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## Introduction

The following report is a summary of the V-STARS work carried out at the Goodrich facility in Riverside, California.

One measurement was undertaken using the V-STARS S6 camera system, PRO-SPOT and the V-STARS M6 system with Probes.

The measurement involved the determination coordinates on a 737-700 lay up mold.



*V-STARS with INCA camera.*

## Requirements

The object measured was a 737-700 lay up tool. The object measured is shown in the adjacent image.

## Equipment Used

1. V-STARS S6 INCA Camera System.
2. PRO-SPOT with 5600 point slide.
3. V-STARS M6 with Probes.

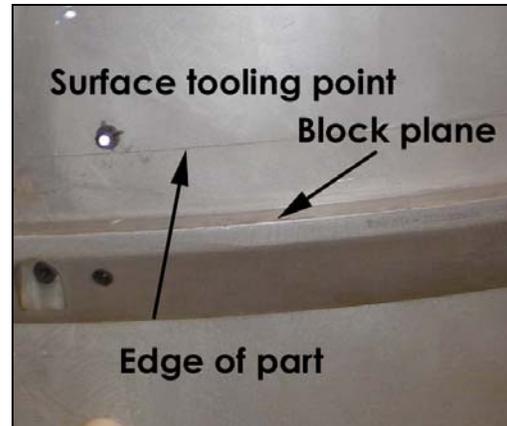


*737-700 Lay up Tool Measured.*

## Measurement Objectives

The following objectives were met.

1. Demonstrate camera use and object targeting.
2. Align data to four tooling holes.
3. Measure edge of part points (EOP). Refer to adjacent image.
4. Measure points on block plane. Refer to adjacent image.
5. Determine location of tooling points on surface. Refer to adjacent image.
6. Determine the location of points on the surface of the lay-up tool.
7. Analyze data to supplied IGES model.

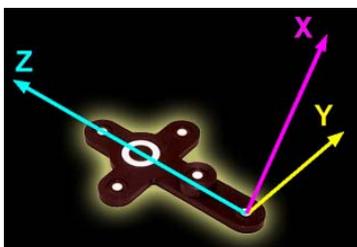
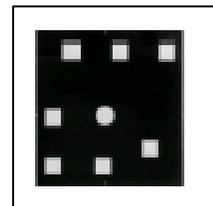


## Measurement Procedure

### Targeting

In order to meet the measurement objectives outlined earlier it was necessary to target the object. In general, targets are placed on points or surfaces that are of interest. For surfaces, strips of retro-reflective tape of variable pitch and dot size are commonly used. They are relatively cheap, disposable and easy to apply. To coordinate tooling datums such as bushed holes or button datums, tooling targets are used. These come in a variety of shank and dot sizes. They are also available in variable orientations.

To automate the measurement process it was necessary to add "coded" targets to each of the objects. These targets are automatically detected and help the software determine the location and orientation of the camera at the time the photograph was taken. They also help tie the entire object into a uniform coordinate system.



The initial coordinates system and approximate scale is determined via the AutoBar. The AutoBar used by the V-STARS system is a fixture with five targets arranged in the form of a cross. The target's known coordinates are used by the resection procedure to determine the camera's orientation relative to the AutoBar. The AutoBar is securely attached on or near the measured object, preferably in a highly visible

location. The AutoBar's default coordinate system has its origin at Target 1 at the bottom of the AutoBar. The positive Z-axis goes through Target 3 at the top of the bar. The positive X-axis is up out of the AutoBar. The diagram on the left shows both the AutoBar and its coordinate system.

To scale a photogrammetric measurement, there must be at least one known distance. Normally this distance comes from a calibrated coded graphite scale bar or invar scale bar (Refer to adjacent image). Typically, multiple scales are used for redundancy. Two scale bars were used to complete each measurement.

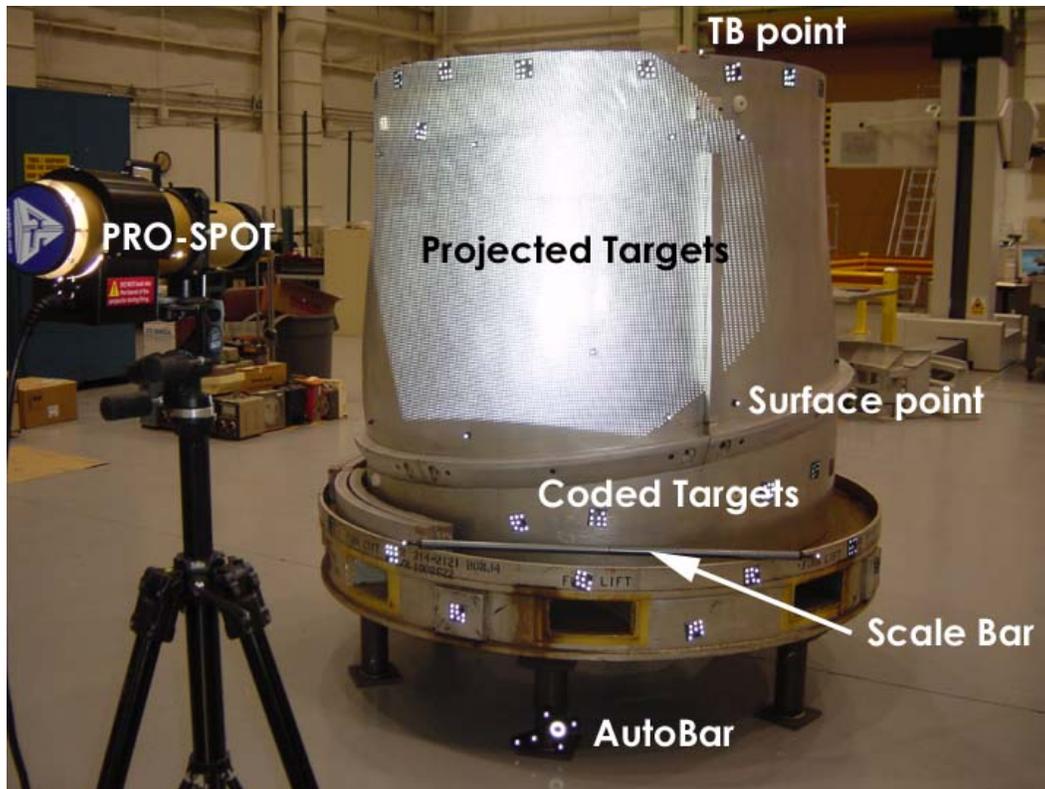


*Invar Scale Bar Kit*

The targeting used is listed below.

