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## IN THIS ISSUE:

Understanding Laser Tracker Targets

*by Kenneth J. Steffey, FARO Technologies Inc.*

Automated Outer Mold Line Measurement and Control

*by Ken R. Vakil and William B. Louder, Northrop Grumman Aerospace Systems*

Design for Measurement-Assisted Determinant Assembly (MADA) of Large Composite Structures

*by Jody E. Muelaner and Paul G. Maropoulos,*

*The Lab for Integrated Metrology Applications, The University of Bath (United Kingdom)*

Determining Laser Tracker Alignment Errors Using a Network Measurement

*by Ben Hughes, Wenjuan Sun, Alistair Forbes, and Andrew Lewis;*

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# Automated Outer Mold Line Measurement and Control

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**S**tringent step and gap tolerance requirements are placed upon outer mold line (OML) components such as fixed skins, panels, and doors. The aircraft design identifies these steps and gaps as key characteristics which must be measured and controlled. The current processes for achieving these requirements are manual, nonrobust, and require several iterations of measurements to achieve the desired results—all which add to the product cost and cycle time.

To address this need, Northrop Grumman Aerospace Systems (NGAS) Manufacturing Technology Development organization is developing OML measurement and control system utilizing state-of-the-art metrology technologies.

One of the systems tested for this application was the laser radar (LR) method in which data were compared with standard calibrated blocks to determine accuracy of the measurements.

A test mock-up was created to simulate the gap and step condition encountered during the skin/panel assembly. Measurements were made using the LR method along the edges. Knowing the thickness and cavity depth condition, the shim size calculation was computed.

On the aircraft assembly, the system will be designed to predict the shim size and location to achieve OML control based upon composite part thickness and the as-built location of the underlying structure, while providing assembly guidance to the mechanics regarding size and location of the shims. The goal is to implement

a robust automated measurement system that meets required measurement accuracy, is affordable, and provides value.

Data and analysis so far indicate that the LR method may be effective for skin and panel measurements, depending upon measurement accuracy requirements. For composite-part thickness measurements, however, additional development work may be required.

This article covers current measurement processes, tight measurement accuracy requirements, LR system, lab test plans, methodology, results, and conclusions, as well as concepts for automated OML measurements.

## STEP AND GAP DEFINITION

OML has two components: step and gap. Step measurement is defined as a vertical distance between the two adjacent planes measured at the center line of the gap, as seen in figure 1. Gap is simply defined as horizontal distance between the two adjacent OML surfaces.

In reality, two adjacent surface edges may have imperfections (caused by paint, edge roughness, etc.), that may distort the step measurement. To minimize this distortion, the following approach may be used to compute the step height.

Small measurement patches 0.25 in. × 0.25 in. may be created about 0.1 in. away from each edge, as seen in figure 2. Planes are

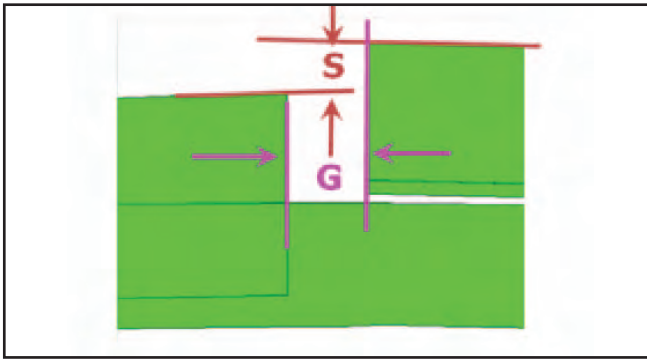


Figure 1. Step and gap definition

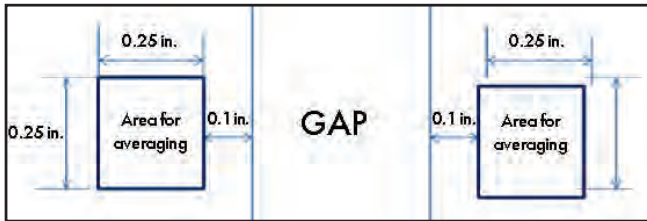


Figure 2. Measurement patches for step calculation

then fitted over these patches and extended over the middle of the gap to determine the step amount. In this case, vertical distance between the two extended planes in the middle of the gap is the step amount.

