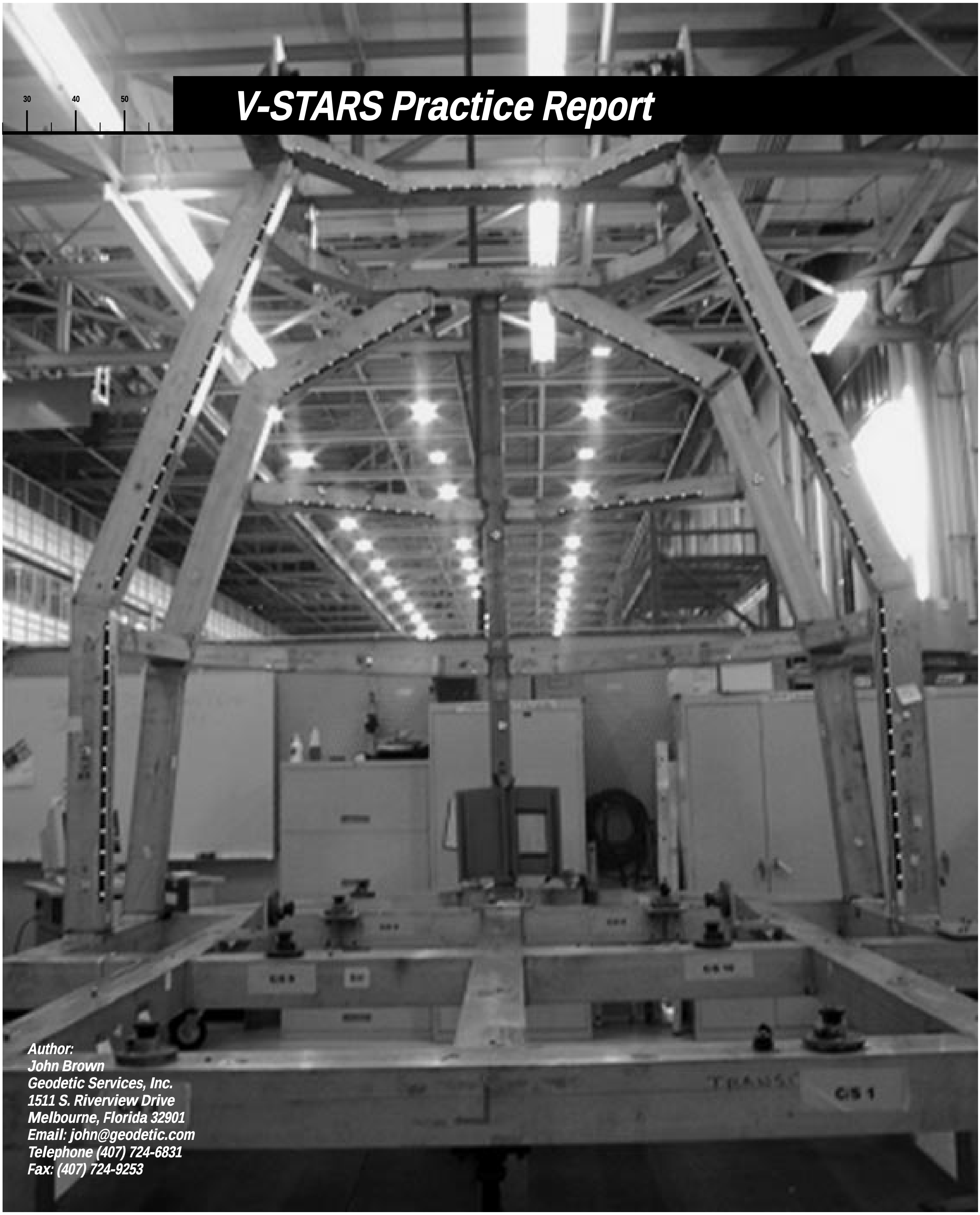
V-STARS Practice Report



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V-STARS/S – Acceptance Test Results

