CMM Shell Inspection (U)"*, MFG-WI-0114 [14], *"Sheffield Gage Inspection Procedure (U)"*, NCD-WI-000018 [15], *"SMM Profile Inspections of JTA Hemishells (U)"*, JTA-Proced-000115 [16], and *"Density Determination (U)"*, NCD-WI-000016 [17].

The data proved that inspectors had been using the wrong surface for datum measurements. This report also documented the use of mass analysis and demonstrated that CMM measurements were closer to estimated mass than rotary contour machines (Sheffield and SMM). This report was also the first to employ the use of ISO 17043, *"Conformity Assessment – General Requirements for Proficiency Testing"* [18]. This proved that the quoted uncertainty for the rotary gages is probably higher than what was being claimed.

2.7 CMM Shell Inspection Phase III Qualification

The second part of the Phase III effort or Qualification, *"CMM Shell Inspection Phase III - Qualification"*, LA-UR-12-00112 [19] analyzed data from plutonium parts. Data was collected in accordance with process qualification plan *"CMM Shell Inspections (U)"*, PM-PQP-178 [13] while working under the following work instructions: *"CMM Shell Inspection (U)"*, MFG-WI-0114 [14], *"Sheffield Gage #2 Inspection Procedure (U)"*, MFG-WI-0029 [20], and *"Final and In-Process Density Determination, Shell Mass Determination Process 601, 306 & 702 (U)"*, MFG-WI-0026 [21].

The major findings during the Qualification Phase III effort were:

1. Radial wall thickness measurements differed by more than 25% of the tolerance.
2. The Hot CMM radial wall thickness is thinner than Sheffield 2 primarily due to differences in the inner contour measurement.
3. Inner contour measurements from Sheffield 1, SMM, and Hot CMM compare much better with each other than with Sheffield 2.
4. Mass comparison values are better when using CMM data versus rotary contour data.
5. All initial indications imply that the Hot CMM may be correct and there might be a systematic error affecting Sheffield 2, primarily on the inner contour.
6. Lack of thermal compensation may be a factor in Sheffield 2 measurements of plutonium parts.

2.8 Mass Comparison

Mass is currently used as a logical quality check for inspection data. A part that is heavier than nominal should have a wall thickness larger than nominal and light for a thin part. CMM Shell Inspection has taken a more analytical approach. Mass values are measured when density inspection is performed. With a density value and using Equations 1-6 below, a numerical or estimated mass can be generated from inspection data. This mass value can then be compared to the actual mass from a balance as a quality check. For further information reference *"Shell Volume Estimation (U)"* [22,23].

The process below assumes:

1. Radii (r_1 and r_2) average values for each polar band inspected.
2. Height (h) values are distance between polar bands.
3. 0° pole measurements do not include pole closure measurements.
4. 90° and 89° points assume the same deviations as 88°.

$$V_1 = \frac{\pi(r_1 - h)^2(2r_1 + h)}{3} \quad (1)$$

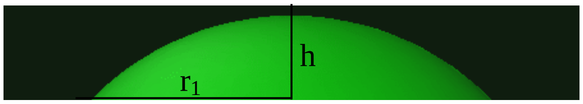

Figure 1. Spherical Pole Section (0°-1° or 180°-179°)

$$V_i = \frac{\pi h(3r_1^2 + 3r_2^2 + h^2)}{6} \quad (2)$$

Where,

i = 2, 3, …90

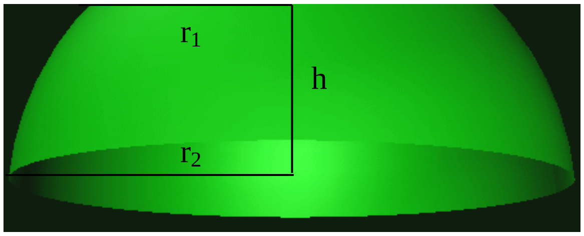

Figure 2. Spherical Section (1°-90° or 179°-90°)

Total estimated volume

$$V_t = \sum_{a=1}^{90} V_O - \sum_{b=1}^{90} V_I \quad (3)$$

Where,

O = outside contour

I = inside contour

Estimated Mass

$$M_e = V_t \times D_m \quad (4)$$

Where,

D_m is the measured density

Result:

$$\Delta M = M_e - M_a \quad (5)$$

Delta Mass = Estimated Mass - Actual Mass

A first order attempt at subtracting systematic error was implemented to account for numerical errors, edge breaks, scribes, etc. This error can be solved for by simply using the equations above on a nominal part and comparing the results to the theoretical value. That error can then be eliminated by applying that difference to the part to create a better estimate. This enhancement was used and can be seen in Equation 6 below.

Estimated Mass

$$M_e = (V_t + V_{Es}) \times D_m \tag{6}$$

Where,

V_{Es} is the volume caused by systematic error

The mass values generated by this process were cross referenced by the Physics group using Fortran and Design Agency using Pro/E. The density values are achieved through the use of Archimedes principle and using *"Density Determination (U)"* [17].

Further work has been explored to improve the mass comparison such as, *"Computational Density Estimates of the CMM Artifact for Pit Manufacturing and Dimensional Inspection (U)"*, LA-UR-11-02665 [24]. The work in this report discusses the use of alternate algorithms but has not been implemented as of yet. Other work such as *"(U) Shell Inspection Verification using Mass Analysis"*, LA-CP-15-00323 [25], used engineering judgement on measurement error and a sensitivity analysis to calculate mass comparison quality limits that are being used.

3.0 Sheffield and CMM Differences

Sheffield gauges were designed for measuring shells. Sheffield has a long history, is a mature inspection process and has the luxury of taking measurements that were used in test shots that are no longer allowed.

CMMs on the other hand are very versatile, are an off-the-shelf industry standard and are recognized by national and international standards for calibration [26]. There are many different types of CMMs but LANL has focused on two – moving bridge and fixed bridge [27].

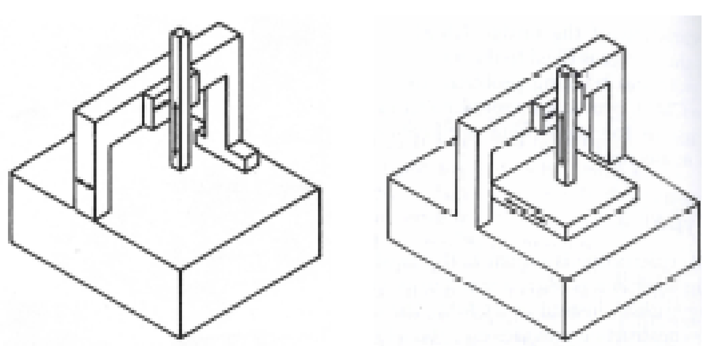

Figure 3. CMM Types: Moving Bridge (left), Fixed Bridge (right)

3.1 Historical Information

Rotary contour shell inspection at other sites such as the Atomic Weapons Establishment (AWE) uses similar rotary contour gauges to the Sheffield known as Rotacon purchased in the mid 1960's [28].

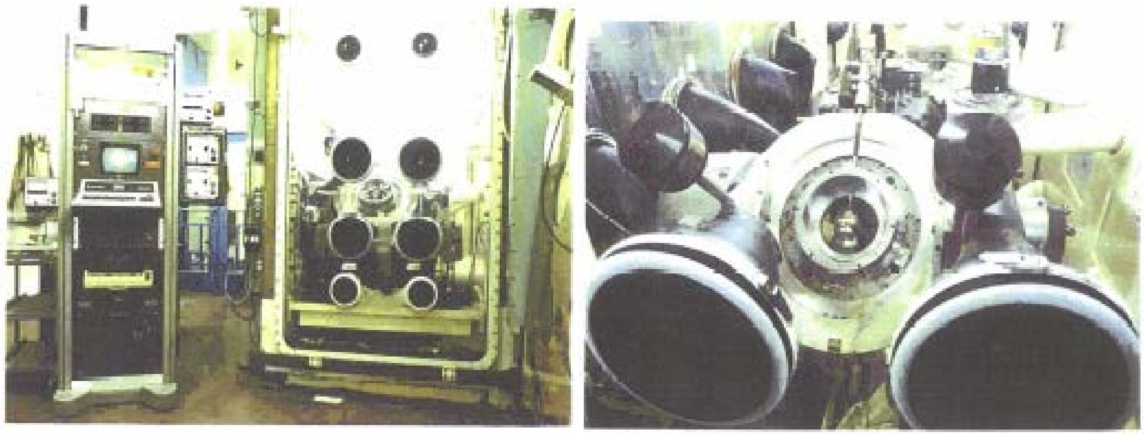

Figure 4. AWE Rotacon

Rocky Flats Plant (RFP) used Sheffield rotary contour gauges and Century Detroit gauges [29]. Lawrence Livermore National Laboratory (LLNL) also uses a Sheffield rotary contour gauge known simply as Sheffield and led an effort to develop a machine known as Precision Shell Measuring Machine or PriSMM [30].

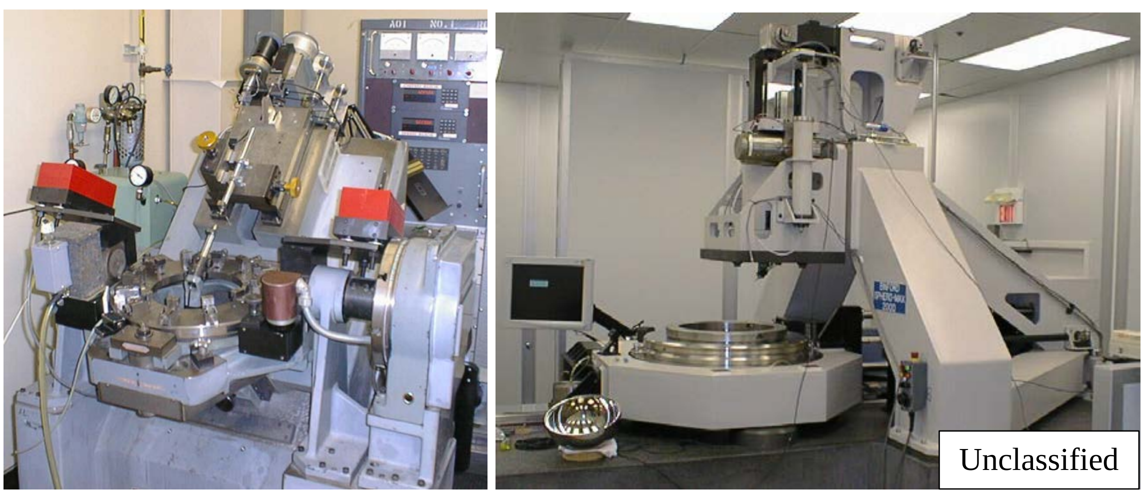

Figure 5. LLNL Sheffield (left), LLNL PriSMM (right)

During the 1970's and 1980's LANL used an AA Gage also known as a Rotary Contour Gage or Rotacon for shell inspection. Significant research was not devoted to this gauge but documentation was found on a quotation offered at a price of $286,500 with optional printer for $8050 in 1972 [31]. Another older document of interest may be *"Computerization of Gaging Equipment"* [32].

Figure 6. AA Gage

As described in the original 1960's Sheffield manual, *"This is a manually operated gage for the inspection of inner contour, outer contour, and wall thickness of an object"* [33]. LANL decided to use the Sheffield and established its ability to perform precision inspections of shell weapon components during November 1996 – December 1997. To establish the contour inspection capability, the Inspection Team refurbished a 40 year-old Sheffield rotary contour gage that had been shipped from the Rocky Flats Plant that was received disassembled and inoperable. The Inspection Team established calibration and inspection procedures, qualified the gage, and trained inspectors. At the time the gage repeatability for wall measurements was 0.0016 mm. The inspection process accuracy, which includes the gage accuracy and inspector influences, was ± 0.002 mm [34].

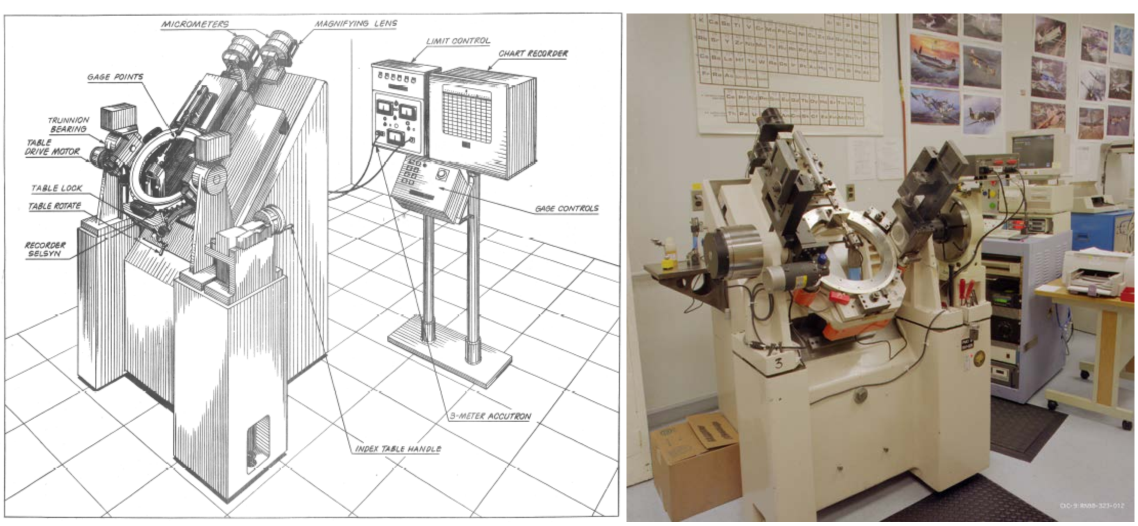

Figure 7. Sheffield 1

Sheffield #2 was refurbished by the Inspection Team to provide contour inspection capability for nuclear shells. A new control system was designed with new software for machine control and data acquisition. Additional gage enhancements included an improved probing system, precision feedback for positioning of the various axes, improved user interface, a more robust inner and outer slide mechanism, and additional inspection options and flexibility. This gage was WR approved in March of 2002. At the time the gage repeatability was 0.002 mm with a process accuracy of ± 0.006 mm. The additional uncertainty in process accuracy is due to the added difficulties associated with working through a glovebox [34,35].

Unclassified

Figure 8. Sheffield 2

The Shell Measuring Machine (SMM) began as a Cooperative Research and Development Agreement (CRADA) No. LA98C10358 between LANL and Moore Tool Company. Work started in December of 1998 with several meetings held with interested parties such as Los Alamos, Oak Ridge, Moore Tool, and North Carolina State University. During 1999-2000 specifications for size and weight were developed, performance error budgets were established, designs were developed, analyses were performed (stiffness and natural frequency), existing part designs were compared to the working SMM volume, peer reviews were conducted, controller requirements were studied, fixture requirements were evaluated, and machine motions were analyzed [36, 37,38].

The contract with Moore Machine Tool was signed in June of 2001 with the first SMM approved for shipment in November of 2003. In addition to providing the same contour inspection capability as the Sheffield, the SMM accepted a larger range of part sizes, offered more inspection flexibility and capability with respect to part characterization, was fully automated, and required less time to perform the inspection process. The SMM gage repeatability was less than 0.001 mm [34,39].

Figure 9. Shell Measuring Machine (SMM)

CMMs have been at the lab starting with the Cordax in the early 1980's [40]. That expanded to a Numerex, a Leitz, and two Dea CMMs by the late 1980's [41]. CMMs are considered the industry standard and can now be found all around the lab including areas such as the main fabrication shop, uranium, beryllium, plutonium, high explosives, detonators, assembly, Sigma, and DHART. CMMs are versatile enough to accommodate the measurement of shells but the versatility adds a level of complexity and understanding in numerous variables such as probe force, scan speed, probing strategy, probe wander (positional error), fixturing, firmware, etc. Precise alignment and indexing of inner and outer profiles must be assured for accurate radial wall thickness calculations. The underlying mathematical algorithms of the CMM programming language must be understood and properly utilized. Erroneous data will result if the numerous CMM parameters are not properly understood and applied, and if the correct methods are not utilized to calculate a radial wall thickness [34].

Figure 10. Coordinate Measuring Machine (CMM) - Global Performance (left), Reference (center), PMM-C (right); Source: Hexagon Metrology

3.2 Calibration

Typical calibration cycles for rotary contour gauges (RCG) are two years whereas CMMs are one year [42]. Because RCGs are unique machines, they are typically calibrated to in-house procedures such as: *"Calibration Procedure for Sheffield Rotary Contour Gage"*, SCL-CP-0840 [43], *"Shell Measuring Machine Calibration Procedure"*, [44], *"Sheffield Rotary Contour Gage Calibration"*, 4-D39-MLD-00006, [45], and *"Method for Evaluation and Certification of the Continuous Path, Sheffield Model 1708, 15-in., Rotary Contour Gage"*, UCRL-50577 [46].

CMMs are typically calibrated to either the American Society of Mechanical Engineers (ASME) B89.4 [47] or the International Organization for Standardization (ISO) 10360 [48,49,50,51,52,53,54,55,56]. CMMs at LANL were calibrated to the B89 standard until 2007 when the switch to the ISO standard began [57]. Although all LANL machines are calibrated to the ISO standard only two are to the 2010 version with the rest remaining on the older 2000 version. The challenge with moving to the new version is it requires in-house experimental testing to establish limits for the additional tests because the older machines were purchased prior to the release of the standard.

3.3 Monitoring

In 1960 when Sheffield was originally created, the manual came with a gauge check procedure [33]. That has since evolved to each gauge (Sheffield 1, Sheffield 2, and SMM) having a dedicated part measured after every five inspections or sooner if required (temperature excursion, hard crash, etc.). A similar approach has been suggested and is being considered for the CMM process. In addition to monitoring the shell inspection process and because CMMs are versatile and used for many different products, a more generic monitoring procedure or interim check to monitor the equipment has been implemented and will be discussed further in section 4.5, "Machine Checking Gauge".

4.0 Design Strategy

Section 2 described lots of work applied to the area of CMM shell inspection. However as alluded to in section 3, because CMMs are so versatile a level of complexity and understanding in numerous variables adds challenges. Many of the tests described in the design strategy of this report are designed to address these variables.

4.1 CMM Data Collection

Lots of effort has been applied to the data integrity ranging from analysis of parametric cubic splines and curve-fitting algorithms to cosine correction and rotary gauge post processing [58,59,60,61,62,63,64]. Some efforts have also been applied to data density and distributions but currently all work continues at replicating Sheffield data as close as possible [65,66,67,68,69,70,71].

Acceptance criteria is one topic that could use some investigation. Part acceptance is specified by GD&T drawing callouts. All shell components are specified with either an inner or outer profile tolerance plus a radial wall thickness. The profile callout specifies that all points on that surface should be within the specified tolerance zone [72]. There is no specific guidance on filtering, outliers, etc. Most parts contain some amount of residual stress causing a part to be out-of-round. According to the profile callout, if a part is out-of-round and exceeds the profile tolerance limit, then the part is out-of-tolerance and would require a nonconformance report (NCR). One possibility is acceptance on part average rather than the entire data set. Acceptance on average would likely require an additional requirement on the amount that a part could be out-of-round as parts too far out would not be able to assemble.

4.1.1 Pole-to-Equator Constrained Scans

Traditional data density for rotary contour machines is gathered by rotating the part in 0.75° increments azimuthally and by 2° increments in the polar angle direction (0-88°). See Figure 11 below. The data density gathered by the CMM process is with a fixed part and using pole to equator scans in 1° increments (0-88°) and 1.5° increments azimuthally. See Figure 12 below.

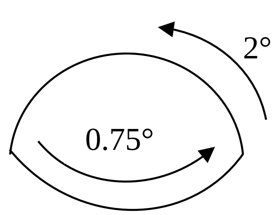

Figure 11. Rotary Contour Inspection Strategy

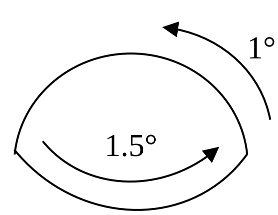

Figure 12. CMM Inspection Strategy

The CMM approach is such that it provides a similar amount of measurement data as the Sheffield process. For the CMM process increasing azimuthal scans adds inspection time whereas increasing polar angle density does not. The opposite is also true for Sheffield – increasing azimuthal density does not add inspection time, but additional polar angles do. Because these parts are turned during fabrication, the direction of interest or the direction where measurement differences are typically seen is pole-to-equator giving the CMM a slight advantage.

As part of the process for measuring a shell on the Sheffield the part must be put into a fixture called a rounding ring, which constrains the shell. As seen in Figure 13, these are typically made of aluminum 7075 and custom fit to each part.

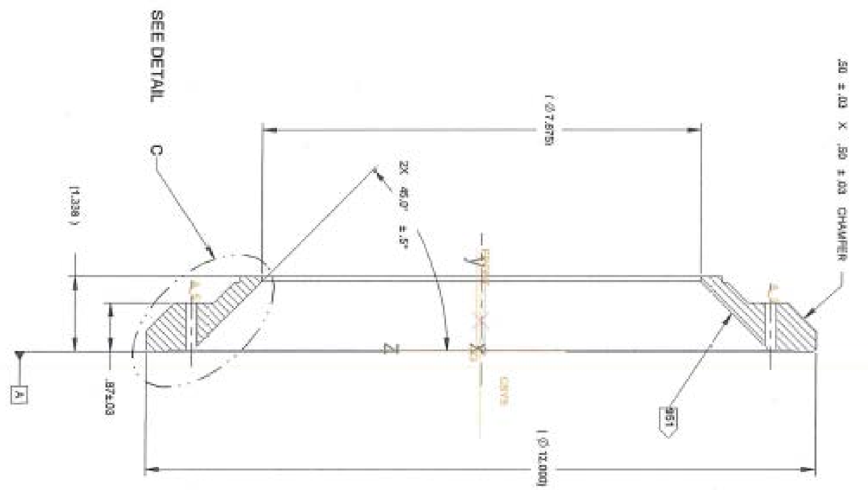

Figure 13. CMM Test Artifact Rounding Ring, 157Y-700374

Part constraining for Sheffield 2 is accomplished through the use of a flexible fixture. As seen in Figure 14, these are designed to handle a family of parts and to minimize waste in a glovebox.

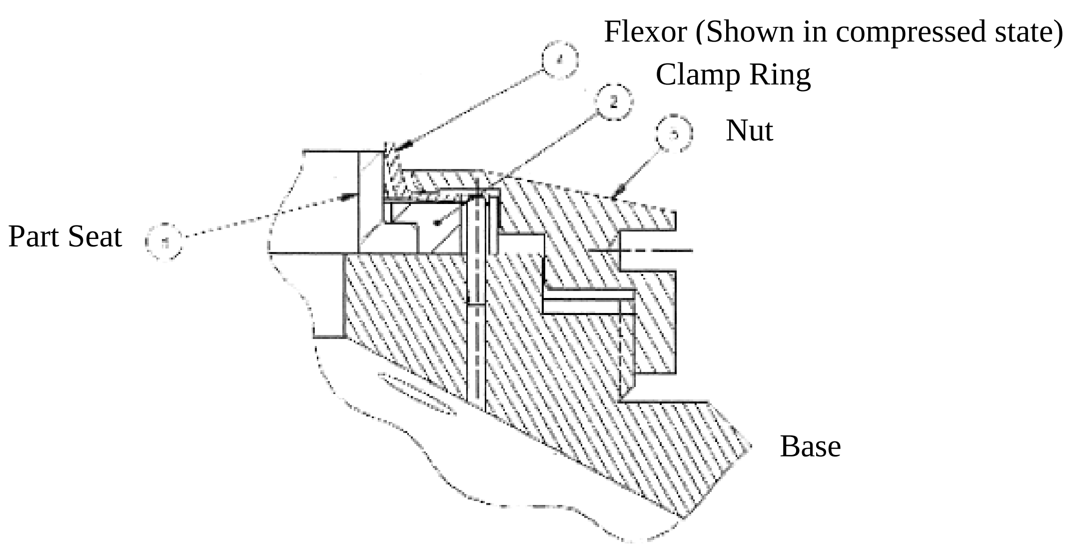

Figure 14. Sheffield 2 Rounding Ring Cross Section

In 2010 LANL paid Kansas City Plant for the development of a universal rounding ring that could handle a large number of parts. The original prototype (KCP drawing number MS4544100) delivered to LANL had a few design issues and has had limited use, seen in Figure 15. KCP however, has resolved most of those issues and is using this for some of their shell inspections.

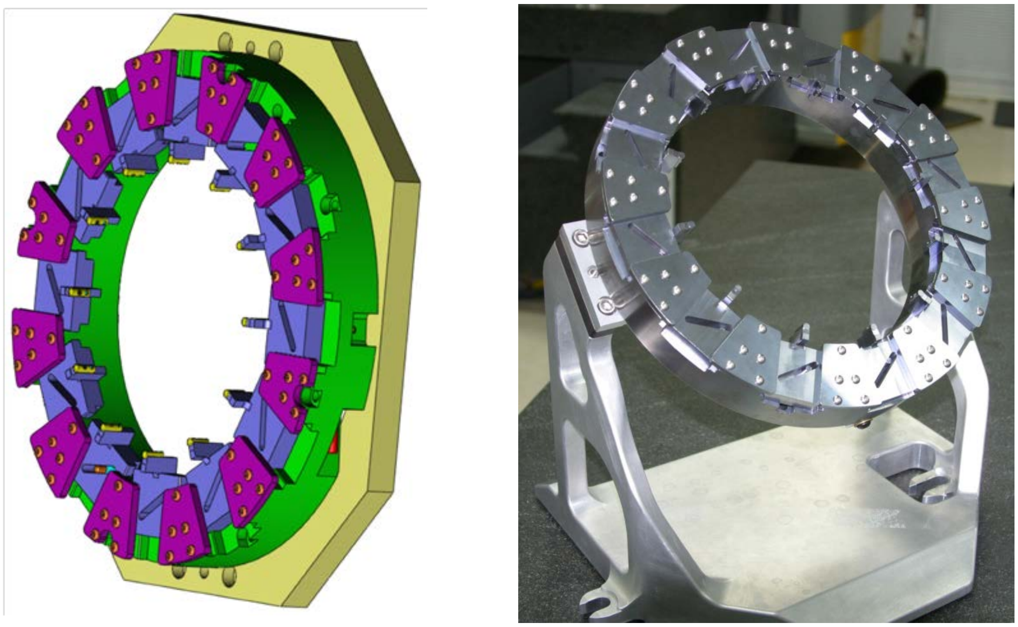

Figure 15. Universal Rounding Ring CMM Fixture, MS4544100

4.1.2 Pole-to-Equator Non-Constrained Scans

There are pros and cons to both a constrained and non-constrained (free state) inspection. First, a free state inspection is closer to the true ASME Y14.5M rule. From section 1.4, *"All dimensions and tolerances apply in a free state condition. This principle does not apply to non-rigid parts"*. Some would argue that shells are non-rigid. Per the ASME definition from section 6.8, *"Free state variation is a term used to describe distortion of a part after removal of forces applied during manufacture. This distortion is principally due to weight and flexibly of the part and the release of this kind, for example, a part with a very thin wall in proportion to its diameter, is referred to as a non-rigid part."* The standard goes on to say that, *"it may be necessary to simulate the mating part interface in order to verify individual or related feature tolerances. This is done by restraining the appropriate features, such as the datum features. The restraining forces are those that would be exerted in the assembly or functioning of the part."* [72]

Second is cost and schedule. Rounding rings require additional material, additional machine time, and time from both an inspector and machinist to custom fit a part and ring. Also, rounding rings are considered classified and require tracking and accountability. On the other hand, elimination of the constrained process is a departure from the way all previous inspections have been performed and different from the method used for in-process inspection or machinist feedback.

There is space to debate the standard, cost and schedule in both directions. However the true technical justification for the best approach is in the CMM data collection algorithm. A CMM is a precision robot that moves in x, y and z Cartesian coordinates. It has motors controlled by a computer through a controller. If a command is given to travel to a specific point in space, the CMM attempts to do that through the use of a proportional-integral-derivative (PID) controller to the best of its ability. The CMM does this through a tolerance which is often referred to as positional accuracy, and each CMM is different. Positional accuracy will also vary for single point probing, scanning and based on other parameters. A scan that starts at the pole and travels to the equator does not happen in an exact straight line with all the points falling within the same plane but rather a weaving line that stays within a machine's accuracy limit, see Figure 16. This error is eliminated through the use of a Quindos command ADJCYL, which *"shifts points along a cylinder surface into a plane"* [73]. This is an acceptable method when a part is round or in a rounding ring. Using this command on a part that is not round will introduce error especially at the equator, see Figure 17. The amount of error will also vary depending on the part roundness, CMM positional accuracy, and polar angle of the measurement.

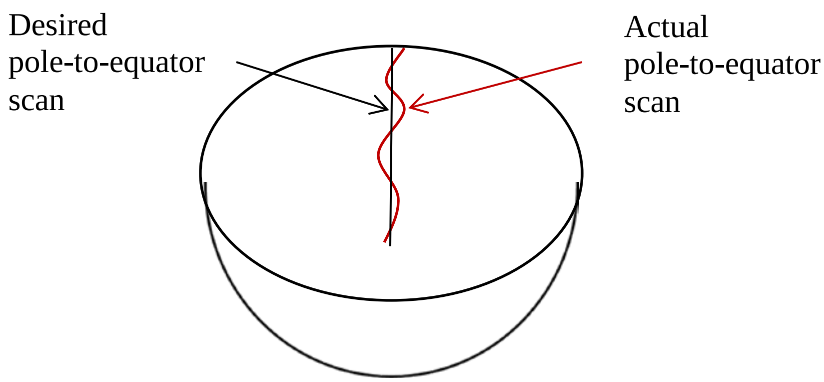

Figure 16. Pole-to-equator Probe Wander Example

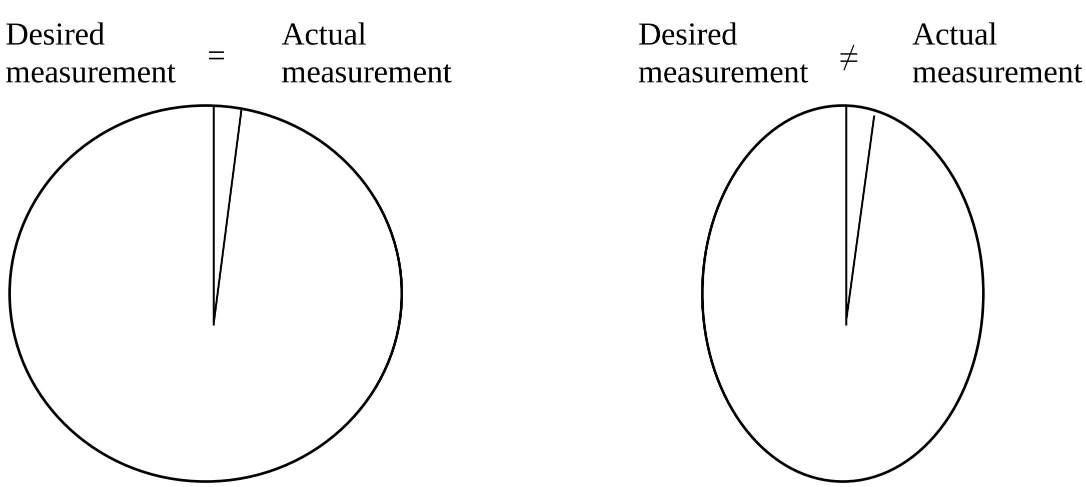

Figure 17. Probe Wander Data Correction (top view of part)

4.1.3 Azimuthal Scans

Azimuthal scans suffer from the same positional accuracy issue discussed in the previous section. CMMs attempting to measure around a part will again weave or wander above and below the actual target plane. In this case, points would be projected onto a plane [74]. Unfortunately, because these parts are turned and each part is unique, points above and below have a different radius than the desired measurement. This error will also vary depending on the part roundness, CMM positional accuracy, polar angle of the measurement and shape of the part.

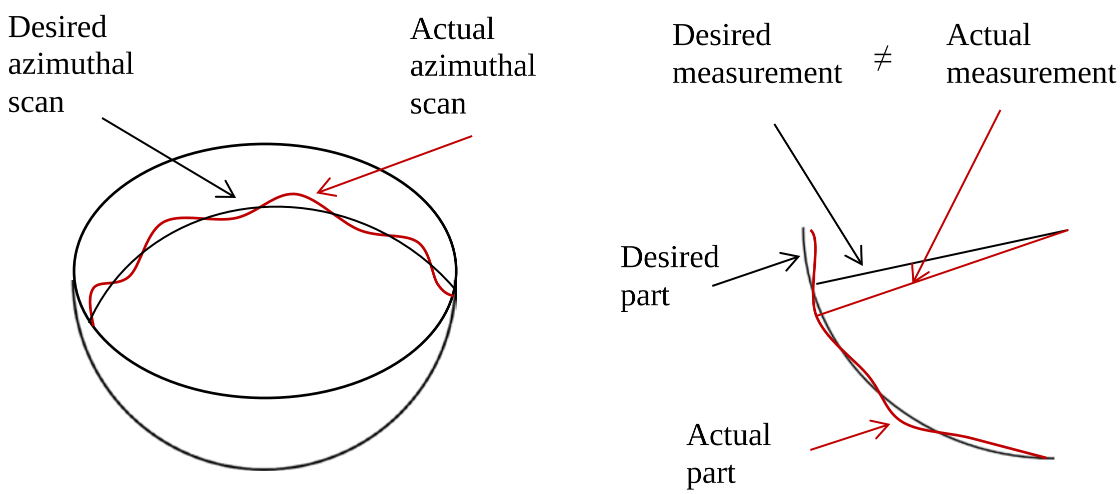

Figure 18. Azimuthal Probe Wander Example

4.2 Dual Inspection

Dual inspection is a simple comparison of a Sheffield and CMM measurement with mass comparison.