## PROBLEM STATEMENT AND HYPOTHESIS

The outer mold line of the aircraft has a step and gap requirement that must be met for design and maintainability reasons. Typical call outs for step requirements can be as tight as  $\pm 0.007$  in., while the gap requirements can vary with a minimum of 0.190 in. to a maximum of 0.350 in., depending on aircraft OML surface area. The + or - sign in front of the tolerance call out indicates relative position of the adjacent OML surface.

Between the gap and step requirement, step requirement is much harder to achieve. Therefore, in this article we will focus on step measurement requirements. Figure 3 shows a notional representation of the skin and panel configuration on the aircraft OML surfaces.

Wherever fixed skin mates with another fixed skin or the panel, there is a requirement to meet both step and gap tolerances. Assuming there are, on the average, 40 points to measure, and about 20 skins and panels per aircraft, there could be as many as 800 points for which step and gap conditions require measurement. An example of the skin measurement plan is seen in figure 4.

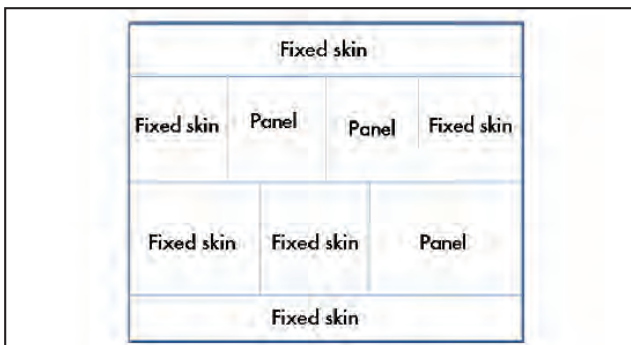


Figure 3. Skin/panel layout—notional view

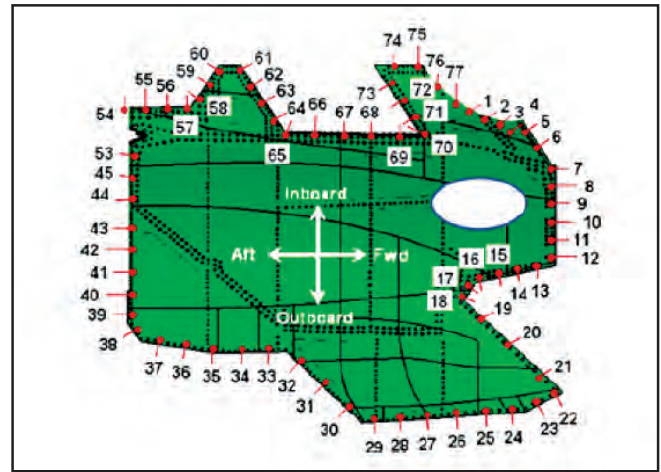


Figure 4. Fixed-skin measurement plan

Available measurement tools for step and gap condition range from mechanical type, such as depth gauge or Tru-Lok gauge, to hand-held laser measurement devices such as the gap gun or laser gauge (as seen in figure 5). These laser devices have a laser beam that is projected on the OML surface and the image is captured on a camera for taking step and gap measurements.

## CURRENT MEASUREMENT PROCESS

The skin and panel assembly process begins with dry fitting of the skin using pilot holes drilled in the skin and the structure. Fixed skins are temporarily attached to the structure and the measurements are taken with any of the devices mentioned above. Recording of shim requirements is done on a sheet of paper or handwritten on a tape applied to the structure. Shim buttons are applied at hole locations to bring adjacent OML surfaces into tolerance. Because the measurement process is not robust, shim size and location determination is repetitive, labor intensive, and ergonomically unsuitable. This adds a significant amount of time to the product cycle.

Further, continuous improvement efforts are almost impossible to achieve as the OML data is not electronically available for statistical process control (SPC) analysis.