Acceptance Test Results

Figure 1a: Cab tool used for acceptance test

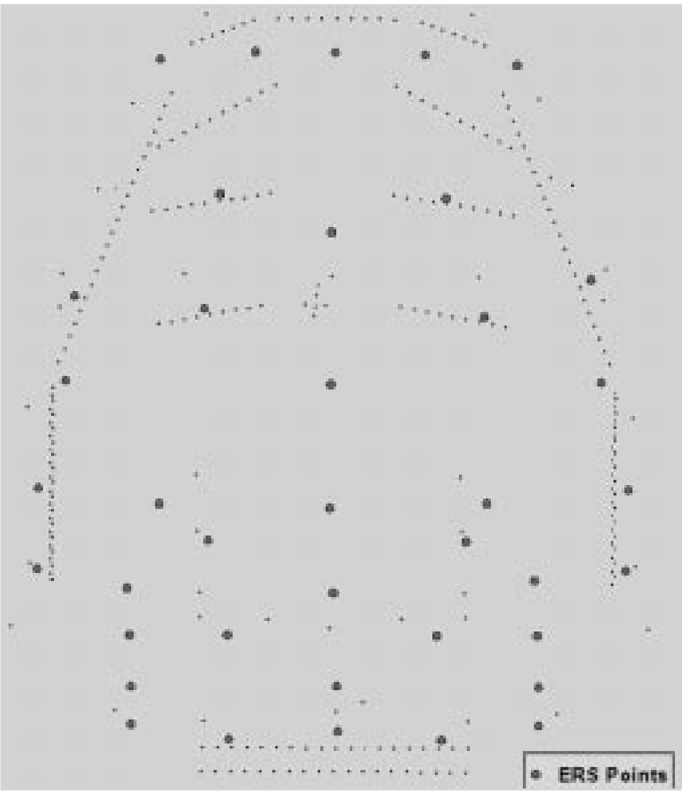


Figure 1b: Cab tool diagram showing 37 comparison points

Abstract

In early 1997, a large aircraft manufacturer conducted a comprehensive acceptance test of Geodetic Services Inc.'s (GSI's) V-STARS/S photogrammetric measurement system. The purpose of the test was to establish the accuracy of V-STARS on typical objects under industrial measurement conditions, using typical equipment, and aerospace company personnel. The tests were performed on two objects that represented a wide variety of potential applications. The two objects were measured in typical industrial measurement conditions, not in laboratory conditions. The objects were photographed using three of GSI's latest generation INCA digital cameras. Company personnel took all the pictures, and measured all the photography. The results were compared to an independent measurement of the object established by a laser tracker. Every practical step was taken to ensure the laser tracker measurement was of the highest possible accuracy. This report describes the tests, the measurement results, and the accuracy achieved.

Overview of Tests

Two different objects were measured. The "Low Aspect Ratio Test" measured a medium sized object that was approximately equal in extent in all three directions. The "High Aspect Ratio Test" measured a large object that was about 10 times as long as it was wide or deep. The two tests are meant to cover a wide variety of potential applications within the aerospace company. Each test is described separately in this report. [Sandwith, 1997]

To establish the measurement accuracy of a system, one can compare the measurement results to an established standard. The standard should be of considerably higher accuracy than the measurement system under test. In addition, the standard and the system should measure the same physical feature (called "target duplication"). For a high-accuracy, large volume, measuring system such as V-STARS that measures retro-reflective targets this is a very difficult task. The client took great efforts to establish a very accurate standard for each test using a laser tracker. In addition, they used a spherical corner cube with the same offset as the standard retro-reflective tooling targets used in the photogrammetry measurement. [Fraser, 1997]

Low Aspect Ratio Test

Description of Test Object

This test measured an Airplane Cab Tool that is used for training. The tool is made of rigid aluminum girders. It is about 3 m wide by 3 m high by 3.7 m long. A picture of the Cab Tool is shown in Figure 1a.

Approximately 200 retro-reflective targets were measured. Thirty-seven retro-reflective targets were placed in bushed holes that were distributed throughout the tool. The bushed holes were also measured by the laser tracker as described later. Since the retro-reflective targets and the spherical corner cubes had the same offset (5⁄16"), these points could be compared directly. The location of the 37 Enhanced Reference System (ERS) targets used in the comparison is shown in Figure 1b.

Description of Accuracy Standard (using laser tracker)

A laser tracker measured the 37 bushed holes on the Airplane Cab Tool. Every practical step was taken to ensure the measurement was of the highest possible accuracy. For example, the laser tracker used a refractometer to compensate for atmospheric effects. Also, the temperature of the object was monitored using several probes so temperature effects could be eliminated.

Although the laser tracker could have measured the object in a single setup, two setups were used to improve the accuracy. Also, the object was measured three times (with two setups for each measurement). The three surveys were then averaged to get the final values for the test comparison.