4.2.1 Initial Presentation for Stakeholders

A presentation by the Inspection Team was given to stakeholders in late July 2015. During this presentation the results of ten parts were presented that were measured on both Sheffield and CMM. Of the ten measurements two of the inspections did not pass the mass comparison quality check. This led to two action items at the end of the meeting. The first item was to continue measuring parts on both Sheffield and CMM and second further develop quality checks to prevent the future release of bad data.

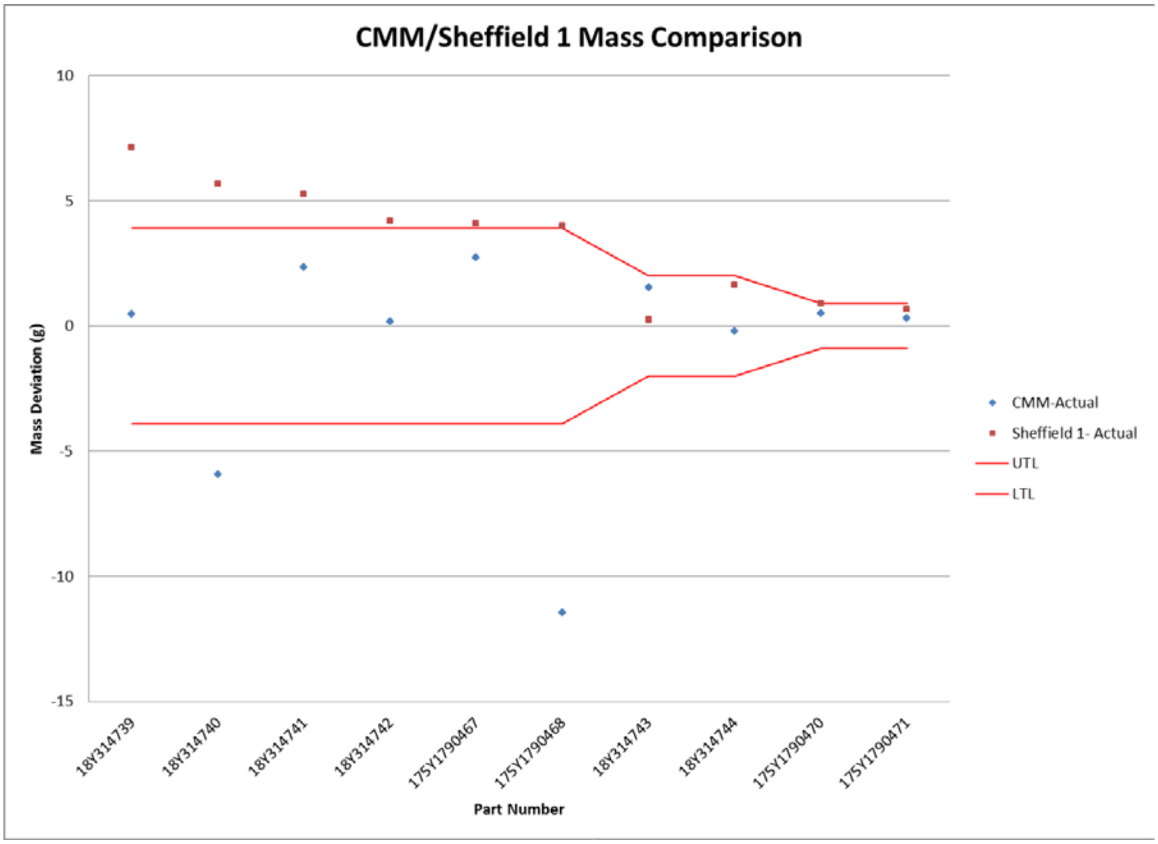

Figure 19. Dual Inspection Mass Comparison Results

4.2.2 Winter Status Update

An internal Inspection Team presentation was given to management as a status update and progress report. Although numerous inspections were performed, key data sets from a bulk of the data were missing for it to be applied to the project. For example dual inspection had not been completed on several parts and density had not been done on all parts. Sometimes there was both CMM and Sheffield but no density. Useable data sets that included Sheffield, CMM, and density measurements along with some quality checks were appended to the original ten and presented in section 4.2.1. Of the five new data sets more than half failed the mass comparison and all were showing significant variability at the pole from multiple styli. In theory the pole should be the same point and provide the same measurement over the duration of an inspection. If that point drifts or changes, it is logical to assume that other points during the inspection may have drifted or changed by at least the same magnitude.

Table 1. Dual Inspection

Part #	Serial #	Data Density	Mass Comparison	IC Pole	OC Pole
~~18Y314739~~	~~04301A-01-0065501~~	~~150~~			
~~18Y314740~~	~~04301A-01-4770703~~	228	Fail		
~~18Y314741~~	~~04401A-01-0065502~~	228		Fail	
~~18Y314742~~	~~04401A-34-4798101~~	~~304~~			
~~18Y314743~~	~~74301B-07-0065503~~	228			Fail
~~18Y314744~~	~~74401B-07-4798101~~	228			Fail
~~175Y1790467~~	~~46701B-34-4796201~~	228			Fail
~~175Y1790468~~	~~46801A-34-4796202~~	228	Fail		
~~175Y1790471~~	~~47101A-09-4796201~~	~~18~~			
~~175Y1790470~~	~~47001A-09-4796201~~	~~18~~			
~~18Y312278-05~~	~~27805C-01-253401~~	228		Fail	
~~18Y312278-06~~	~~27806C-01-257701~~	228	Fail	Fail	Fail
~~152Y1769050~~	~~01B-A4B~~	228			Fail
~~152Y1769050~~	~~01B-A4B~~	228	Fail	Fail	
~~152Y1769051~~	~~01C-B4B~~	228	Fail	Fail	

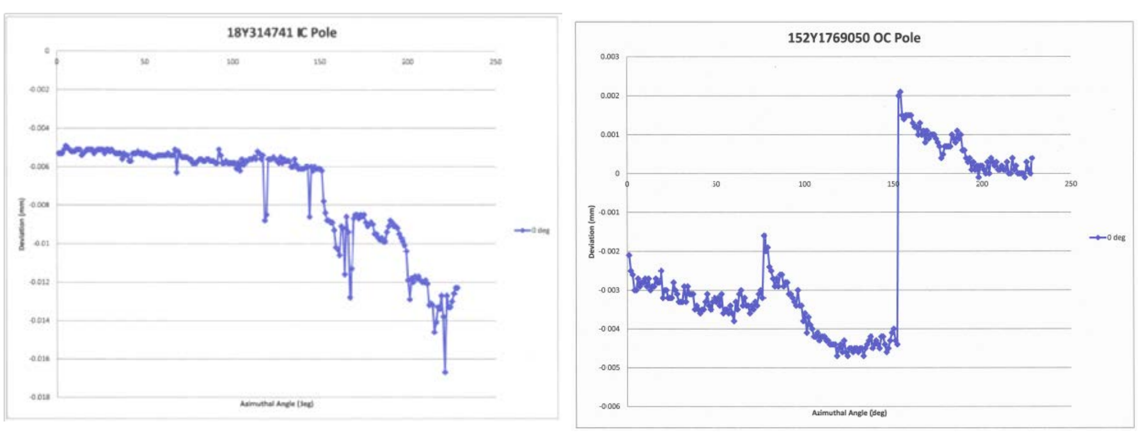

Figure 20. Inner Contour Pole Example (left), Outer Contour Pole Example (right)

4.2.3 Project Transition

Shortly after the winter status update the management team asked the author of this report to lead the CMM/Sheffield Project. Under the new direction a slightly different approach was suggested. The first proposal was to collect CMM data in a constrained state. Previous dual inspection efforts were attempting to compare Sheffield measurements in a constrained state to CMM measurements in free-state. The recommendation was to limit the variables and first gather data from Sheffield and CMM in the same configuration. This also provided a measurement with less error (see section 4.1.2). The initial plan was to show both machines are equivalent, and then investigate the differences in constrained/free-state. The second suggestion was to limit efforts on dual inspection to only what is needed. There were two primary reasons for this. First the parts are actual product needed for experiments and were not around long enough for repeatability studies. Second was because of limited resources in staff and money. The third proposal was a multitude of experiments to establish a defendable process for shell inspection on CMMs. These included use of a standard, interim checking of machines, design of experiments, machine comparison, process comparisons, and gauge repeatability and reproducibility studies.

4.2.4 Summer Status Update

The data from four parts were presented. Of these parts only one had density and was considered a complete data set for presentations purposes in this report (Part number 18Y314740 serial number A1D). Figures 21 - 26 display the average CMM and average Sheffield results for inner, outer and radial wall thickness and differences between the two measurements. As seen in the plots the inner contour has a difference ranging from +7 microns to -10 microns. The outer contour starts with a +6 micron difference at the pole and slowly drops to 0 microns then proceeds to a +12 micron difference at the equator. The radial wall thickness starts off at a -1 micron and goes up to +3 microns, drops down to -2 microns then proceeds to a +20 micron difference. These differences did not meet the established goals set forth by the project.

Figures 27 and 28 show the maximum and minimum results from the inner and outer contour and reveal how free-state and constrained inspections differ. Figures 26 and 27 are histograms of data distributions at the equator. The distributions for free-state CMM inspections are far from a normal or Gaussian distribution. In cases like these it may be better to use the median instead of average as the measure of central tendency. Another benefit is the median is resistive to outliers [75]. Figures 31 - 36 are similar to 21 - 26 but include median values. As seen contour comparisons are much better and the radial wall thickness is improved but still has a +17 micron difference from Sheffield. A summary difference between averages and median values is shown in Figure 37.