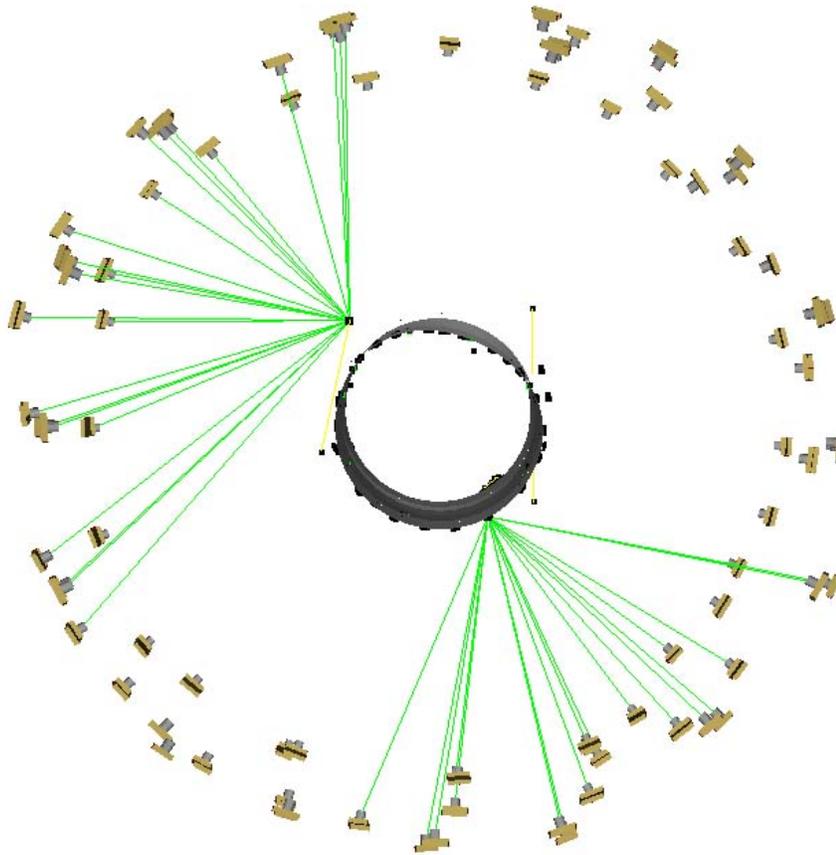
1. AutoBar for initial coordinate system.
2. Coded targets to tie photography together.
3. Two scale bars to scale the network.
4. Tooling targets to get into the tool coordinate system.
5. Tooling targets to locate defined surface points
6. PRO-SPOT projected targets.

Some of the typical targeting features are shown in the image below.



## Photography

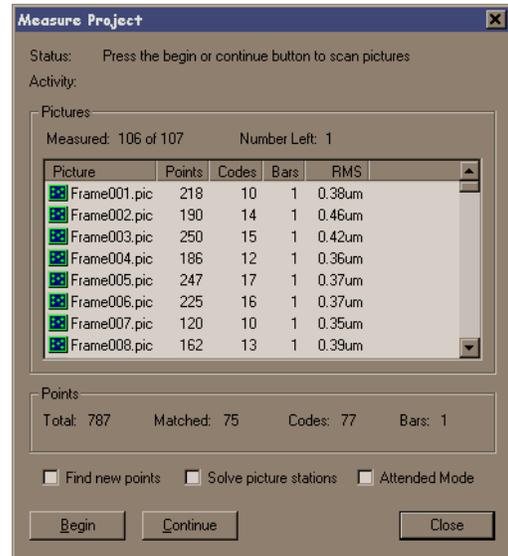
The photography is carried out once the object targeting is completed. Put simply, the aim of the photography is to record each of the targeted points in as many images as possible from as wide a range of angles as possible. To improve the accuracy of the measurement, generally photos are taken both close to the ground and from an elevated position. The number of photos taken depends on the complexity of the measurement and accuracy requirements. In this measurement the photography was very straightforward. The geometry used to create the initial control for the measurement is illustrated in the image below.



## Processing

Once the photography has been completed the images are transferred to the system laptop. The images are stored on an IBM MicroDrive hard drive and V-STARS accesses these images directly from the drive.

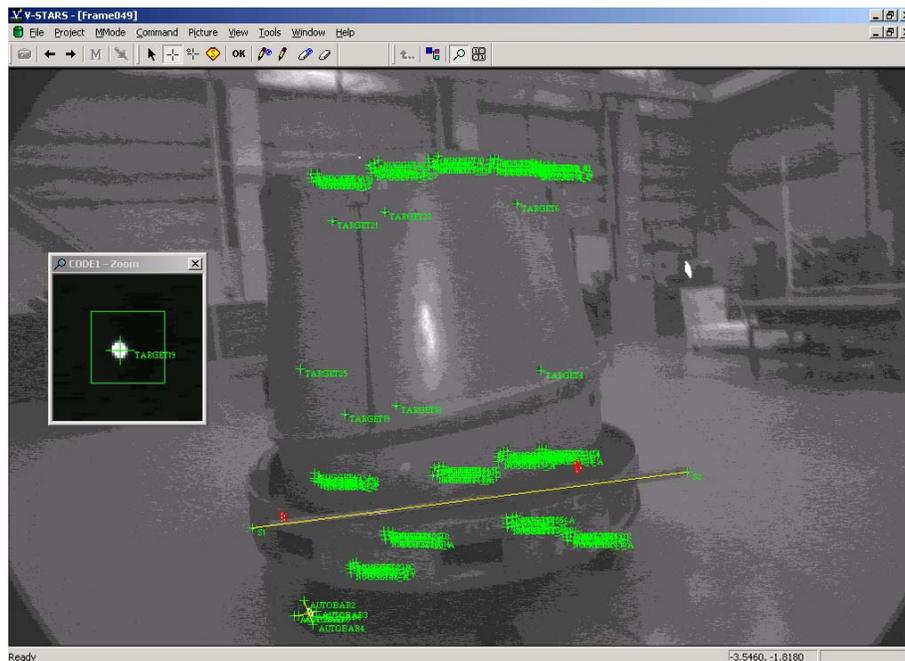
Almost all of the measurement process is automated. The images are processed and the coordinates extracted by the "AutoMeasure" command. A typical AutoMeasure dialog box is shown on the right. The AutoMeasure command will open each of the images, determine the camera location, find new target points and finally adjust all the measurements in the "Bundle Adjustment". At the conclusion the user is left with the XYZ coordinates for all the target points in the network. The AutoMeasure procedure is very powerful as it allows the user to continue working while it processes the data. It also means that relatively unskilled workers can be used to process the data.



*Typical AutoMeasure Dialog*

The AutoMeasure routine will assign random labels to the points it finds. These labels start with the key word "TARGET" followed by a number. If specific labeling is required the random labels can be easily changed to labels defined by the user. This is possible in both the picture view and the graphical 3D view. For this measurement, the points were relabeled to simplify the analysis.

A typical measurement image from the initial control network is shown in the image below.



The green crosses represent points that have been located in this particular image. Note that the image appears a little dark and difficult to see. This is intentional as the best photogrammetric measurements are made on images that have dark backgrounds and bright targets. One of these targets is shown in the zoom window in the corner. If the scale bar is visible then a yellow line will be drawn between the two ends.

At the conclusion of the AutoMeasure the 3D data is written to a file. A typical point listing from the 3D file is shown below.