The basic hypothesis is that metrology software and hardware technology has advanced to the point that it can be leveraged to automate the OML measurement and control process.

## PROJECT OBJECTIVES

NGAS is evaluating different technologies available for measuring and achieving OML requirements. One of the options is a (LR) method for its applicability in aircraft production.

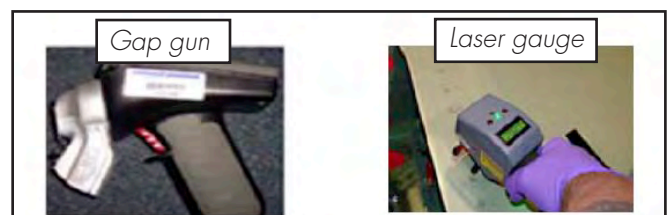


Figure 5. Gap gun and laser gauge

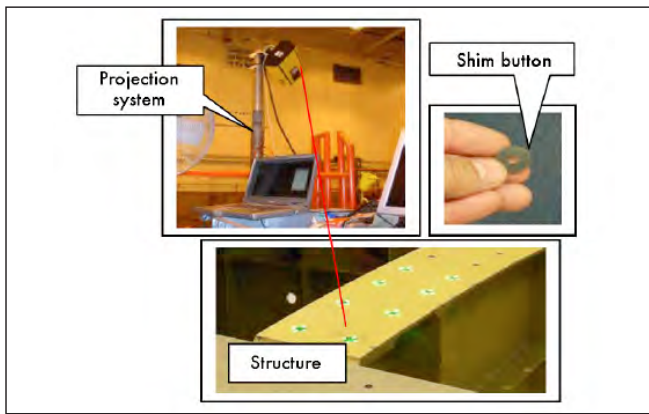


Figure 6. Shim size and location projection

Significant improvements in both labor and product cycle time are expected by automating the measurement, control, and reporting process. The three major areas of automation opportunities are:

1. Composite-part thickness measurement
2. Skin/panel assembly system which measures OML features and the as-built structure
3. Automatic projection of shim size and location based upon part thickness and as-built structure condition (as seen in figure 6)

## LR TESTING APPROACH AND SYSTEM

The testing and evaluation of the system was conducted using standard calibrated blocks, and on a specially designed simulated test fixture.

### System hardware

The Nikon (formerly Metris) LR system consists of a measurement head mounted on gimbals that provides 360° rotation. For improving measurement coverage, it can be securely mounted on a tall Brunson stand. As seen in figure 7, the measurement unit is connected to the system controller, which directs head motions, compiles collected data, and presents the user information in an easy to understand format.

The rationale for the selection was:

- Provides automated noncontact measurement capability for large volume applications up to 60 m
- Rapid data collection up to 1,000 points/second without photogrammetric targets
- A published 3-D accuracy ( $2\sigma$ ): 16  $\mu\text{m}$  (0.00064 in.) at 1 m and 240  $\mu\text{m}$  (0.0096 in.) at 24 m

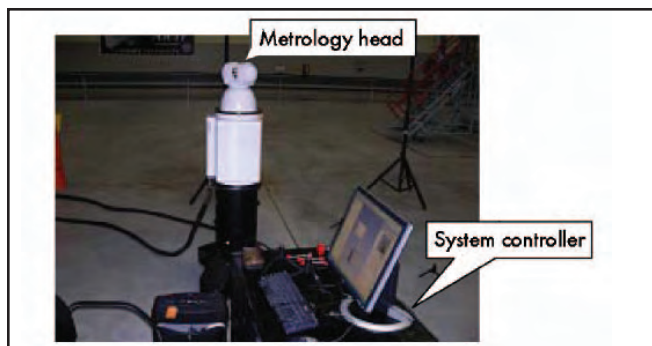


Figure 7. Fixed-skin measurement plan

Feature	Tolerance	Accuracy
Step	+/- 0.007in.	+/- 0.001in.
Gap	+/- 0.007in.	+/- 0.001in.
Part thickness	+/- 0.007in.	+/- 0.001in.