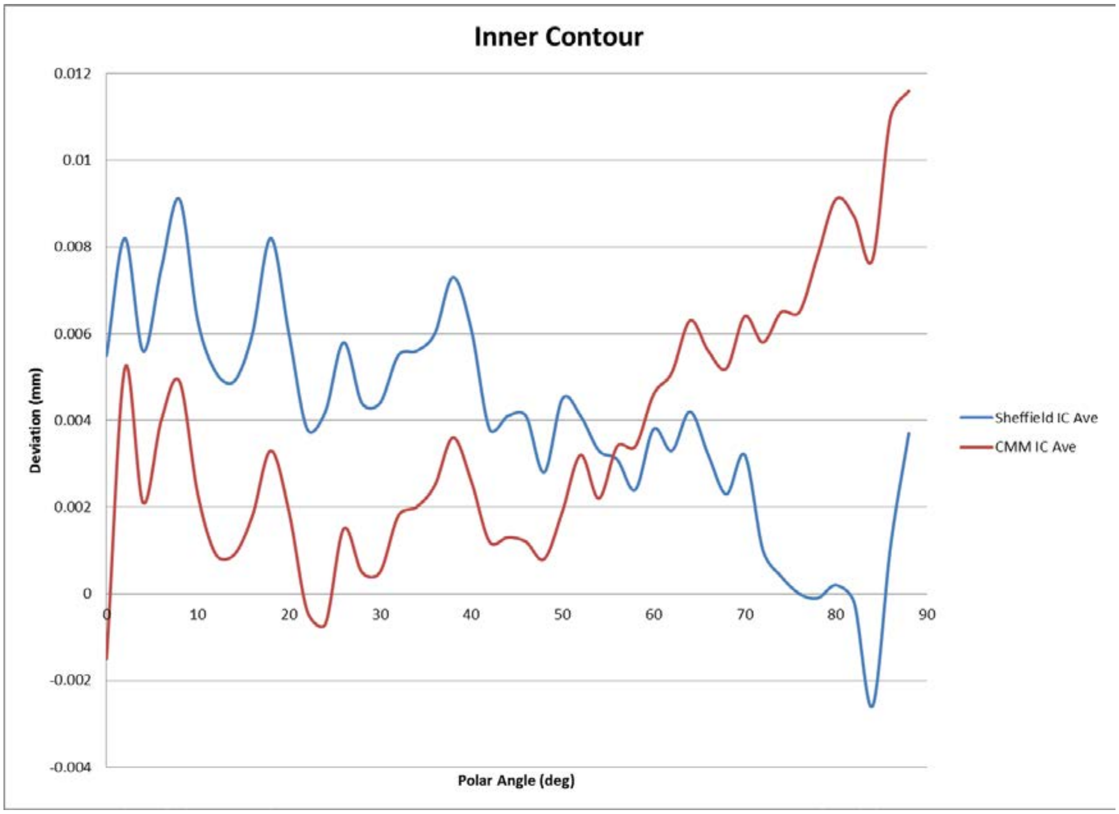

Figure 21. 18Y314740-A1D Inner Contour Comparison

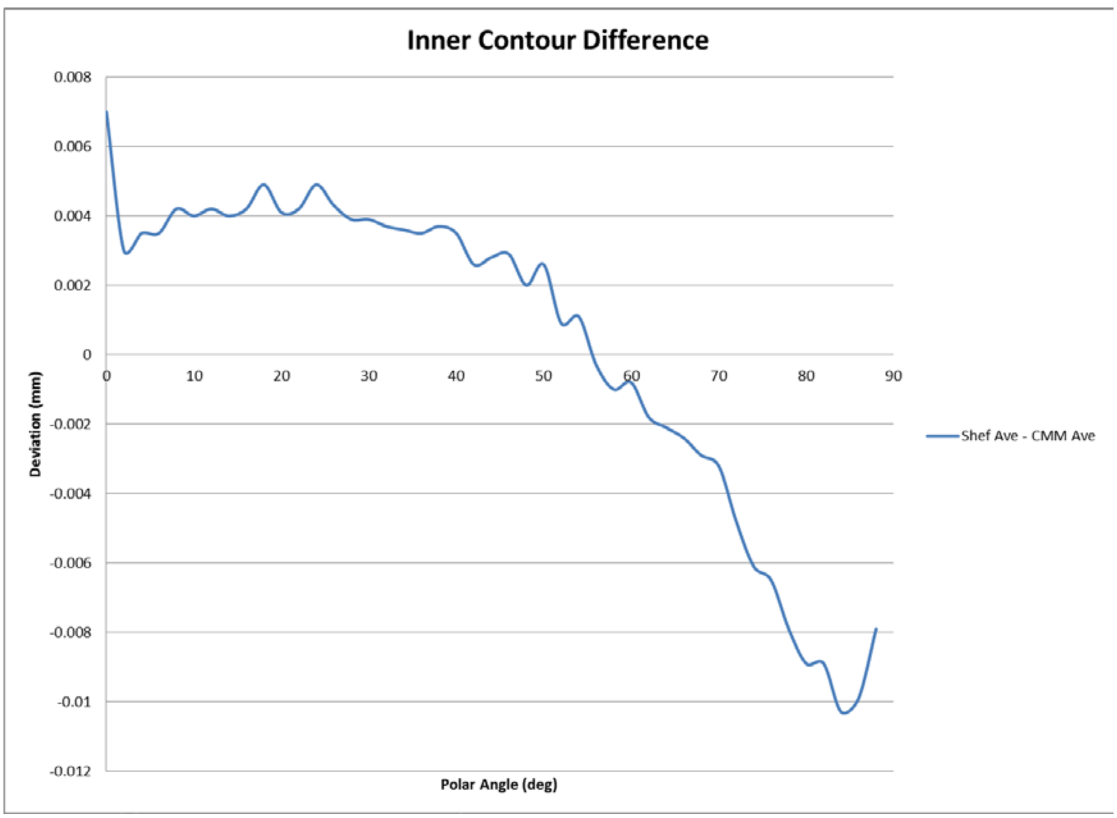

Figure 22. 18Y314740-A1D Inner Contour Difference

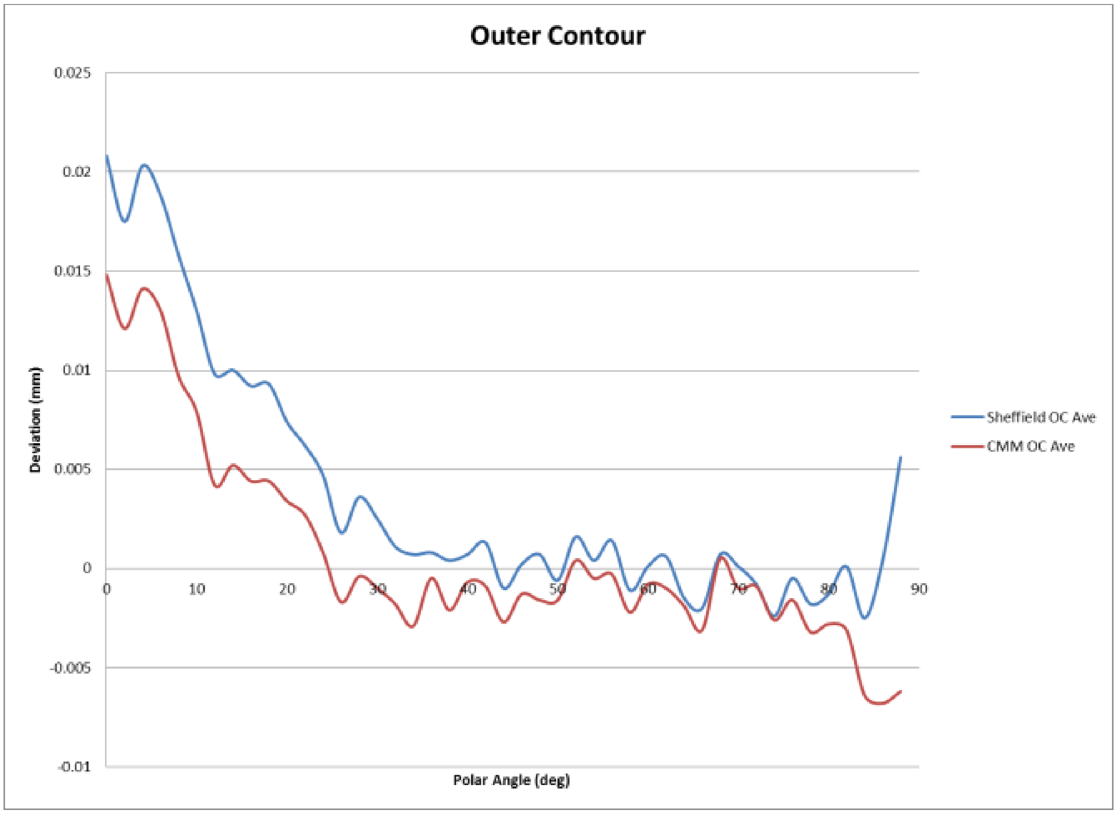

Figure 23. 18Y314740-A1D Outer Contour Comparison

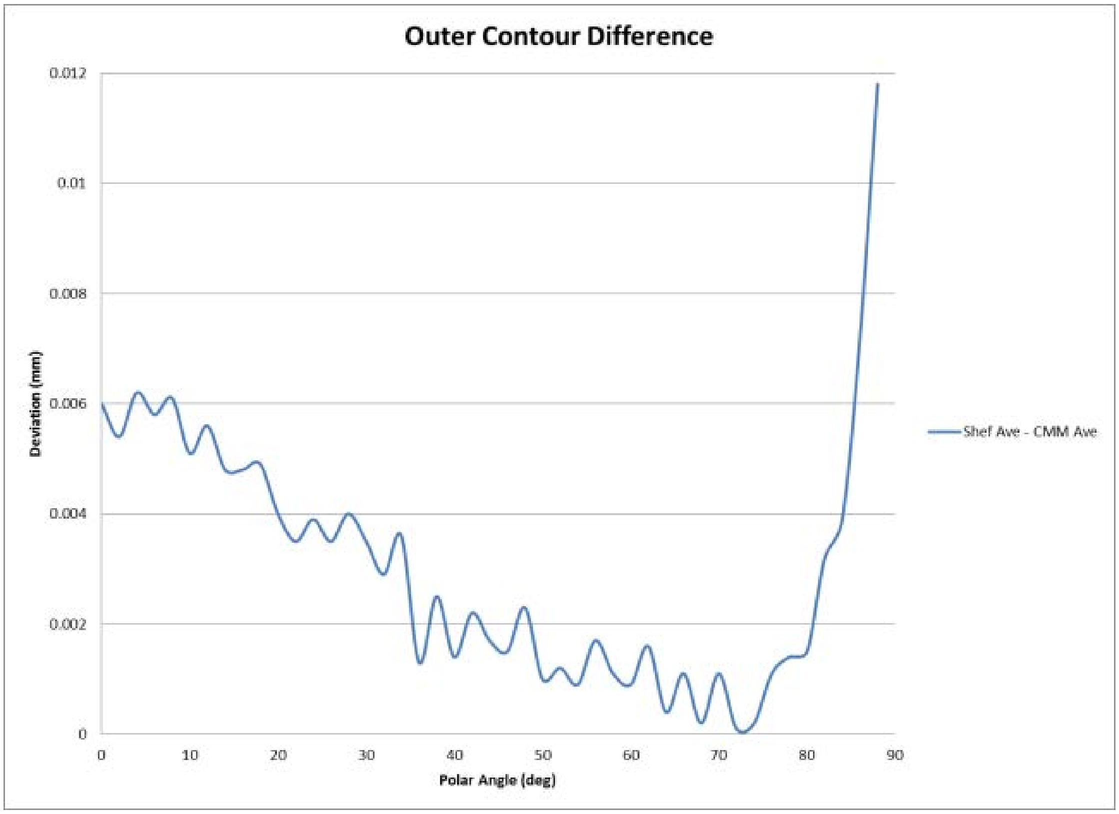

Figure 24. 18Y314740-A1D Outer Contour Difference

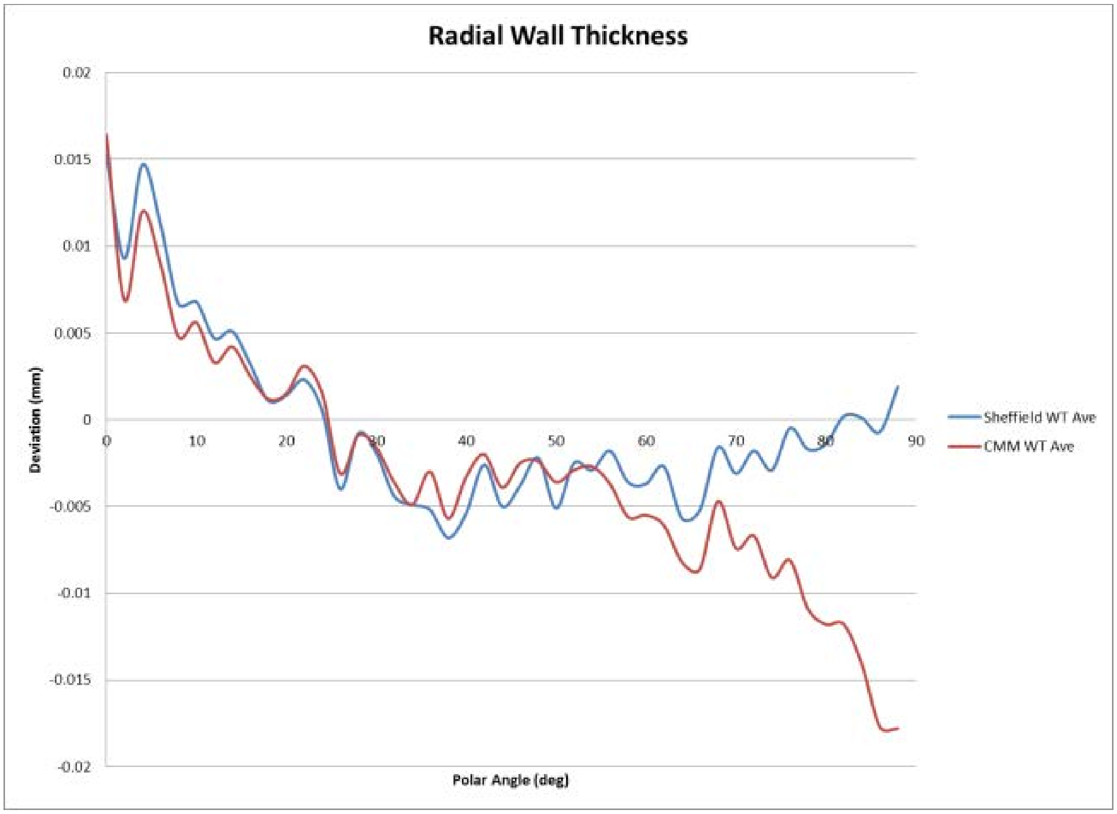

Figure 25. 18Y314740-A1D Radial Wall Thickness Comparison

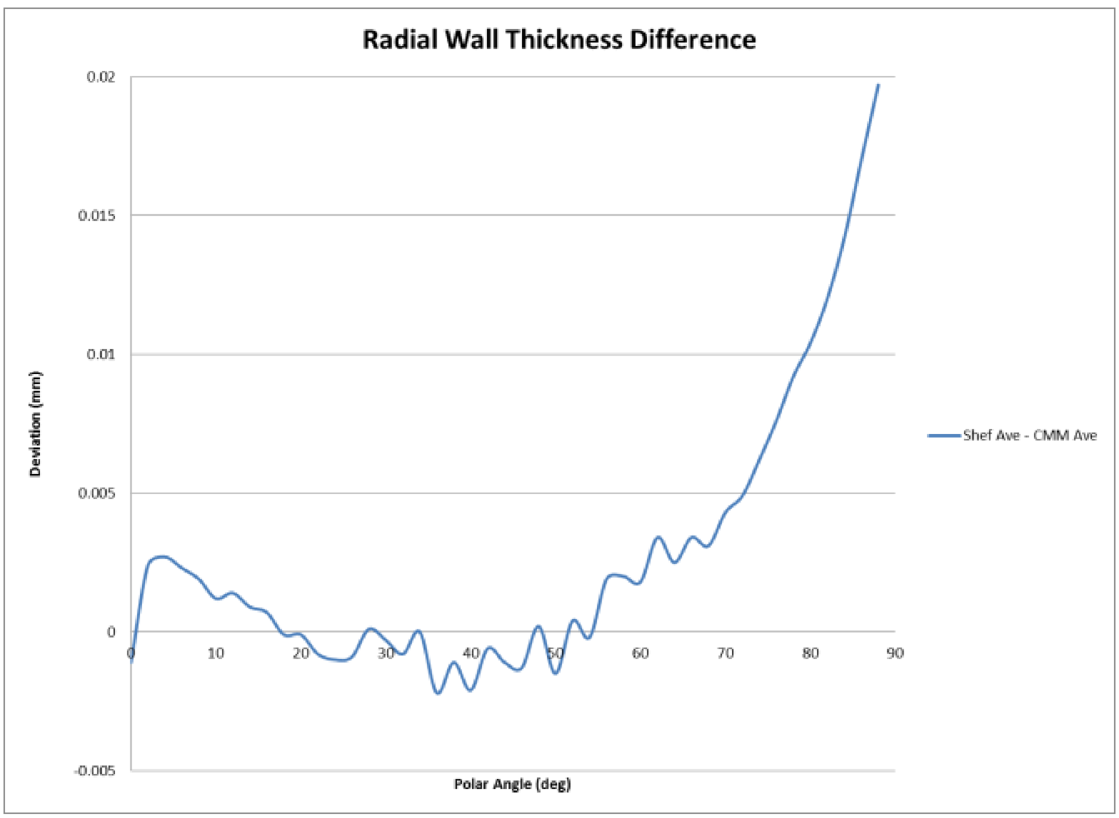

Figure 26. 18Y314740-A1D Radial Wall Thickness Difference

Figure 27. 18Y314740-A1D Inner Contour Max/Min Comparison

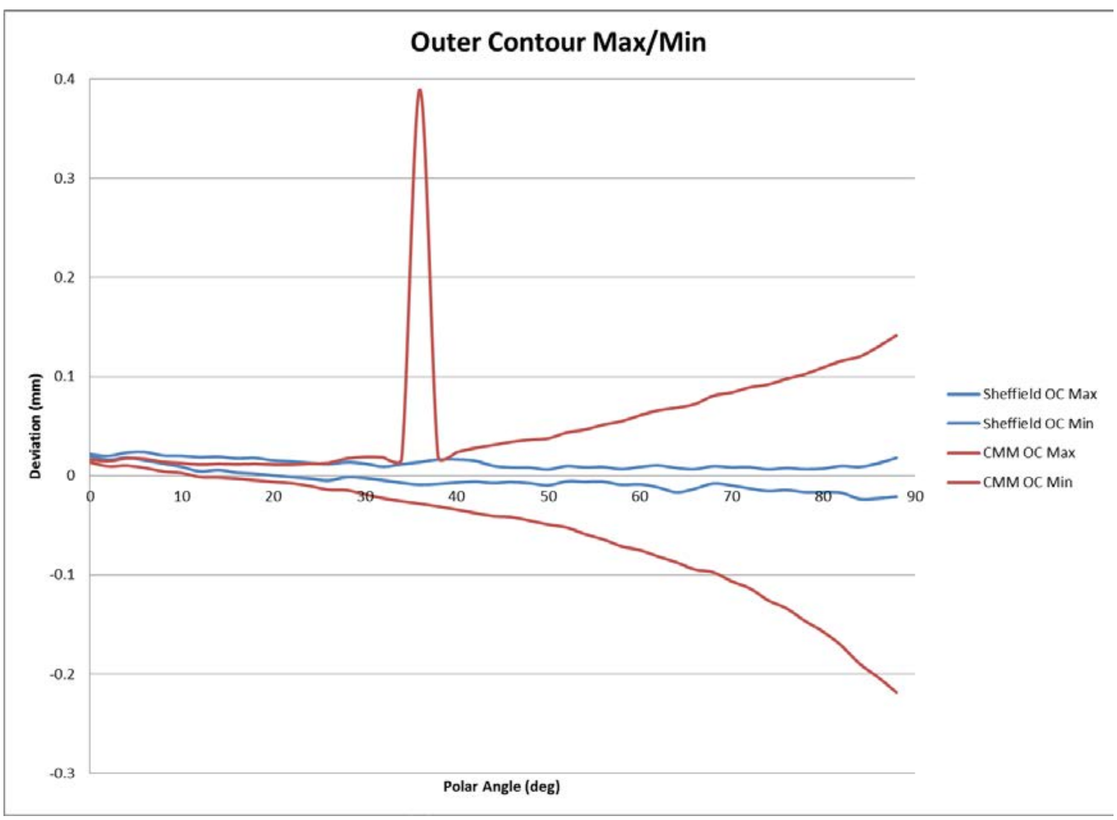

Figure 28. 18Y314740-A1D Outer Contour Max/Min Comparison

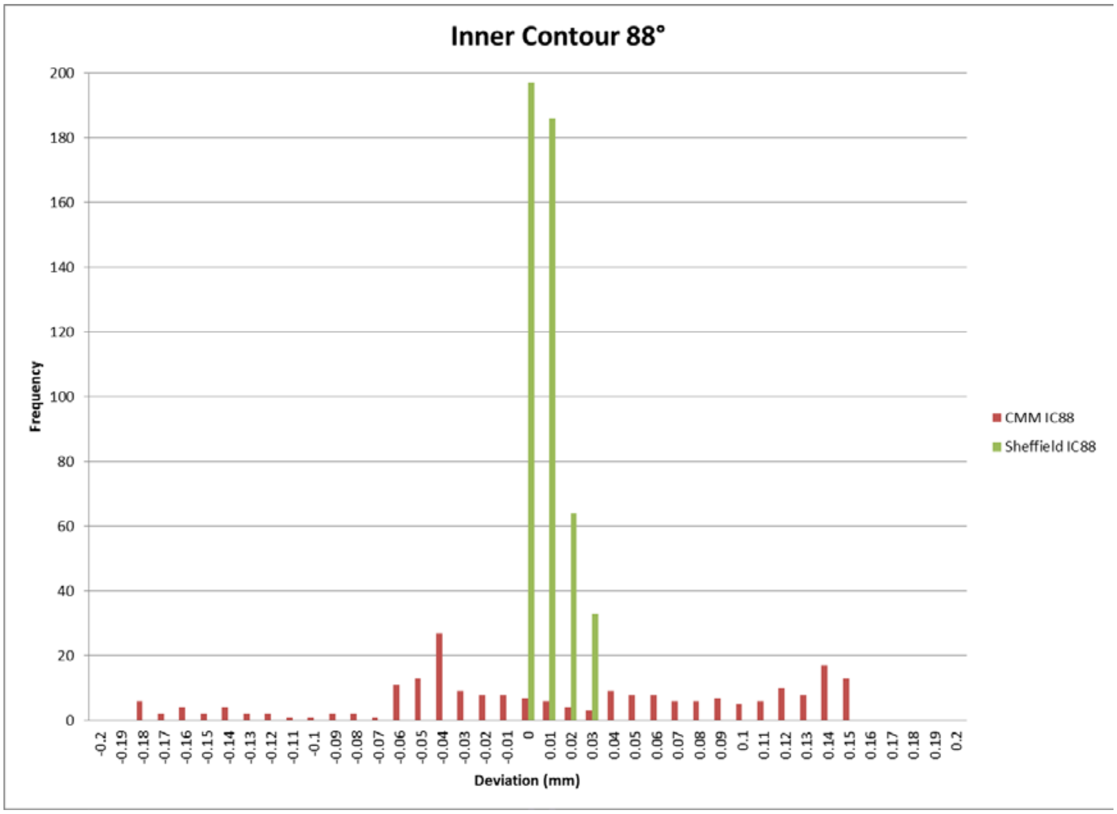

Figure 29. 18Y314740-A1D Inner Contour Equator Histogram Comparison

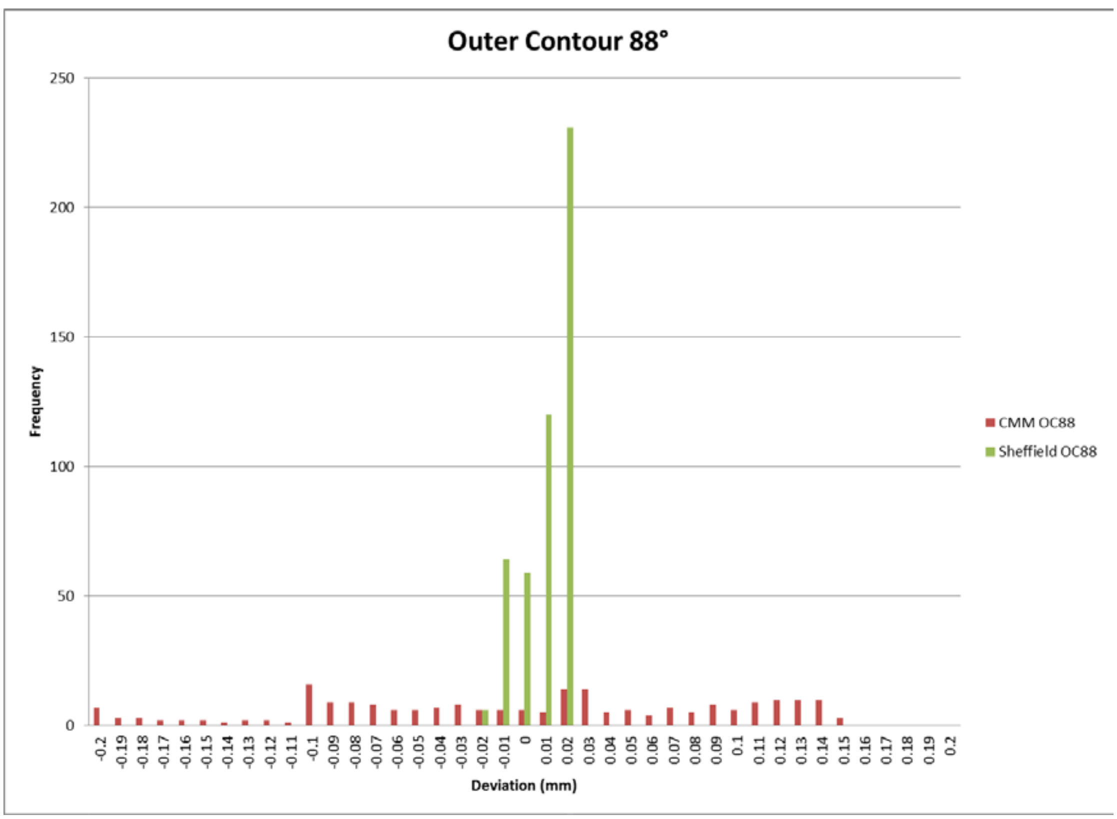

Figure 30. 18Y314740-A1D Outer Contour Equator Histogram Comparison

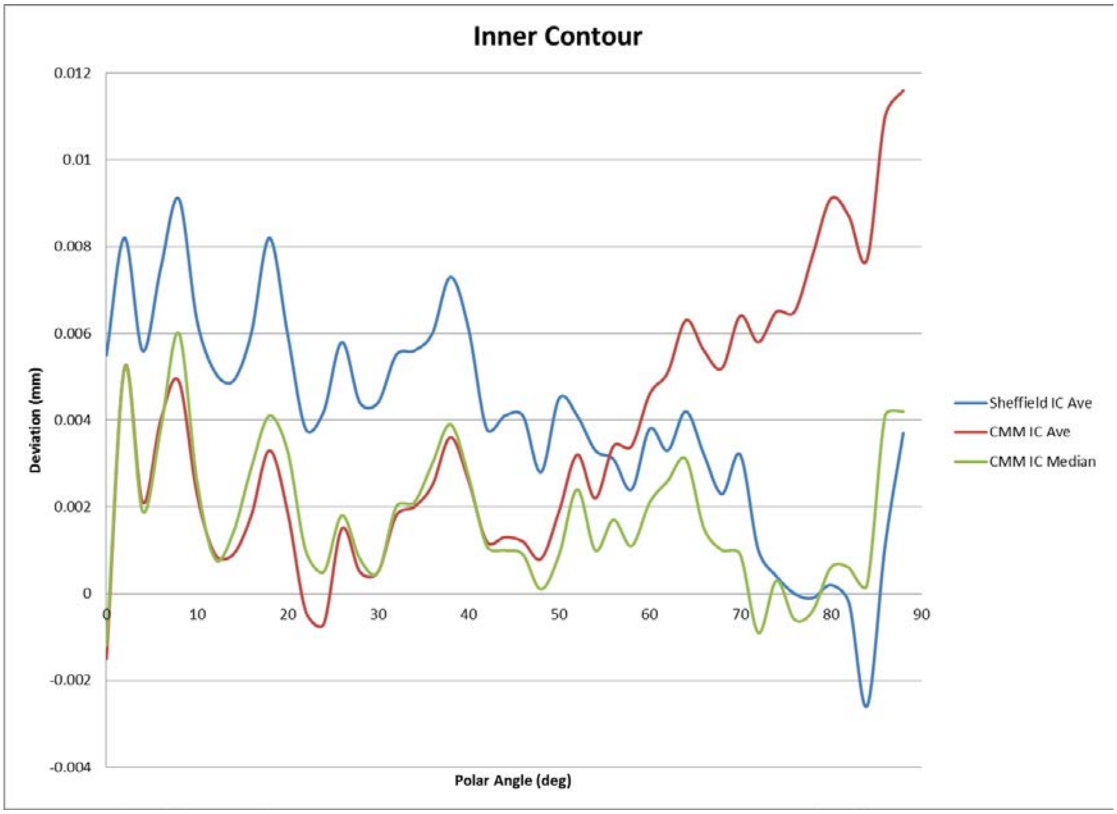

Figure 31. 18Y314740-A1D Inner Contour (Ave/Median) Comparison

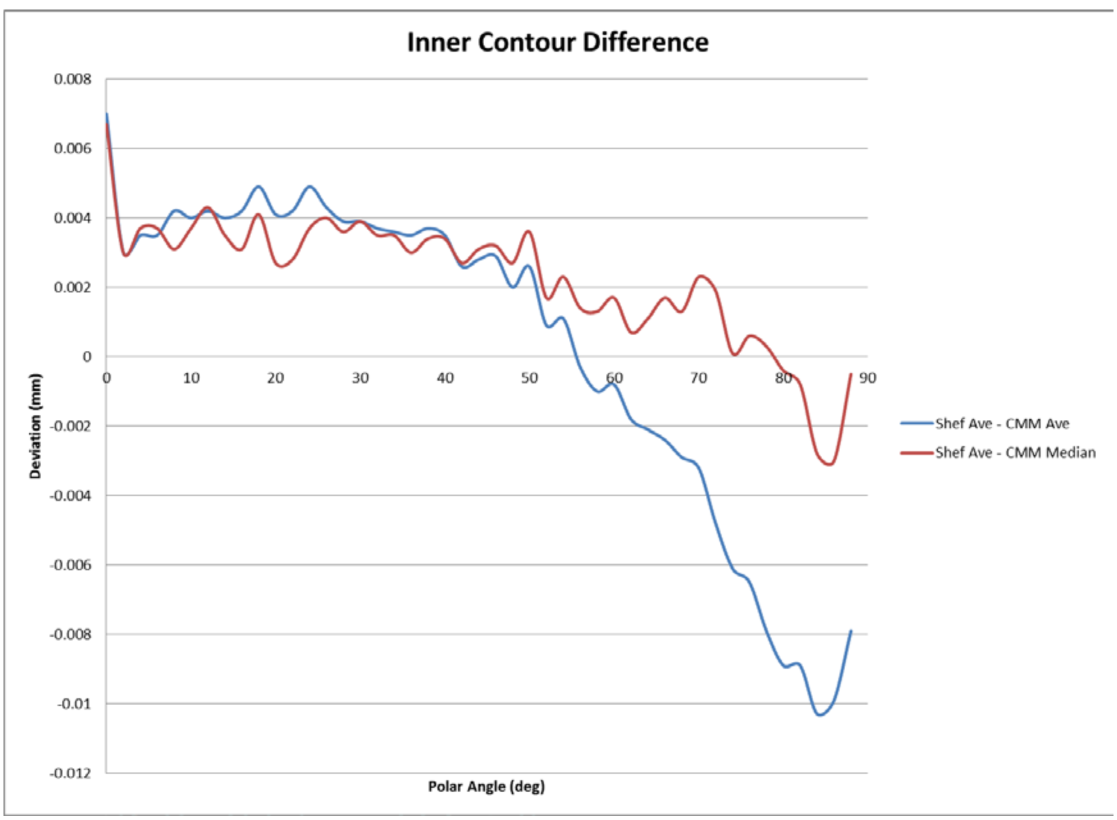

Figure 32. 18Y314740-A1D Inner Contour (Ave/Median) Difference

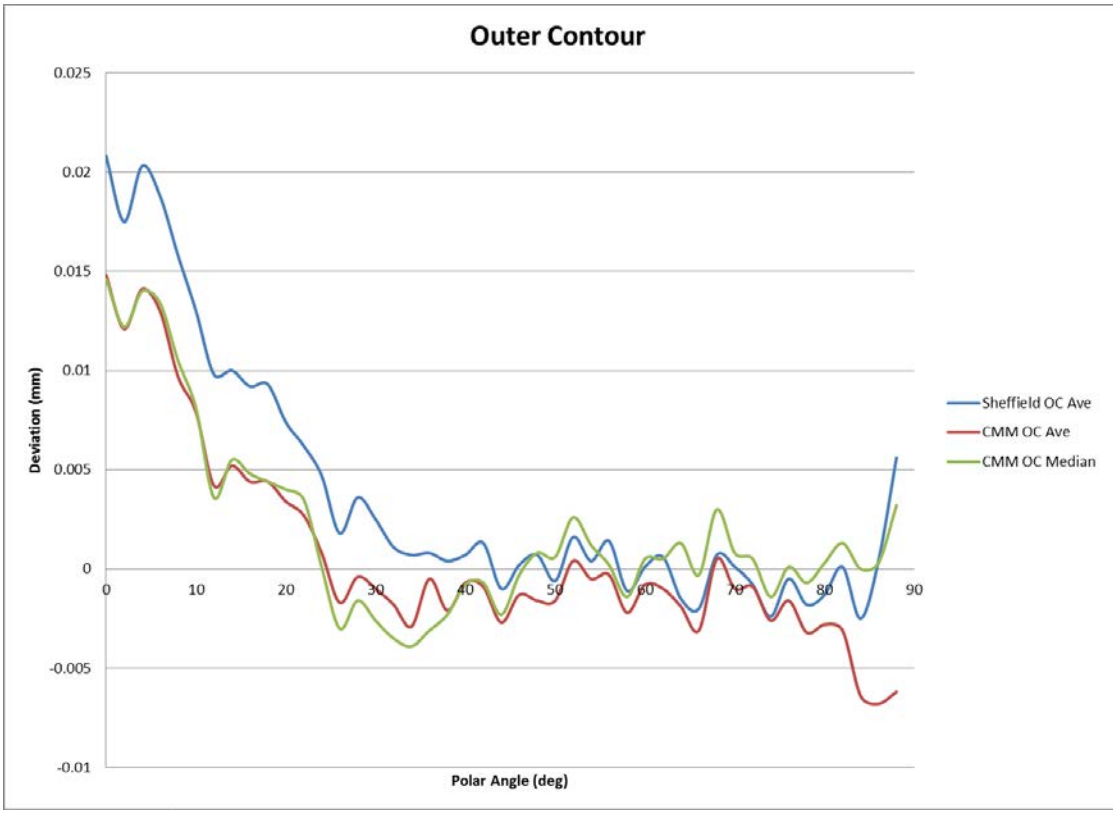

Figure 33. 18Y314740-A1D Outer Contour (Ave/Median) Comparison

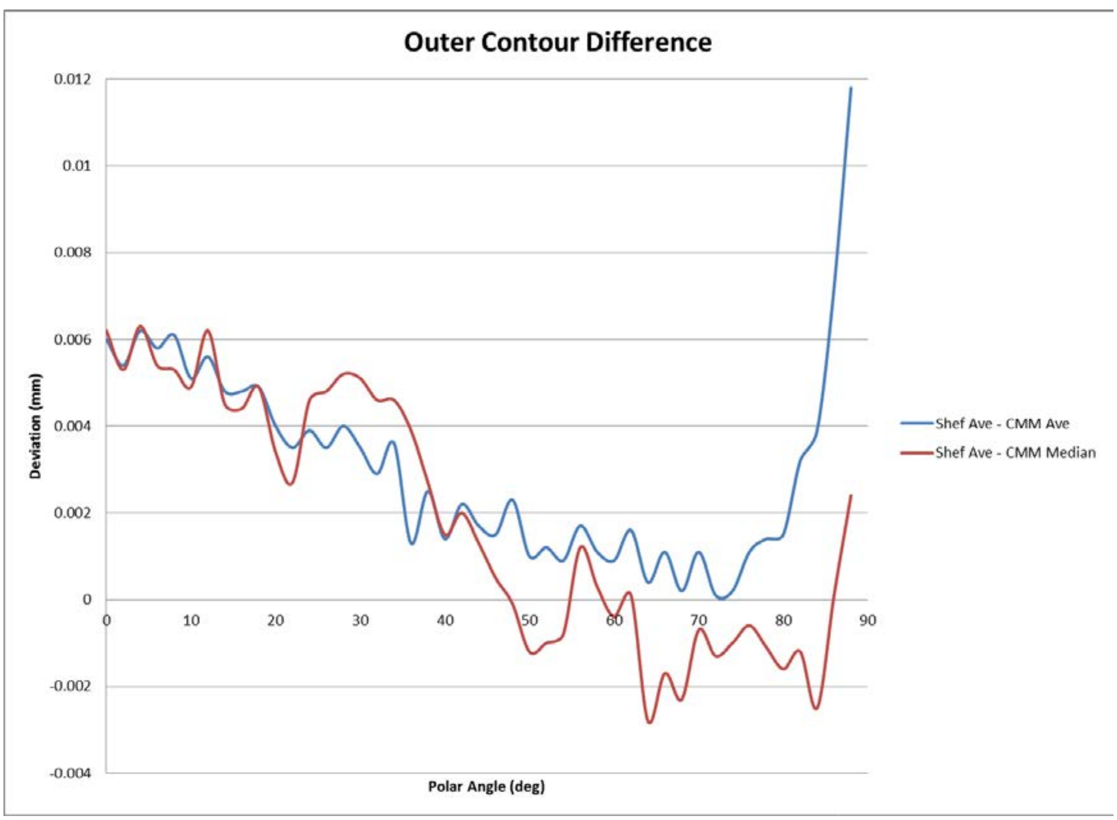

Figure 34. 18Y314740-A1D Outer Contour (Ave/Median) Difference

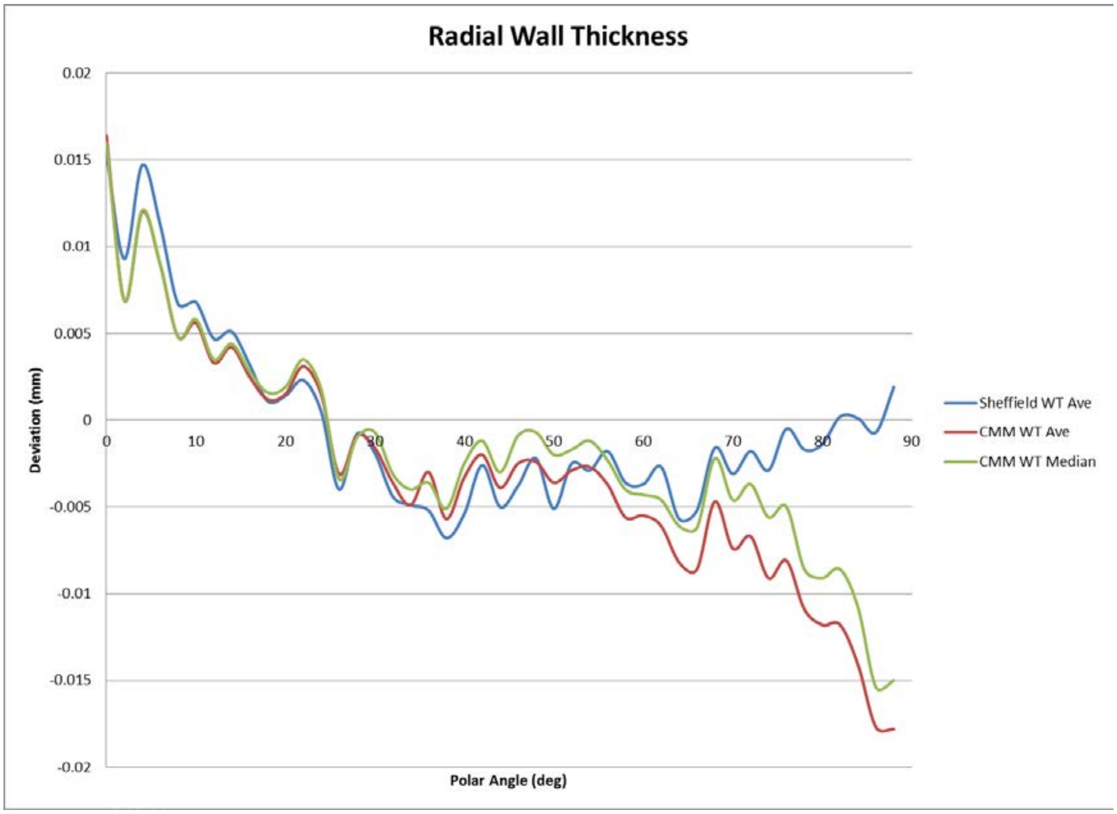

Figure 35. 18Y314740-A1D Radial Wall Thickness (Ave/Median) Comparison

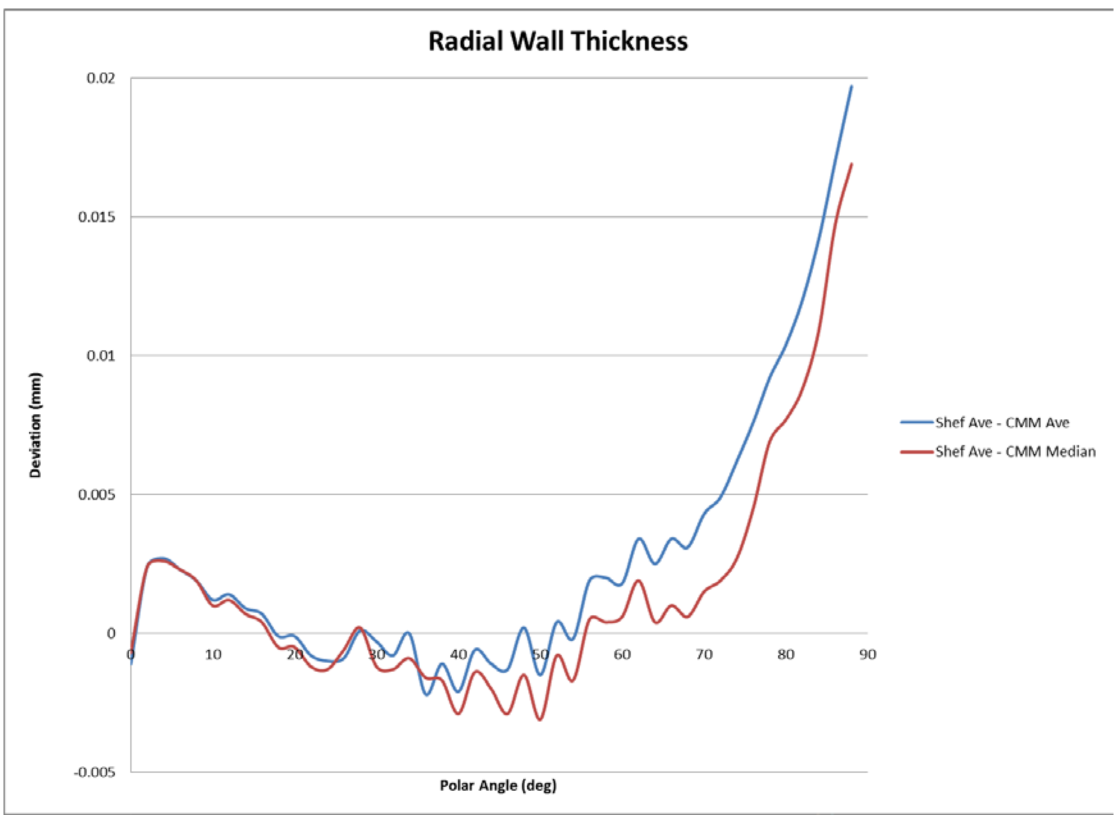

Figure 36. 18Y314740-A1D Radial Wall Thickness (Ave/Median) Difference

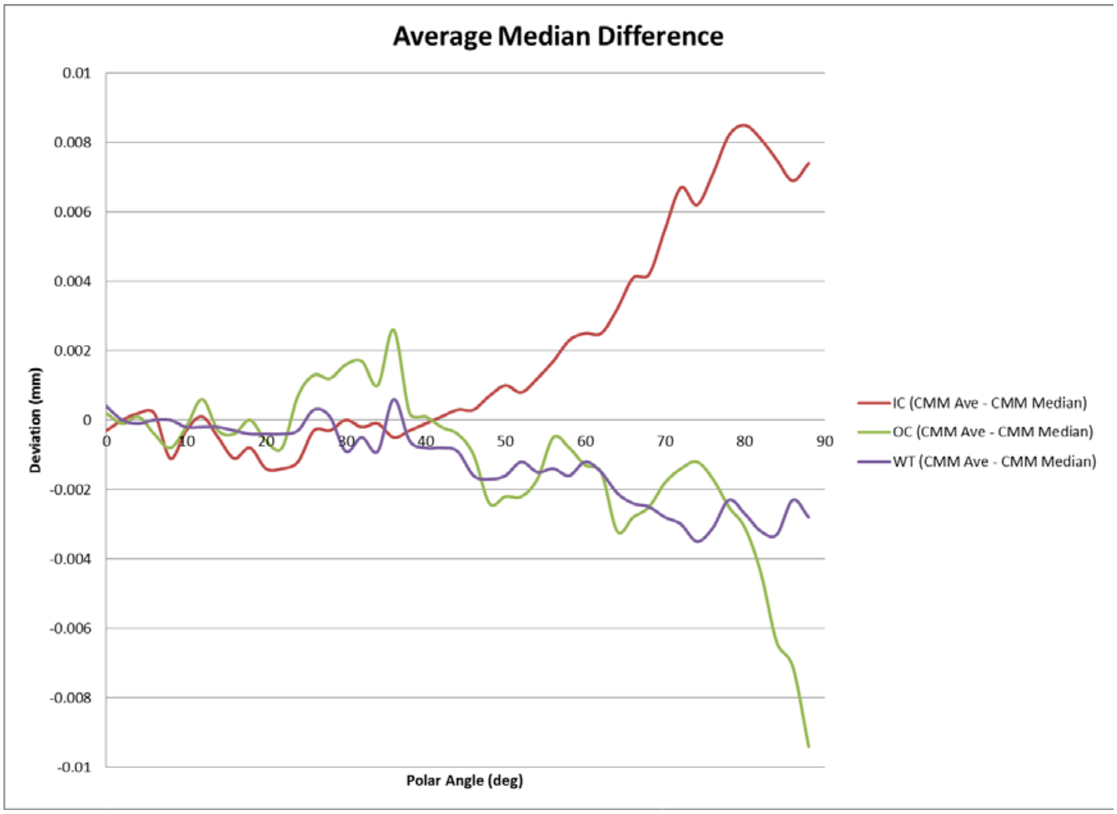

Figure 37. 18Y314740-A1D Average/Median Difference

4.3 Quality Checks

There are a number of techniques that the Inspection Team employs to provide confidence that a measurement is valid. A number of quality checks have been in development for the CMM shell inspection process and are discussed below.

Temperature and Probe Qualification:
Temperate is a critical parameter that can affect dimensional measurements and is monitored over the duration of the inspection as seen in Figure 38. Along with temperature, the shell inspection process begins with a verification that probe qualification was within specifications. A probe that is above limit will prompt the inspector to clean the qualification sphere and try again.

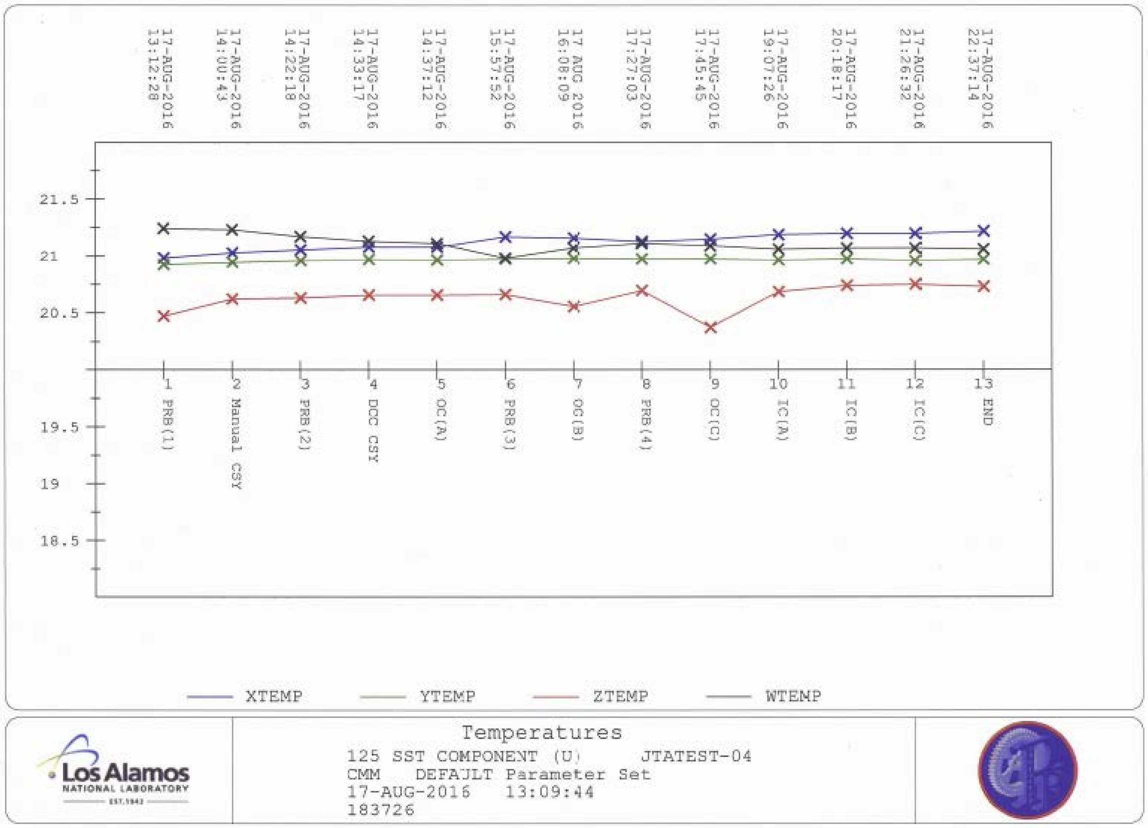

Figure 38. CMM Temperature Plot

Datum and Pole Check:
Both Datum A and Datum B are inspected and produce plots for the inspector. Parts that are significantly out-of-round can affect the flatness of Datum A which in turn can affect inner and outer contour measurements. A physical check of the outer pole or open setup measurement is made using a granite surface plate and height gauge. This value is entered into the program and compared to CMM point-to-point measurements as seen in Figure 39 below. In this example the CMM is measuring the pole within about 3 microns of the open setup measurement but that value drifts to 7 microns towards the end of the inspection.

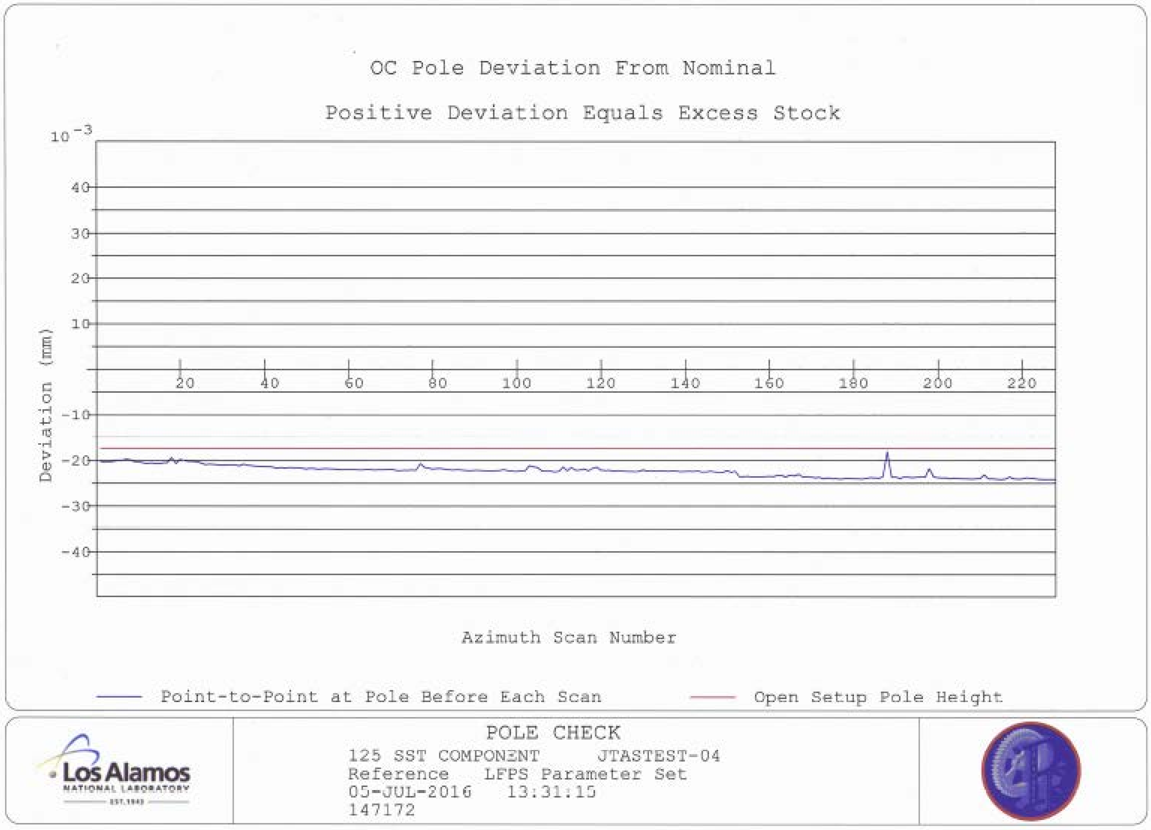

Figure 39. Open setup to Touch Trigger Check

Because the part is inspected using scanning, a second point-to-point check to scanning comparison is also made and can be seen in Figure 40. In this example the difference between the two methods starts at about 4 microns and increases to 6 microns. Point-to-point is considered more accurate but not used because the data acquisition is much slower.

Lastly, equator checks have also been implemented. Azimuthal scans of the inner and outer contour are made at the beginning and end of the inspection to verify that significant changes have not been made either through part movement or equipment drift.

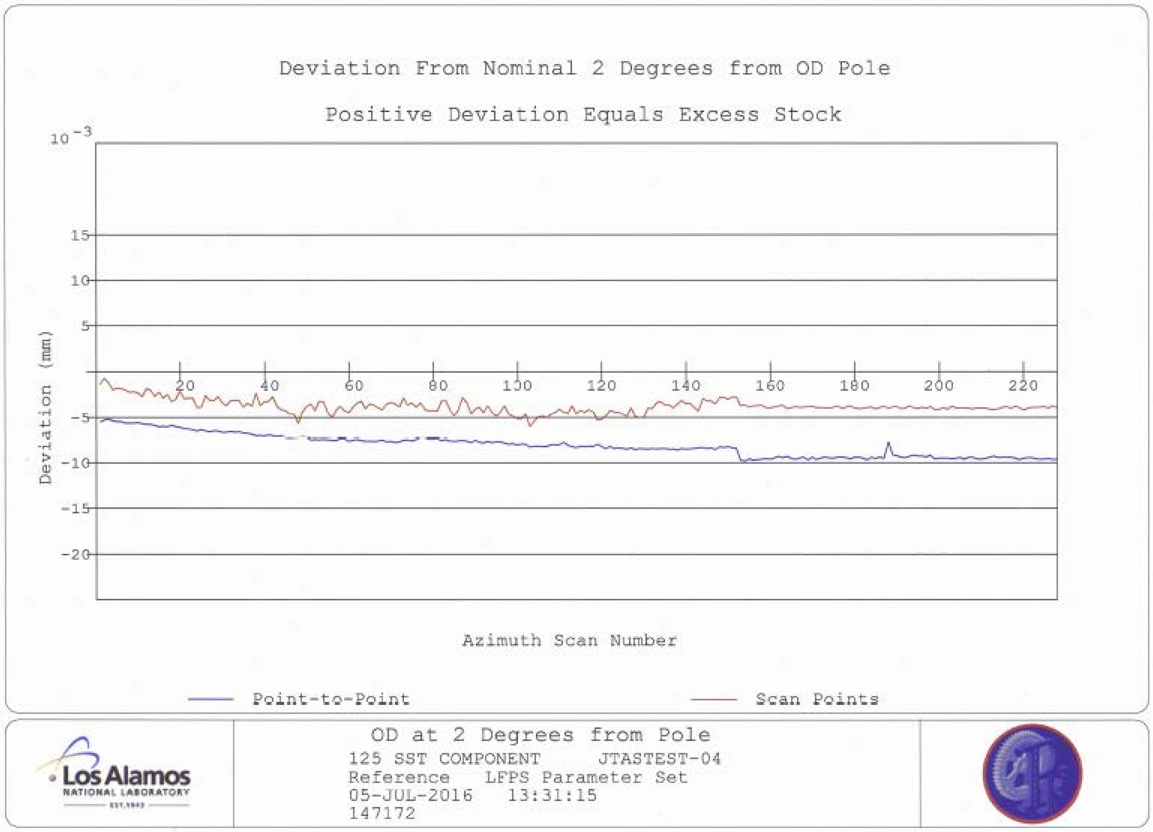

Figure 40. Touch Trigger to Scanning Check

4.4 Artifact

A review of nuclear weapons complex (NWC) unclassifed shell artifacts was performed in an effort to create the best possible artifact for LANL's CMM shell inspection needs. The drawings listed in Table 2 were reviewed.