Point Label	X	Y	Z	Sigma X	Sigma Y	Sigma Z	Offset	Descri
AUTOBAR1	0.0002	-0.0000	-0.0002	0.0001	0.0000	0.0000	0.0000	
AUTOBAR2	0.0002	-0.0507	0.1139	0.0001	0.0000	0.0000	0.0000	
AUTOBAR3	0.0000	0.0000	0.1773	0.0001	0.0000	0.0000	0.0000	
AUTOBAR4	0.0000	0.0507	0.1140	0.0001	0.0000	0.0000	0.0000	
AUTOBAR5	0.0128	0.0000	0.0569	0.0001	0.0000	0.0000	0.0000	
AUTOBAR6	0.0001	0.0001	0.1272	0.0001	0.0000	0.0000	0.0000	
BP1	-2.4124	0.0070	9.8901	0.0006	0.0002	0.0002	0.0002	
BS1	-2.3785	0.7986	-9.7041	0.0002	0.0001	0.0001	0.0000	
CODE1	-2.6836	4.2835	4.8204	0.0002	0.0002	0.0001	0.0000	
CODE2	0.3899	1.9055	-8.4028	0.0002	0.0002	0.0002	0.0000	
CODE5	-1.0329	0.7115	-3.9881	0.0001	0.0001	0.0001	0.0000	
CODE6	-0.1347	-0.2348	-9.2510	0.0001	0.0001	0.0001	0.0000	
CODE7	-2.0924	-0.7831	2.8637	0.0001	0.0000	0.0001	0.0000	
CODE8	-12.2461	6.7397	-1.5250	0.0003	0.0001	0.0001	0.0000	
CODE9	-2.7518	4.0206	3.0958	0.0003	0.0003	0.0001	0.0000	
CODE10	0.3867	1.7759	-5.9284	0.0002	0.0001	0.0001	0.0000	
CODE11	-1.5465	4.0758	0.2547	0.0001	0.0001	0.0001	0.0000	
CODE13	-2.7290	4.3392	-3.5758	0.0003	0.0002	0.0001	0.0000	
CODE14	-12.2748	6.6771	-3.3706	0.0002	0.0001	0.0001	0.0000	
CODE15	-2.4332	3.3067	-0.9534	0.0002	0.0001	0.0001	0.0000	
CODE17	-2.3241	3.9971	-5.2726	0.0003	0.0002	0.0001	0.0000	
CODE18	-12.8074	4.2349	0.2771	0.0002	0.0001	0.0001	0.0000	
CODE19	-13.2119	2.4353	1.4138	0.0001	0.0000	0.0001	0.0000	
CODE20	-12.2666	6.4742	3.7455	0.0003	0.0001	0.0001	0.0000	
CODE21	-12.4317	5.8322	1.0635	0.0003	0.0001	0.0001	0.0000	
CODE22	-12.5722	5.0806	5.0848	0.0002	0.0001	0.0001	0.0000	
CODE23	12.5020	5.7443	4.1014	0.0003	0.0001	0.0001	0.0000	

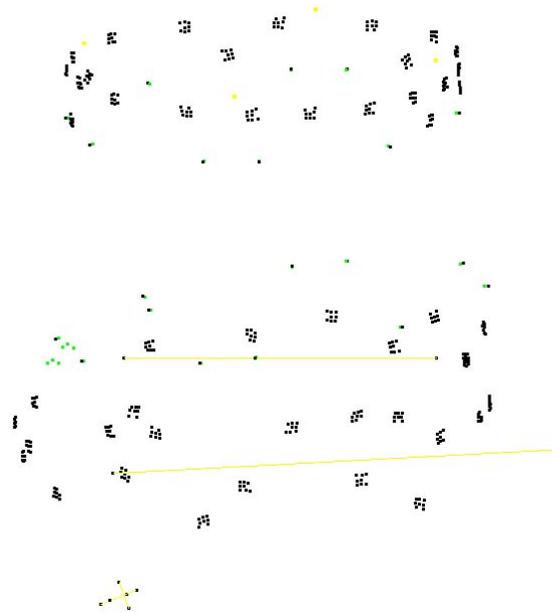
This point data can be analyzed within the V-STARS' SOLIDS module, easily exported to almost any CAD platform or other analysis program.

## Measurement Results

### Single Camera Results – S-Mode

#### Initial Control Network Statistics

No. of photos	87
No. of points	435
No. of scales	2
Scale Agreement	0.0004"
Accuracy RMS X,Y,Z	
X	0.0003"
Y	0.0003"
Z	0.0003"



*Single Camera Point Cloud*

### Point Probing Results – M-Mode

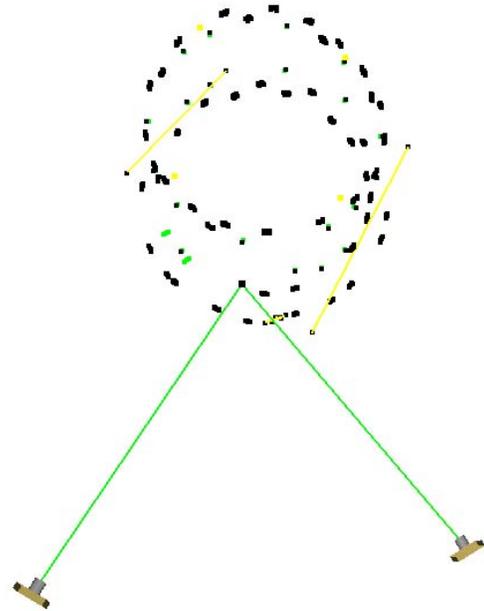
In order to establish the edge of part, surface points and bottom plane location it was necessary to configure the system for use in M or Multi camera mode. In this mode two or more cameras are used to determine the location of a wireless hand held probe. Sixteen different probes, each of which uses standard interchangeable CMM tips are available.



The probes themselves are interchangeable during a measurement. If the probe is changed, V-STARS automatically recognizes the new probe. The use of these

probes is typically called for when features that are cannot be readily targeted are required. These features might include edge points, holes or scribe lines.

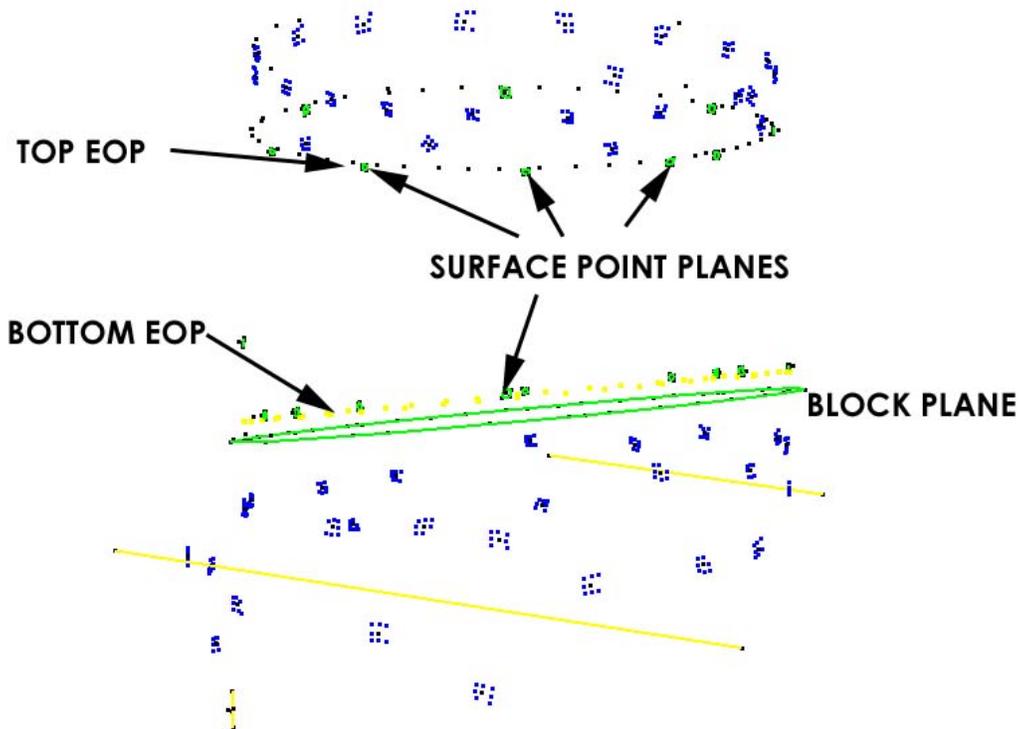
To work in M-Mode a coordinated reference frame is required. This reference frame is used to determine the location of the cameras after each flash. Fortunately no additional work is required to establish this reference as it was established during the initial single camera network. Once an image has been acquired the cameras are capable of determining their orientation relative to the object. This information is presented graphically so that the user can decide whether the positioning is suitable for the area of interest. Typical M-mode geometry is shown in the adjacent image.