Figure 8. Measurement accuracy requirements

### Interface software

Verisurf software was selected due to its easy interfacing capability with the LR system. Computer-aided design (CAD) models of the skin and the structure were imported into the system software. A specially written program then directed the LR metrology head to measure the OML points, acquire the data, provide deviation analysis, and create inspection reports.

## SHIMMING COMPUTATION ALGORITHM

To bring adjacent skins and panels to meet the tolerance requirements, calculated shims are placed around edges on the mounting holes of the fixed skins. The number of measurement points selected for each skin can be as many as 20 percent of the total number of skin-attach holes. Since the panels are interchangeable and replaceable, it is the fixed-skin edge holes that get the shim to bring skin/panel interface into OML tolerance.

There are a number of ways to compute shim thickness, depending upon the selected shim-computation method. One method for shim-thickness selection is described below.

When a fixed skin meets another fixed skin, relative step measurements between the two surfaces are made. Shim size and location are determined to bring the two surfaces into step tolerance. For a case where the skin and panel meet, cavity height constant values may be predetermined by engineering and documented on the skin/panel assembly drawings. Shim size is computed by the following formula:

$$\text{Shim size} = \text{Cavity height constant} - \text{As-built cavity depth} - \text{Skin thickness}$$

Therefore, to achieve OML, the following measurements are required:

1. Thickness of the part around the edges
2. Relative step between the fixed skins
3. As-built cavity depth where panels are fitted

## MEASUREMENT ACCURACY REQUIREMENTS

For our tests, these requirements were detailed in the testing documents. They are summarized in the table in figure 8.

The required process capability of the system can be as high as  $3\sigma$ . This means that 99.7 percent of the time, the measured reading will be between +/-0.001 in.

### LR system test

To compare the LR measurement accuracy, standard calibrated blocks in 2-in., 3-in., and 4-in. lengths were used. The radar beam was directed on the front face of the block and the reference plane from approximately 15 feet, as seen in figure 9.

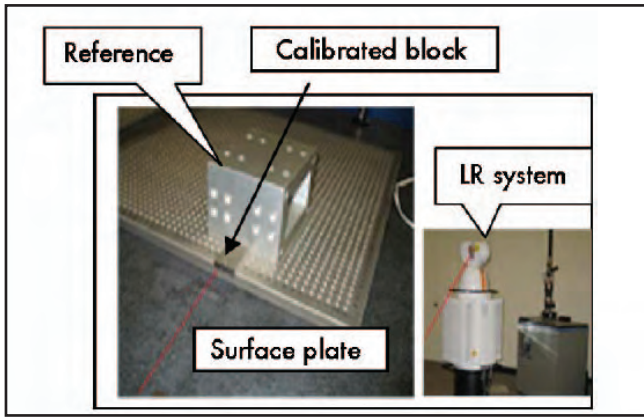


Figure 9. Measurement of calibrated block

The deviation between LR and the standard block measurement ranged from 0.0006 in. to 0.0032 in. (as seen in the table in figure 10). Figure 11 shows LR deviation, and figure 12 shows the histogram with a mean thickness of 0.001969 in. and a standard deviation of 0.00077 in.

### Simulated test article

A simulated test article was fabricated to test the software, and validate the performance and usability of the human machine interface. The test article consists of three pieces—a constant thickness skin with full-size hole pattern, a metallic base which represents air frame with full-size hole pattern, and different thickness shim buttons for driving the skin to OML. This was accomplished by creating a CAD model that represents a skin with constant thickness and a replication of air frame with exaggerated step condition (as seen in figures 13 and 14). The CAD model was sent to be N/C machined out of aluminum to a tolerance of  $\pm 0.0025$  in., and CMM inspected to verify machining accuracy.

The base was machined with a slight curvature and varying cavity depths around its periphery to represent aircraft mold line. The constant thickness skin, when assembled in the base with proper calculated shims, would achieve a nominal (0.000 in.) OML.