Table 2. Unclassified NWC Shell Artifacts

Site	Drawing
Los Alamos National Laboratory	157Y700373, SK-FT-CMM-02-001, 142Y802444, SK-FT-CMM-02-002
Lawrence Livermore National Laboratory	AAA96-101235-00
Y-12	T2D801877A007
Rocky Flats Plant	P32599
Pantex	Number not visible on drawing
Atomic Weapons Establishment	SK/1/00716

The AWE design was chosen because the part had a flange providing for exceptional stability at the equator minimizing out-of-round issues. The flange in many ways serves as a built-in rounding ring. Most of the original design was preserved but a couple of small modifications were implemented such as a flat on the flange to serve as Datum C for clocking purposes. In addition to the geometry of the part, materials were also reviewed. The author had discussions with the Primary Standards Lab (PSL) at Sandia National Laboratory that included low coefficient of thermal expansion materials such as Zerodur and Invar. The final material chosen was AISI-A2 with a specific heat-treat and sub-zero stabilization for long term dimensional stability.

The final design is documented in drawing 157Y701533 and two artifacts were fabricated at Apex Machine Tool in Connecticut.

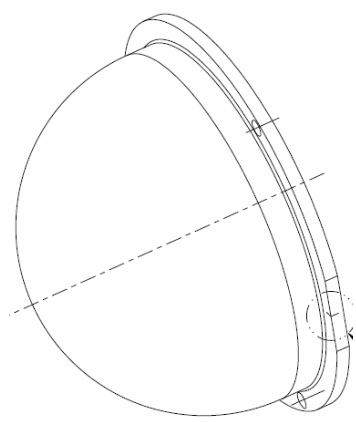

Figure 41. NIST Artifact Inspection Fixture (U), 157Y701533

The PSL has a CMM with a better certified accuracy than any of LANL's CMMs and performed five low density inspections on 157Y701533 SN 0002. The mass of this part is greater than 3800 grams and the PSL mass comparison was less than 1/3 of a gram. These measurements represent the best estimate at the true size and geometry for this part.

Table 3. 157Y701533-0002 Inspections

Machine	Number of Runs	Number of Scans	CMM Manufacture's Specification [57,76,77,78]	CMM Calibrated Specification [79]	Mass Comparison
Sheffield 1	3	480	N/A	N/A	-1.5 g
PSL	5	18	0.3 + L/850	0.3 + L/850	-0.3 g
PMM-C (102)	3	228	0.5 + L/700	1.0 + L/250	-1.9 g
PMM-C (28C)	2	228	0.6 + L/600	1.0 + L/400	+0.6 g
Reference	TBD	TBD	0.9 + L/350	1.2 + L/350	TBD
PMM	TBD	TBD	1.2 + L/300	1.7 + L/200	TBD
Global	TBD	TBD	1.5 + L/333	1.7 + L/220	TBD

In theory the PMM-C in SM102 is the Inspection Team's most accurate CMM. As seen in Figures 42 – 47, this machine is an outlier. Further investigation has shown that the CMM firmware was the issue and upgrades are planned to resolve it. This machine was calibrated at the time of the inspection and demonstrates the importance of process and equipment checks.

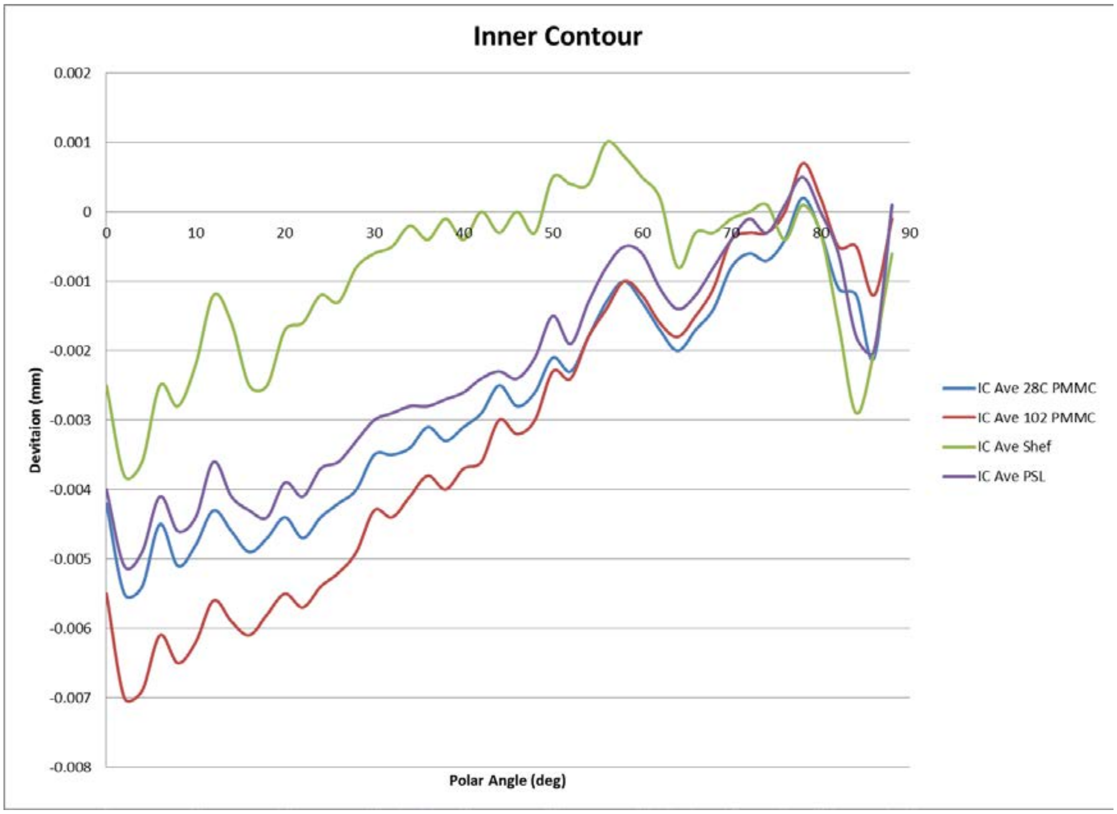

Figure 42. 157Y701533-0002 Inner Contour Comparison

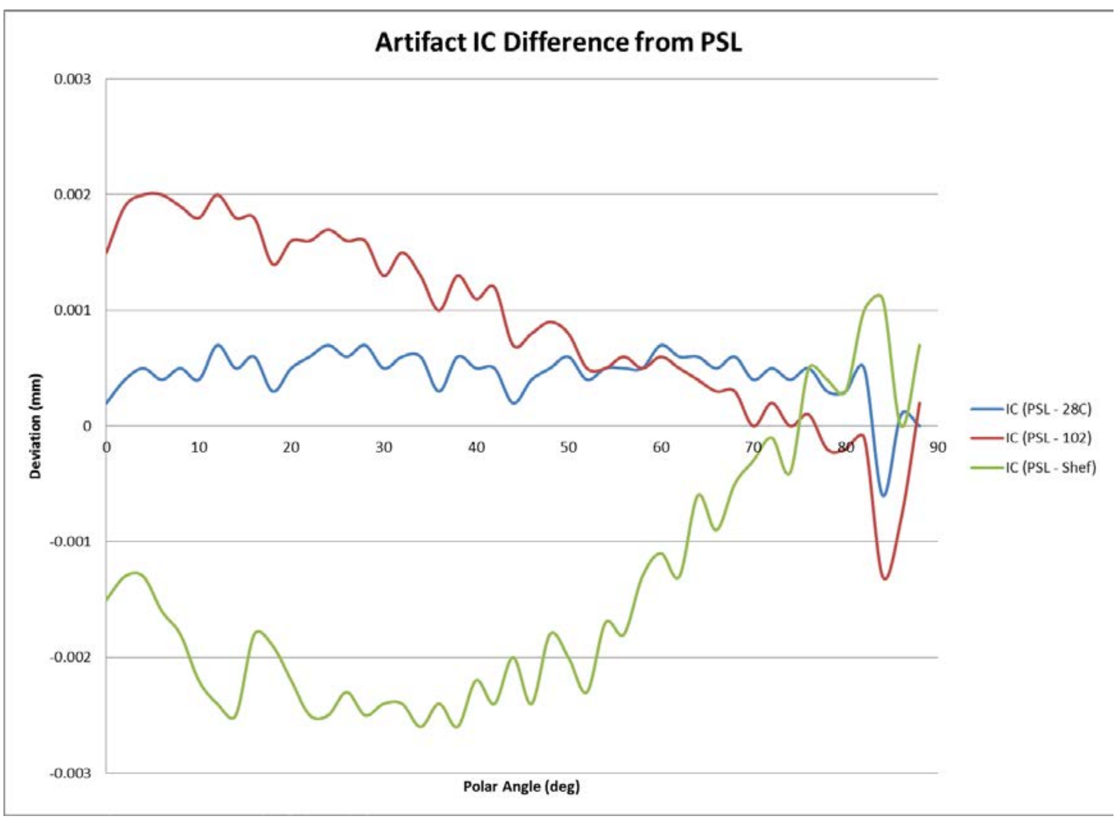

Figure 43. 157Y701533-0002 Inner Contour Difference

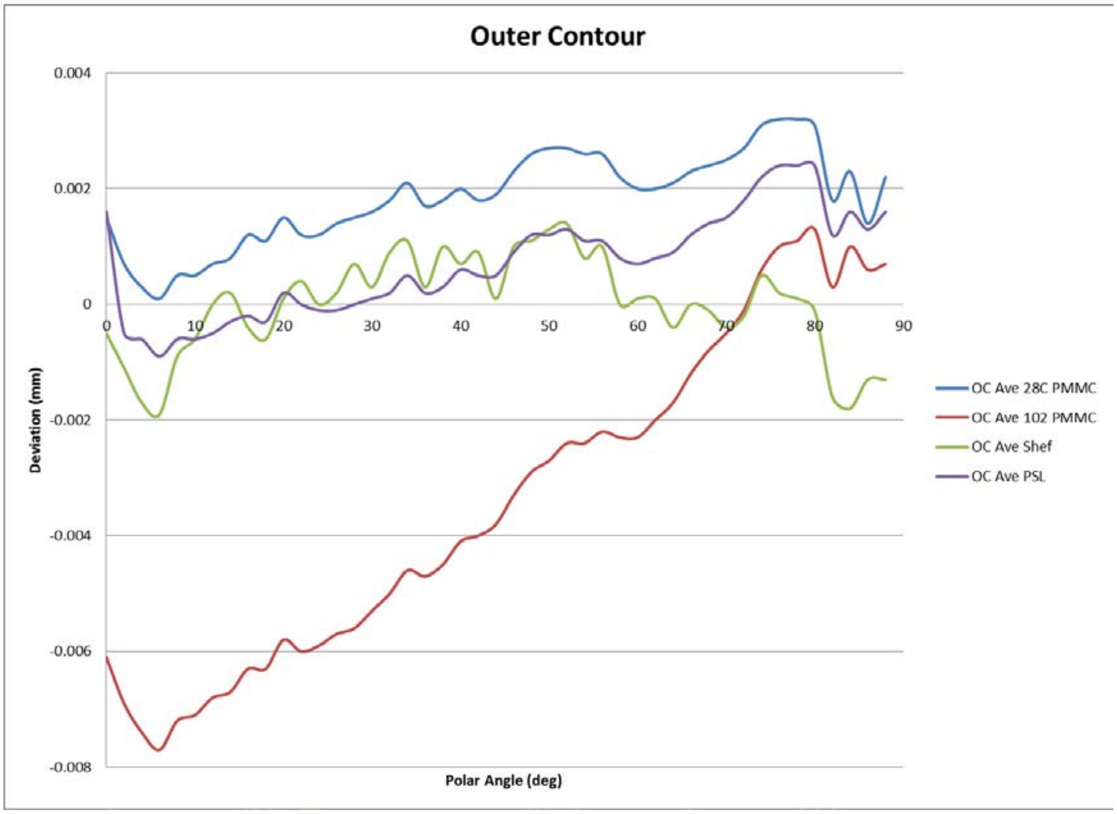

Figure 44. 157Y701533-0002 Outer Contour Comparison

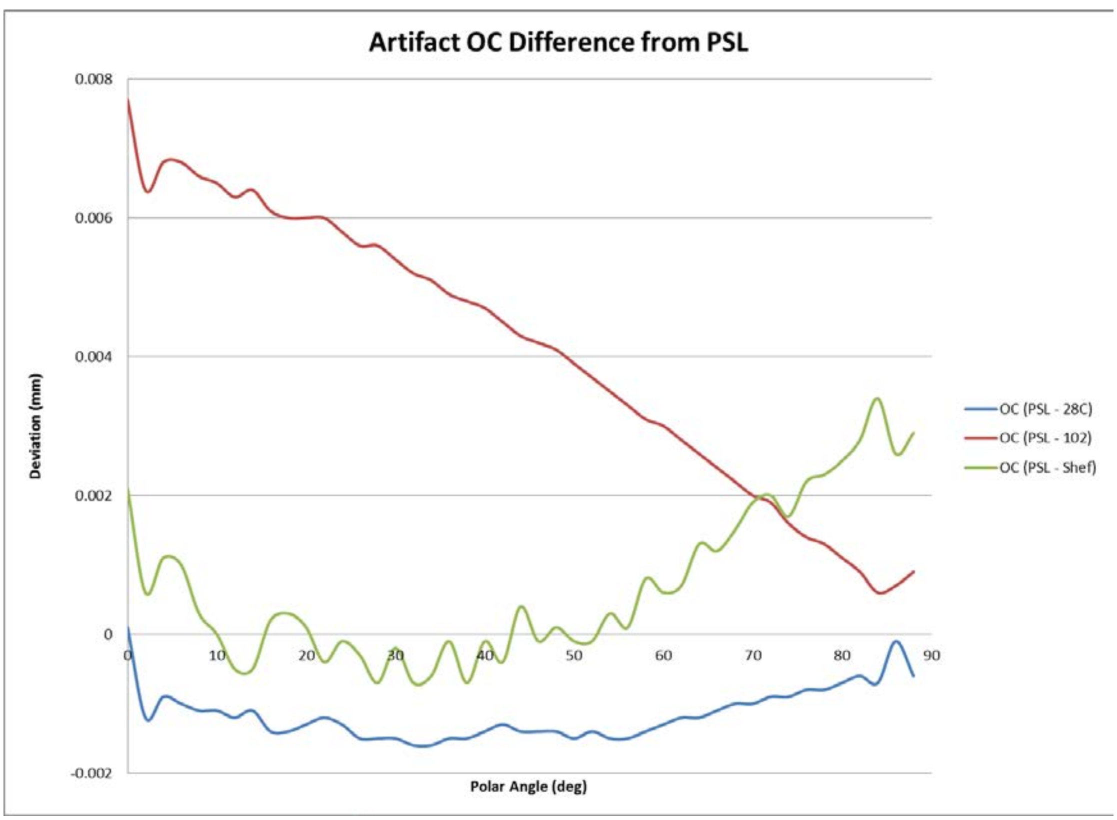

Figure 45. 157Y701533-0002 Outer Contour Difference

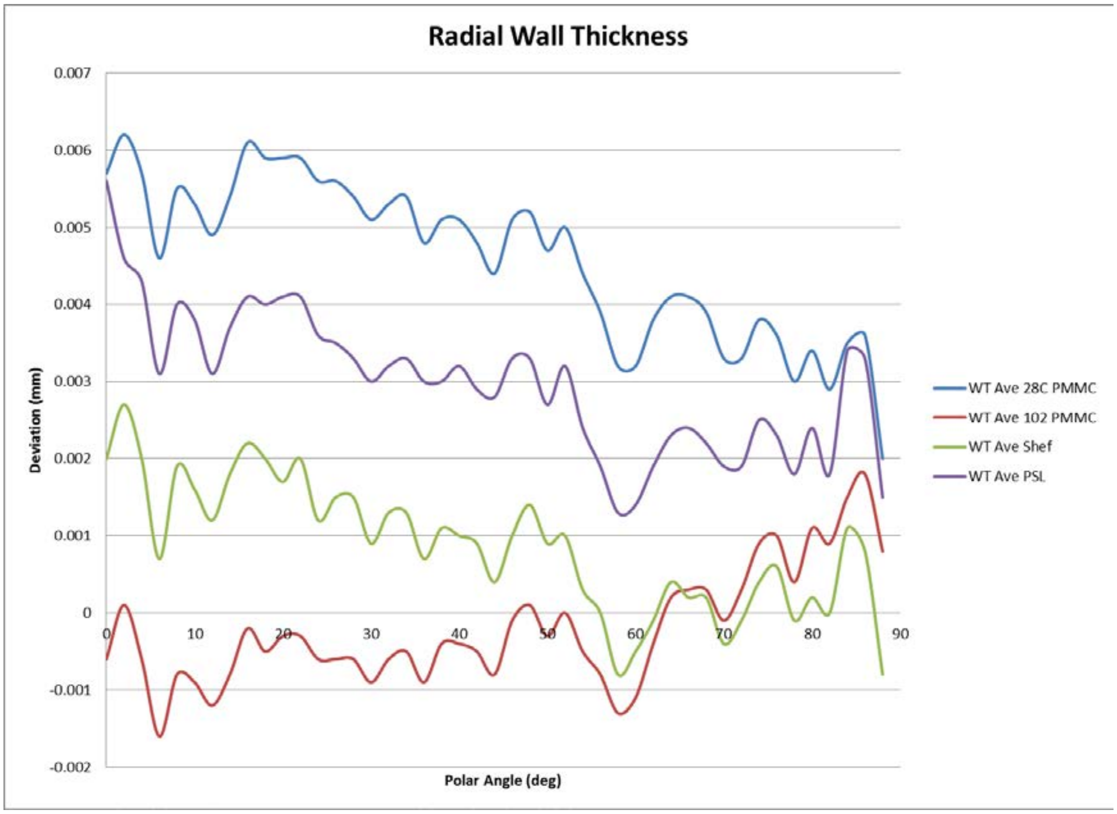

Figure 46. 157Y701533-0002 Radial Wall Thickness Comparison

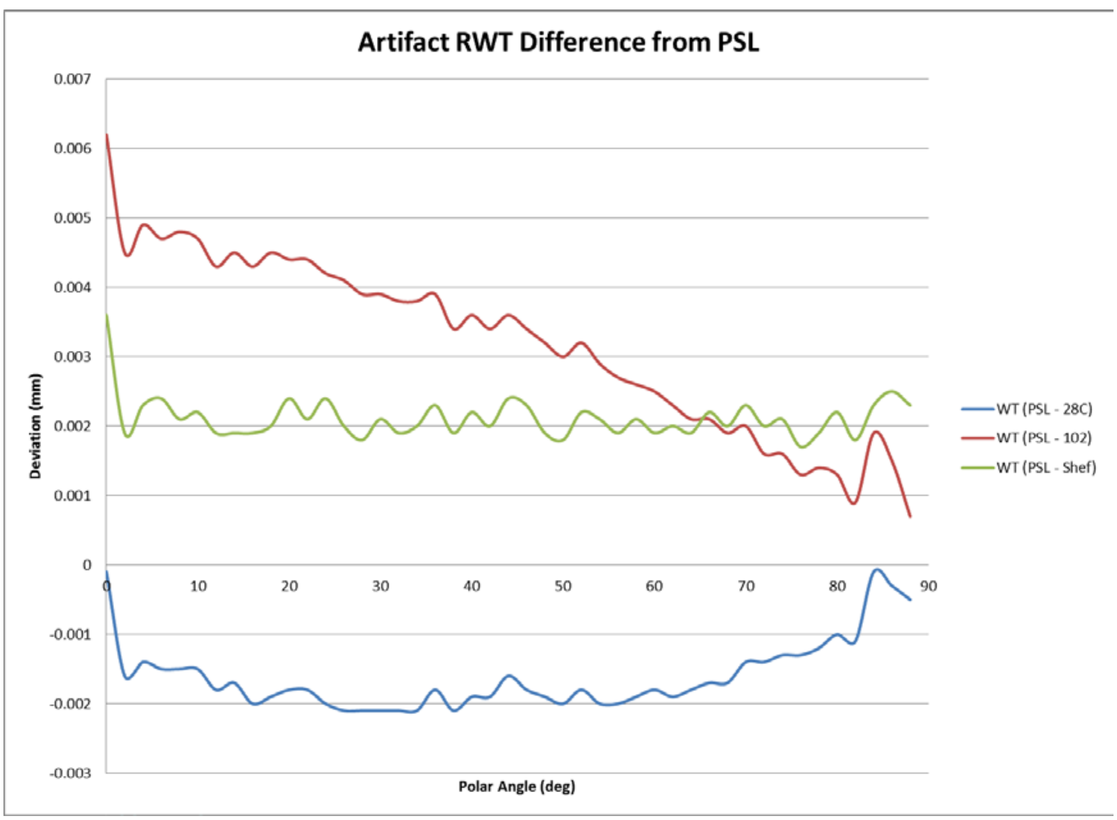

Figure 47. 157Y701533-0002 Radial Wall Thickness Difference

4.5 Machine Checking Gauge

The artifact is a good process monitor and the machine checking gauge (MCG) is a good equipment monitor. The international standard for certifying Coordinate Measuring Machines (CMM), ISO 10360-2 states, *"It is strongly recommended that the CMM be checked regularity during the periods between periodic reverification"* [49]. CMM calibrations at LANL are completed annually [42]. LANL intends to use Renishaw's Machine Checking Gauge (MCG) as an interim check between calibration cycles. The interim check discussed in *"CMM Interim Check (U)"*, LA-UR-15-22103 makes use of Renishaw's Machine Checking Gauge [80]. This off-the-shelf product simulates a large sphere within a CMM's measurement volume and allows for error estimation. The report discuses data gathered, analyzed, and simulated from seven machines in seventeen different configurations to create statistical process control run charts for on-the-floor monitoring. The main shop has implemented this check and requires it to be run weekly [81]. Each run takes approximately 30 minutes per machine.

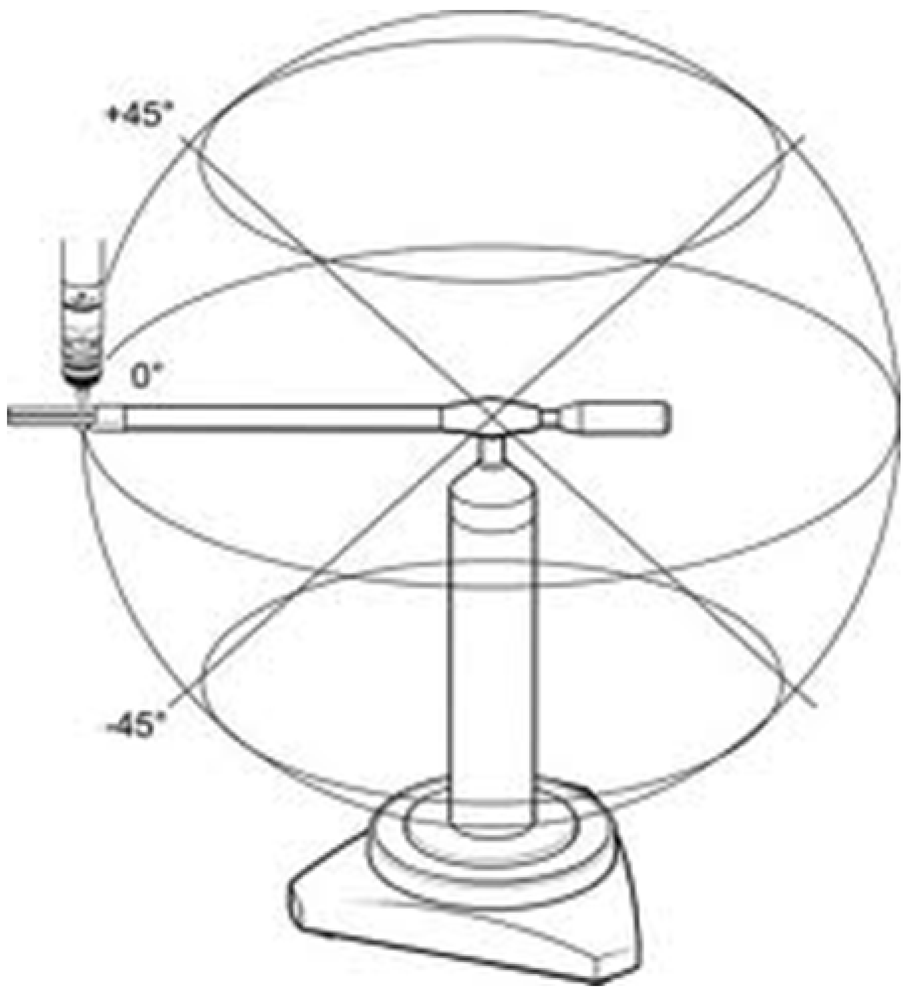

Figure 48. Renishaw Machine Checking Gauge [82]

4.6 Design of Experiments

The American Society for Quality (ASQ) defines a Design of Experiments (DOE) as *"a branch of applied statistics that deals with planning, conducting, analyzing and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters"* [83]. A four factor, three level full factorial design was originally proposed but was considered too ambitions given resource constraints and the number of runs (162) it would take to accomplish the experiment. The test was scaled down to a four factor, two level full factorial design, and had a significant reduction in required work (32 runs).

Table 4. DOE Factors and Levels

Factor	**Level**
Machine	PMM-C, Reference, ~~Global~~
Material	Stainless, U238, ~~Beryllium~~
Inspector	A, B, ~~C~~
Probe Force	Default, Low Force, ~~Ultra Low Force~~

$$Levels^{Factors}\ x\ Reps = Tests$$

$$\cancel{3^4\ x\ 2 = 162}$$

$$2^4\ x\ 2 = 32$$

Randomization is always recommended in a DOE but was intentionally limited to minimize handling of the radioactive U238 part [84]. This was accomplished by scheduling all the stainless steel runs to be completed on the Reference CMM while all the U238 runs would be completed on the PMM-C. After the runs were complete, there would be one part swap and the second half of the DOE would be gathered. The first run began on May 31, 2016 using the Reference CMM only since PMM-C was in need of calibration. During the DOE two issues arouse. First some unplanned events further postponed the PMM-C calibration. Second, it was becoming obvious from the data set gathered on the Reference that something was wrong with the machine. Further investigation revealed that the Reference was suffering from a similar firmware issue as the PMM-C discussed in section 4.4. The project paused after the last stainless steel run so that machine could receive upgraded firmware and software.

Table 5. CMM Design of Experiments Test

		102 PMM-C					28C Reference					
Date		**MCG**	**Material**	**Inspector**	**Force**		**MCG**	**Material**	**Inspector**	**Force**		**Comment**
Tuesday	5/31/2016							Stainless	B	Default		5/31/2016
Wednesday	6/1/2016	N/A						Stainless	A	Default		6/1/2016
Thursday	6/2/2016							Stainless	B	LFPS		6/2/2016
Monday	6/6/2016		Calibrate Machine					Stainless	A	LFPS		7/5/2016
Tuesday	6/7/2016							Stainless	B	Default		6/6/2016
Wednesday	6/8/2016	N/A						Stainless	A	Default		6/7/2016
Thursday	6/9/2016							Stainless	B	LFPS		6/9/2016
Monday	6/13/2016		D38	A	Default			Stainless	A	LFPS		6/8/2016
Tuesday	6/14/2016		D38	B	Default			Artifact	B	Default		no program
Wednesday	6/15/2016		D38	A	LFPS			Stainless	B	Default	*	6/7/2016
Thursday	6/16/2016		D38	B	LFPS			Stainless	A	Default	*	6/13/2016
Monday	6/20/2016		Artifact	A	LFPS			Stainless	B	LFPS	*	6/14/2016
Tuesday	6/21/2016		D38	A	Default			Stainless	A	LFPS	*	6/15/2016
Wednesday	6/22/2016		D38	B	Default			Artifact	A	LFPS		no program
Thursday	6/23/2016		D38	A	LFPS							
Monday	6/27/2016		D38	B	LFPS							
Tuesday	6/28/2016		Artifact	B	Default							Swap parts
Wednesday	6/29/2016		Stainless	A	Default			D38	B	Default		between labs.
Thursday	6/30/2016		Stainless	B	Default			D38	A	Default		
Tuesday	7/5/2016		Stainless	A	LFPS			D38	B	LFPS		
Wednesday	7/6/2016		Stainless	B	LFPS			D38	A	LFPS		
Thursday	7/7/2016		Stainless	A	Default			Artifact	B	LFPS		
Monday	7/11/2016		Stainless	B	Default			D38	B	Default		
Tuesday	7/12/2016		Artifact	A	Default			D38	A	Default		
Wednesday	7/13/2016		Stainless	A	LFPS			D38	B	LFPS		
Thursday	7/14/2016		Stainless	B	LFPS			D38	A	LFPS		
Monday	7/18/2016		Stainless	B	Default	*		Artifact	A	Default		
Tuesday	7/19/2016		Stainless	A	Default	*						
Wednesday	7/20/2016		Stainless	B	LFPS	*						
Thursday	7/21/2016		Stainless	A	LFPS	*		*needed for machine comparison (not DOE)				
Monday	7/25/2016		Artifact	B	LFPS							

As seen in the Table 5, the unfinished DOE resulted in 12 runs all on the same machine and using the same part with half by inspector A and half by inspector B, and half in default force and half in low-force. This data essentially created a two level, two factor full factorial design and was analyzed [85,86].