Once collection has been completed in a particular area, the cameras are simply relocated into the next measurement location. Re-establishment into the coordinate system is completed automatically. Point probing is illustrated in the image below.



The M-Mode data collected is shown in the image below.



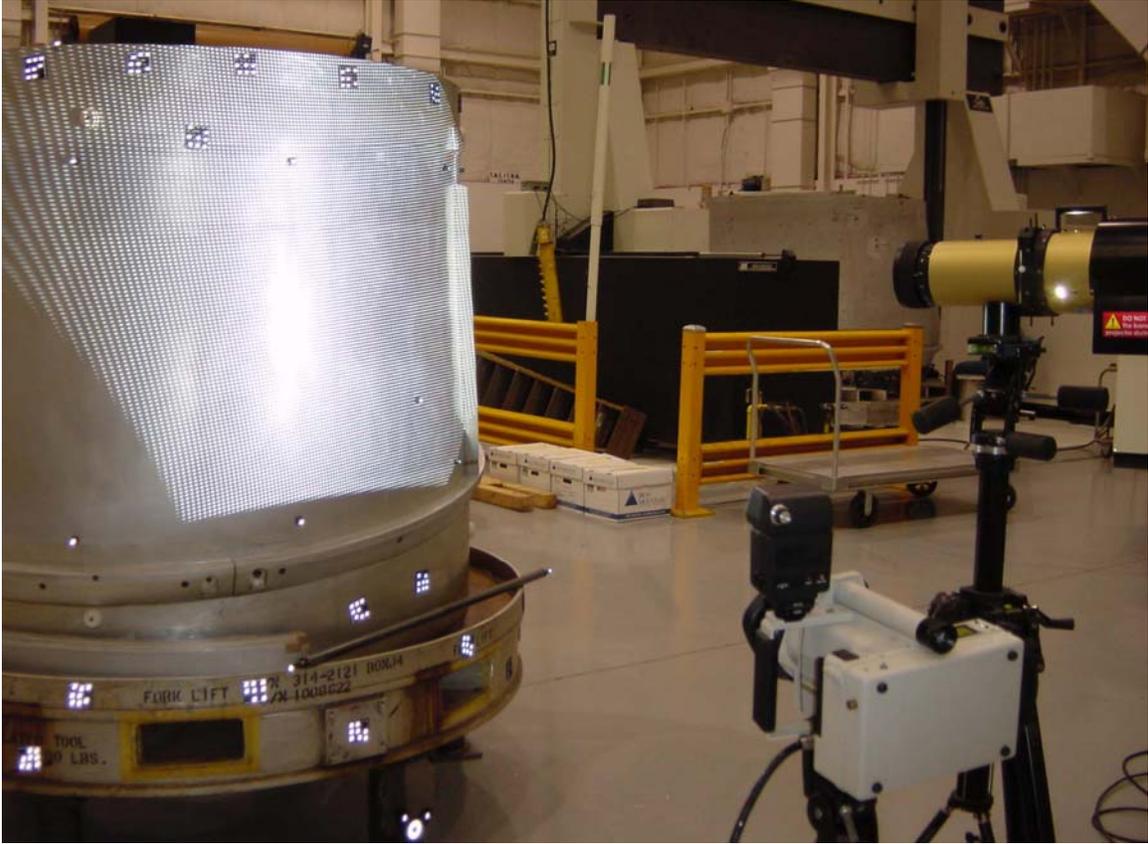
## Surface Collection Results– PRO-SPOT

PRO-SPOT works by projecting thousands of dots the measurement surface. These dots are measured by a single camera V-STARS/S system. The tool was covered with six PRO-SPOT set-ups. The results are shown below.

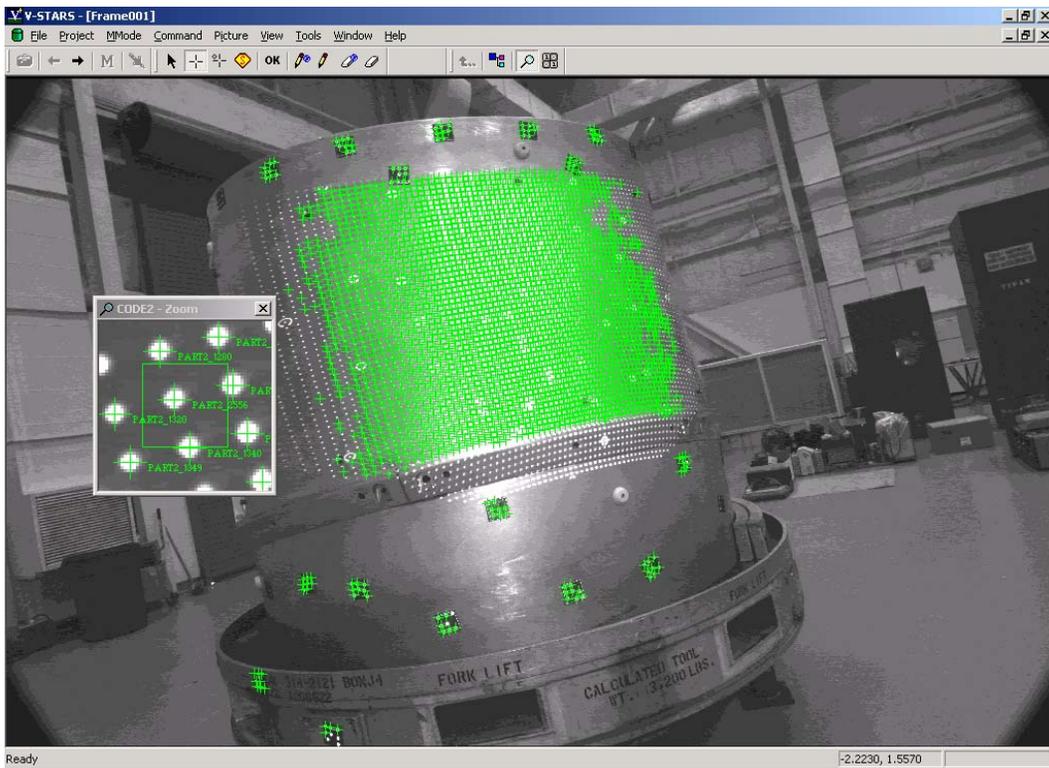
### PRO-SPOT (Typical results from 6 set-ups)

No. of photos	10-14
No. of points	1100-1450
Accuracy RMS X,Y,Z	X 0.0005"
	Y 0.0005"
	Z 0.0008"

Surface points were collected at an approximate spacing of 0.6".

