Report of V-STARS Measurement at the National Radio Astronomy Observatory (NRAO)

Overview

The following is a summary of the results from the demonstration of the Geodetic Systems, Inc. V-STARS system. V-STARS is a powerful, portable and precise system that uses one or more high-resolution digital cameras to measure objects via photogrammetry. The system is widely used throughout industry for part and tool inspection. GSI performed the demonstration at NRAO's Very Large Array (VLA) facility in Socorro, New Mexico in 1998. Since numerous improvements have been made since then, this paper has been updated to reflect the current state of the art with respect to the equipment and systems available. In particular, improvements in equipment and techniques have increased accuracy to the point that we estimate accuracies on the reflector would now be about 50-75µm(0.002-.003") for the 25 meter diameter VLA antenna versus the 100-125µm accuracy (0.004-0.005") achieved in 1998.

Image courtesy of NRAO/AUI

For the demonstration, a 25 meter diameter VLA reflector (similar to the one shown above) was measured in three different orientations; 90˚, 45˚, and 0˚. The intention was to measure the main surface of the reflector five times; two times at 90˚, twice at 45˚ (once before adjustment, once after adjustment), and once at 0˚. All these measurements were accomplished on the first night. In addition, the VLA's subreflector was measured twice on the first afternoon. Also, a VLBA subreflector located on the ground was measured on the first afternoon three times. As the geometry turned out to be less than optimal for the 45˚ measurements (due to crane limitations), the visit was extended and the main surface of the reflector was measured six more times the following day and night. In total 11 measurements were made of the main reflector over the two day period of the visit.

The V-STARS Systems

A brief description of the V-STARS systems is provided in this section. For a more complete description, please see the product literature available from GSI.

The V-STARS systems are photogrammetric coordinate measurement systems that use single or multiple digital cameras to obtain images. The images are processed to obtain spatial three-dimensional coordinates. V-STARS has been very successful with over 450 systems sold since its introduction in 1994. The latest generation of camera (called INCA3 for **IN**telligent **Ca**mera), was introduced for use with V-STARS in 2002. The INCA line of cameras has been very successful with over 300 built including over 50 built for Boeing.

There are two basic V-STARS configurations: V-STARS/S, the single-camera system, and V-STARS/M, the multiple camera system. The V-STARS/S system was used for the demonstration. Although it was not used, the V-STARS/M system is briefly described in this report.

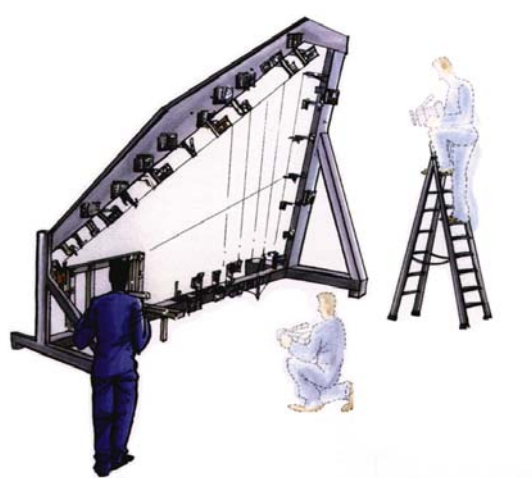
V-STARS/S System

The V-STARS/S system is an <u>intelligent</u> single camera 3-dimensional coordinate measurement system based on photogrammetry. The S model consist of a notebook computer, a single high-resolution intelligent digital camera (INCA), a V-STARS/S single-camera software license, and some accessories.

The INCA camera provided with the S model incorporates a high-resolution digital camera, and an Industrial PC with a built-in PCMCIA interface. The system can be operated in off-line mode or in on-line mode. In off-line mode, images are stored on a removable disk storage card for subsequent processing. In on-line mode, the camera is connected directly to the computer (via the Ethernet network kit) so images can be immediately processed. Images can also be transferred through the optional wireless connection. The achievable accuracy with the system is typically better than 5µm + 5µm/m.