$$2^2 \ x \ 3 = 12$$

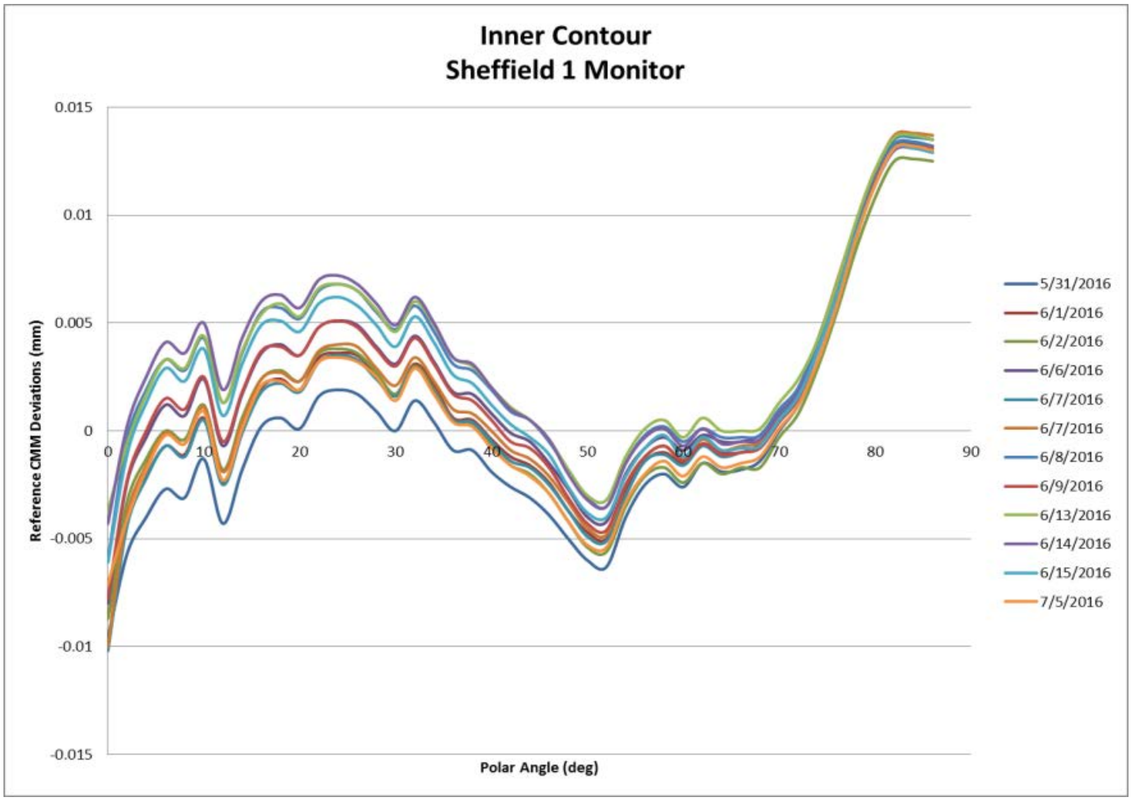

Figure 49. Sheffield Monitor Inner Contour Measurements

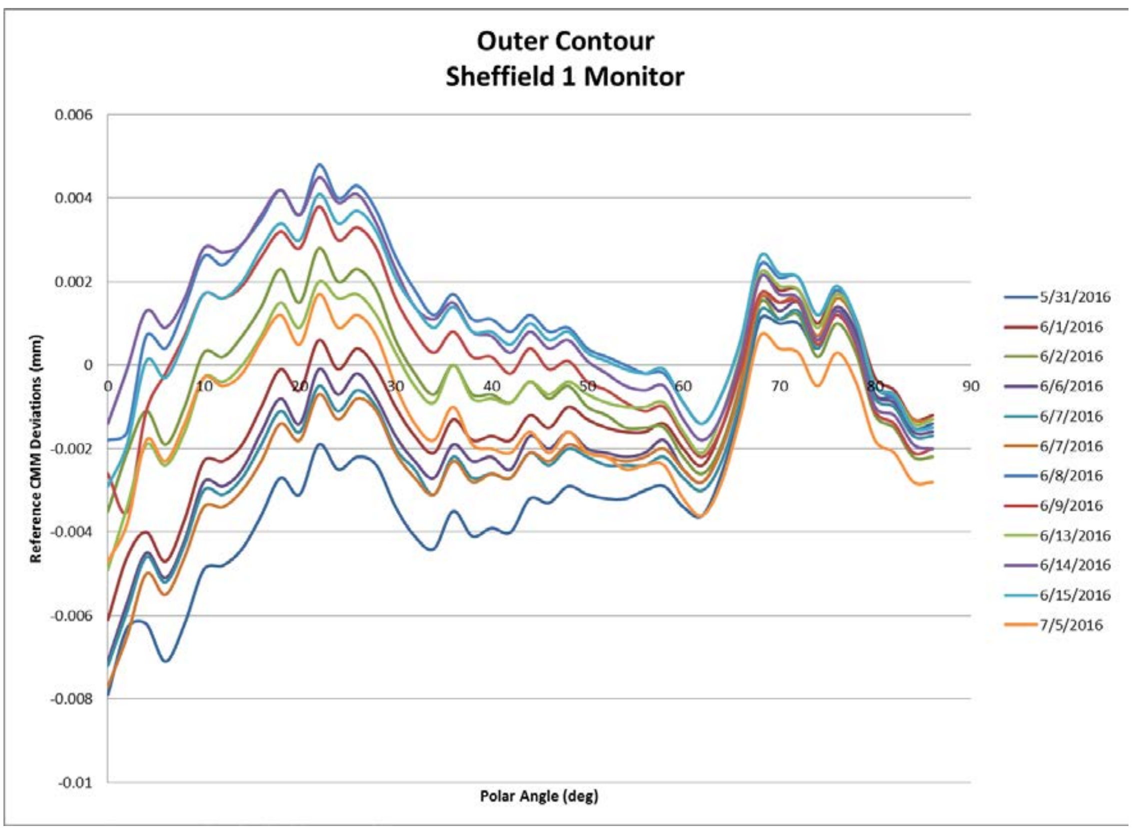

Figure 50. Sheffield Monitor Outer Contour Measurements

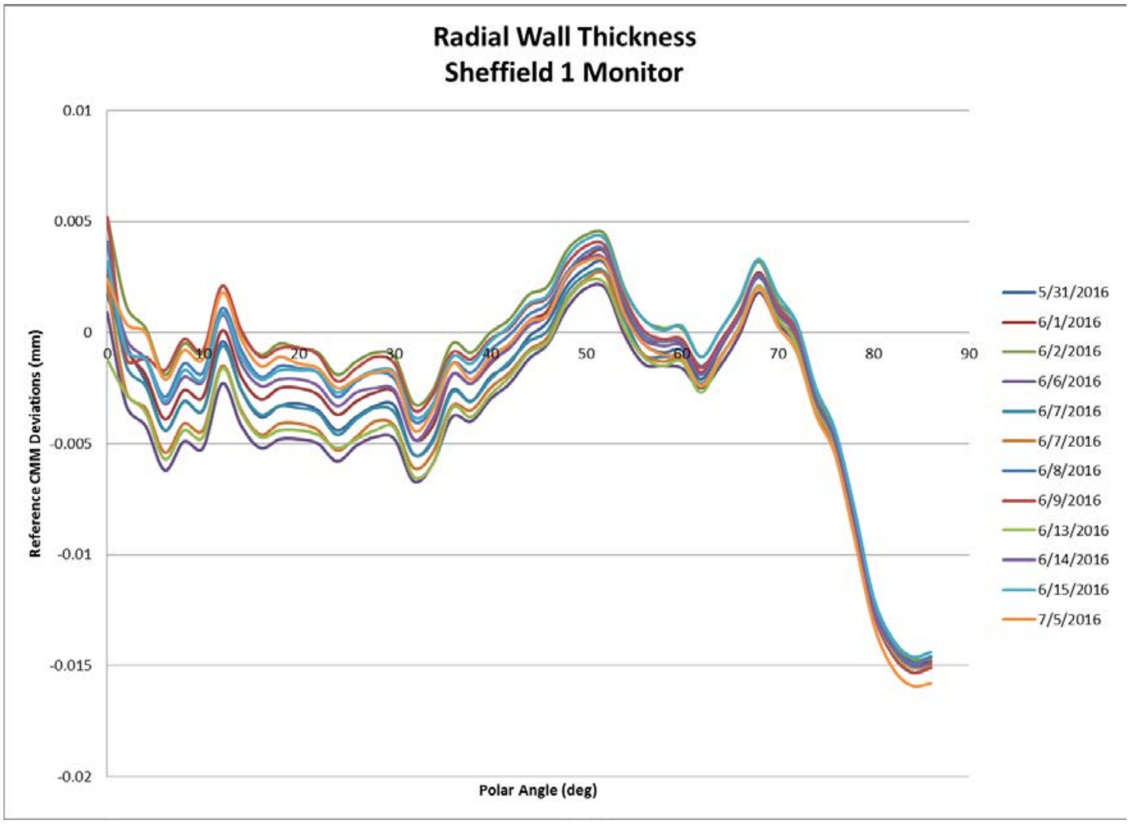

Figure 51. Sheffield Monitor Radial Wall Thickness Measurements

Typically a DOE is conducted to compare a single measurement to a single measurement. Shell inspection however generates thousands of measurements (one at each polar angle and at every 1.5° azimuthally) during each inspection. For the DOE to be valid each measurement should be compared to each measurement. To minimize computation polar averages were used. Thousands of ANOVA calculations were reduced to hundreds. Each dot in the plots below represent an ANOVA computation conducted for inner, outer, radial wall thickness and for each factor force, inspector, and interaction. Please note that a P-value less than alpha ($P < 0.05$) or F>F-crit indicate a difference.

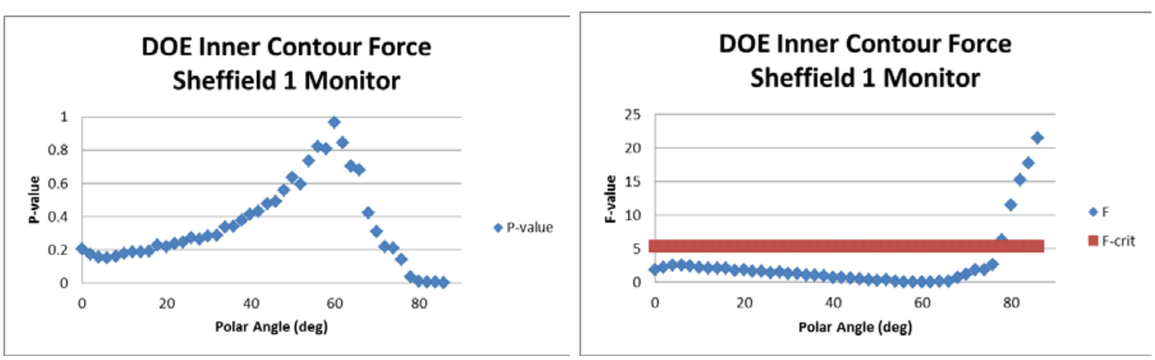

Figure 52. Inner Contour Force Results

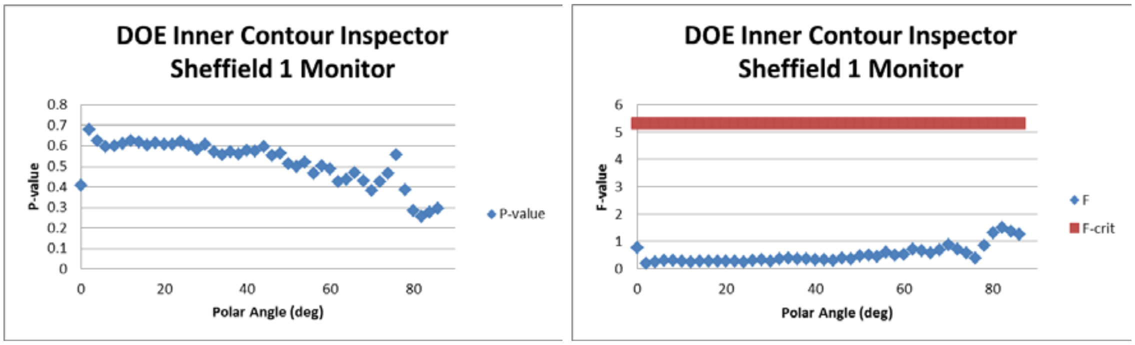

Figure 53. Inner Contour Inspector Results

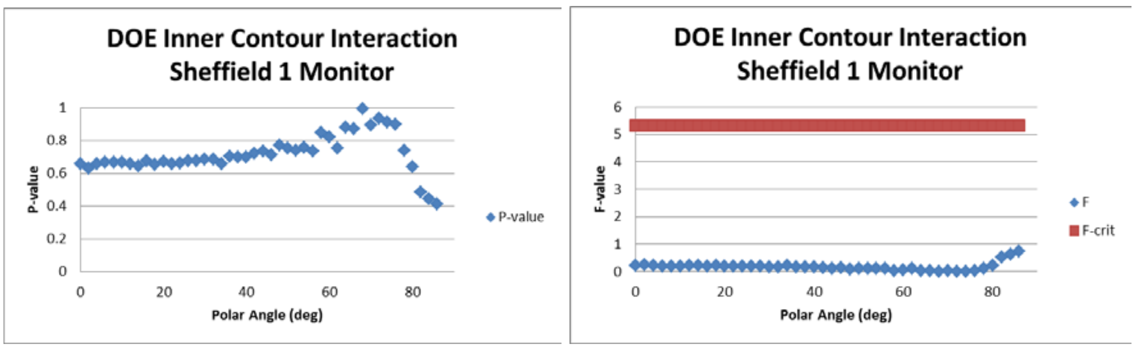

Figure 54. Inner Contour Interaction Results

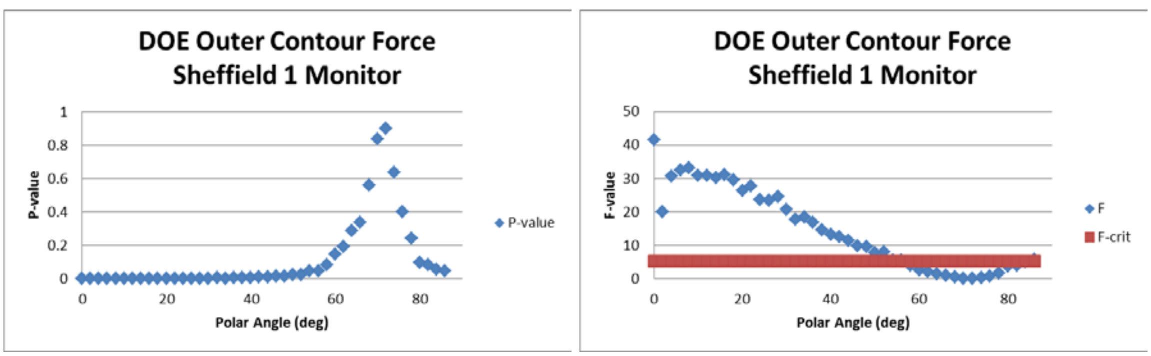

Figure 55. Outer Contour Force Results

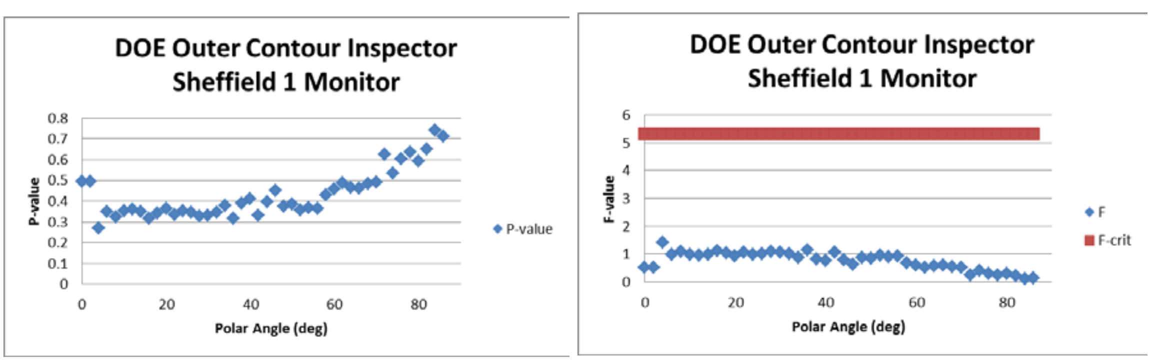

Figure 56. Outer Contour Inspector Results

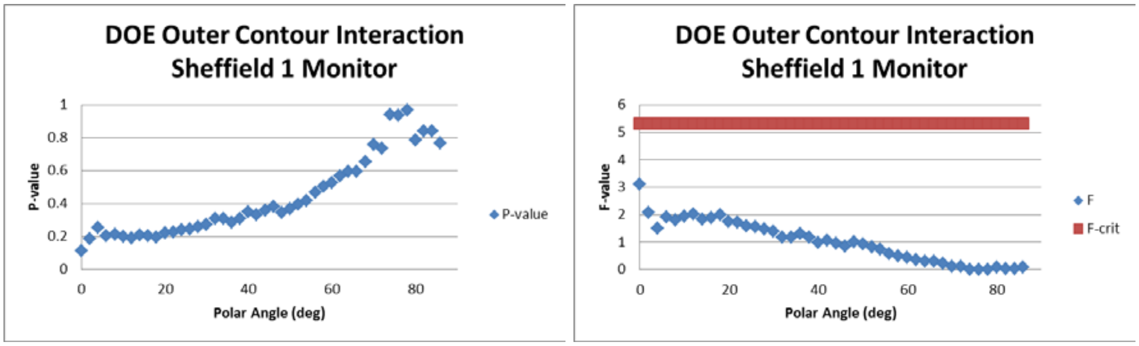

Figure 57. Outer Contour Interaction Results

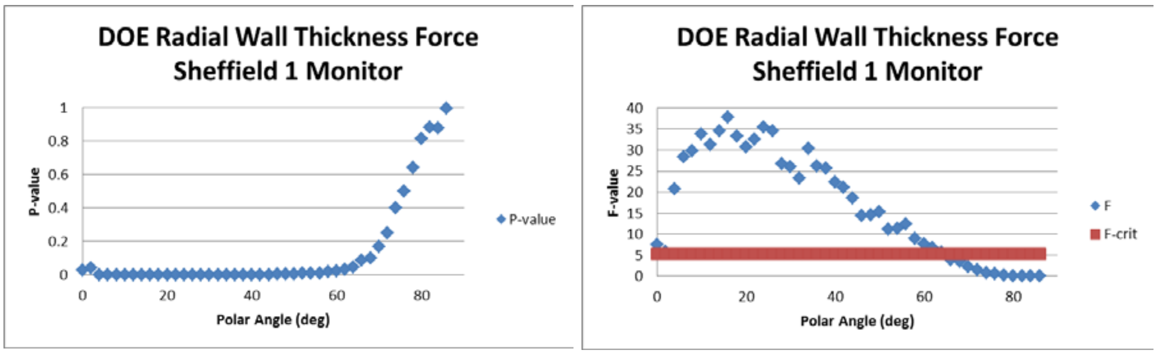

Figure 58. Radial Wall Thickness Force Results

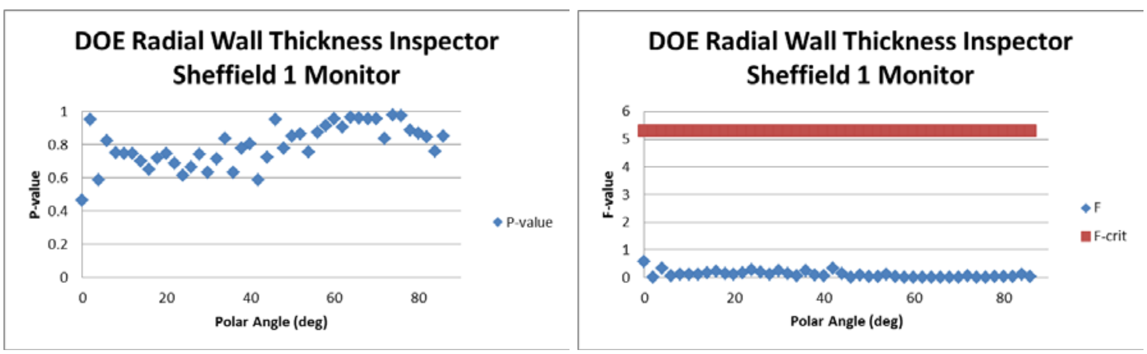

Figure 59. Radial Wall Thickness Inspector Results

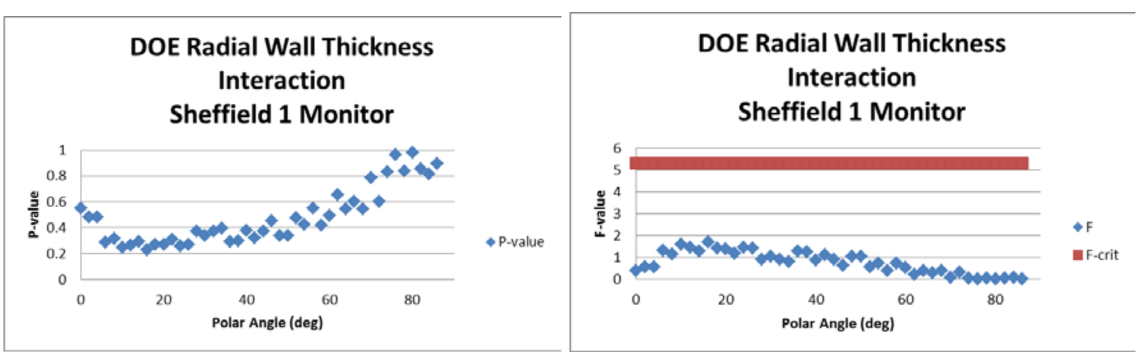

Figure 60. Radial Wall Thickness Interaction Results

What can be seen is that force is an influencing factor for CMM shell inspection while the inspector and interaction are not. Another look at Figures 49, 50, and 51 now separated by force as seen in Figures 61, 62, and 63 agree with those findings.

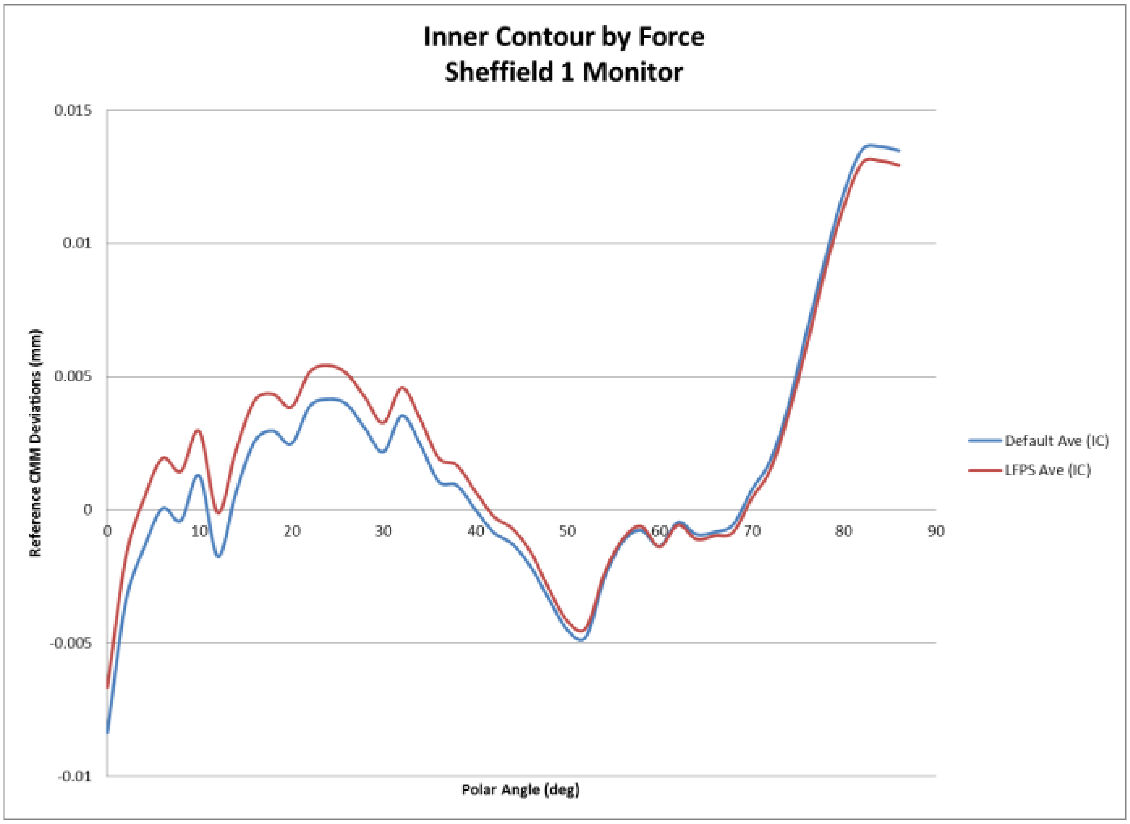

Figure 61. Sheffield Monitor Inner Contour Measurements by Force

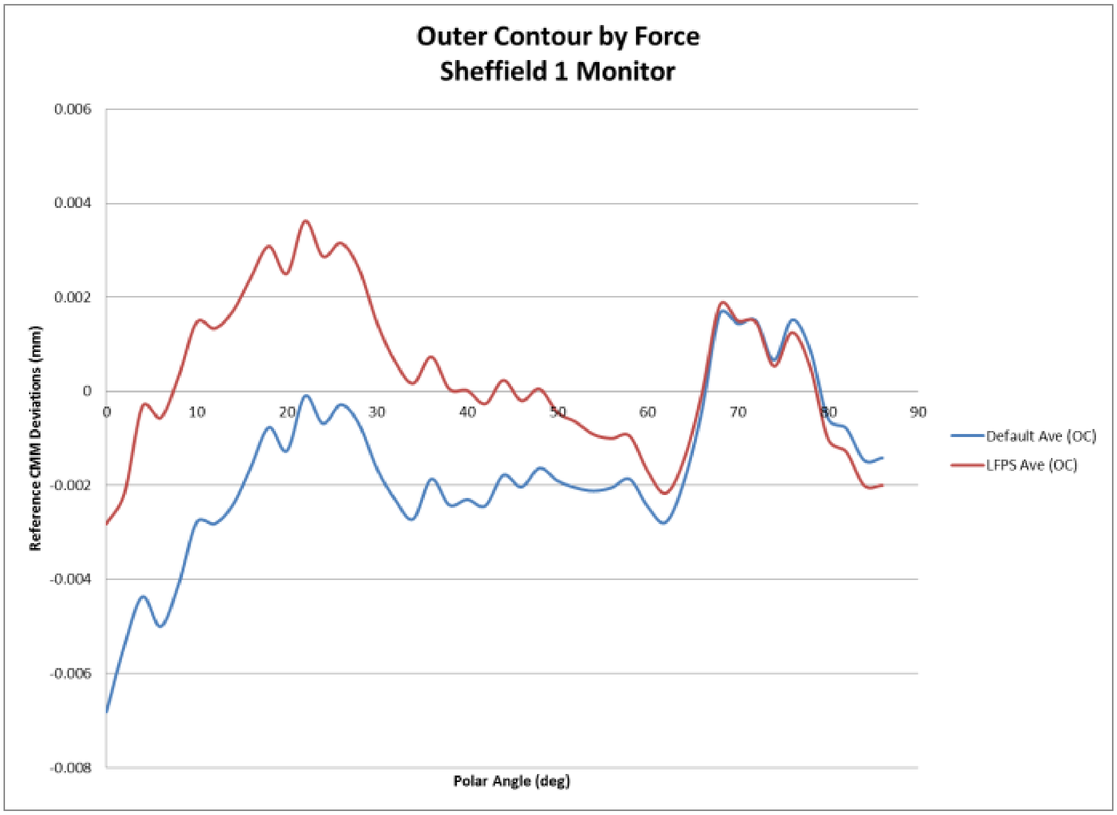

Figure 62. Sheffield Monitor Outer Contour Measurements by Force

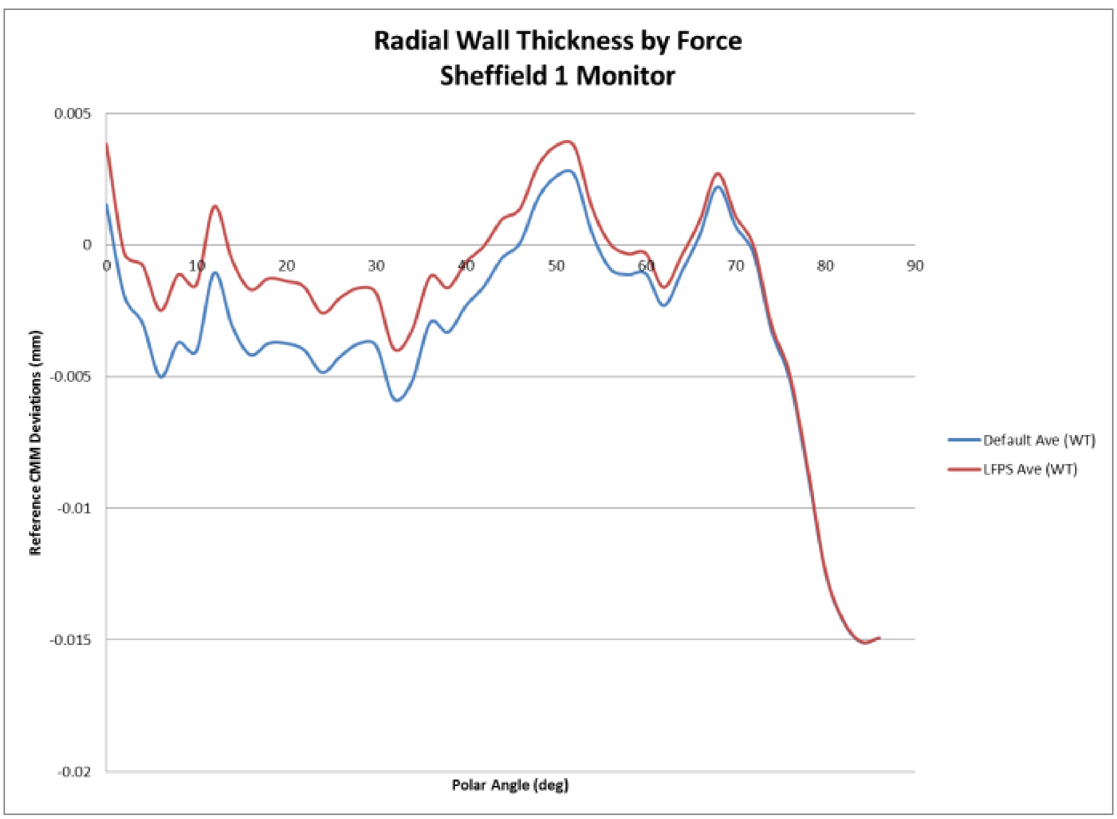

Figure 63. Sheffield Monitor Radial Wall Thickness Measurements by Force

4.7 Machine Comparison

As previously stated it was obvious that the data was not comparing due to firmware or some type of machine issue. Aside from that, a machine comparison was still conducted in an effort to demonstrate the analysis and technique.

As shown in the previous section inspector and interaction were both non-contributors to variance. Force did impact measurements so ideally the force with the smaller variation is preferred. In this case that was low-force, of which half the data or six runs were performed in this configuration. To compare the six CMM runs the last six Sheffield runs on this part were collected. To compare the two machines a two sample t-test assuming unequal variances was used [75,87,88]. Similar to the ANOVA test above the t-test is intended for a specific measurement to be compared to a specific measurement. Each dot below represents the individual result of a t-test computation.

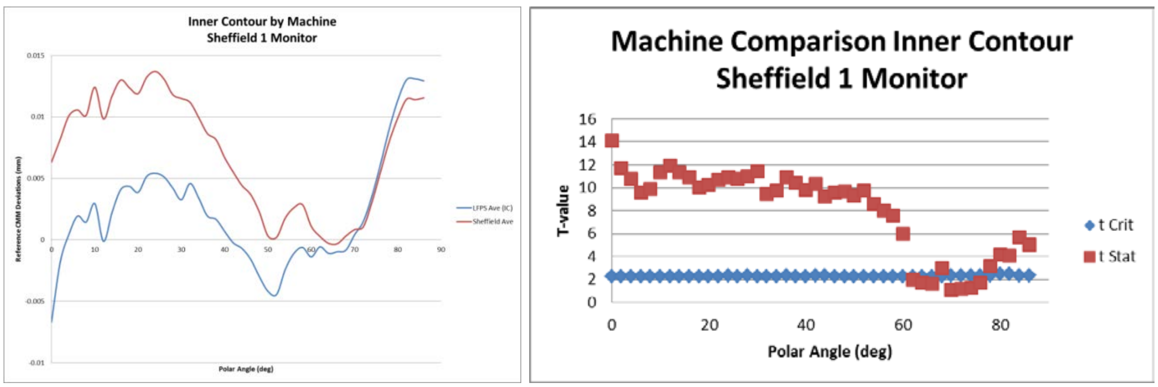

Figure 64. Inner Contour Machine Comparison

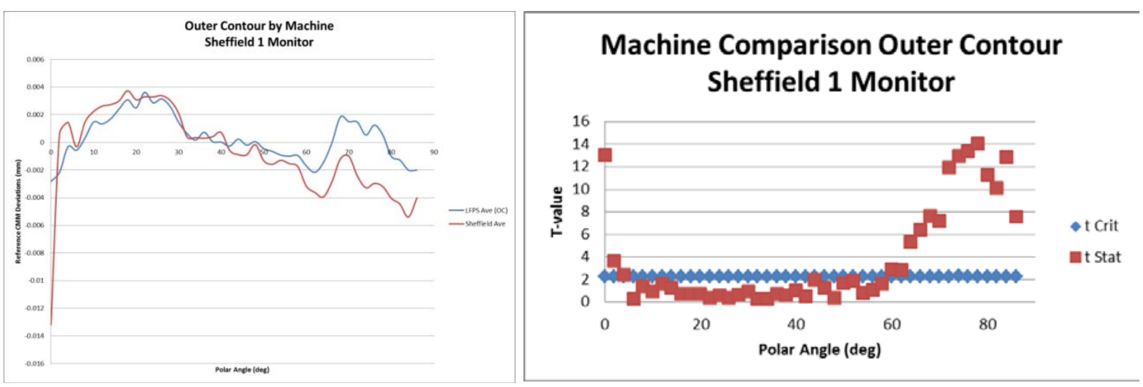

Figure 65. Outer Contour Machine Comparison

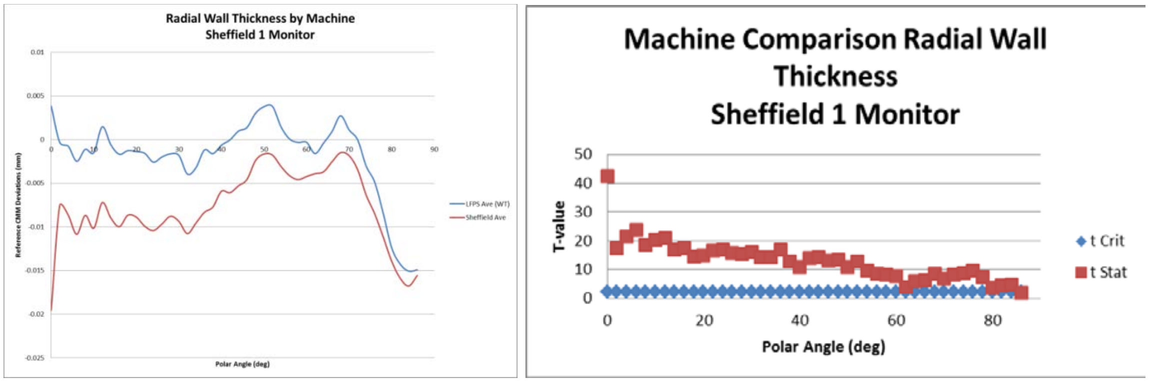

Figure 66. Radial Wall Thickness Machine Comparison

As suspected there are limited locations where the CMM and Sheffield compare (t < t-crit).

4.8 Mass Comparison Results

The mass comparison as described in section 2.8 was conducted on the 12 CMM inspections from the DOE and six Sheffield inspections with the following results.