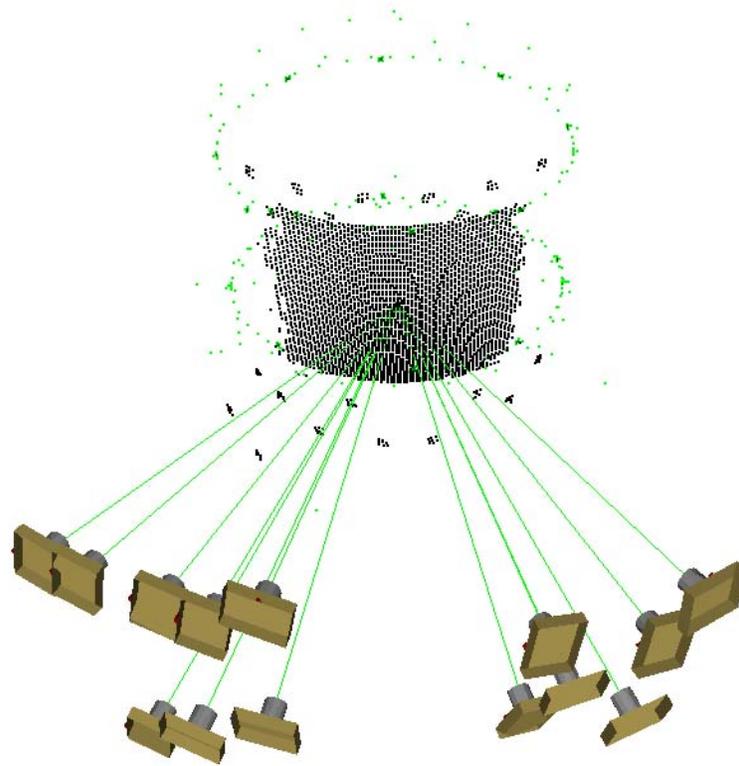


Typical PRO-SPOT set-up

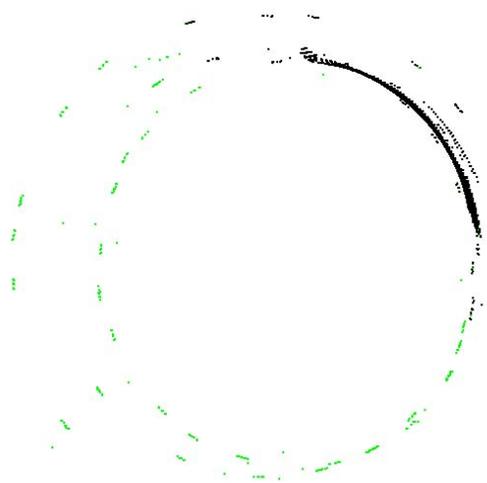


Typical PRO-SPOT measurement image

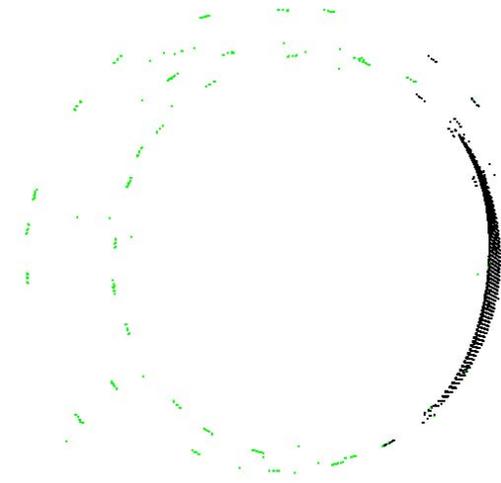
The diagram below illustrates the typical geometry used to create each of the patches.



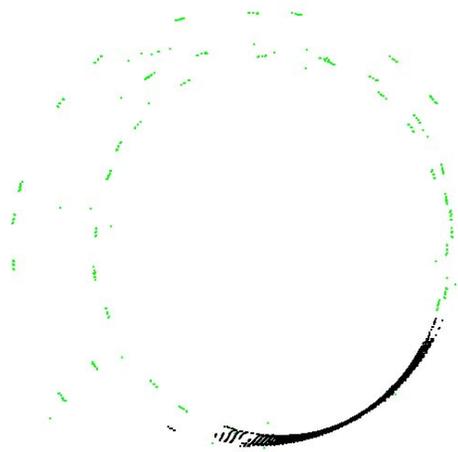
The diagrams below illustrate the PRO-SPOT patches collected and their location on the mold surface. These are the point clouds prior to the removal of points that fell outside of the Edge of Part boundaries.



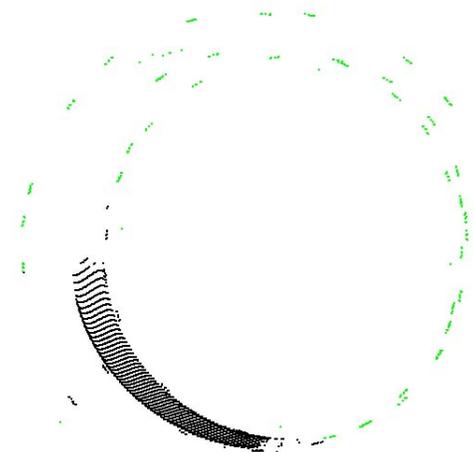
PART1  
3564 original points. 2938 after stripping.



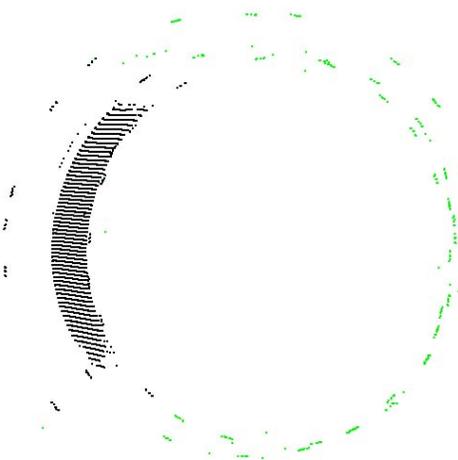
PART2  
3383 original points. 2947 after stripping.



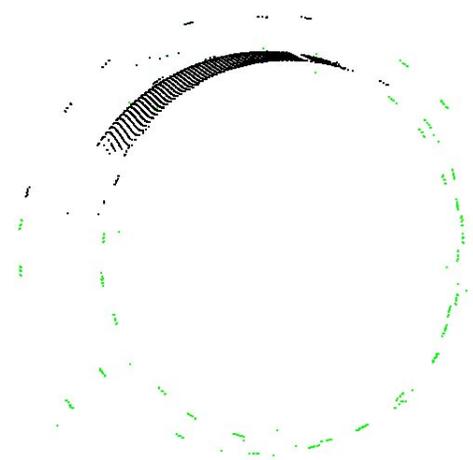
PART3  
3038 original points. 2736 after stripping.



PART4  
3351 original points. 2902 after stripping.