In operation, the single camera system is used to take pictures of the measured object from several different locations. The different camera locations are needed to ensure all points on the object are seen from enough geometrically diverse locations to get good intersection angles for triangulation. The V-STARS/S system measures retro-reflective target points. High contrast retro-targets make measurement fast, reliable, and highly automatic.

The single camera system is extremely portable. The entire system (including notebook, camera and accessories) fits into two small cases that can be hand carried aboard an airplane. So the system can go with you anywhere in the world, and be immediately available for work.



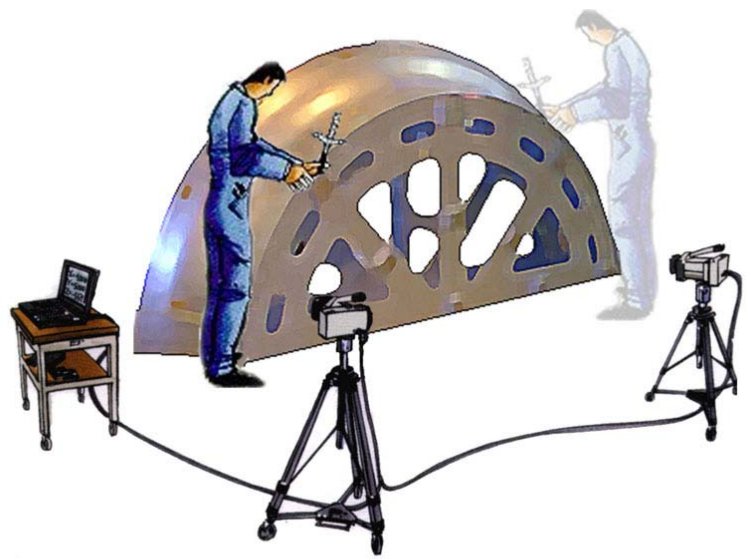
V-STARS/S Camera in typical operation

V-STARS/M System

The V-STARS/M software extends the single-camera V-STARS/S system and enables multiple INCA cameras to be directly connected to the Notebook computer to produce a real-time measurement system.

The object is photographed simultaneously by two or more INCA cameras from different viewing points. The images are transferred via the Ethernet cables to the Notebook where they are immediately processed and the results provided within seconds. The achievable accuracy with the system is typically better than 10μm + 10μm/Meter.

The system can operate in stable mode, which provides a quick set up, but relies on the cameras remaining unmoved during the measurement period. Alternatively a non-stable mode is available that allows vibration or movement of the cameras to occur without loss of accuracy. This mode locates the cameras each and every time a set of pictures is taken using a stable field of control points on the object. Thus, movement of the cameras is fully accounted for and of no consequence. Typically, the control field is established by a quick single-camera measurement.