The coordinate system of the Airplane Cab Tool standard was defined so the Y-Z plane is parallel to the floor, and the X-axis is pointing down. The estimated accuracy of the Airplane Cab Tool coordinates determined by the laser tracker is 0.020 mm RMS (one sigma) in each coordinate.

Description of V-STARS Measurement (using three INCA cameras)

The purpose of the test was to establish the accuracy of V-STARS on a typical low aspect ratio object under typical measurement conditions using typical equipment, and aerospace personnel. Accordingly, three INCA cameras (Serial Numbers 7, 8 and 9) were used to measure the Airplane Cab Tool. Each camera measured the tool twice for a total of six independent measurements. Three operators took the photography. Each operator took about 30 photographs of the tool. Photography typically took less than 30 minutes per measurement. To minimize temperature effects, the three operators took pictures one after the other. The layout of the camera stations is shown below in Figure 2.

Several different operators measured the photographs after they received GSI's standard one-week basic training course.

Description of Measurement Results

The results for each of the six measurements were compared to the standard after transformation into the coordinate system defined by the laser tracker. The scale established by the laser tracker was used to scale the photogrammetric measurement. The results of the comparison to the laser tracker standard are summarized in Table 1 below.

The RMS of the differences range from 0.031mm to 0.043mm. Notice the three cameras have similar differences. There is little variation in camera results.

Figures 3a, 3b, 3c show the individual point differences for all six measurements in X, Y and Z respectively. In some cases, the individual differences for the six measurements agree very well with each other indicating a systematic difference between the laser tracker and V-STARS. This could be due to target differences or some other unresolved effect. Still, the overall agreement is quite good.

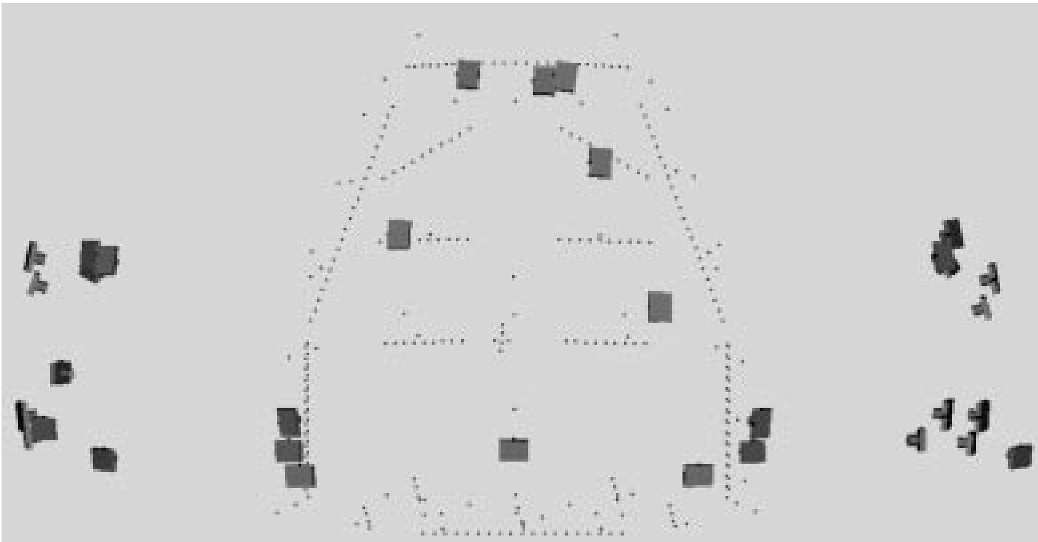
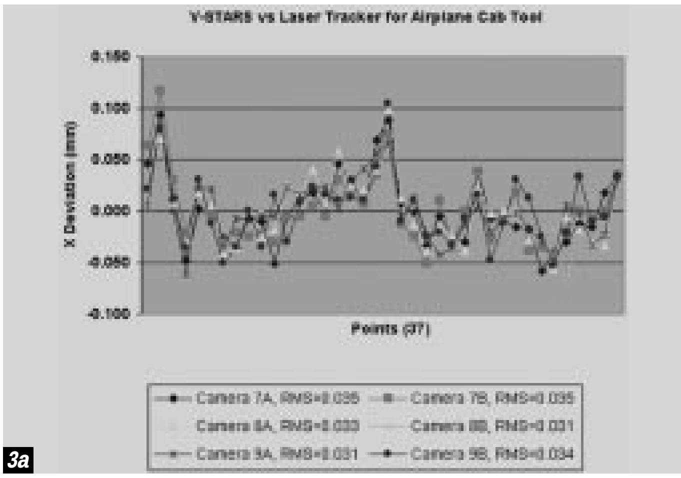