Block Length	LR	Deviation
2.0000 in.	2.0023 in.	0.0023 in.
2.0000 in.	2.0019 in.	0.0019 in.
2.0000 in.	2.0021 in.	0.0021 in.
2.0000 in.	2.0006 in.	0.0006 in.
3.0000 in.	3.0018 in.	0.0018 in.
3.0000 in.	3.0032 in.	0.0032 in.
3.0000 in.	3.0026 in.	0.0026 in.
3.0000 in.	3.0024 in.	0.0024 in.
3.0000 in.	3.0030 in.	0.0030 in.
4.0000 in.	4.0015 in.	0.0015 in.
4.0000 in.	4.0010 in.	0.0010 in.
4.0000 in.	4.0011 in.	0.0011 in.
4.0000 in.	4.0021 in.	0.0021 in.

Figure 10. Deviation from calibrated blocks

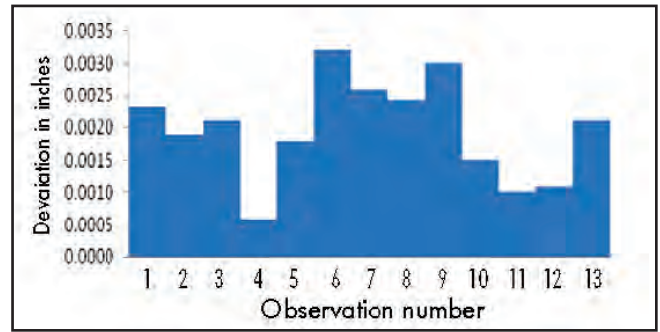


Figure 11. LR deviation from calibrated blocks

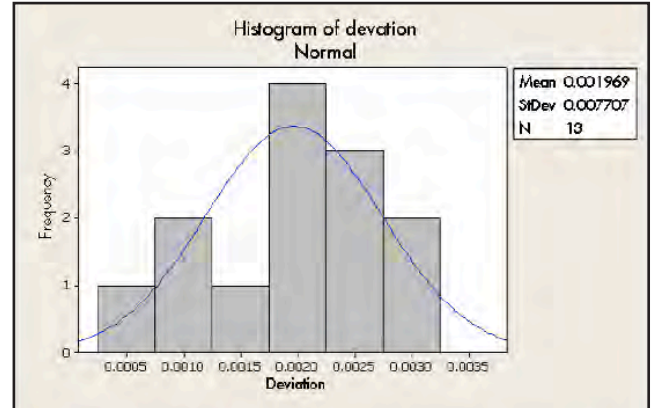


Figure 12. Histogram thickness deviation

### Skin-thickness measurement

An automated set of 11 points were selected on the OML side of the skin. The first set of measurements automatically created vectors that are needed for thickness calculations. The skin was turned around and the second set of points was taken on the exact vector lines created from the first measurements. Skin thickness at these points was calculated by the distance between the two points.