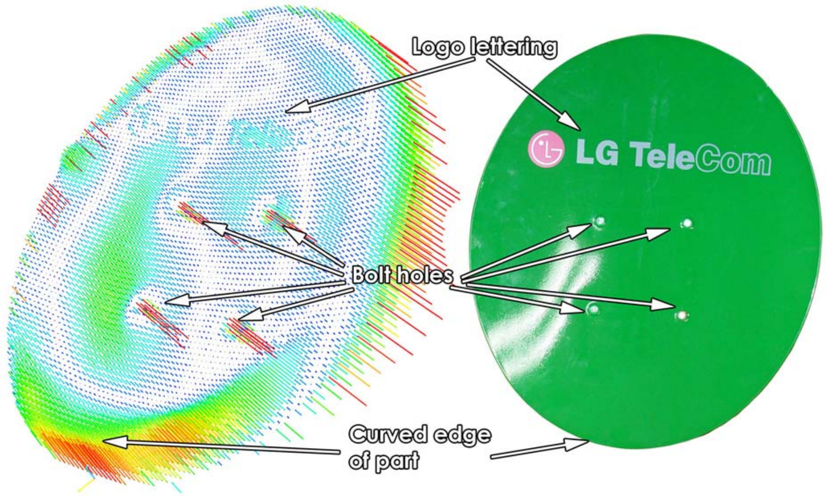


The system can measure individual retro-reflective targets. It can also measure untargeted points using small, wireless, hand held probes that are targeted and have a standard CMM tip attached. Using the pre-defined and calibrated locations of the targets on the probe, it is easy to derive the spatial location of the probe tip. Several different interchangeable probes are available (four are standard, but up to 16 are supported) so you can use the right probe and probe tip for the task at hand. The different probes are automatically recognized by the system. A measurement is triggered remotely using the infrared triggering device provided with the system.

PRO-SPOT Target Projector

GSI has developed a target projection system that can be used to measure thousands of points on a surface without applying a single target. The system is suited to rapid surface measurement for inspection or adjustment purposes. Up to 23,000 points can be collected in one set up. The PRO-SPOT works in both V-STARS/S and V-STARS/M modes.

In V-STARS/S, points are measured the same way they are measured in any other single camera network. The small antenna in the adjacent image was measured using PRO-SPOT. The point cloud was then used to create the best-fit parabolic model.
A typical M-Mode set up is shown below. When used in this manner, a point cloud can be produced in a matter of second.



V-STARS/S Measurement Features

The single-camera measurement allowed us to demonstrate the use and application of the system for measuring individual targets. The features to note about single-camera measurement in general are:

- The system is immune to instability and vibration. This means the camera can be hand-held and pictures can be taken from a ladder, crane or platform if necessary.
- Part or tool downtime is low because much of the preparation work (setup, targeting, tear-down) can be done on a non-interference basis with production. Then, photography is very fast; usually taking just a few minutes. Also, the camera requires no warm-up time and no time for pre-calibration. You can just unpack it and start taking pictures.

- The system is extremely portable. All components can fit into two small cases that can be carried aboard an airplane. The system's portability makes it extremely well suited to field measurements and on-site inspection at vendor's facilities.
- Although it takes some time to target and measure the object initially, repeat measurements are extremely fast. In situations where the targets can be left on the object, (such as tool stability checks or part deformation studies for example), the repeat measurement takes little more time than the time to re-photograph the object.
- Although sometimes measuring target points is a burden, in other cases it is exactly what you want to do. Measuring the same targeted point each time is often preferable to having to probe in the general vicinity of the point each time. Also, in cases where touching the object is difficult or may cause movement or deformation, the object can be targeted and measured instead.

Summary of Measurement and Results

Main Surface Measurements

Prior to photography, five retro-reflective targets were applied to each of the 172 panels that make up the reflector surface. One target was placed in each corner and a target was placed in the center of each panel. Therefore, there were a total of 860 surface targets. A few targets were also applied to the quadropod legs, and to the top of the feed structure. In addition, a three meter scale bar and a two meter scale bar were attached to the antenna to provide scale for the measurement. A small reference bar with five known points (called the AutoBar) was also placed on the reflector. Finally, about 40 special targets, called coded targets, were applied to the surface of the antenna. Each coded target is surrounded by a unique pattern of retro-reflective squares so it can be automatically identified. With the AutoBar and the coded targets, the pictures can be processed completely automatically. Targeting time took about three hours.

The antenna was measured eleven times. Each measurement of the antenna used about 100 photographs taken from various locations and heights all around the antenna. The on-site cranes were used for the photography. The different camera locations were needed to ensure all points on the object were seen from enough geometrically diverse locations to get good intersection angles for triangulation.