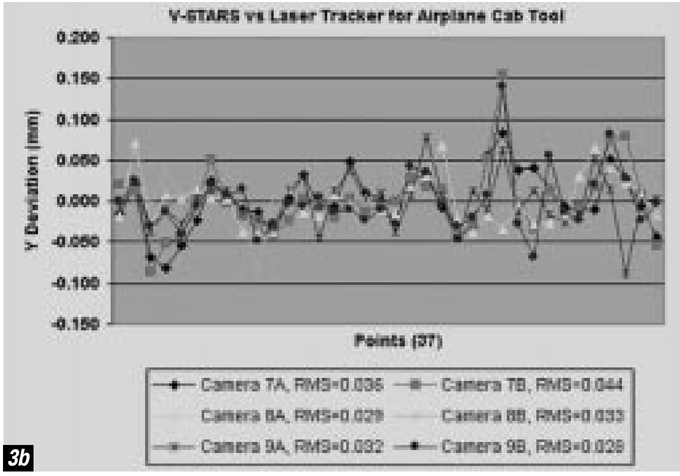
Figure 2: Location and distribution of camera stations around Cab Tool

		RMS of Differences (mm)		
Case	*# Points*	*RMS X*	*RMS Y*	*RMS Z*
Camera 7-1	*37*	*0.035*	*0.035*	*0.041*
Camera 7-2	*37*	*0.035*	*0.043*	*0.038*
Camera 8-3	*37*	*0.033*	*0.031*	*0.035*
Camera 8-4	*37*	*0.031*	*0.033*	*0.038*
Camera 9-5	*37*	*0.031*	*0.033*	*0.035*
Camera 9-6	*37*	*0.033*	*0.038*	*0.041*

***Notes**:*
1) RMS differences are after rigid body transformation of each measurement into a common coordinate system using 37 ERS points

Table 1:V-STARS Vs Laser Tracker Results for Airplane Cab Tool





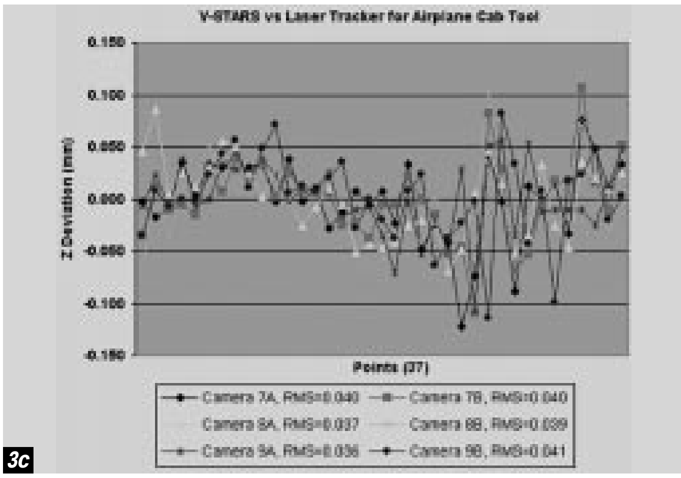


Figure 3a: X Deviations V-STARS Vs Laser Tracker Results for Airplane Cab Tool

Figure 3b:Y Deviations V-STARS Vs Laser Tracker Results for Airplane Cab Tool

Figure 3c: Z Deviations V-STARS Vs Laser Tracker Results for Airplane Cab Tool

		RMS of Differences (mm)			*Estimated Accuracy (ppm)*		
Case	*# Points*	*RMS X*	*RMS Y*	*RMS Z*	*X*	*Y*	*Z*
Camera 7-1	*37*	*0.035*	*0.035*	*0.041*	*7.7*	*7.7*	*9.2*
Camera 7-2	*37*	*0.035*	*0.043*	*0.038*	*7.7*	*10.0*	*8.5*
Camera 8-3	*37*	*0.033*	*0.031*	*0.035*	*6.8*	*6.0*	*7.7*
Camera 8-4	*37*	*0.031*	*0.033*	*0.038*	*6.0*	*6.8*	*8.5*
Camera 9-5	*37*	*0.031*	*0.033*	*0.035*	*6.0*	*6.8*	*7.7*
Camera 9-6	*37*	*0.033*	*0.038*	*0.041*	*6.8*	*8.5*	*9.2*