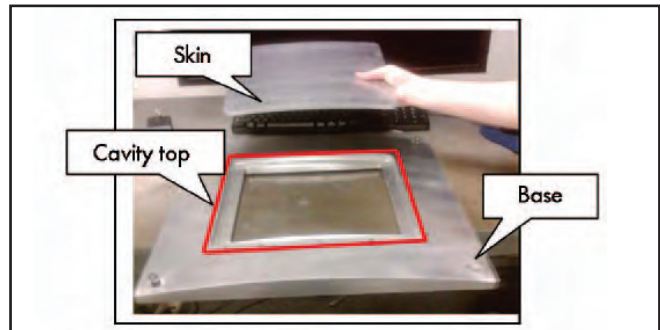


Figure 13. Cavity top measurement locations

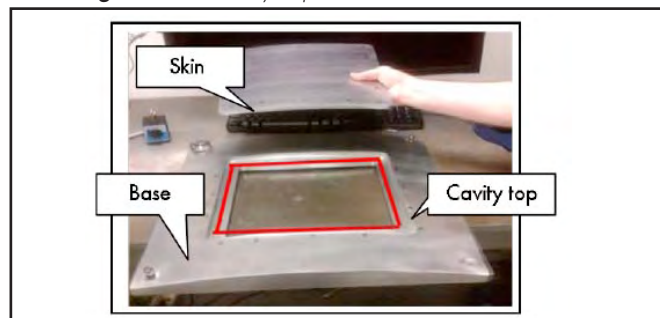


Figure 14. Cavity bottom measurement locations

Point	Skin	Base	Deviation
1	0.001 in.	-0.005 in.	0.006 in.
2	0.003 in.	0.003 in.	0.000 in.
3	-0.003 in.	0.000 in.	0.003 in.
4	-0.001 in.	0.0018 in.	0.0028 in.
5	0.001 in.	0.002 in.	0.001 in.
6	-0.002 in.	0.001 in.	0.003 in.
7	0.004 in.	0.003 in.	0.001 in.
8	0.001 in.	0.0025 in.	0.0015 in.
9	-0.0025 in.	0.0010 in.	0.0035 in.
10	0.0020 in.	0.0018 in.	0.0002 in.
11	0.0018 in.	-0.001 in.	0.0028 in.

Figure 15. OML deviation from nominal = 0.000 in.

### OML measurements

Step measurements were taken to determine the depth of the cavity where OML skin will fit. Cavity depth was taken by the LR by fitting into the simulation tool reference system using the CAD model.

An automated set of 11 points were taken on the OML of the upper part of the step of the simulated air frame tool. Another automated set of 11 points were taken in front of but offset to the first set. Cavity depth was calculated by the distance between the intersection points of the first and second measurements.

The shim thickness was calculated as:

$$\text{Shim thickness} = \text{Cavity depth} - \text{Skin thickness}$$

After the computed shims were placed between the base and the skin in the cavity, the base and skins were assembled and the OML between the base and the skin was measured.

The deviation from nominal value is shown in the table in figure 15.

Figures 16 and 17 graphically show the OML deviation data, with a mean deviation of 0.0023 in. and a standard deviation of 0.0017 in.

### Automated part-thickness measurement

For automating part-thickness measurement using LR, one could consider the following process:

1. Attach four tooling balls to the skin to create a reference plane.

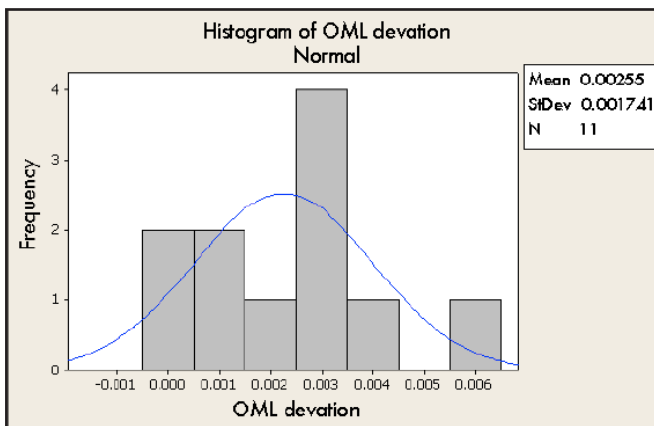


Figure 16. Histogram of deviations

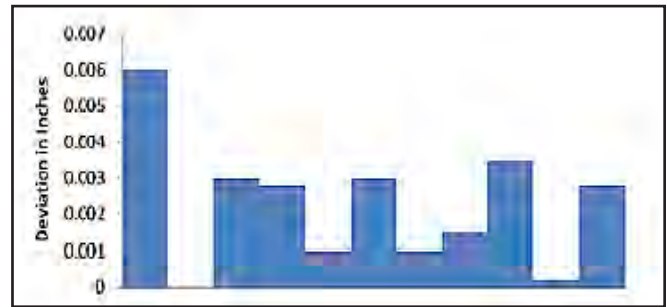


Figure 17. Deviation from nominal

2. Auto-measure with LR measurement points per plan (as seen in figure 18).
3. Create and project normal vector on the other side from the same point.
4. Turn the part around (as seen in figure 19).
5. Measure tooling balls and realign to the same reference plane.
6. Measure same points where normal vector was earlier projected.
7. Compute thickness from the distance between the two points.