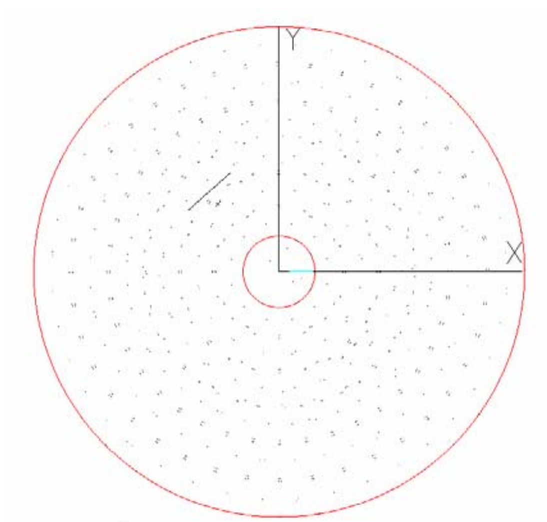
The photography time varied depending on the number of pictures and the orientation of the antenna but usually took 60 to 90 minutes. The processing time also varied depending on whether the measurement was an initial or a repeat measurement. In a repeat measurement, the processing time is about half since the approximate locations of the targets are already known. Processing time varied from about 30 to 60 minutes.

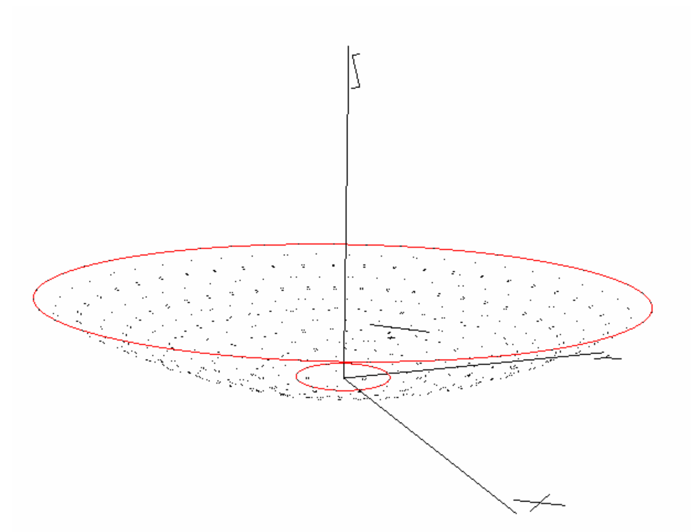
Each measured point is assigned a label to help identify it. The prefix of the label identifies what kind of point it is. The following labeling scheme was adopted.

- R#_# – Reference points on the main surface of the reflector. The first number of the label represents the ring number with the outermost ring being ring #1 and the innermost ring being ring #18. The second number represents the point's location on the ring. The topmost point on a ring is #1, and the numbers increase in a clockwise direction around the ring (as you face the front of the reflector). For example, R3_12 is the 12th point clockwise from the top on the third ring from the edge.

- QUAD – Points on the quadropods
- FEED – Points on the top of the Feed
- CODE – Special coded targets used to automate the measurement
- AUTOBAR – Points on the reference bar used to initialize the first measurement
- A – Points on the “A” scale bar
- B – Points on the “B” scale bar

The photogrammetric measurements produced results in an arbitrary working coordinate system defined by the AutoBar reference bar. These coordinates were transformed into a more meaningful coordinate system defined in the following manner. A best-fit parabola was fit to all the surface points from measurement #9 (File: 45˚ #4B.XYZ) because this was the most representative of all the measurements. The origin of the coordinate system is at the vertex, and the positive Z axis goes thru the focus. Thus, the X-Y plane is parallel to the face of the reflector. Finally, the Y axis goes through the perpendicular projection of the reference point at the top of the reflector (Point R1_1) on the X-Y plane. The coordinate system is illustrated in the two figures below.





The main reflector surface was measured 11 times. The measurements are summarized in the table below. The files containing the results for each measurement were previously provided to NRAO.