Notes:

1) RMS differences are after rigid body transformation of each measurement into a common coordinate system using 37 ERS points

2) Maximum Dimensional Length (MDL) = 3810mm

3) Standard's accuracy is estimated as follows:
Laser tracker accuracy = 0.010mm (RMS, one sigma)
Laser tracker target accuracy = 0.013mm (RMS, one sigma)
Retro-reflector target accuracy = 0.013mm (RMS, one sigma)

Total standard accuracy $= \sqrt{(0.010^2 + 0.013^2 + 0.013^2)} = 0.020$ *mm*

4) Estimated accuracies are in parts per million (ppm) computed as follows:

Estimated accuracies $= 1{,}000{,}000 \times \sqrt{(\text{RMS Value}^2 - \text{Standard's Accuracy}^2)} / \text{MDL}$

for example, with MDL = 3810 mm, RMS = 0.038 mm, and Standard's Accuracy of 0.020 mm)

Estimated Accuracy $= 1{,}000{,}000 \times \sqrt{(0.038^2 - 0.020^2)} / 3810 = 8.5$ *ppm*

Table 2: V-STARS Accuracy Analysis

Accuracy Analysis

Given these results, what is the measurement accuracy of the V-STARS system? If the standard were perfectly accurate, the accuracy would be readily established as the RMS of the differences listed above. However, the standard is not perfect. Given that the overall accuracy of the laser tracker standard is estimated by the aerospace company at 0.020 mm in each coordinate, the accuracies expressed in parts per million (ppm) are shown in Table 2.

The accuracy estimates resulting from the six measurements are all equal to or better than the 10 ppm RMS (one sigma) typical accuracy specification of the system.

High Aspect Ratio Test

Description of Test Object

This test measured an Empennage Assembly Tool that is used for production. The tool is made of steel. It is about 13.2 m long by 1.32 m high by 1.2 m wide. A picture of the Empennage Tool is shown in Figure 4a.

Approximately 400 retro-reflective targets were measured. Thirty-one retro-reflective targets were placed in bushed holes that were distributed throughout the tool. The bushed holes were also measured by the laser tracker as described later. Since the retro-reflective targets and the spherical corner cubes had the same offset (5⁄16”), these points could be compared directly. The location of the 31 ERS targets used in the comparison is shown in Figure 4b.

Description of Accuracy Standard (using laser tracker)

A laser tracker measured the 31 bushed holes on the Empennage Assembly Tool. Every practical step was taken to ensure the measurement was of the highest possible accuracy. For example, the laser tracker used a refractometer to compensate for atmospheric effects. Also, the temperature of the object was monitored using several probes so temperature effects could be eliminated.

Although the laser tracker could have measured the object in two setups, three setups were used to improve the accuracy. Also, the object was measured three times (with three setups for each measurement). The three surveys were then averaged to get the final values for the test comparison.