Table 6. DOE Mass Comparison

Inspector	Force	Date	Machine	Mass Deviation (g)	UTL (g)	LTL (g)
Vigil	Default	5/31/2016	CMM	3.95	2	-2
Nohl	Default	6/1/2016	CMM	4.17	2	-2
Vigil	LFPS	6/2/2016	CMM	4.69	2	-2
Nohl	LFPS	6/6/2016	CMM	7.73	2	-2
Vigil	Default	6/6/2016	CMM	3.43	2	-2
Nohl	Default	6/7/2016	CMM	3.77	2	-2
Vigil	Default	6/7/2016	CMM	3.64	2	-2
Nohl	LFPS	6/8/2016	CMM	4.36	2	-2
Vigil	LFPS	6/9/2016	CMM	4.45	2	-2
Nohl	Default	6/13/2016	CMM	3.6	2	-2
Vigil	LFPS	6/14/2016	CMM	4.17	2	-2
Nohl	LFPS	6/15/2016	CMM	4.58	2	-2
Nohl	LFPS	7/5/2016	CMM	4.05	2	-2
Naranjo	Sheffield	6/7/2015	Sheffield	1.26	2	-2
Naranjo	Sheffield	8/17/2015	Sheffield	2.22	2	-2
Naranjo	Sheffield	9/16/2015	Sheffield	2.27	2	-2
Naranjo	Sheffield	11/16/2015	Sheffield	1.66	2	-2
Naranjo	Sheffield	3/1/2016	Sheffield	0.82	2	-2
Naranjo	Sheffield	4/22/2016	Sheffield	1.52	2	-2

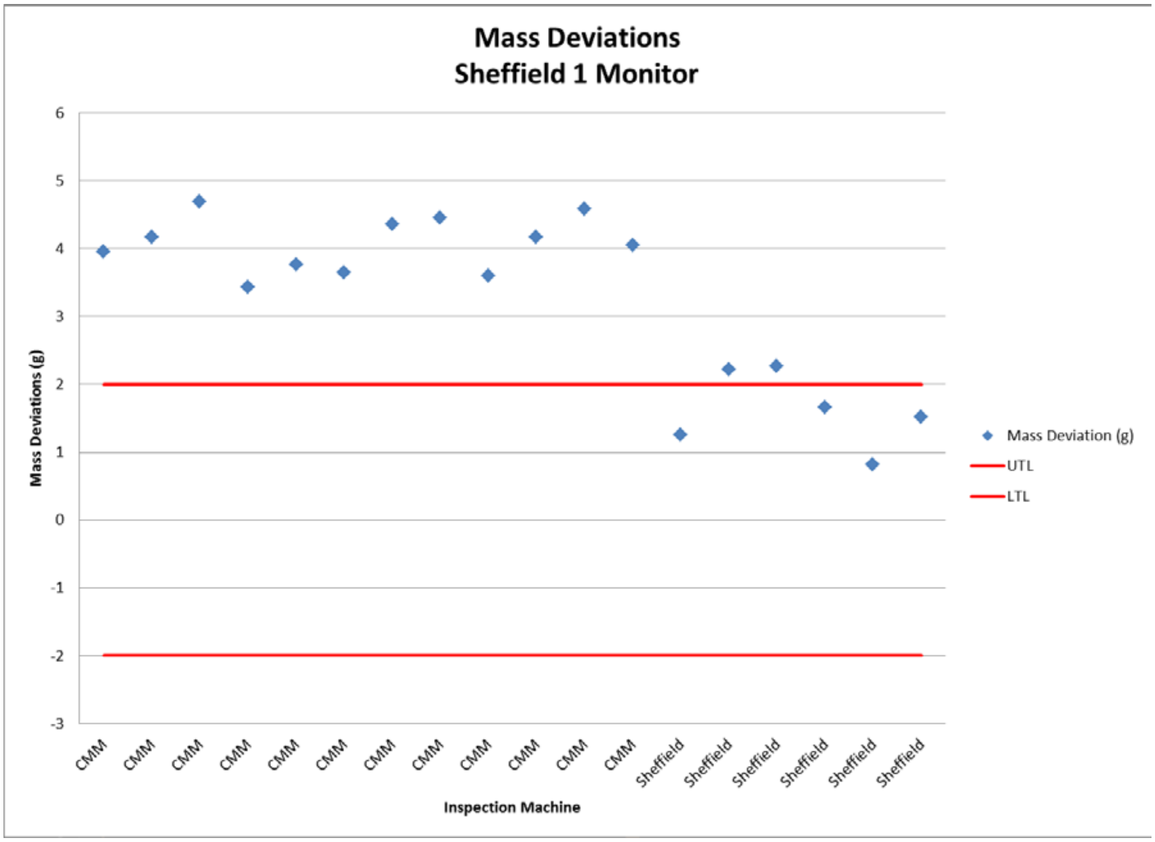

Figure 67. DOE Mass Comparison Results

4.9 Process Comparison

With a versatile machine like a CMM the old idiom, *"there is more than one way to skin a cat"* very much holds true. Two process variations that are of immediate interest are constrained versus non-constrained and 3-peg versus 45°.

4.9.1 Constrained versus Non-Constrained

As previously discussed a constrained inspection better represents an assembled test and is more useful for machining feedback. Unconstrained better represents the assembly process and provides a cheaper and faster turnaround for customers.

For testing purposes three inspections were performed on the Sheffield Monitor in a constrained state, three inspections in a non-constrained/free-state, and the last three Sheffield inspections were all compared. Please note that all six CMM runs were performed using the 3-peg fixture with half in the free-state shown in Figure 68.

Similar to the free-state data presented in the Summer Status (section 4.2.4), the max and min data reveals out-of-round conditions. Median values again provide a slightly better comparison to Sheffield at the equator, but constrained inspections have the best contour comparison. Of the six CMM runs only one passed the mass comparison.