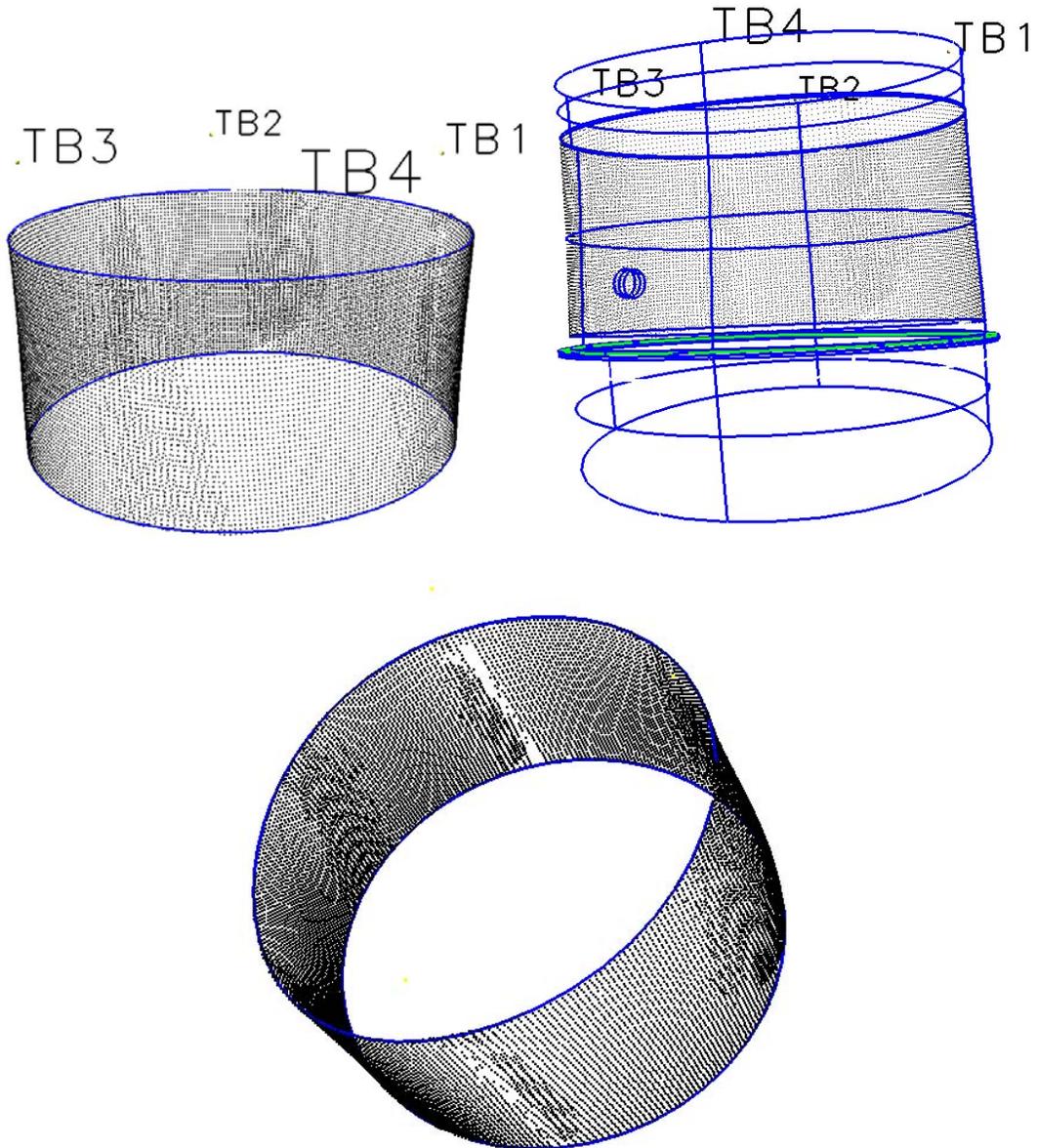
PART5  
3395 original points. 2984 after stripping.



PART6  
3048 original points. 2725 after stripping.

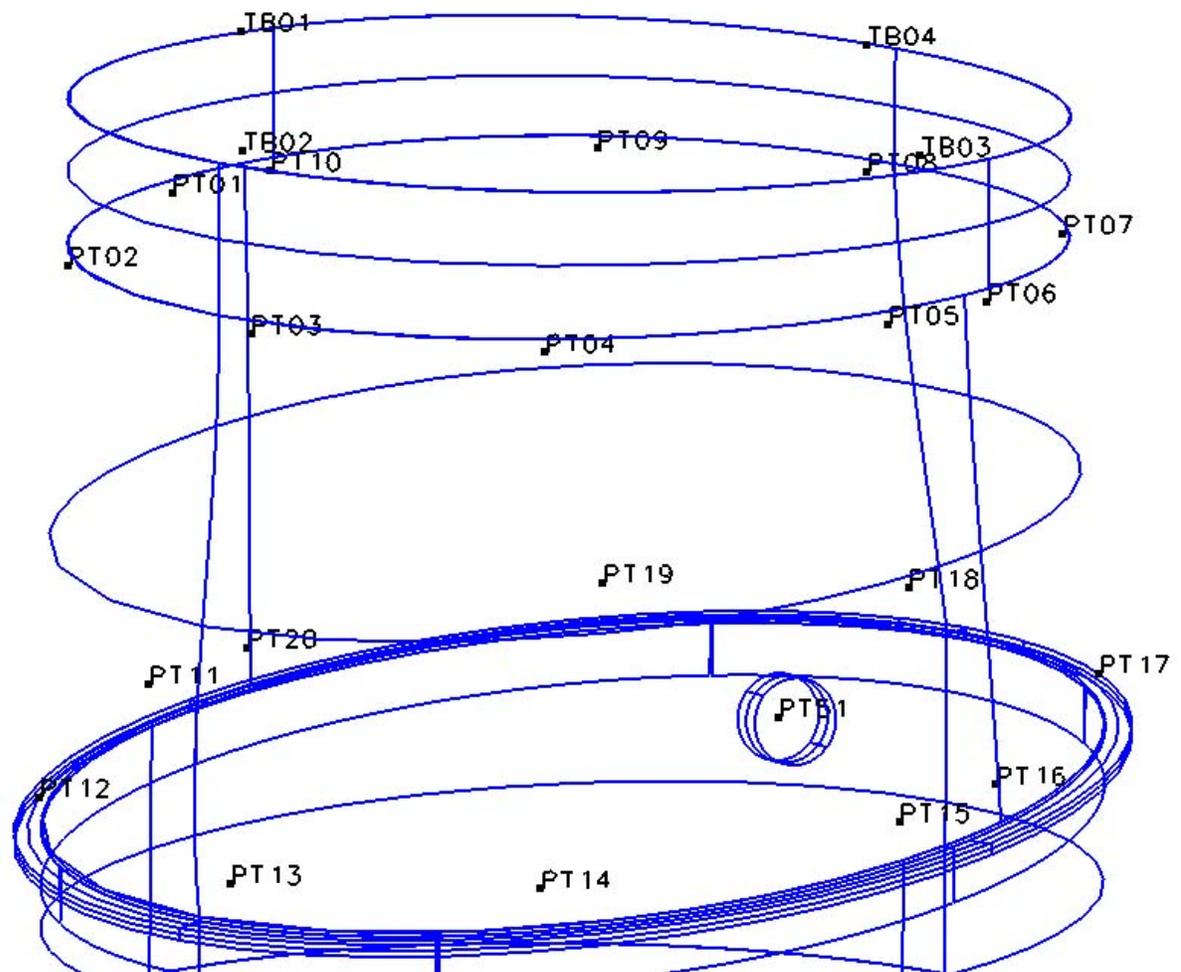
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The diagram below illustrates the combined PRO-SPOT patches and their relationship relative to the TB points. The six patches combined produced a combined file with a total of **19641** points. Points that fell outside the Edge of Part were removed. The final point cloud was made up of **17232** points. The point clouds are shown in the images below.