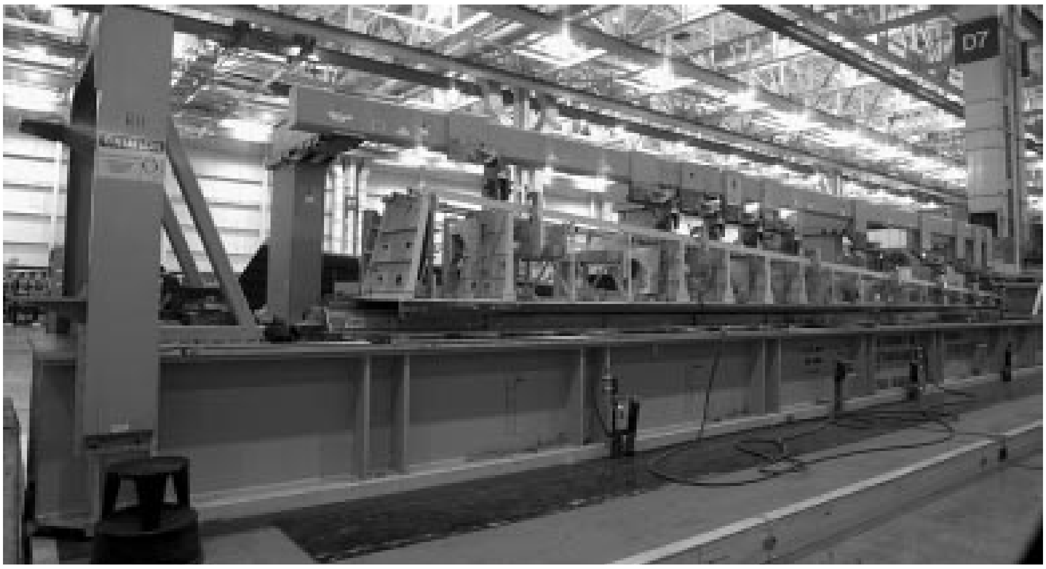


Figure 4a: Empennage Assembly Tool used for acceptance test

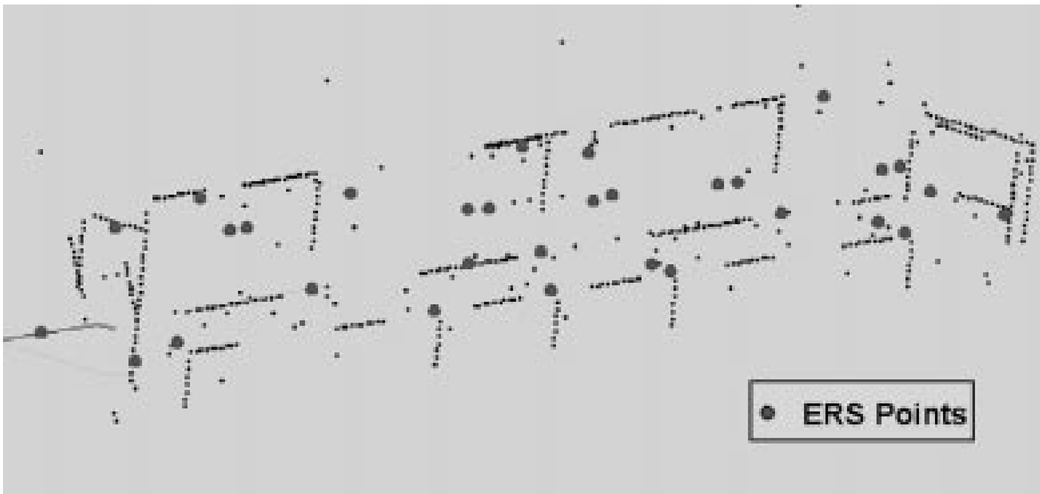


Figure 4b: Empennage Assembly Tool diagram showing 31 comparison points

The coordinate system of the Empennage Assembly Tool standard was defined so the X-axis was along the long side of the tool. The X-Y plane is parallel to the floor, and the Z-axis is pointing down. The estimated accuracy of the Empennage Assembly Tool coordinates is 0.023 mm RMS (one sigma) in each coordinate.

Description of V-STARS Measurement (using three INCA cameras)

The purpose of the test was to establish the accuracy of V-STARS on a typical high aspect ratio object under typical measurement conditions using typical equipment, and aerospace company personnel. Accordingly, three INCA cameras (Serial Numbers 7,8 and 9) were used to measure the tool. Unfortunately, tool availability limited the test to a single measurement from each camera.

A different operator took each set of photography. Ninety-nine (99) photographs were taken for each measurement of the tool. Photography typically took less than 45 minutes per measurement. To minimize temperature effects, the three operators took pictures one after the other. The layout of the camera stations is shown in Figure 5.

Several different operators measured the photographs after they received GSI’s standard one-week basic training course.