Figure 68. 3-peg Fixture

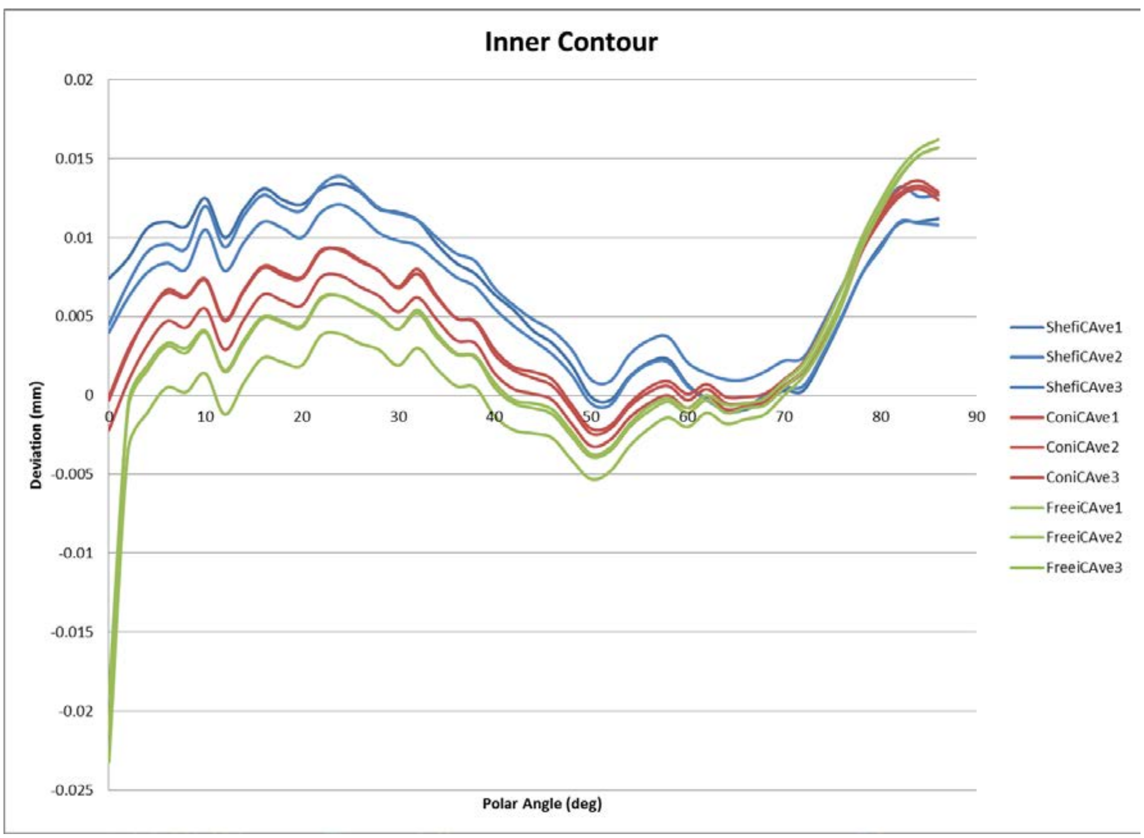

Figure 69. Sheffield Monitor Constrained/Free Inner Contour Measurements

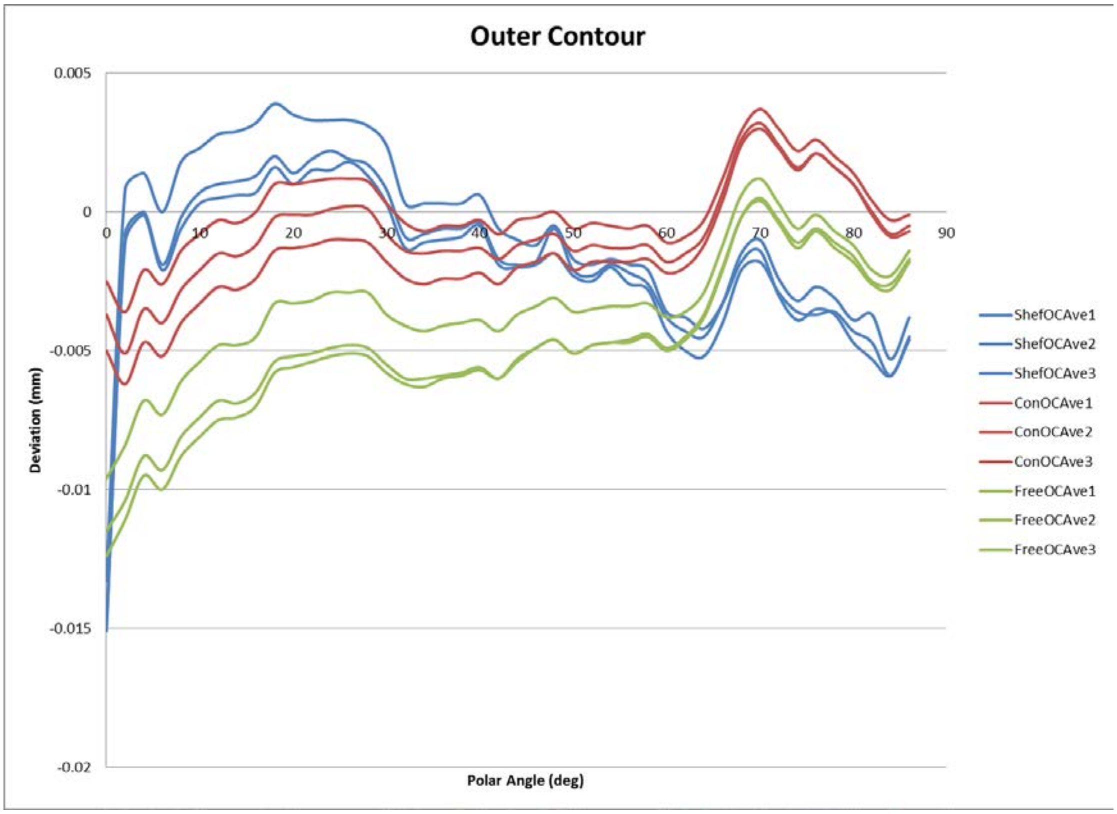

Figure 70. Sheffield Monitor Constrained/Free Outer Contour Measurements

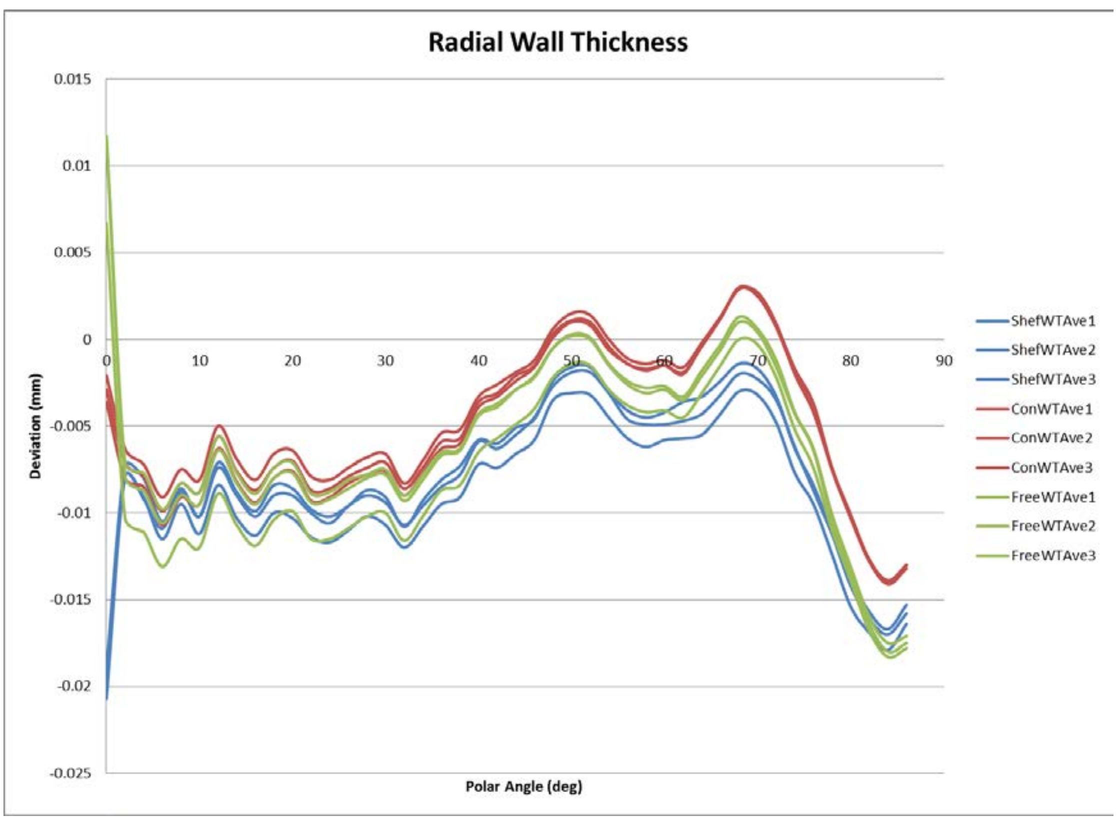

Figure 71. Sheffield Monitor Constrained/Free Radial Wall Thickness Measurements

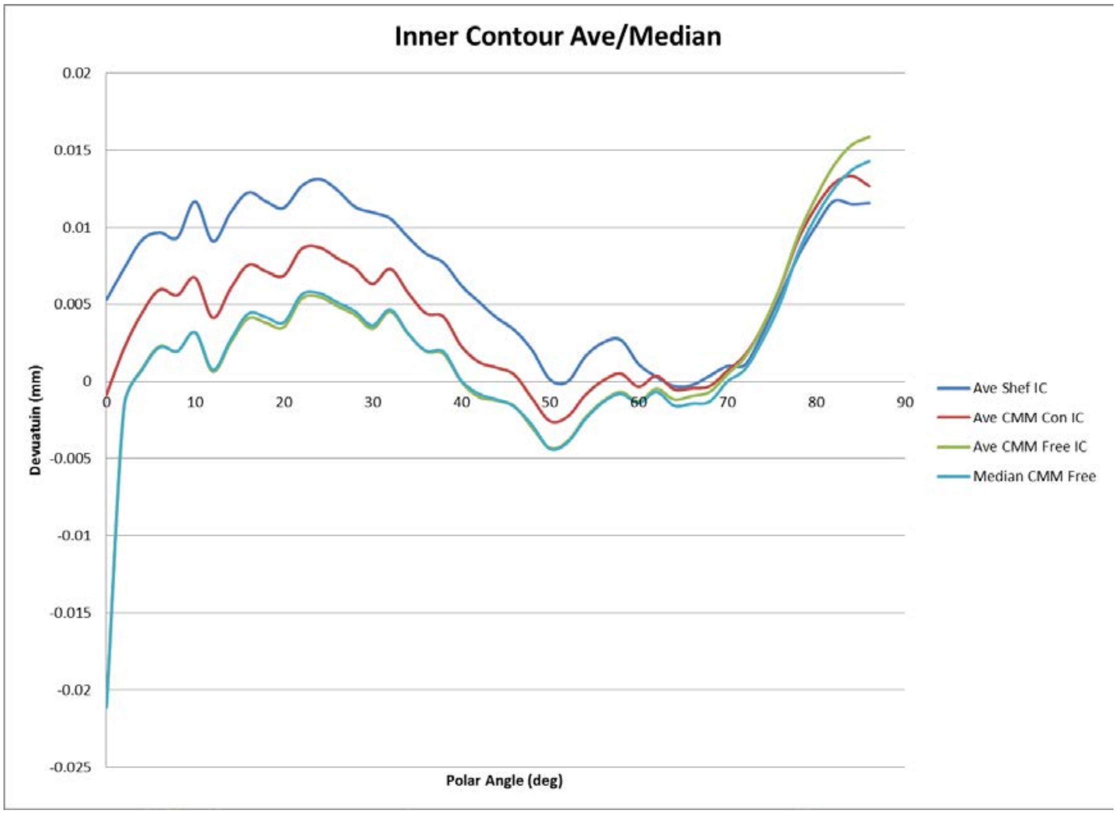

Figure 72. Sheffield Monitor Ave/Median Inner Contour Measurements

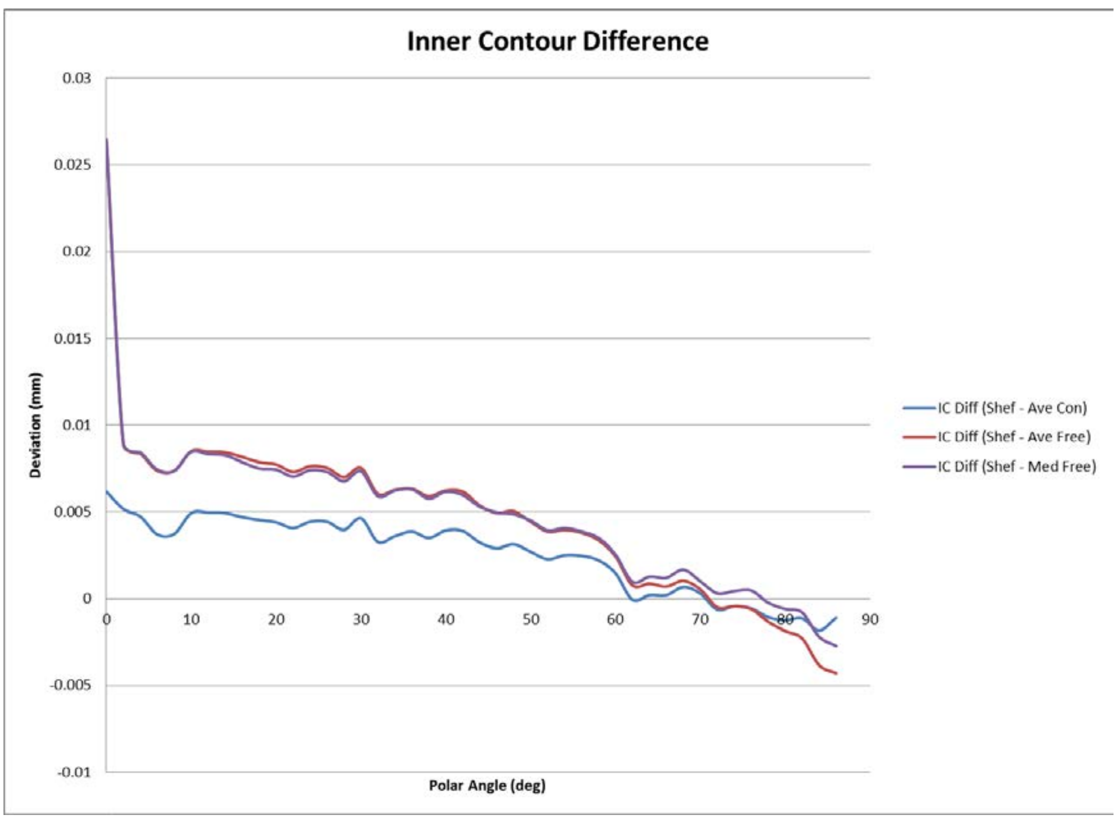

Figure 73. Sheffield Monitor Ave/Median Inner Contour Difference

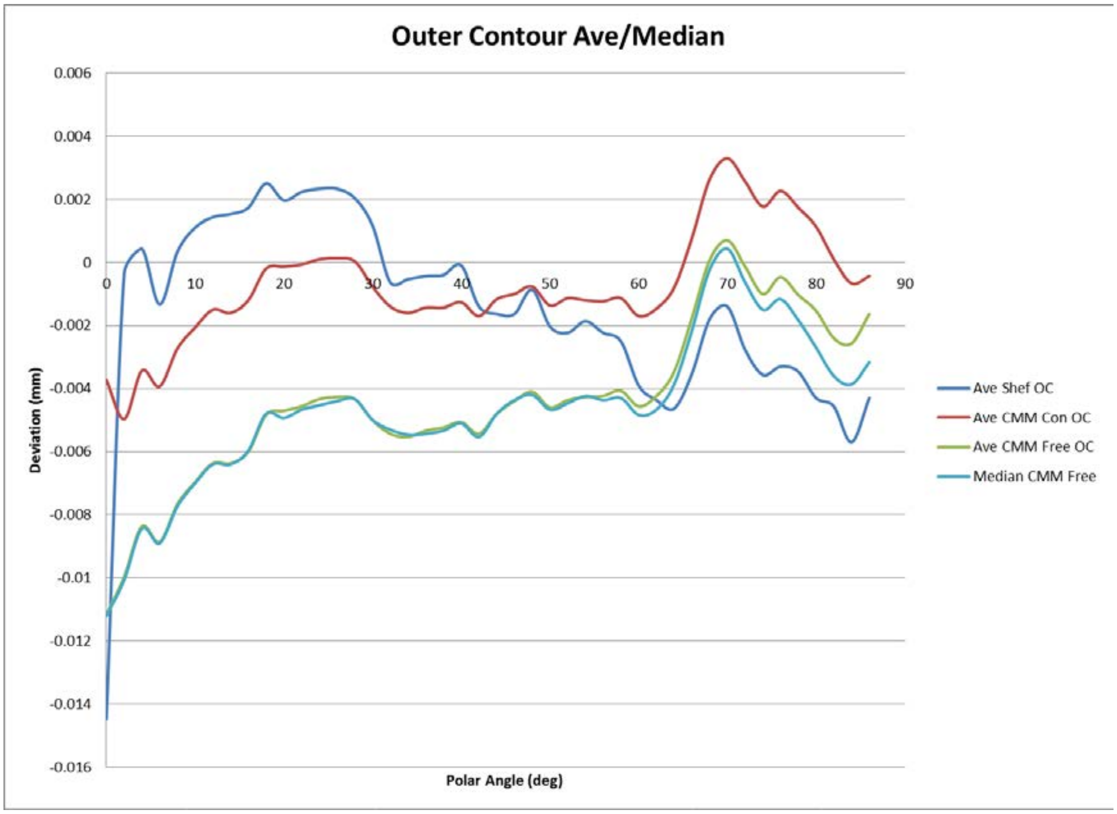

Figure 74. Sheffield Monitor Ave/Median Outer Contour Measurements

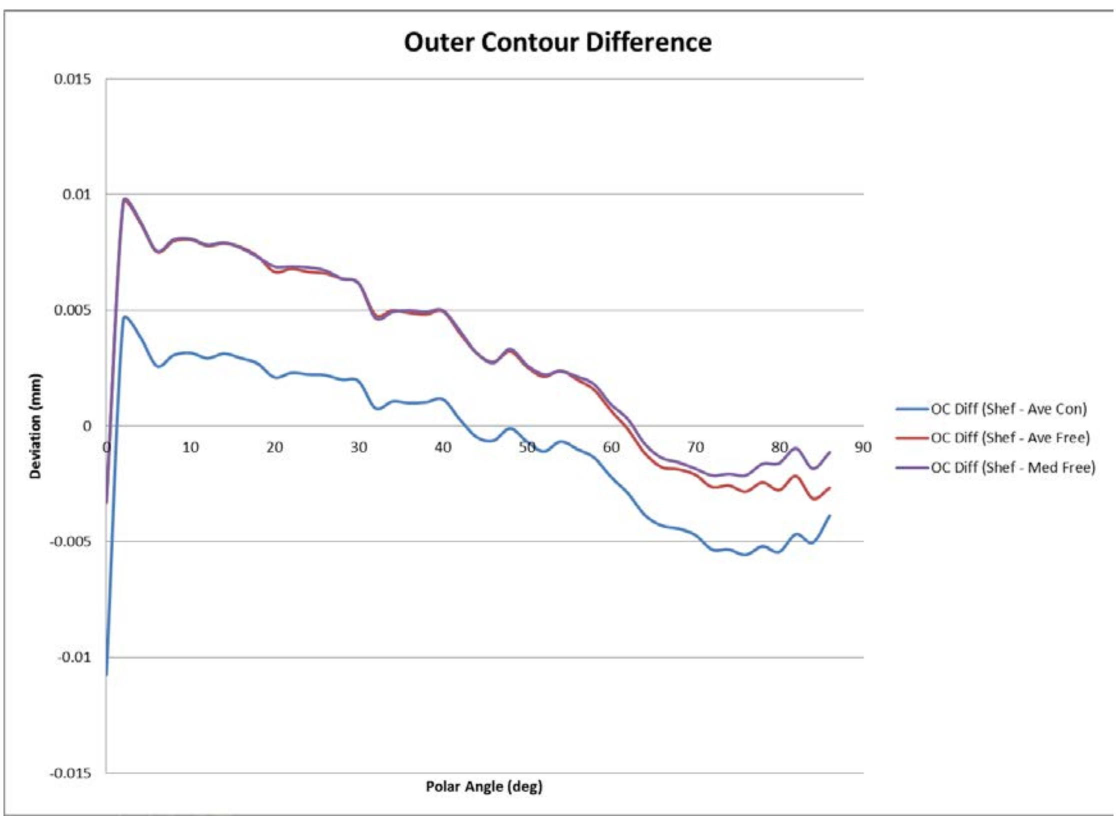

Figure 75. Sheffield Monitor Ave/Median Outer Contour Difference

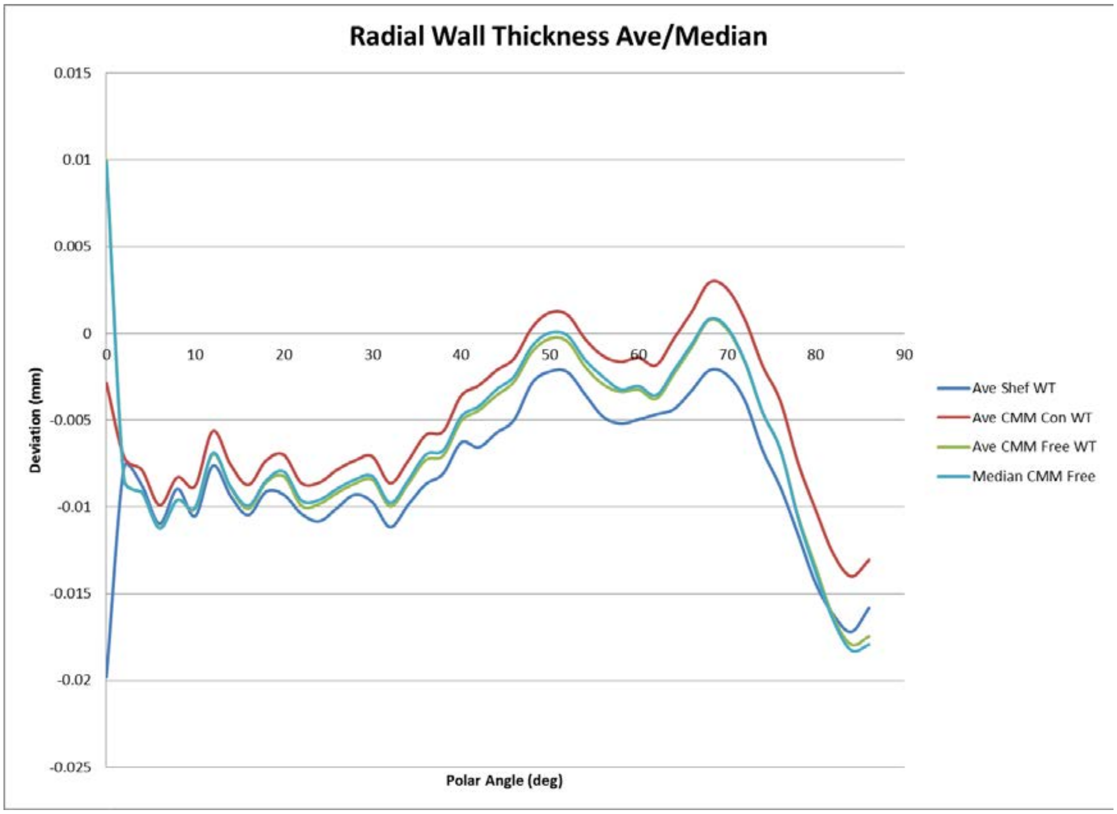

Figure 76. Sheffield Monitor Ave/Median Radial Wall Thickness Measurements

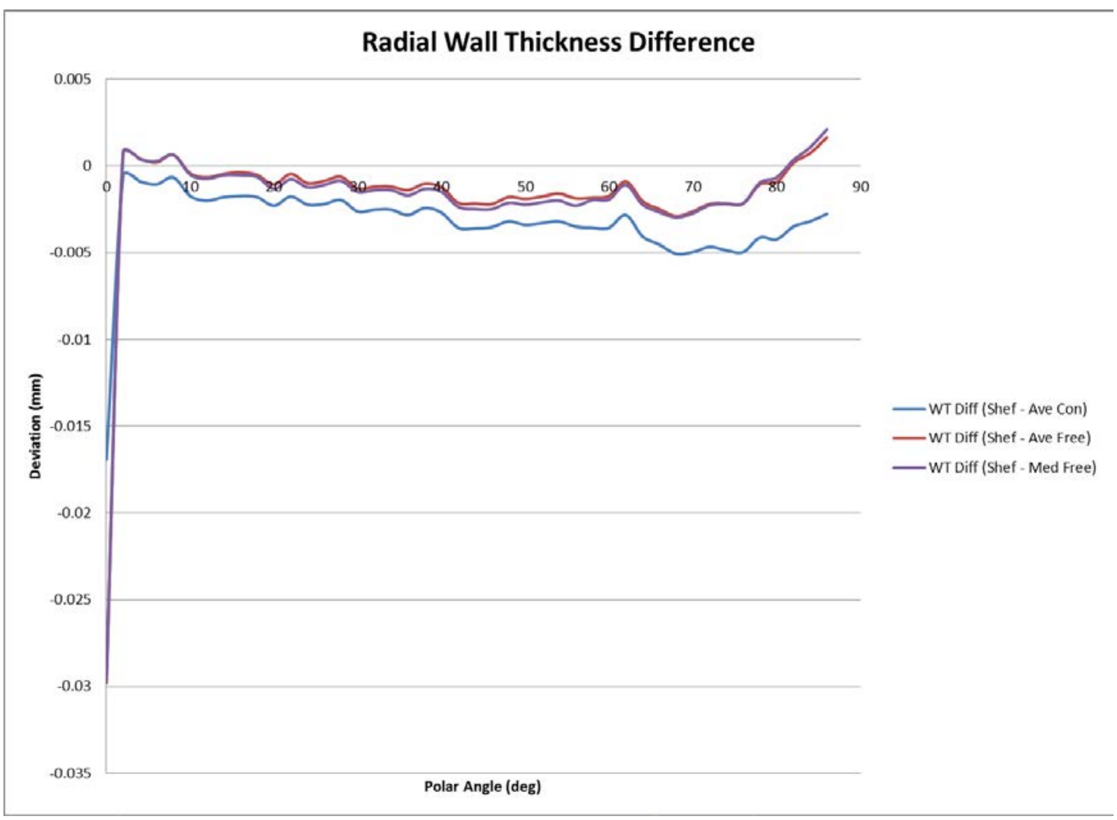

Figure 77. Sheffield Monitor Ave/Median Radial Wall Thickness Difference

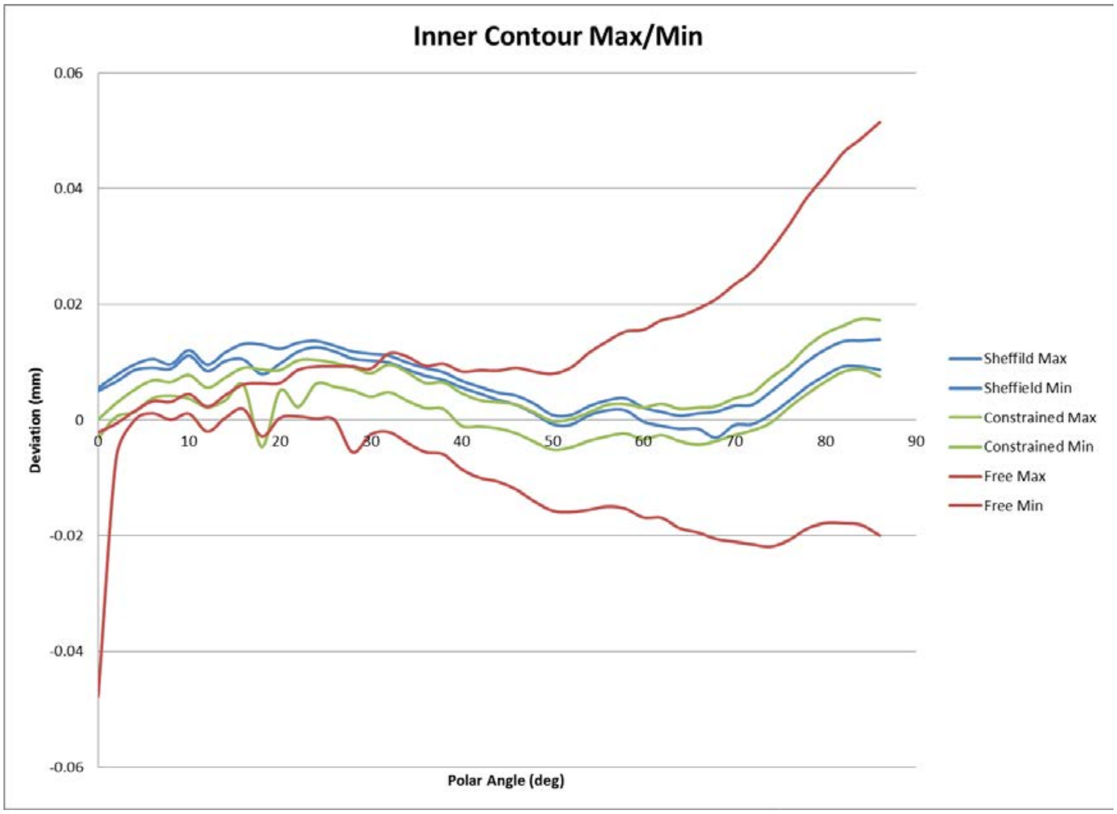

Figure 78. Sheffield Monitor Max/Min Inner Contour Comparison

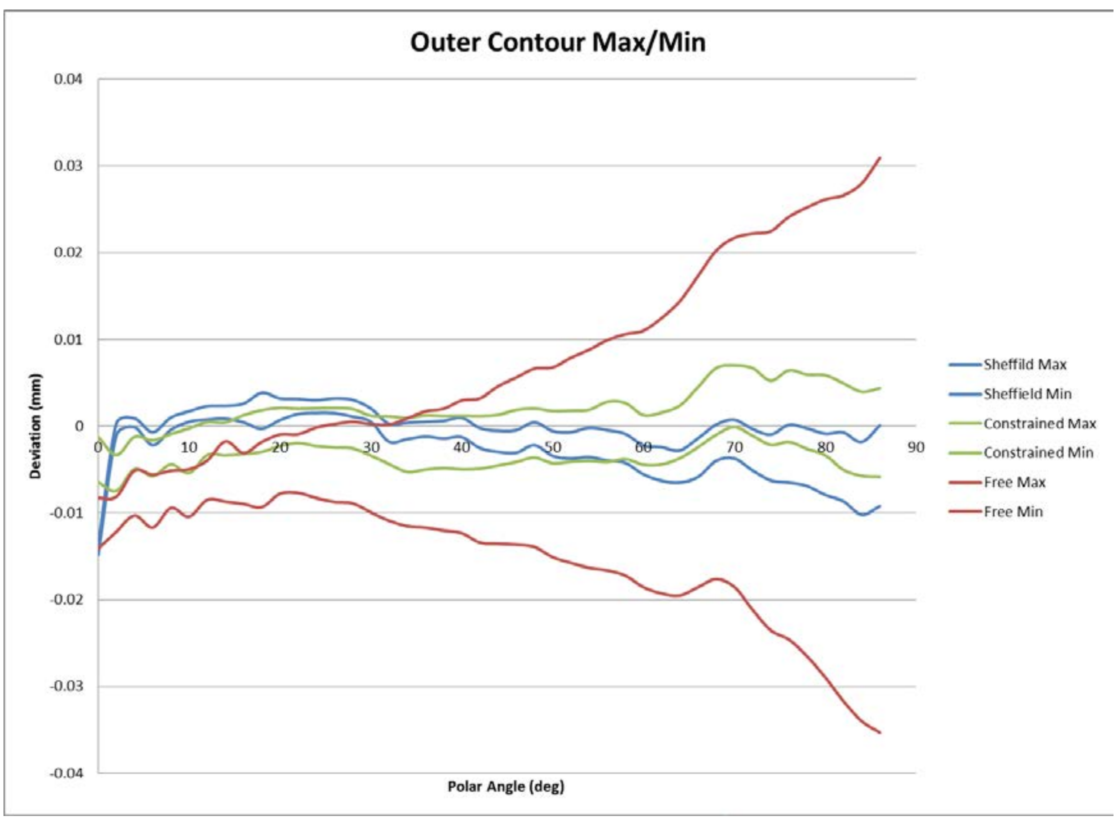

Figure 79. Sheffield Monitor Max/Min Outer Contour Comparison

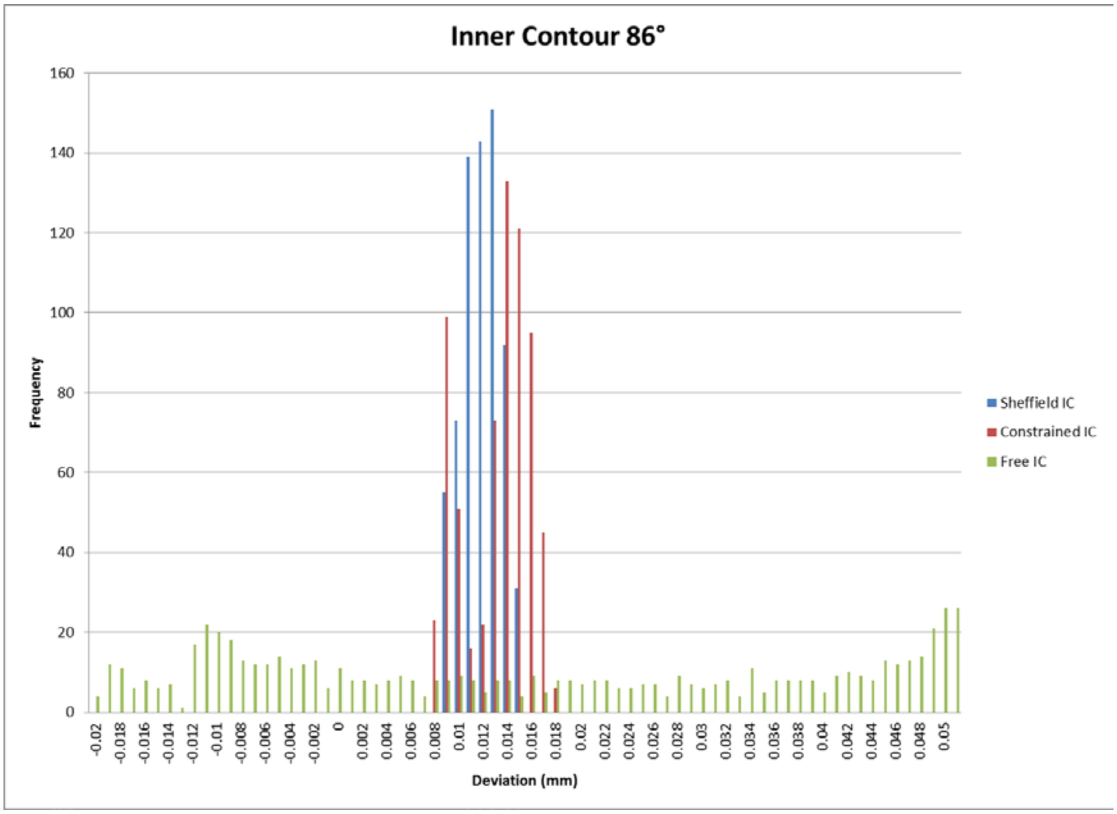

Figure 80. Sheffield Monitor Inner Contour Equator Histogram Comparison

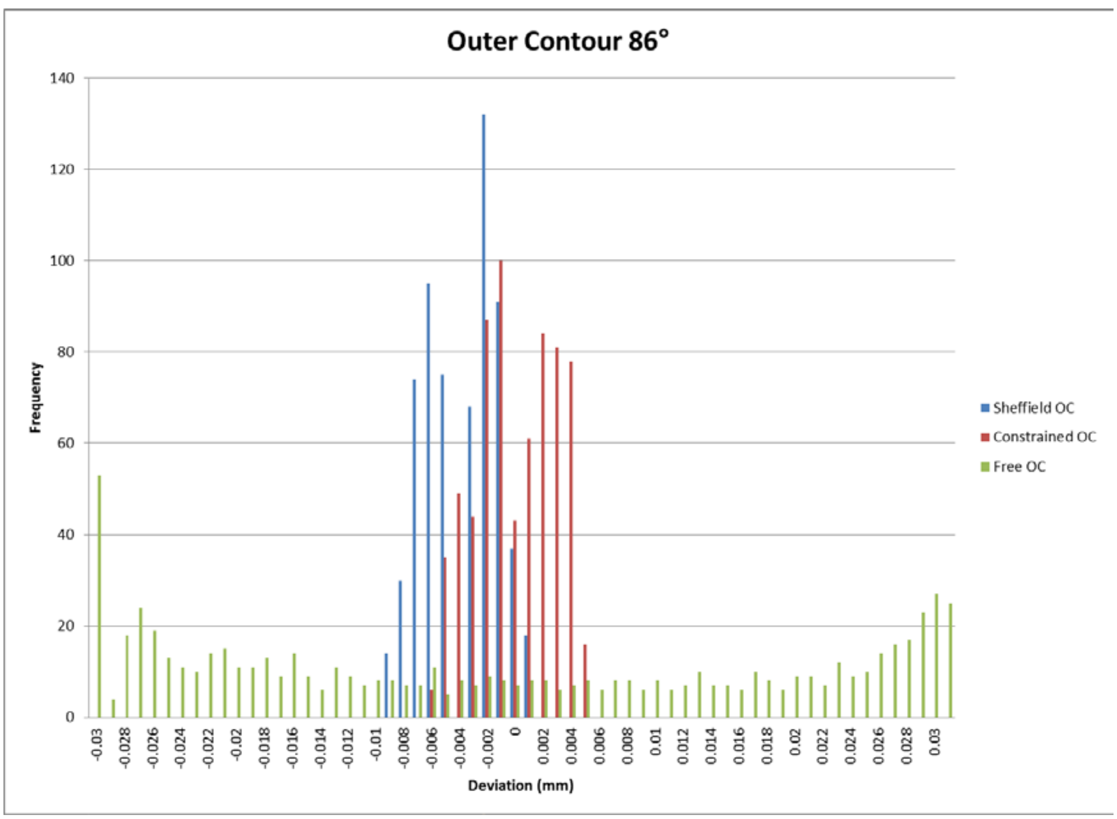

Figure 81. Sheffield Monitor Outer Contour Equator Histogram Comparison

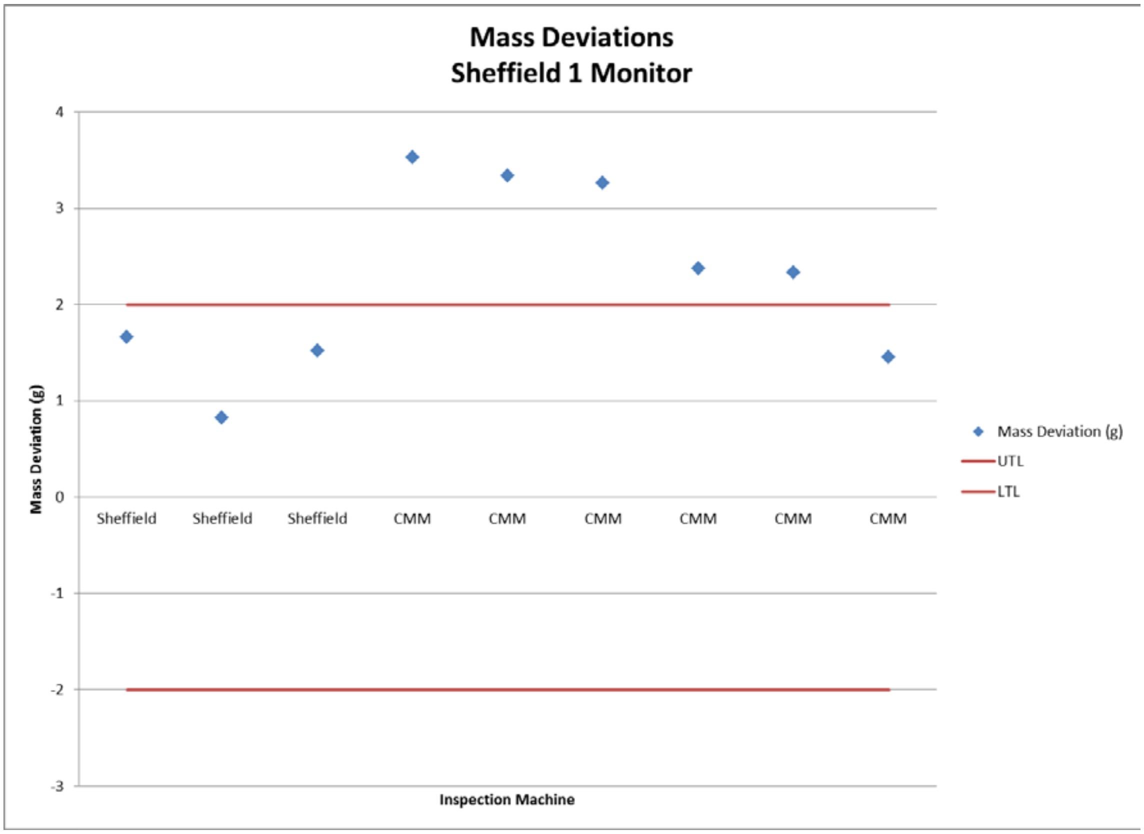

Figure 82. Sheffield Monitor Mass Comparison

4.9.2 3-peg versus 45° Fixture

The 3-peg process has advantages of a low cost fixture and ability to easily transition from a constrained process to non-constrained as seen in the previous section. The 45° Fixture Process has advantages of no data dead spots. It also has existing process development efforts at TA-55 (Phase III) and has fewer probes.

Because the 3-peg process was having issues with probe shift between the different styli as seen in Figure 20 a purchase request (#450144) with the CMM manufacturer, Hexagon Manufacturing Intelligence, was funded. The program was written for an inspection using only one styli in effect eliminating 10360-5 error from the measurement. For a total price of $21,000, Hexagon delivered a generic program with custom menus, relevant plots, data output, detailed documentation and training [89]. The code eliminates the need for individual programs and has sufficient comments throughout allowing for programming suggestions and subroutine enhancements of LANL generated code. TA-55 inspection has already expressed interest in possibly using this software for future glovebox work.

Testing is not able to begin on this until the new version of CMM software (Quindos) can be installed on LANL CMMs. Although an upgrade may sound trivial, each CMM is calibrated to a specific version of software. To upgrade each machine a calibration closeout and recertification using the new version (7.11.15351 or higher) will be needed.

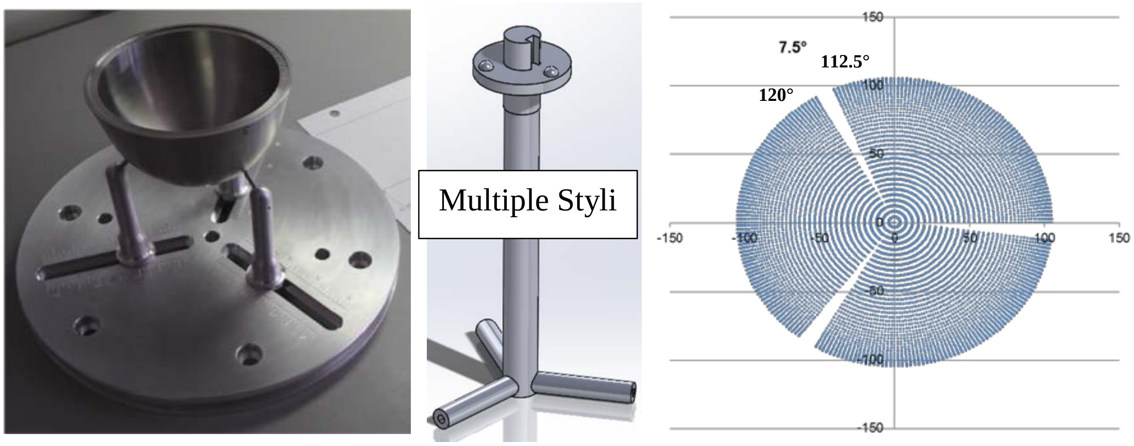

Figure 83. 3-peg Fixture (left), 3-peg Probe (center), 3-peg Data Density (right)

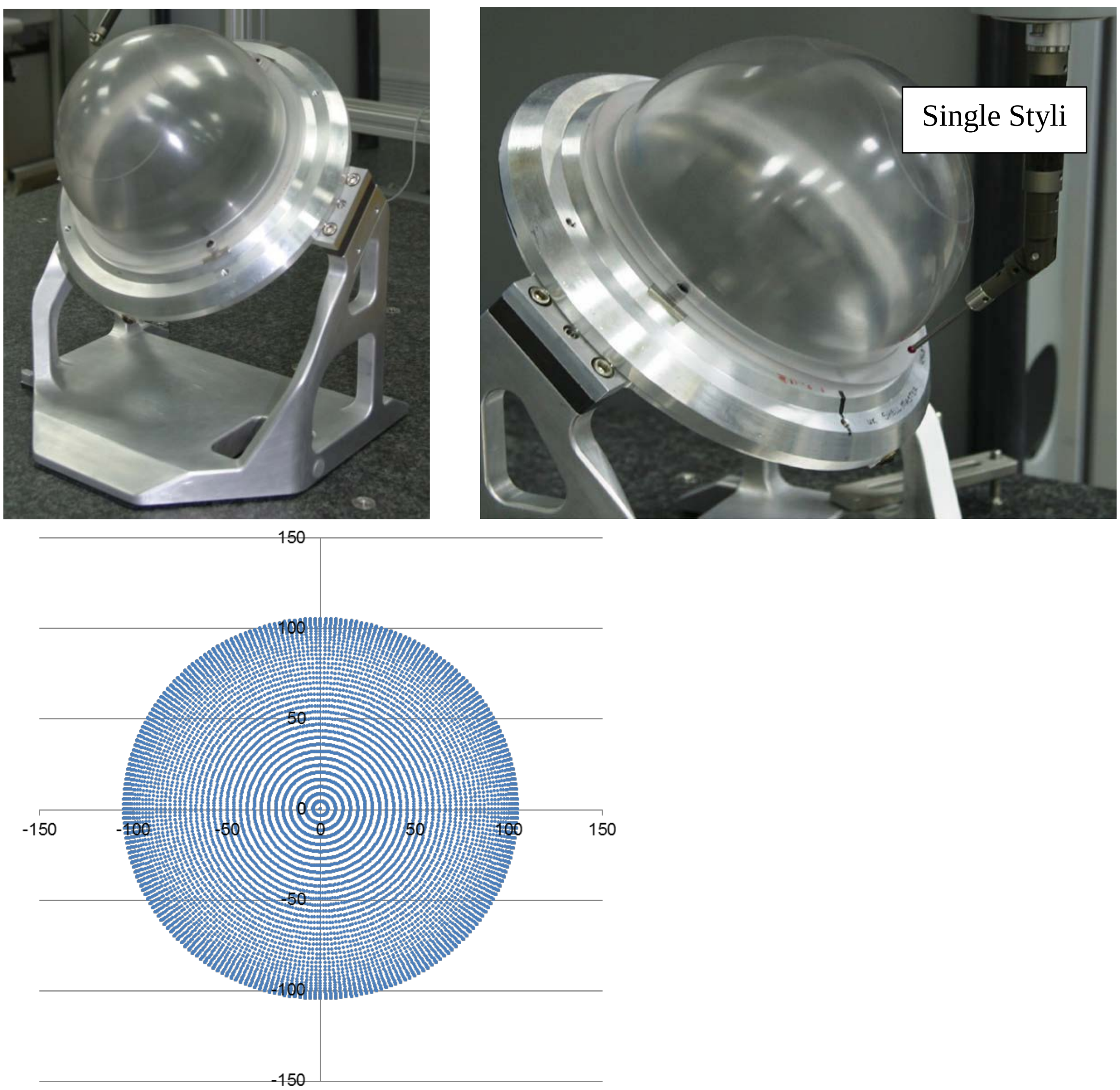

Figure 84. 45° Fixture (top, left), 45° Probe (top, right), 45° Data Density (bottom, left)

4.10 Gauge Repeatability and Reproducibility

A gauge repeatability and reproducibility (GR&R) test breaks down variation due to equipment (repeatability) and operators (reproducibility). The GR&R test proposed would focus on a lower end CMM such as the B&S Global at BTF or Leitz Reference in 28C and complement *"Gauge Repeatability and Reproducibility Study on a Hemi-shell with a Brown & Sharpe Coordinate Measuring Machine (U)"*, LA-UR-11-02559 [90]. Ideally, the GR&R would be conducted in the final machine parameter set thus this effort has been tabled for later to complete DOE and other tests first.

4.11 Data Archiving

Data from Sheffield 1, Sheffield 2, and SMM were all stored in the Dimensional Information Inspection System (DIIS), later renamed to Shell Information Inspection System (SIIS). Sheffield 1 used Pascal while Sheffield 2 and the SMM used LabView to generate a metafile for each shell inspection which was uploaded to a database and given a unique identification number [91]. The database had a web interface where users could easily browse and download data. Pulldown menus for part number, serial number and date made data easily accessible. A similar system was proposed for CMMs. Unfortunately, the older DIIS/SIIS was unavailable without significant investment since the database was written on old mostly unsupported software. Platforms such as Microsoft Sharepoint and others were considered but eventually PTC's Windchill was selected.

A desktop client program was generated for simple drag-and-drop functionality directly from Windows Explorer or other standard Windows file browsers. The program reads the text files for information about the inspection (JobBoss code, the project name or shot number, the part number, serial number, inspection date, and the inspector ZNumber). Once the information is filled in the "Upload" button uploads all the files to Windchill and places it into a folder based on the meta information. A XML file is generated which contains all the metadata (including the ZNumber of the person who uploaded the data and when.)

One area of development that will happen as the CMM process matures is what information is included in the metafile. As an example, an older version of a rotary contour metafile can be seen in Appendix B.

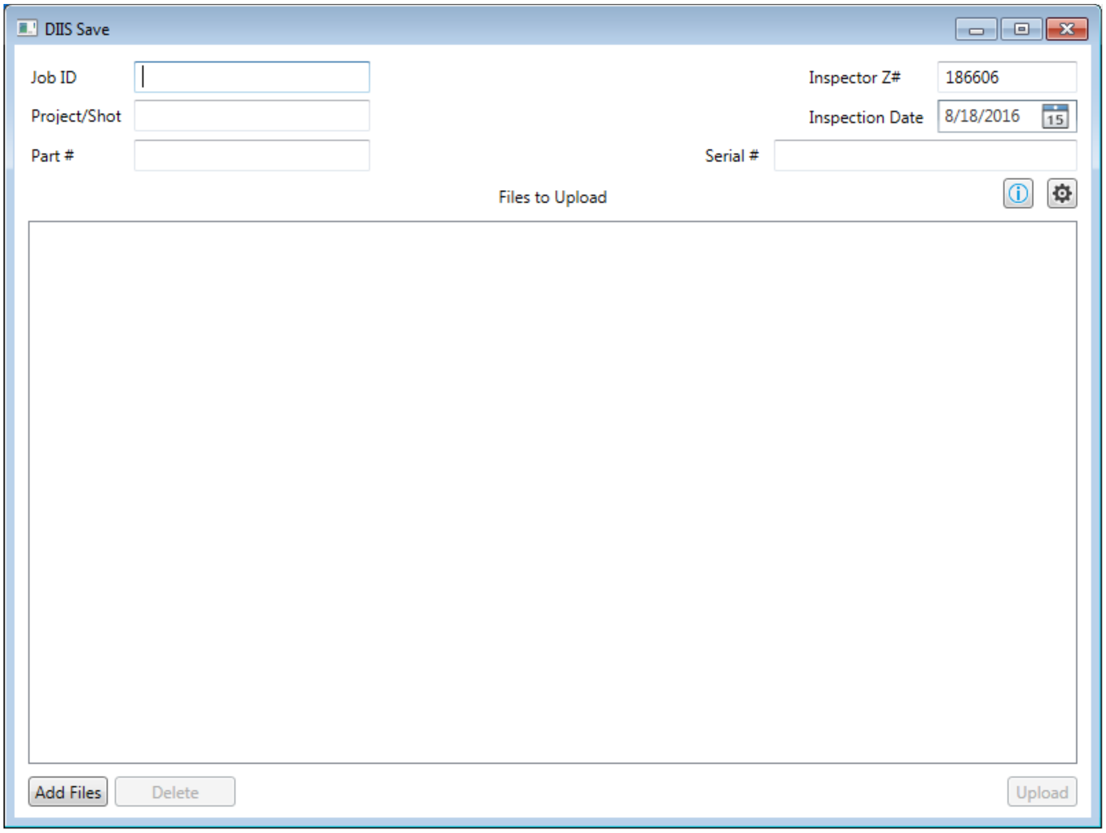

Figure 85. CMM Data Desktop Client

5.0 Conclusions

In conclusion, this status report presents a number of results from a variety of different tests. Some of the tests can be viewed either in a positive or negative manner such as the artifact inspection on the PMM-C. Some might point out that the best machine produced the worst results while others might recognize that the Inspection Team is putting in place many of security nets to catch error contributors. Probe shift errors at the pole have led to some clever quality checks. For the design of experiments, efforts were paused midstream. Again this could be a viewed as failed attempt or positive when considering the data produced defendable results showing inspectors do not influence measurement results. That statement in itself is huge and removes a single point failure that the inspection team has struggled with for decades. Minimal inspector influence opens the door to multiple people on multiple CMMs.

There have been many challenges during the execution of the tests described in this report. Resources such as limited staff and funds are always a challenge but one of the biggest issues was priority. All the R&D efforts described are being squeezed in with the routine daily work supporting numerous hydro tests and other critical deliverables. At one point the HVAC went down and the required ±20°C environment was lost. Severe loss of environment requires each CMM to be rechecked and sometimes corrected and recalibrated. Another unfortunate event was the loss of the rednet server. Replacement servers had to be ordered and data restored from tape backups. The successes of this report speak volumes to the dedication and staff on the Inspection team, Rednet team, and other supporting staff.

Lastly, this report raises some important questions that will need resolution. Questions like, "Are data dead spots okay?" If they are not that directly impacts the way inspections are performed. "Is constrained or free-state preferred, optional or required?" This will also change the way inspections are performed.

6.0 Future Work Recommendations

This document is a status report and implies that many of the tasks discussed (DOE, machine comparison, etc.) will continue in the future. A few topics not discussed in this report such as measurement uncertainty, fixture design and styli selection are also important and should also be investigated.

A progressive approach similar to that discussed in *"TA-55 CMM Shell Inspection Uncertainty Approach (U)"and "Uncertainty Budget Analysis for Dimensional Inspection Processes"* [92,93] is currently underway to arrive at uncertainty for CMM measurements of shells. The first and simplest step is to follow the design guidance and meet the 4:1 limit established under the 9900000 specification [1]. Second is to apply the *"Conformity Assessment – General Requirements for Proficiency Testing"* [18] technique to demonstrate that the CMMs compare to other existing, documented and qualified processes for measurement [94]. Third is to model the inspection process using PunditCMM™ software by Metrosage which utilizes Monte Carlo simulations to arrive at uncertainty values.

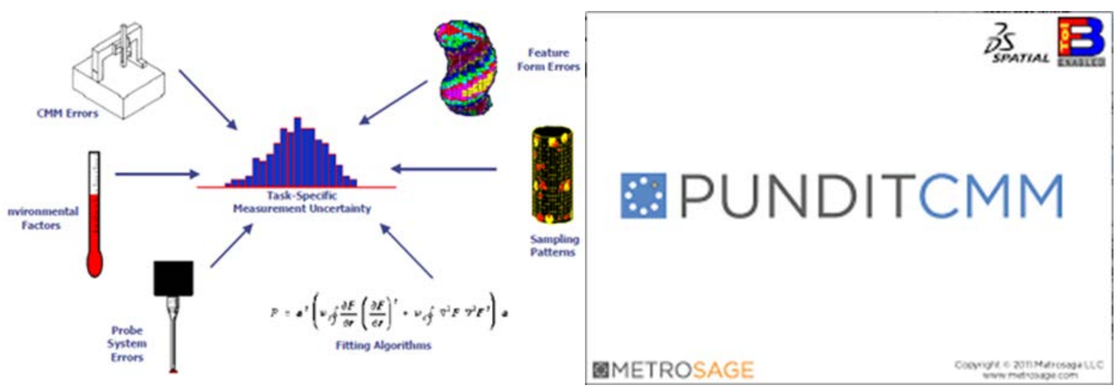

Figure 86. PunditCMM; Source: Metrosage

Fixture design is critical to CMM shell inspection. Using a Sheffield 1 style rounding ring, a flexible Sheffield 2 type, or even the universal concept, will all impact measurement results. Finite element analysis studies such as *"Analysis of Thin Shell Hemisphere Under Gravity Loads"* [95] and *"Analysis of Hemisphere with Rounding Ring Loads"* [96] found, *"small (but measureable) horizontal and vertical displacements"*. At a minimum it would be ideal to calculate the optimal location to position the 3-pegs.

Styli could in itself be another small study. Extensions are offered in materials such as tungsten carbide, steel, aluminum, ceramic, carbon fiber, and titanium. Some thermally stable extensions are also offered where a positive thermal expansion coefficient in the titanium connecting component is matched to a negative thermal expansion coefficient from carbon fiber to cancel each other offering a low expansion over a wide temperature range [97].

Other considerations could be given to the ball material. Styli are often offered in ruby, silicon nitride and zirconia. Ruby after diamond is one of the hardest materials known. Silicon nitride is an exceptional wear resistant ceramic and ideal for aluminum. Silicon nitride unlike ruby is not attracted to aluminum and particles will not be deposited on the ball. Zirconia is ideal for abrasive work such as cast iron. Companies such as Renishaw are also starting to market higher Grade 3 quality balls [98].

Table 7. Ball Grades [99]

Grade	Size Deviation (microns)	Ball Diameter Variation (microns)	Surface Roughness (microns)
3	±5.32	0.08	0.010
5	±5.63	0.13	0.014
10	±9.75	0.25	0.020

7.0 References

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9.0 Appendices

9.0 Appendix A: Draft Procedure

1. Place part on ring.
2. Check stack (should be less than 3 microns).
3. Set fixture pegs at 3 inches.
4. Level part within 25.4 microns (0.001 inch) on 3-peg fixture.
5. Align first digit with first scan.
6. Glue part to fixture using Epoxy QuickCure5.
7. Set qualification sphere and workpiece thermocouple in center of CMM.
8. Verify CMM has 4x80 probes in garage.
9. Create folder for part inspection.
10. Launch Quindos 64-bit and home machine if needed.
11. Execute CLRALL command.
12. Load program.
13. Execute all and follow on screen instructions.
14. After inspection is complete execute desktop client to move data from part folder to Windchill.