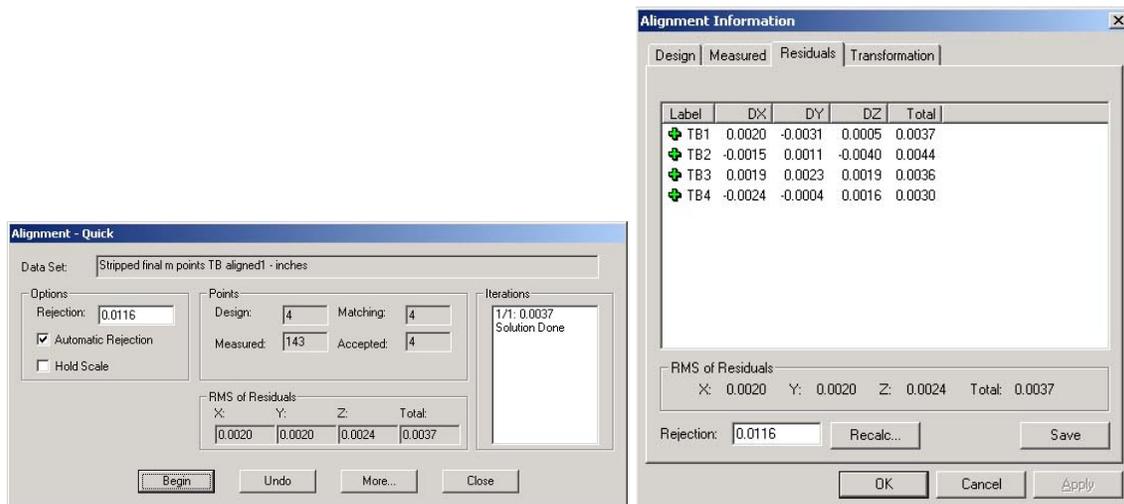
## Numbering Guide

- Individual points in each PRO-SPOT part were named PART1\_??, PART2\_??, etc. etc.
- Tooling points labeled TB1 to TB4 as per the stamped names on the tooling fixture.
- Surface points were labeled as per the designated design names shown below.
- The block plane points were labeled BLOCK??.
- The edge of part points were labeled TEOP?? and BEOP??

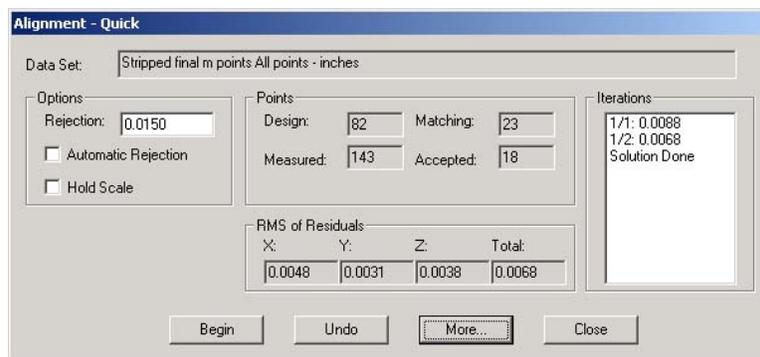


# Alignment

Typically one of the last tasks is alignment into the coordinate system of the object being measured. There are two basic types of alignment. The first is a simple Axis or 3-2-1 alignment. This alignment is based on three points – an origin, an axis point and a third point to define the plane in which the axis lies. The second type of alignment uses point correspondence from a known alignment (such as the CAD model) to transform the data into that coordinate system. This is a “best-fit” solution and is preferred as it involves greater redundancy. In this measurement the alignment was carried out using the four tooling points (TB) on top of the tool. The distribution of these points is shown in the previous image. The results of the alignment are shown below. The RMS of the best-fit between the measured and nominal values was 0.0037”.



The RMS of the best-fit between the measured and nominal values for the TB and surface points was 0.0068”. Five points were rejected. Four of the points were the TB points. This indicates that there is an alignment error between the TB points and the surface points. This error seems to have a magnitude of 0.030” in the X direction.



The individual RMS figures are shown in the following images.

Label	DX	DY	DZ	Total
PT51	0.0233	0.0081	-0.0025	0.0248
TB1	-0.0289	-0.0072	-0.0040	0.0300
TB2	-0.0330	-0.0000	-0.0046	0.0333
TB3	-0.0250	0.0051	-0.0013	0.0256
TB4	-0.0291	-0.0007	-0.0049	0.0296
PT01	0.0045	0.0022	-0.0002	0.0050
PT02	-0.0059	-0.0010	-0.0070	0.0092
PT03	-0.0030	-0.0039	-0.0043	0.0066
PT04	-0.0052	0.0001	-0.0017	0.0055
PT06	0.0024	0.0036	-0.0020	0.0048
PT07	-0.0029	0.0052	0.0032	0.0068

RMS of Residuals  
X: 0.0048 Y: 0.0031 Z: 0.0038 Total: 0.0068

Rejection:  Recalc... Save

OK Cancel Apply

Label	DX	DY	DZ	Total
PT08	-0.0071	0.0011	0.0053	0.0089
PT09	-0.0051	0.0041	-0.0005	0.0066
PT10	-0.0030	0.0059	0.0019	0.0069
PT13	-0.0006	0.0007	0.0026	0.0028
PT14	0.0020	-0.0038	-0.0004	0.0043
PT16	0.0021	-0.0020	-0.0059	0.0065
PT17	-0.0007	-0.0013	-0.0017	0.0023
PT18	0.0011	-0.0028	0.0097	0.0102
PT19	0.0002	-0.0037	-0.0000	0.0037
PT118	0.0112	-0.0037	0.0003	0.0118
PT119	0.0092	0.0003	0.0012	0.0093

RMS of Residuals  
X: 0.0048 Y: 0.0031 Z: 0.0038 Total: 0.0068

Rejection:  Recalc... Save

OK Cancel Apply

## Analysis

SOLIDS is the geometric analysis module of V-STARS. For example, consider a simple function like determining the distance between two points. Computing the point-to-point distance is as simple as highlighting the two points and pressing "d". The result appears on the screen and is also written to the 3D file.

Calculation of the Best-fit plane is also very simple. The plane points are highlighted and the "P" key is pressed. The plane dialog is shown in the adjacent image. The dialog gives you a few options and reports the results of the operation.

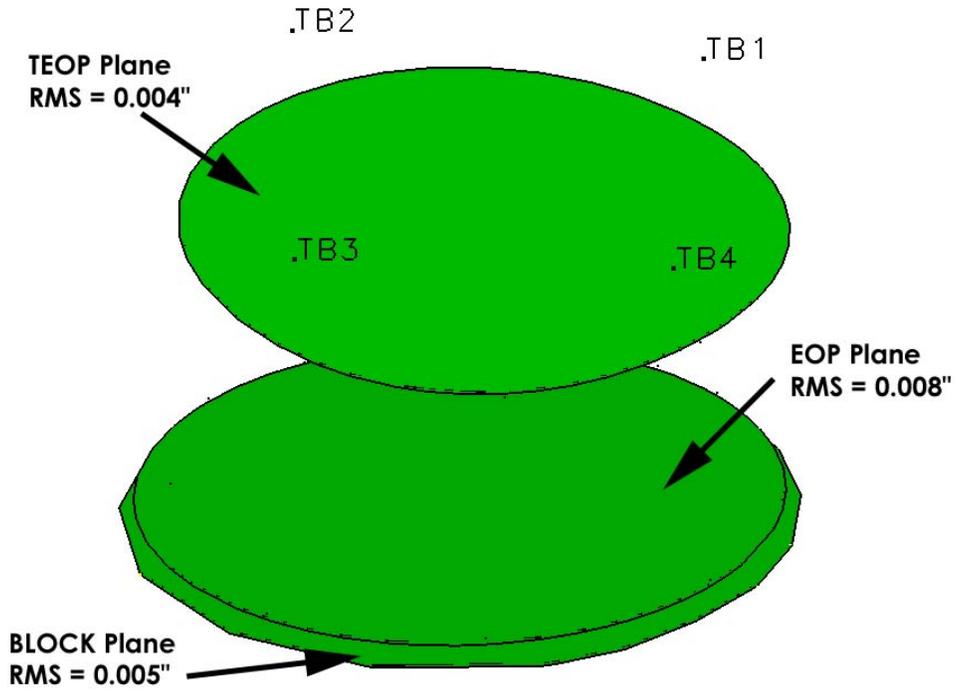
Similarly, best-fit lines, circles, spheres etc. can also be calculated. SOLIDS also has the ability to measure between objects. For example, by selecting a point and a plane the normal distance can be computed. This makes SOLIDS a very useful analysis tool.