### Automated OML measurements

The following concept is presented for automation of OML measurements using LR, as seen in figure 20:

1. Elevate LR for a clear view of the structure.
2. Create LR reference plane using tooling balls that may be available in the workstand.
3. Write an automated measurement plan for LR to take measurements at the designated points.
4. Dry-fit skin and cleco it to the structure.
5. Take OML measurements using the existing method.
6. Measure OML using LR measurements of at the same locations.
7. Compare measurement data between LR and existing method for verification.

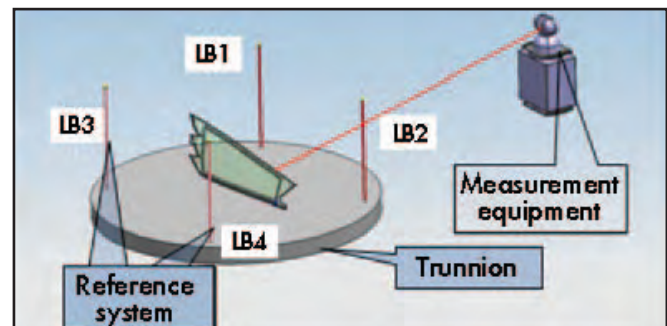


Figure 18. LR measurement—front side

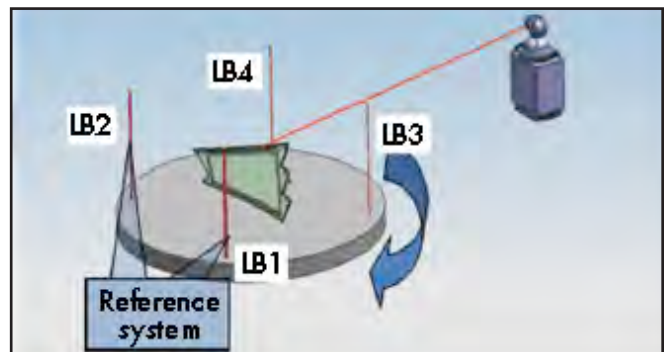


Figure 19. LR measurement—back side

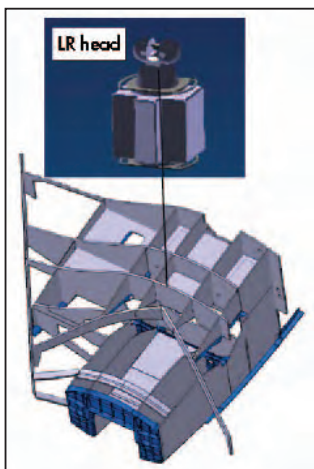


Figure 20. Automated OML using LR

Locating LR so that it can cover the entire aircraft's measurement range can be a challenging task. It is a lot easier to perform upper mold line measurements for top skins, panels, and structure than it is to measure lower mold line skins, panels, and structure. There are creative ways available to surmount this difficulty. One way is to have the LR beam bounced off a mirror surface to overcome the line-of-sight issue. The accuracy of such a method may require further investigation.

For automating measurement sequencing, LR needs to be directed to go to specific points from the CAD drawing of the skin. To do that, one might need an interface software package.

## CONCLUSIONS

LR may be used as a noncontact method for automating the OML measurement process. Once the interface program is written according to the measurement plan, it can sequence itself for automated measurements.

The most important requirement of the measurement system is its capability to provide accurate measurements consistently. The next factor is affordability, meaning the capital invested can sustain a reasonable rate of return on the investment made.

Several packages are available, such as Verisurf, Spatial Analyzer, and PolyWorks, to name a few. With any of these software packages, some level of customization will be required to meet the user's specific measurement requirements.

Mean value of LR measurement of standard calibrated block varied by about 0.002 in. at an approximate distance of 15 feet. In the simulated test, we were able to get OML mean accuracy of 0.0023 in. at an approximate distance of 20 feet.

Additional testing may be required for thickness measurement of the composite parts. Higher variability in the thickness measurement is anticipated due to factors such as paint on the part and composite material composition.

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- Scott Collier, district sales manager, Nikon Metrology Systems (formerly Metris USA Inc.)

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