9.0 Appendix B: Sheffield Metafile

SHEFFIELD #1 META DATA FILE

SECTION 1. ---- DESIGN MODEL TRACKING INFORMATION ----

DESIGN SOFTWARE VERSION:	N/A
PART NUMBER:	157Y-700373-00
DRAWING NUMBER:	157Y-700373 1A
TYPE NUMBER:	N/A
SHOT NUMBER:	CMM TEST ARTIFACT
MODEL FILE NAME:	N/A
MODEL INSTANCE:	N/A
DESIGN MODEL DATE:	N/A
DESIGN ISSUE:	N/A
PROJECT NAME:	CMM_ARTIFACT
INNER DEFINITION:	N/A
OUTER DEFINITION:	N/A
DESIGN ANGULAR UNITS:	DEG
INNER DEFINITION ENTRY ANGLE:	N/A
INNER DEFINITION ENTRY ANGLE TYPE:	N/A
INNER DEFINITION EXIT ANGLE:	N/A
INNER DEFINITION EXIT ANGLE TYPE:	N/A
OUTER DEFINITION ENTRY ANGLE:	N/A
OUTER DEFINITION ENTRY ANGLE TYPE:	N/A
OUTER DEFINITION EXIT ANGLE:	N/A
OUTER DEFINITION EXIT ANGLE TYPE:	N/A
MODEL NOTES:	N/A

SECTION 2. ---- PART DEFINITION TRACKING INFORMATION ----

PROGRAM DRAWING NUMBER:	N/A
PROGRAM DATE:	N/A
PROGRAM LOCATION:	N/A
PROGRAM REVISION:	N/A
PROGRAMMER (NAME, ZNO):	N/A, N/A
PROGRAM NOTES:	N/A

SECTION 3. ---- DIMENSIONS AND TOLERANCES ----

DESIGN DIMENSION UNITS:	MM
DESIGN OUTER POLE HEIGHT:	N/A
DESIGN INNER POLE HEIGHT:	N/A
DESIGN WALL POLE THICKNESS:	N/A
DESIGN DEFINITION OFFSET(FROM DTM A):	N/A
DESIGN STEP DEPTH:	N/A

DESIGN STEP DIAMETER:	N/A
DESIGN INNER PROFILE TOLERANCE(+/-):	.025
DESIGN OUTER PROFILE TOLERANCE(+/-):	N/A
DESIGN TAPER TOLERANCE:	N/A
DESIGN INNER TAPER TOLERANCE(@00.0)(+/-):	N/A
DESIGN INNER TAPER TOLERANCE(@90.0)(+/-):	N/A
DESIGN OUTER TAPER TOLERANCE(@00.0)(+/-):	N/A
DESIGN OUTER TAPER TOLERANCE(@90.0)(+/-):	N/A
DESIGN WALL TOLERANCE (MIN):	-.025
DESIGN WALL TOLERANCE (MAX):	.025
DESIGN PROBE NOMINAL TIP DIAMETER:	N/A
DIMENSION AND TOLERANCE NOTES:	N/A

SECTION 4. ---- DESIGN MASS DATA ----

DESIGN MASS UNITS:	KG
DESIGN VOLUME UNITS:	CU MM
DESIGN DENSITY UNITS:	KG/CU MM
DESIGN MATERIAL:	N/A
DESIGN DENSITY:	N/A
DESIGN VOLUME:	N/A
DESIGN MASS:	N/A
DESIGN IR OFFSET VOLUME:	N/A
DESIGN IR OFFSET MASS:	N/A
DESIGN IR DELTA MASS:	N/A
DESIGN IR DELTA MASS (%):	N/A
MASS NOTES:	N/A

SECTION 5. ---- SHEFFIELD OPERATING PARAMETERS ----

INSPECTION TABLE ROTATION (RPM):	N/A
INSPECTION ANGULAR UNITS:	DEG
INSPECTION AZIMUTH SPACING:	0.7500
INSPECTION POLAR SPACING:	1.0
INSPECTION MODE:	IR/WALL
STABILIZING TIME UNITS:	MIN
STABILIZING TEMPERATURE UNITS:	F
STABILIZING TIME:	N/A
STABILIZING TEMPERATURE:	N/A
STABILIZING TEMPERATURE RANGE (MIN):	N/A
STABILIZING TEMPERATURE RANGE (MAX):	N/A
SHEFFIELD OPERATING NOTES:	N/A

SECTION 6. ---- SHEFFIELD PART DEFINITION DATA ----

THETA	SHEF-IRD	SHEF-WALL

N/A	N/A	N/A

SECTION 7. ---- SHEFFIELD CONTACT DATA ----

THETA	IRD X	IRD Y	ORD X	ORD Y
N/A	N/A	N/A	N/A	N/A

SECTION 8. ---- INSPECTION SETUP PARAMETERS ----

CONTROLLER SOFTWARE VERSION:	LANL-0001-A/2 DATE: 1-15-98
INSPECTOR (NAME, ZNO):	M. Naranjo, N/A
ORDER NUMBER:	-----
SERIAL NUMBER:	000
MEASURED DIMENSION UNITS:	MM
MEASURED OVERALL OUTER POLE OPEN SETUP HEIGHT:	N/A
MEASURED STEP DEPTH:	N/A
MEASURED STEP DIAMETER:	N/A
MEASURED WALL POLE OPEN SETUP THICKNESS:	N/A
MEASURED FIXTURE OPEN SETUP HEIGHT (FROM DTM A):	N/A
MEASURED FIXTURE & PART OPEN SETUP HEIGHT:	N/A
CALCULATED DIMENSION UNITS:	MM
CALCULATED OUTER POLE OPEN SETUP HEIGHT:	N/A
CALCULATED INNER POLE OPEN SETUP HEIGHT:	N/A
CALCULATED FIXTURE & PART OPEN SETUP HEIGHT:	N/A
CALCULATED OUTER POLE HEIGHT OPEN SETUP DEVIATION:	N/A
CALCULATED INNER POLE HEIGHT OPEN SETUP DEVIATION:	N/A
CALCULATED WALL POLE THICKNESS OPEN SETUP DEVIATION:	N/A
CALCULATED FIXTURE & PART HEIGHT OPEN SETUP DEVIATION:	N/A
CALCULATED DELTA BETWEEN FIXTURES:	N/A
CALCULATED DELTA BETWEEN FIXTURES AND OFFSET:	N/A
CALCULATED GAUGE SETTING FOR HEIGHT MASTER:	N/A
CRITERIA DIMENSION UNITS:	N/A
CRITERIA OPEN SETUP ACTION FLAG:	N/A
ACTION OPEN SETUP FLAG:	N/A
INSPECTION SETUP NOTES:	N/A

SECTION 9. ---- MEASURED MASS ----

SECTION 9A. ---- COMMON MASS PARAMETERS ----

MEASUREMENT BY:	N/A
MEASUREMENT DATE:	N/A
MEASUREMENT TIME:	N/A
MEASURED WEIGHT UNITS:	G
MEASURED VOLUME UNITS:	CU CM
MEASURED DENSITY UNITS:	G/CU CM

MEASURED TEMPERATURE UNITS:	C
CALCULATED WEIGHT UNITS:	G
CALCULATED VOLUME UNITS:	CU CM
CALCULATED DENSITY UNITS:	G/CU CM
MEASURED SOLUTION TYPE:	N/A
MEASURED SOLUTION TEMPERATURE:	N/A
MEASURED SOLUTION DENSITY:	N/A
MEASURED PART WEIGHT IN AIR:	N/A
CALCULATED PART DENSITY:	N/A
CALCULATED DELTA WEIGHT (DESIGN-MEASURED):	N/A

SECTION 9B. ---- SM102 WEIGHT PARAMETERS ----

MEASURED PART NUMBER:	N/A
MEASURED SERIAL NUMBER:	N/A
MEASURED BAROMETRIC PRESSURE UNITS:	IN-HG
MEASURED RELATIVE HUMIDITY UNITS:	%
MEASURED BAROMETRIC PRESSURE:	N/A
MEASURED RELATIVE HUMIDITY:	N/A
MEASURED AIR TEMPERATURE:	N/A
MEASURED PART WEIGHT IN WATER:	N/A
MEASURED DENSITY PROGRAM NAME:	N/A
MEASURED DENSITY PROGRAM VERSION:	N/A
CALCULATED AIR DENSITY:	N/A
CALCULATED WATER DENSITY:	N/A
CALCULATED PART DENSITY UNCERTAINTY:	N/A
MEASURED MASS NOTES:	N/A

SECTION 10. ---- INSPECTION PARAMETERS ----

INSPECTION DATE:	2-21-03
INSPECTION START TIME:	12:05
INSPECTION END TIME:	N/A
INSPECTION SEQUENCE NUMBER:	1
GAGE LOCATION:	TA-3_SM102_RM112
GAGE ID:	SHEFFIELD#1
CALIBRATION APPROVAL DATE:	11-26-02
CALIBRATION EXPIRATION DATE:	N/A
CALIBRATION MASTER HEIGHT EXPIRATION DATE:	N/A
CALIBRATION MASTER RADIUS EXPIRATION DATE:	N/A
CALIBRATION MASTER TILT BLOCK EXPIRATION DATE:	N/A
GAUGE MASTER HEIGHT SN:	N/A
GAUGE MASTER RADIUS SN:	N/A
GAUGE MASTER TILT BLOCK SN:	N/A
MASTER DIMENSION UNITS:	MM
MASTER ANGULAR UNITS:	DEG

MASTER HEIGHT:	N/A
MASTER HEIGHT FIXTURE HEIGHT:	N/A
MASTER RADIUS:	N/A
MASTER WALL THICKNESS:	N/A
MASTER TILT BLOCK THICKNESS:	N/A
MASTERING TILT TEST ANGLE:	N/A
MASTERING INITIAL TILT TEST RESULT:	N/A
CRITERIA INITIAL TILT TEST RESULT:	N/A
ACTION INITIAL TILT TEST RESULT FLAG:	N/A
MASTERING FINAL TILT TEST RESULT:	N/A
CRITERIA FINAL TILT TEST RESULT:	N/A
ACTION FINAL TILT TEST RESULT FLAG:	N/A
MASTERING INNER OFFSET:	85.0165
MASTERING OUTER OFFSET:	-0.0145
INSPECTION TEMPERATURE UNITS:	F
INSPECTION ROOM TEMPERATURE:	67.1
INSPECTION GLOVE BOX TEMPERATURE:	N/A
INSPECTION PART TEMPERATURE INITIAL:	67.1
INSPECTION PART TEMPERATURE FINAL:	67.1
INSPECTION DIMENSION UNITS:	MM
INSPECTION AZIMUTH START POINT (ZERO):	SCRIBE LINE
GAUGE PROBE TYPE:	N/A
GAUGE PROBE NOMINAL FORCE (GRAMS):	N/A
INSPECTION DROPPED POINTS:	9121, 26881

INSPECTION NOTES:

INNER: ZERO = 0 ON MIC
OUTER: ZERO = 2 ON MIC
THIS IS THE SECOND MEASUREMENT OF THE CMM TEST ARTIFACT.
MUCH OF THIS PART IS OUT OF TOLERANCE.

SECTION 11. ---- DEVIATION COMPARISONS ----

INSPECTION INITIAL AVERAGE OUTER POLE DEVIATION:	0.0312
INSPECTION INITIAL AVERAGE INNER POLE DEVIATION:	-.0722
INSPECTION INITIAL AVERAGE WALL POLE DEVIATION:	0.1034
INSPECTION FINAL AVERAGE OUTER POLE DEVIATION:	0.0309
INSPECTION FINAL AVERAGE INNER POLE DEVIATION:	-.0721
INSPECTION FINAL AVERAGE WALL POLE DEVIATION:	0.1030
CALCULATED OUTER POLE FINAL INSPECTION DEVIATION:	N/A
CALCULATED INNER POLE FINAL INSPECTION DEVIATION:	N/A
CALCULATED WALL POLE FINAL INSPECTION DEVIATION:	N/A
CALCULATED OUTER POLE DEVIATION DELTA:	0.0003
CALCULATED INNER POLE DEVIATION DELTA:	0.0001
CALCULATED WALL POLE DEVIATION DELTA:	0.0004
CRITERIA POLE DEVIATION DELTA:	0.005

ACTION OUTER POLE DEVIATION DELTA FLAG:	CHECK OK
ACTION INNER POLE DEVIATION DELTA FLAG:	CHECK OK
ACTION WALL POLE DEVIATION DELTA FLAG:	CHECK OK
CRITERIA OUTER POLE FINAL INSPECTION DEVIATION:	N/A
CRITERIA INNER POLE FINAL INSPECTION DEVIATION:	N/A
CRITERIA WALL POLE FINAL INSPECTION DEVIATION:	N/A
ACTION OUTER POLE FINAL DEVIATION FLAG:	N/A
ACTION INNER POLE FINAL DEVIATION FLAG:	N/A
ACTION WALL POLE FINAL DEVIATION FLAG:	N/A
INSPECTION HIGH OUTER CLOUD DEVIATION:	0.0316
INSPECTION HIGH OUTER CLOUD POLAR ANGLE:	0.00
INSPECTION HIGH OUTER CLOUD AZIMUTH ANGLE:	150.00
INSPECTION HIGH OUTER CLOUD POINTS OUT OF TOLERANCE:	N/A
INSPECTION LOW OUTER CLOUD DEVIATION:	-.0209
INSPECTION LOW OUTER CLOUD POLAR ANGLE:	65.00
INSPECTION LOW OUTER CLOUD AZIMUTH ANGLE:	291.00
INSPECTION LOW OUTER CLOUD POINTS OUT OF TOLERANCE:	N/A
INSPECTION HIGH INNER CLOUD DEVIATION:	0.0274
INSPECTION HIGH INNER CLOUD POLAR ANGLE:	40.00
INSPECTION HIGH INNER CLOUD AZIMUTH ANGLE:	47.25
INSPECTION HIGH INNER CLOUD POINTS OUT OF TOLERANCE:	1374
INSPECTION LOW INNER CLOUD DEVIATION:	-.0728
INSPECTION LOW INNER CLOUD POLAR ANGLE:	0.00
INSPECTION LOW INNER CLOUD AZIMUTH ANGLE:	0.75
INSPECTION LOW INNER CLOUD POINTS OUT OF TOLERANCE:	10917
INSPECTION HIGH WALL CLOUD DEVIATION:	0.1037
INSPECTION HIGH WALL CLOUD POLAR ANGLE:	0.00
INSPECTION HIGH WALL CLOUD AZIMUTH ANGLE:	39.75
INSPECTION HIGH WALL CLOUD POINTS OUT OF TOLERANCE:	9318
INSPECTION LOW WALL CLOUD DEVIATION:	-.0431
INSPECTION LOW WALL CLOUD POLAR ANGLE:	39.00
INSPECTION LOW WALL CLOUD AZIMUTH ANGLE:	247.50
INSPECTION LOW WALL CLOUD POINTS OUT OF TOLERANCE:	10988
CRITERIA INSPECTION OUTER CLOUD DEVIATION FLAG (%):	0.05
CRITERIA INSPECTION INNER CLOUD DEVIATION FLAG (%):	0.05
CRITERIA INSPECTION WALL CLOUD DEVIATION FLAG (%):	0.05
ACTION INSPECTION OUTER CLOUD DEVIATION FLAG:	N/A
ACTION INSPECTION INNER CLOUD DEVIATION FLAG:	NOTIFY TL
ACTION INSPECTION WALL CLOUD DEVIATION FLAG:	NOTIFY TL
DEVIATION COMPARISON NOTES:	N/A

SECTION 12. ---- SHEFFIELD AVERAGE DEVIATIONS ----

SECTION 12A. ---- SHEFFIELD INNER CONTOUR DEVIATIONS ----

POLAR	I.C.	HIGH	HIGH	LOW	LOW	NUMBER POINTS

ANGLE	AVERAGE	VALUES	AZIMUTH	VALUES	AZIMUTH	OUT TOLERANCE
0.00	-0.0722	-0.0719	144.00	-0.0728	0.75	480
90.00	0.0045	0.0063	90.75	0.0019	134.25	0
89.00	0.0046	0.0067	356.25	0.0024	147.75	0
88.00	0.0048	0.0063	75.75	0.0025	263.25	0
87.00	0.0049	0.0063	73.50	0.0024	267.75	0
86.00	0.0044	0.0062	74.25	0.0018	270.00	0
85.00	0.0039	0.0055	73.50	0.0012	270.00	0
84.00	0.0035	0.0050	80.25	0.0012	265.50	0
83.00	0.0038	0.0052	81.75	0.0014	270.75	0
82.00	0.0030	0.0043	86.25	0.0008	268.50	0
81.00	0.0038	0.0056	81.75	0.0017	258.75	0
80.00	0.0038	0.0052	77.25	0.0017	129.75	0
79.00	0.0039	0.0054	340.50	0.0020	12.75	0
78.00	0.0045	0.0058	74.25	0.0025	145.50	0
77.00	0.0040	0.0052	78.00	0.0022	145.50	0
76.00	0.0041	0.0053	331.50	0.0022	140.25	0
75.00	0.0041	0.0053	36.00	0.0023	141.00	0
74.00	0.0018	0.0037	74.25	0.0000	125.25	0
73.00	0.0012	0.0027	81.75	-0.0004	131.25	0
72.00	0.0014	0.0030	18.00	-0.0004	147.75	0
71.00	0.0008	0.0019	18.00	-0.0009	158.25	0
70.00	0.0011	0.0027	17.25	-0.0005	149.25	0
69.00	0.0010	0.0026	0.75	-0.0005	142.50	0
68.00	0.0001	0.0016	171.75	-0.0019	150.75	0
67.00	0.0000	0.0016	15.00	-0.0013	150.75	0
66.00	-0.0001	0.0010	17.25	-0.0017	152.25	0
65.00	-0.0008	0.0004	26.25	-0.0019	148.50	0
64.00	-0.0003	0.0010	0.00	-0.0021	190.50	0
63.00	0.0007	0.0019	30.00	-0.0025	198.75	0
62.00	0.0013	0.0028	30.75	0.0003	156.00	0
61.00	0.0030	0.0044	23.25	0.0017	151.50	0
60.00	0.0057	0.0071	27.00	0.0046	153.75	0
59.00	0.0071	0.0084	17.25	0.0060	153.75	0
58.00	0.0097	0.0109	24.75	0.0086	150.75	0
57.00	0.0119	0.0133	36.75	0.0106	101.25	0
56.00	0.0132	0.0148	24.75	0.0120	110.25	0
55.00	0.0145	0.0162	38.25	0.0132	101.25	0
54.00	0.0162	0.0178	37.50	0.0147	104.25	0
53.00	0.0169	0.0185	31.50	0.0155	103.50	0
52.00	0.0168	0.0186	36.75	0.0153	102.00	0
51.00	0.0183	0.0199	27.00	0.0168	111.00	0
50.00	0.0199	0.0216	25.50	0.0183	101.25	0
49.00	0.0207	0.0225	44.25	0.0190	108.00	0
48.00	0.0220	0.0237	32.25	0.0203	105.75	0

47.00	0.0229	0.0246	53.25	0.0212	106.50	0
46.00	0.0226	0.0245	42.00	0.0208	106.50	0
45.00	0.0226	0.0244	27.75	0.0208	101.25	0
44.00	0.0238	0.0257	42.00	0.0220	108.75	73
43.00	0.0244	0.0263	34.50	0.0224	107.25	134
42.00	0.0245	0.0264	36.75	0.0226	102.75	176
41.00	0.0246	0.0265	50.25	0.0229	110.25	160
40.00	0.0253	0.0274	47.25	0.0235	162.00	298
39.00	0.0255	0.0274	29.25	0.0237	99.75	322
38.00	0.0248	0.0266	37.50	0.0230	157.50	189
37.00	0.0236	0.0252	51.00	0.0217	163.50	22
36.00	0.0221	0.0236	29.25	0.0200	145.50	0
35.00	0.0209	0.0228	48.75	0.0189	162.75	0
34.00	0.0202	0.0218	36.75	0.0183	102.00	0
33.00	0.0182	0.0200	44.25	0.0165	107.25	0
32.00	0.0151	0.0168	41.25	0.0133	99.75	0
31.00	0.0119	0.0135	45.75	0.0105	93.75	0
30.00	0.0090	0.0105	33.00	0.0075	91.50	0
29.00	0.0048	0.0063	45.75	0.0035	93.75	0
28.00	0.0002	0.0012	27.75	-0.0011	335.25	0
27.00	-0.0041	-0.0029	27.00	-0.0072	207.75	0
26.00	-0.0073	-0.0063	43.50	-0.0087	342.00	0
25.00	-0.0109	-0.0099	215.25	-0.0126	126.75	0
24.00	-0.0143	-0.0134	186.00	-0.0158	334.50	0
23.00	-0.0179	-0.0166	200.25	-0.0193	343.50	0
22.00	-0.0217	-0.0203	194.25	-0.0232	327.00	0
21.00	-0.0257	-0.0244	186.00	-0.0274	1.50	357
20.00	-0.0279	-0.0262	175.50	-0.0297	346.50	480
19.00	-0.0304	-0.0289	191.25	-0.0317	333.00	480
18.00	-0.0331	-0.0312	166.50	-0.0347	336.75	480
17.00	-0.0359	-0.0340	180.75	-0.0375	0.75	480
16.00	-0.0381	-0.0363	153.75	-0.0415	336.00	480
15.00	-0.0395	-0.0373	179.25	-0.0411	0.75	480
14.00	-0.0416	-0.0396	170.25	-0.0432	0.75	480
13.00	-0.0442	-0.0423	175.50	-0.0456	0.75	480
12.00	-0.0462	-0.0442	178.50	-0.0477	0.75	480
11.00	-0.0479	-0.0460	162.00	-0.0492	0.00	480
10.00	-0.0495	-0.0475	177.00	-0.0513	0.75	480
9.00	-0.0503	-0.0483	207.00	-0.0520	0.75	480
8.00	-0.0504	-0.0484	209.25	-0.0520	0.75	480
7.00	-0.0519	-0.0482	243.75	-0.0537	46.50	480
6.00	-0.0530	-0.0510	218.25	-0.0547	0.75	480
5.00	-0.0527	-0.0505	206.25	-0.0544	3.00	480
4.00	-0.0528	-0.0507	208.50	-0.0547	46.50	480
3.00	-0.0527	-0.0504	224.25	-0.0545	38.25	480
2.00	-0.0525	-0.0508	174.00	-0.0543	57.00	480

1.00	-0.0590	-0.0583	174.00	-0.0600	69.75	480
0.00	-0.0721	-0.0716	162.75	-0.0726	3.00	480

SECTION 12B. ---- SHEFFIELD OUTER CONTOUR DEVIATIONS ----

POLAR ANGLE	O.C. AVERAGE	HIGH VALUES	HIGH AZIMUTH	LOW VALUES	LOW AZIMUTH	NUMBER POINTS OUT TOLERANCE
0.00	0.0312	0.0316	150.00	0.0306	0.75	N/A
90.00	0.0131	0.0154	96.00	0.0094	151.50	N/A
89.00	0.0114	0.0141	87.00	0.0083	142.50	N/A
88.00	0.0110	0.0136	81.75	0.0078	151.50	N/A
87.00	0.0104	0.0124	93.75	0.0074	143.25	N/A
86.00	0.0107	0.0131	84.00	0.0075	143.25	N/A
85.00	0.0099	0.0122	87.00	0.0071	150.00	N/A
84.00	0.0093	0.0127	261.00	0.0060	148.50	N/A
83.00	0.0091	0.0110	78.00	0.0062	147.75	N/A
82.00	0.0081	0.0099	87.75	0.0056	147.00	N/A
81.00	0.0090	0.0108	80.25	0.0063	148.50	N/A
80.00	0.0081	0.0098	82.50	0.0049	147.75	N/A
79.00	0.0064	0.0081	77.25	0.0035	145.50	N/A
78.00	0.0071	0.0088	31.50	0.0050	139.50	N/A
77.00	0.0054	0.0069	20.25	0.0031	141.75	N/A
76.00	0.0060	0.0076	31.50	0.0034	141.00	N/A
75.00	0.0045	0.0062	27.00	0.0020	147.75	N/A
74.00	0.0031	0.0046	23.25	0.0007	148.50	N/A
73.00	0.0025	0.0041	24.00	0.0004	137.25	N/A
72.00	0.0007	0.0021	76.50	-0.0014	147.75	N/A
71.00	-0.0020	-0.0004	40.50	-0.0040	149.25	N/A
70.00	-0.0037	-0.0018	33.00	-0.0063	300.75	N/A
69.00	-0.0066	0.0037	0.75	-0.0176	303.00	N/A
68.00	-0.0085	0.0010	0.00	-0.0182	291.00	N/A
67.00	-0.0098	-0.0003	0.75	-0.0187	294.00	N/A
66.00	-0.0111	-0.0023	0.00	-0.0200	294.75	N/A
65.00	-0.0122	-0.0034	0.00	-0.0209	291.00	N/A
64.00	-0.0111	-0.0033	0.00	-0.0194	291.00	N/A
63.00	-0.0112	-0.0039	0.75	-0.0192	300.00	N/A
62.00	-0.0120	-0.0047	0.75	-0.0194	297.75	N/A
61.00	-0.0111	-0.0039	0.75	-0.0187	290.25	N/A
60.00	-0.0099	-0.0031	6.00	-0.0171	296.25	N/A
59.00	-0.0105	-0.0039	15.75	-0.0176	299.25	N/A
58.00	-0.0110	-0.0050	103.50	-0.0178	288.75	N/A
57.00	-0.0114	-0.0056	7.50	-0.0180	294.00	N/A
56.00	-0.0115	-0.0061	10.50	-0.0177	292.50	N/A
55.00	-0.0113	-0.0056	94.50	-0.0177	288.75	N/A
54.00	-0.0099	-0.0046	23.25	-0.0161	286.50	N/A

53.00	-0.0099	-0.0043	12.75	-0.0157	280.50	N/A
52.00	-0.0103	-0.0050	80.25	-0.0165	289.50	N/A
51.00	-0.0094	-0.0042	19.50	-0.0149	289.50	N/A
50.00	-0.0097	-0.0042	68.25	-0.0151	285.00	N/A
49.00	-0.0102	-0.0051	40.50	-0.0153	286.50	N/A
48.00	-0.0108	-0.0056	21.00	-0.0159	281.25	N/A
47.00	-0.0101	-0.0053	39.75	-0.0152	288.00	N/A
46.00	-0.0106	-0.0057	37.50	-0.0149	278.25	N/A
45.00	-0.0114	-0.0063	47.25	-0.0161	283.50	N/A
44.00	-0.0110	-0.0061	46.50	-0.0167	273.00	N/A
43.00	-0.0109	-0.0061	29.25	-0.0150	292.50	N/A
42.00	-0.0105	-0.0058	51.75	-0.0149	281.25	N/A
41.00	-0.0115	-0.0064	63.00	-0.0155	288.00	N/A
40.00	-0.0125	-0.0079	56.25	-0.0165	288.75	N/A
39.00	-0.0128	-0.0078	59.25	-0.0168	256.50	N/A
38.00	-0.0137	-0.0090	58.50	-0.0175	271.50	N/A
37.00	-0.0136	-0.0095	57.75	-0.0174	288.75	N/A
36.00	-0.0133	-0.0090	45.00	-0.0168	217.50	N/A
35.00	-0.0127	-0.0083	39.75	-0.0163	261.75	N/A
34.00	-0.0119	-0.0076	37.50	-0.0157	268.50	N/A
33.00	-0.0127	-0.0085	84.00	-0.0166	266.25	N/A
32.00	-0.0122	-0.0083	55.50	-0.0157	249.75	N/A
31.00	-0.0115	-0.0078	53.25	-0.0146	266.25	N/A
30.00	-0.0109	-0.0069	57.75	-0.0144	256.50	N/A
29.00	-0.0107	-0.0071	53.25	-0.0141	270.00	N/A
28.00	-0.0100	-0.0064	51.75	-0.0130	232.50	N/A
27.00	-0.0108	-0.0072	53.25	-0.0139	229.50	N/A
26.00	-0.0093	-0.0060	45.00	-0.0121	257.25	N/A
25.00	-0.0088	-0.0057	48.75	-0.0117	234.75	N/A
24.00	-0.0084	-0.0056	51.00	-0.0110	248.25	N/A
23.00	-0.0077	-0.0047	58.50	-0.0104	250.50	N/A
22.00	-0.0092	-0.0062	53.25	-0.0117	249.75	N/A
21.00	-0.0106	-0.0078	67.50	-0.0132	234.00	N/A
20.00	-0.0103	-0.0076	57.00	-0.0126	225.00	N/A
19.00	-0.0093	-0.0063	60.75	-0.0119	247.50	N/A
18.00	-0.0086	-0.0060	63.00	-0.0109	229.50	N/A
17.00	-0.0080	-0.0056	60.75	-0.0100	251.25	N/A
16.00	-0.0076	-0.0055	61.50	-0.0095	222.00	N/A
15.00	-0.0070	-0.0056	67.50	-0.0087	276.00	N/A
14.00	-0.0056	-0.0037	56.25	-0.0073	268.50	N/A
13.00	-0.0050	-0.0031	61.50	-0.0066	276.75	N/A
12.00	-0.0037	-0.0017	54.00	-0.0056	253.50	N/A
11.00	-0.0024	-0.0005	45.00	-0.0042	226.50	N/A
10.00	-0.0011	0.0010	47.25	-0.0029	237.00	N/A
9.00	0.0001	0.0017	42.75	-0.0013	201.75	N/A
8.00	0.0018	0.0027	50.25	0.0010	194.25	N/A

7.00	0.0025	0.0036	53.25	0.0011	220.50	N/A
6.00	0.0049	0.0059	52.50	0.0037	249.75	N/A
5.00	0.0066	0.0074	86.25	0.0053	288.00	N/A
4.00	0.0092	0.0099	21.00	0.0079	260.25	N/A
3.00	0.0115	0.0122	191.25	0.0105	1.50	N/A
2.00	0.0199	0.0206	165.75	0.0192	261.75	N/A
1.00	0.0306	0.0315	33.00	0.0298	104.25	N/A
0.00	0.0309	0.0314	141.00	0.0304	0.75	N/A

SECTION 12C. ---- SHEFFIELD WALL DEVIATIONS ----

POLAR ANGLE	WALL AVERAGE	HIGH VALUES	HIGH AZIMUTH	LOW VALUES	LOW AZIMUTH	NUMBER POINTS OUT TOLERANCE
0.00	0.1034	0.1037	39.75	0.1029	6.75	480
90.00	0.0086	0.0099	107.25	0.0068	280.50	0
89.00	0.0068	0.0089	1.50	0.0052	282.75	0
88.00	0.0063	0.0084	1.50	0.0046	276.75	0
87.00	0.0055	0.0068	226.50	0.0038	276.75	0
86.00	0.0063	0.0085	270.75	0.0045	283.50	0
85.00	0.0059	0.0080	271.50	0.0042	284.25	0
84.00	0.0058	0.0111	261.00	0.0039	169.50	0
83.00	0.0053	0.0081	268.50	0.0033	312.00	0
82.00	0.0051	0.0065	108.00	0.0039	174.75	0
81.00	0.0052	0.0061	108.75	0.0040	285.00	0
80.00	0.0043	0.0057	1.50	0.0028	168.75	0
79.00	0.0025	0.0054	12.75	0.0013	151.50	0
78.00	0.0026	0.0038	105.00	0.0014	280.50	0
77.00	0.0014	0.0030	120.00	0.0001	174.00	0
76.00	0.0019	0.0030	51.75	0.0006	153.75	0
75.00	0.0003	0.0015	110.25	-0.0008	152.25	0
74.00	0.0013	0.0026	54.75	0.0000	318.75	0
73.00	0.0013	0.0028	0.75	-0.0004	168.00	0
72.00	-0.0008	0.0007	105.00	-0.0023	281.25	0
71.00	-0.0027	-0.0013	224.25	-0.0041	312.75	0
70.00	-0.0048	-0.0034	100.50	-0.0077	303.75	0
69.00	-0.0076	0.0022	117.00	-0.0185	303.00	0
68.00	-0.0086	0.0017	116.25	-0.0185	290.25	0
67.00	-0.0097	-0.0006	2.25	-0.0186	294.75	0
66.00	-0.0110	-0.0018	116.25	-0.0200	294.75	0
65.00	-0.0114	-0.0029	111.75	-0.0201	294.75	0
64.00	-0.0109	-0.0025	114.75	-0.0193	291.00	0
63.00	-0.0118	-0.0026	108.75	-0.0198	293.25	0
62.00	-0.0133	-0.0057	110.25	-0.0209	297.75	0
61.00	-0.0141	-0.0062	109.50	-0.0215	291.00	0
60.00	-0.0156	-0.0083	115.50	-0.0229	299.25	0

59.00	-0.0176	-0.0105	108.00	-0.0250	299.25	0
58.00	-0.0207	-0.0137	118.50	-0.0278	306.00	80
57.00	-0.0233	-0.0164	107.25	-0.0301	300.00	216
56.00	-0.0248	-0.0181	106.50	-0.0312	300.75	248
55.00	-0.0258	-0.0188	103.50	-0.0324	297.75	263
54.00	-0.0261	-0.0196	101.25	-0.0324	282.00	264
53.00	-0.0267	-0.0200	104.25	-0.0328	292.50	271
52.00	-0.0272	-0.0203	103.50	-0.0337	295.50	278
51.00	-0.0277	-0.0218	99.75	-0.0337	294.00	290
50.00	-0.0296	-0.0230	100.50	-0.0354	295.50	410
49.00	-0.0309	-0.0243	99.00	-0.0368	301.50	454
48.00	-0.0328	-0.0268	102.75	-0.0384	297.00	480
47.00	-0.0330	-0.0271	99.75	-0.0386	297.00	480
46.00	-0.0332	-0.0274	96.00	-0.0380	298.50	480
45.00	-0.0341	-0.0279	100.50	-0.0393	299.25	480
44.00	-0.0348	-0.0287	99.75	-0.0404	273.00	480
43.00	-0.0353	-0.0297	98.25	-0.0400	298.50	480
42.00	-0.0350	-0.0293	97.50	-0.0399	294.75	480
41.00	-0.0360	-0.0302	96.00	-0.0407	288.00	480
40.00	-0.0378	-0.0325	92.25	-0.0424	299.25	480
39.00	-0.0383	-0.0321	86.25	-0.0431	247.50	480
38.00	-0.0385	-0.0336	96.75	-0.0426	261.00	480
37.00	-0.0371	-0.0322	93.00	-0.0414	246.75	480
36.00	-0.0353	-0.0301	91.50	-0.0400	240.75	480
35.00	-0.0336	-0.0286	95.25	-0.0380	251.25	479
34.00	-0.0321	-0.0272	99.00	-0.0366	237.75	480
33.00	-0.0309	-0.0257	91.50	-0.0357	236.25	480
32.00	-0.0273	-0.0228	92.25	-0.0319	248.25	363
31.00	-0.0234	-0.0192	91.50	-0.0274	235.50	172
30.00	-0.0200	-0.0150	86.25	-0.0243	234.00	0
29.00	-0.0155	-0.0114	93.75	-0.0195	237.75	0
28.00	-0.0102	-0.0062	93.00	-0.0141	232.50	0
27.00	-0.0066	-0.0030	83.25	-0.0105	229.50	0
26.00	-0.0020	0.0014	84.00	-0.0052	230.25	0
25.00	0.0020	0.0055	75.75	-0.0016	234.00	0
24.00	0.0059	0.0089	75.00	0.0027	219.75	0
23.00	0.0102	0.0138	81.00	0.0068	205.50	0
22.00	0.0125	0.0157	90.75	0.0093	214.50	0
21.00	0.0151	0.0183	77.25	0.0118	213.75	0
20.00	0.0176	0.0207	73.50	0.0141	198.75	0
19.00	0.0211	0.0244	72.00	0.0175	206.25	0
18.00	0.0245	0.0277	68.25	0.0210	215.25	219
17.00	0.0279	0.0309	81.00	0.0249	189.75	459
16.00	0.0305	0.0335	336.00	0.0276	222.00	480
15.00	0.0325	0.0347	24.75	0.0300	182.25	480
14.00	0.0360	0.0386	56.25	0.0335	183.75	480

13.00	0.0392	0.0420	60.75	0.0365	199.50	480
12.00	0.0426	0.0456	25.50	0.0392	195.75	480
11.00	0.0454	0.0483	42.75	0.0424	189.00	480
10.00	0.0484	0.0518	44.25	0.0449	214.50	480
9.00	0.0504	0.0534	52.50	0.0471	204.75	480
8.00	0.0521	0.0547	50.25	0.0494	216.00	480
7.00	0.0543	0.0572	53.25	0.0494	243.75	480
6.00	0.0578	0.0606	41.25	0.0549	241.50	480
5.00	0.0592	0.0617	51.75	0.0564	246.75	480
4.00	0.0619	0.0645	46.50	0.0590	227.25	480
3.00	0.0642	0.0661	38.25	0.0617	225.00	480
2.00	0.0725	0.0745	57.00	0.0708	252.00	480
1.00	0.0896	0.0913	43.50	0.0886	131.25	480
0.00	0.1030	0.1033	142.50	0.1025	4.50	480

AVERAGE DEVIATION NOTES: N/A

SECTION 13. ---- META DATA FROM SHEFFIELD ----

POINT#	AZIMUTH	POLAR	IRD	ORD	WALL
<**>					
1	0.00	0.00	-0.0720	0.0313	0.1033
…					
4160	359.25	0.00	-0.0720	0.0309	0.1030

END OF FILE