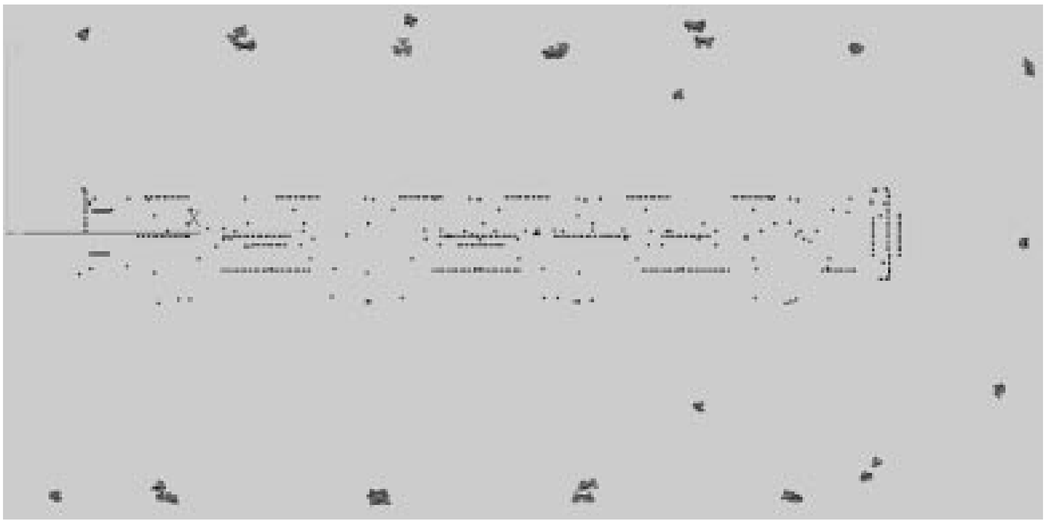


Figure 5: Location and distribution of camera stations around Empennage Assembly Tool

		RMS of Differences (mm)		
Case	*# Points*	*RMS X*	*RMS Y*	*RMS Z*
Camera 7-1	*31*	*0.043*	*0.071*	*0.051*
Camera 8-3	*31*	*0.076*	*0.091*	*0.043*
Camera 9-5	*31*	*0.046*	*0.066*	*0.043*

Notes:

1) RMS differences are after rigid body transformation of each measurement into a common coordinate system using 31 ERS points

Table 3: V-STARS Vs Laser Tracker Results for Assembly Tool

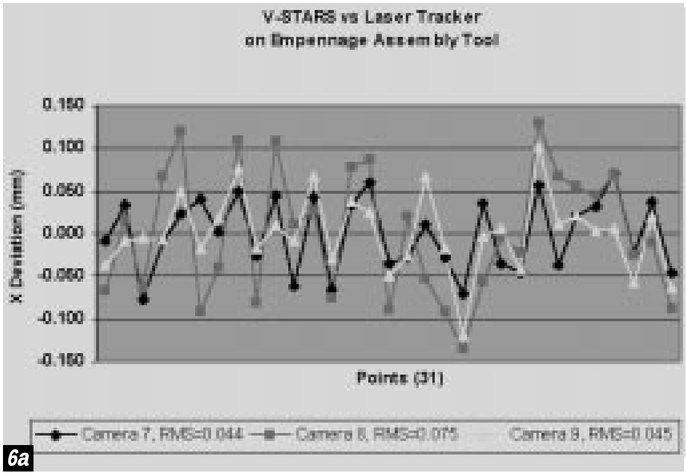


Figure 6a: X Deviations V-STARS Vs Laser Tracker Results for Empennage Assembly Tool

Figure 6b: Y Deviations V-STARS Vs Laser Tracker Results for Empennage Assembly Tool

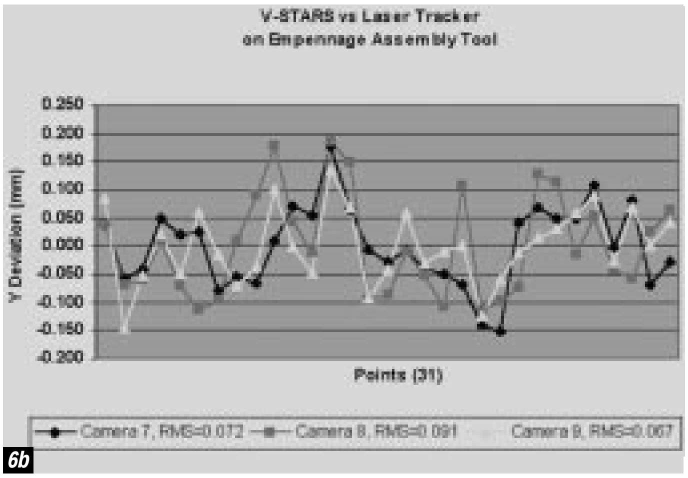
Figure 6c: Z Deviations V-STARS Vs. Laser Tracker Results for Empennage Assembly Tool