Label	Residuals
+ CODE118	0.0017
+ NUGGET118_1	0.0004
+ NUGGET118_9	0.0001
+ NUGGET118_14	0.0011

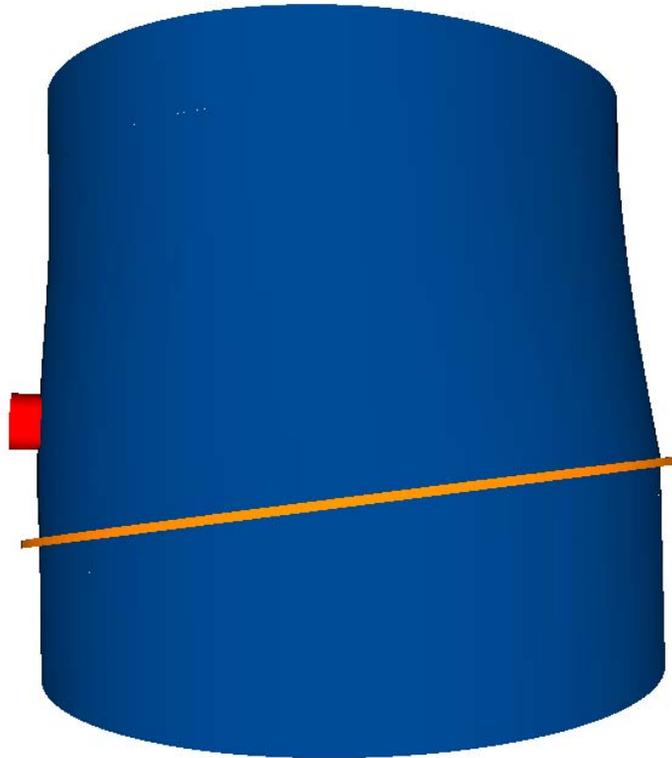
*Typical Plane Dialog*

For this measurement best-fit planes were calculated for the BLOCK data and TOP and BOTTOM EOP points.

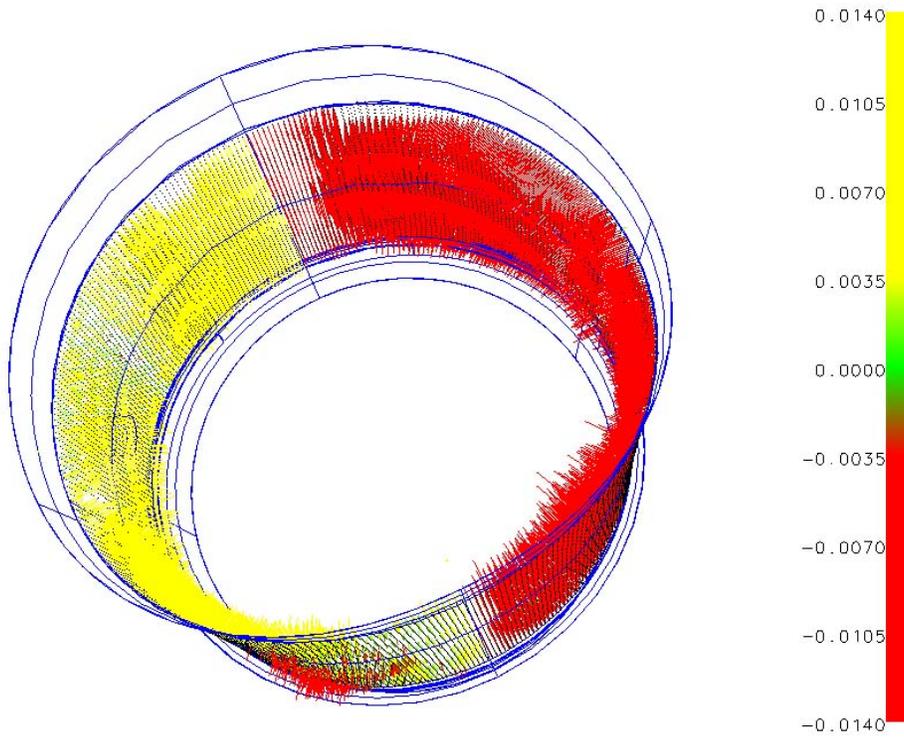
The supplied IGES model was used to calculate surface deviations.  
The diagram below shows the planes calculated and their final RMS value.



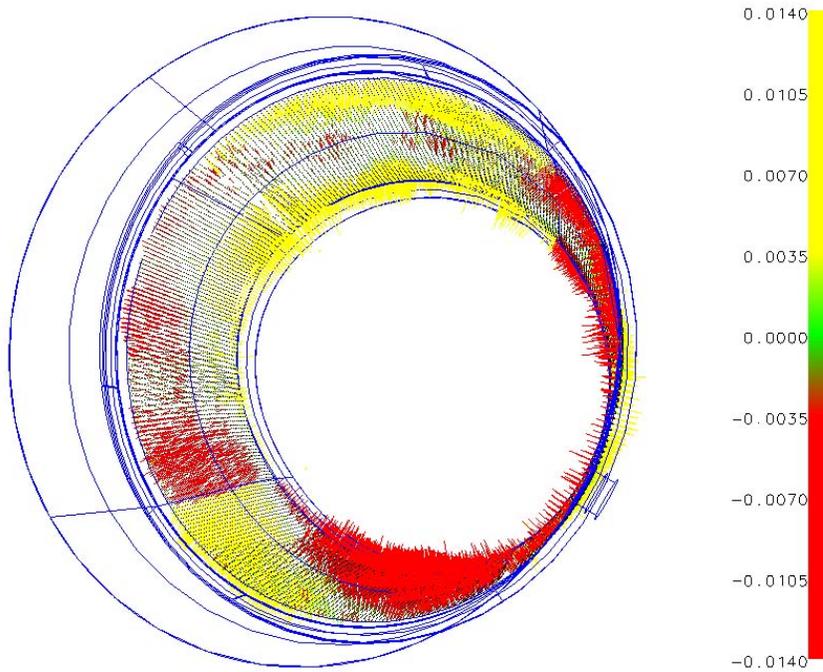
The IGES model of the tool supplied is shown in the diagram below.



The diagram below illustrates the surfaced measurement deviations based on alignment to the TB values. A clear alignment error trend is visible.



The diagram below illustrates the surfaced measurement deviations based on alignment to the points on the surface. This is known as a surface alignment. There is still a trend, but it appears less pronounced.



## Time Summary

Control Targeting	5 minutes
Control Photography	5 minutes
Control Processing	5 minutes
Alignment	5 minutes
Probing	40 minutes
PRO-SPOT Collection	30 minutes
6 set ups @ 5 mins per set up	
Data Analysis	60 minutes
Total	<b>150 minutes</b>

## Concluding Remarks

The measurements undertaken have shown that V-STARS with the INCA S6 system, probes and PRO-SPOT projection system can be a very powerful measurement tool. The results of the measurement undertaken were very accurate and more importantly were produced quickly.

GSI would like to thank Goodrich, Riverside for welcoming us into their facility. We will be happy to discuss the results of this report or any other aspect of the technology presented.