#	Description	Filename
1	90˚ #1 – Day 1 night (even pictures)	4B vs 90˚ – even.XYZ
2	90˚ #2 – Day 1 night (odd pictures)	4B vs 90˚ – odd.XYZ
3	45˚ #1 – Day 1 night before adjusting	4B vs 1.XYZ
4	45˚ #2 – Day 1 night after adjusting	4B vs 2.XYZ
5	0˚– Day 1 night after adjusting	4B vs 0˚.XYZ
6	45˚ #3A – Day 2 daytime before re-adjusting	4B vs 3A.XYZ
7	45˚ #3B – Day 2 daytime before re-adjusting	4B vs 3B.XYZ
8	45˚ #4A – Day 2 night before re-adjusting	4B vs 4A.XYZ
9	45˚ #4B – Day 2 night before re-adjusting	45˚ #4B.XYZ
10	45˚ #5 – Day 2 night after re-adjusting	4B vs 5.XYZ
11	45˚ #6 – Day 2 night after re-adjusting	4B vs 6 two cameras.XYZ

A brief description of each measurement is provided below.

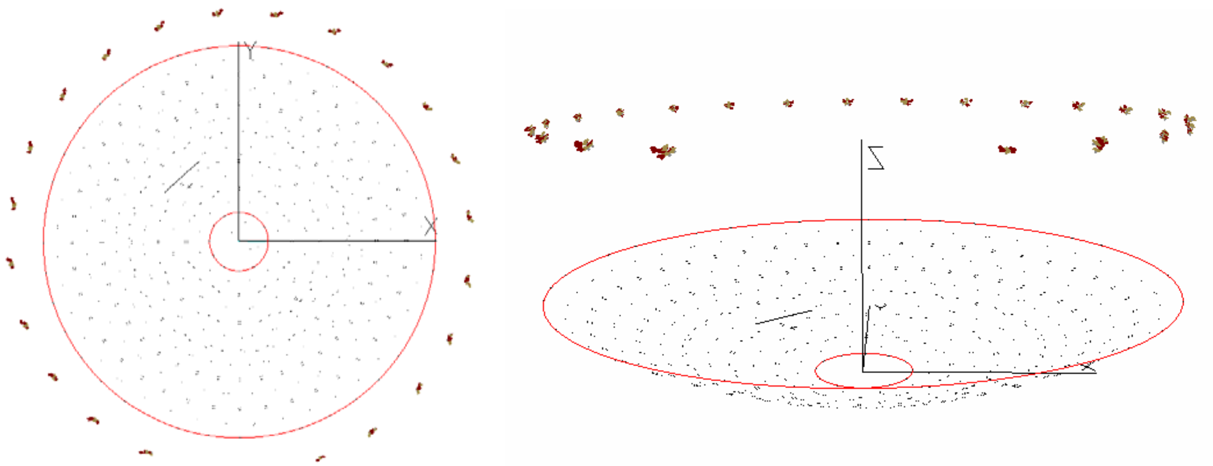
Measurements #1 and #2 – 90˚ measurement (Day 1 night).

The first measurements were done on the first night starting at about 7PM so the antenna had some time to stabilize thermally after sunset. The antenna was oriented at 90˚ (zenith). Enough pictures were taken so the measurement could be divided into two independent measurements of about 100 pictures each. Unlike the other cases, no pictures were taken from the center of the reflector because the crane could not position the camera there. Instead, all the pictures were all taken at a height about 10 meters above the antenna's vertex (about 6 meters above the edge), and about 14 meters out from the center (about 1.5 meters from the edge). Since it was easier to rotate the antenna than to move the crane, the antenna was rotated to each position and two sets of pictures were taken that collectively covered the entire reflector.

Although the other measurements called for pictures at eight locations spaced nominally every 45˚ around the edge of the dish, the plan here called for a set of pictures every 15˚ around the edge. The extra locations compensated for the lack of pictures from the center of the reflector. Fortunately, because the reflector was rotated it was much easier to take pictures from many different locations than in the other orientations (where the crane had to be moved to each location). In fact photography was much faster and easier than for the other cases; both sets of measurements took only about half an hour combined (for about 200 pictures).