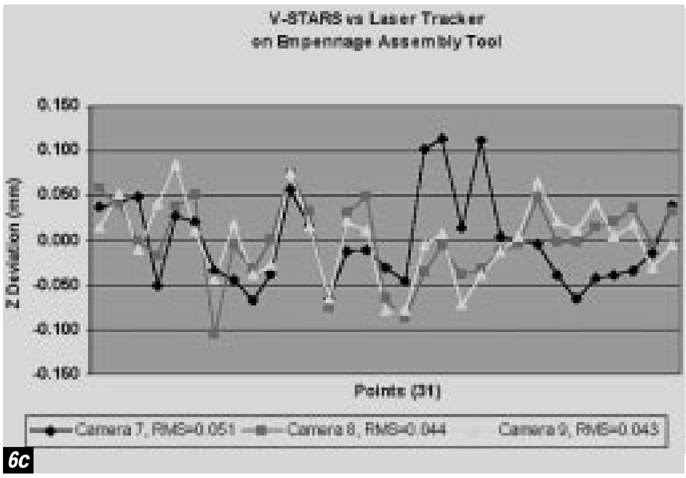
Description of Measurement Results

The results for each of the three measurements were compared to the standard after transformation into the coordinate system defined by the laser tracker. The scale established by the laser tracker was used to scale the photogrammetric measurement. The results of the comparison to the laser tracker standard are summarized in Table 3.

The RMS of the differences range from 0.043 mm to 0.091 mm. Notice cameras 7 and 9 have similar results, and are extremely good. The differences for camera 8 are somewhat larger but still quite good.

Figures 6a, 6b, 6c show the individual point differences for all three measurements in X, Y and Z respectively. In some cases, the individual differences for the three measurements agree very well with each other indicating a systematic difference between the laser tracker and V-STARS. This could be due to target differences or some other unresolved effect. Also, the differences for camera 8 are noticeably larger than those for the other two cameras. Still, the overall agreement is quite good.





Accuracy Analysis

Given these results, what is the measurement accuracy of the V-STARS system? If the standard were perfectly accurate, the accuracy would be readily established as the RMS of the differences listed above. However, the standard is not perfect. Given that the overall accuracy of the laser tracker standard is estimated by the aerospace company at 0.023 mm, the accuracies expressed in parts per million (ppm) are given in Table 4.

The accuracy estimates resulting from the three measurements are all much better than the 10 ppm RMS (one sigma) typical accuracy specification of the system. This is true even for camera 8. However, the results for camera 8 are intriguing. The camera had similar results to the other two cameras in the Low Aspect Ratio Test, and also in GSI's acceptance testing. Also, the internal accuracy estimates for all 3 surveys are similar. GSI is investigating this difference, and will try to improve system accuracies.

Conclusion

The acceptance tests at Boeing established that the V-STARS.S system meets its established accuracy specifications, and is a reliable metrology system when used with proper procedures. The testing showed the system accuracy can be met in a wide variety of potential applications. In addition, the results were achieved using typical equipment in an industrial measuring environment using and trained aerospace personnel.

		RMS of Differences (mm)			Estimated Accuracy (ppm)		
Case	# Points	RMS X	RMS Y	RMS Z	X	Y	Z
Camera 7-1	31	0.043	0.071	0.051	2.8	5.1	3.4
Camera 8-3	31	0.076	0.091	0.043	5.5	6.7	2.8
Camera 9-5	31	0.046	0.066	0.043	3.0	4.7	2.8

Notes:

1) RMS differences are after rigid body transformation of each measurement into a common coordinate system using 31 ERS points

2) Maximum Dimensional Length (MDL) = 13200mm

3) Standard's accuracy is estimated as follows:
Laser tracker accuracy = 0.015mm (RMS, one sigma)
Laser tracker target accuracy = 0.013mm (RMS, one sigma)
Retro-reflector target accuracy = 0.013mm (RMS, one sigma)

Total standard accuracy = $\sqrt{(0.015^2 + 0.013^2 + 0.013^2)}$ *= 0.023mm*

4) Estimated accuracies are in parts per million (ppm) computed as follows:

Estimated accuracies = 1,000,000 x $\sqrt{(\text{RMS Value}^2 - \text{Standard's Accuracy}^2)}$ */ MDL*
for example, with MDL = 132000mm, RMS = 0.051mm, and Standard's Accuracy of 0.023mm)

Estimated Accuracy = 1,000,000 x $\sqrt{(0.051^2 - 0.023^2)}$ */ 13200 = 3.4 ppm*

Table 4: V-STARS Accuracy Analysis

Remarks

The author wishes to note that the results contained in this report are representative of the analysis carried out by GSI and not that of the aerospace company.

References

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SANDWITH, S., Proc. SPIE Vol. 3204, p. 36-47, Three-Dimensional Imaging and Laser-based Systems for Metrology and Inspection III, Kevin G. Harding; Donald J.Svetkoff; Eds.

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