Unfortunately, the camera flash did not operate at the last few locations so there is a gap of about 60˚ around the antenna where no pictures were measurable. Due to the large size of the dish we used a different flash than usual, and unbeknownst to me that flash had a "sleep" mode and had turned itself off. Luckily, it turned itself off near the end of the photography so the missing pictures degraded the measurement accuracy only slightly. The layout of the cameras around the antenna is shown below (each patch represents a cluster of pictures taken to cover the entire reflector). Notice the gap at the bottom of the reflector where no pictures were taken due to the flash problem.

90˚ measurement camera layout



Top view **Side view**

The pictures were separated into two independent measurements (called even and odd). The measurements were automatically processed and the results are summarized below.

Case	# of pictures	# of points	RMS of measurement	Accuracy Estimates X Y Z
90˚s – Odd pictures	86	934	0.26µm	0.0021” 0.0021” 0.0030”
90˚s - Even pictures	85	934	0.25µm	0.0022” 0.0024” 0.0030”

The accuracy estimates are generated by the algorithm that processes the pictures (called the bundle adjustment). The RMS of measurement can be thought of as a quality factor; the lower the number the better the measurement. A number around 0.30 microns is typical.

Since these are two independent measurements, we would expect the RMS of the differences between them to be the RSS (Root Sum of Squares) of the estimated accuracies for the individual measurements. The computation of the expected differences is shown below.

Estimated RMS of differences in X = $\sqrt{(0.0021^2 + 0.0022^2)}$ = 0.0030”
Estimated RMS of differences in Y = $\sqrt{(0.0021^2 + 0.0024^2)}$ = 0.0032”
Estimated RMS of differences in Z = $\sqrt{(0.0030^2 + 0.0030^2)}$ = 0.0042”

The actual differences between the two measurements were computed, and the RMS of those differences is shown in the table below.

Repeatability Case	# of points	RMS of Differences X Y Z
90˚s – even pictures vs odd pictures	932	0.0035” 0.0033” 0.0039”

The analysis above shows that the repeatability is very consistent with the estimated accuracies provided by the bundle adjustment.

Measurements #3 and #4 – 45˚s before and after adjustment (First night)

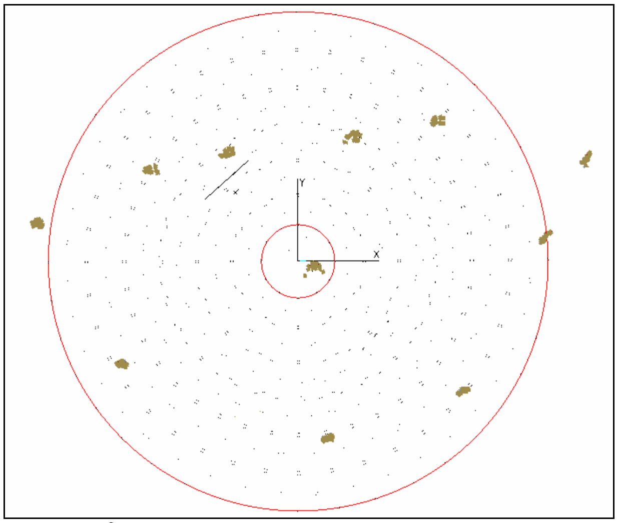
After the 90˚ measurements, the antenna was measured twice at the 45˚ orientation. The antenna was measured once, and then moved to the 90˚ orientation so several panels could be moved. Then, the antenna was returned to 45˚s and measured again.

In each case the plan was to take a set of outer pictures at eight locations spaced nominally every 45˚s around the edge of the dish. The plan for the outer pictures was to take them at a height about 10 meters above the antenna's vertex (about 6 meters above the edge), and about 13.5 meters out from the center (about one meter from the edge). However, the crane was unable to reach the topmost location, so the pictures were taken as close to this location as possible. At each location, a set of pictures was taken that collectively covered the entire reflector. Also, since it was possible for the crane to position the camera at the center of the reflector, some pictures were taken just below the subreflector that collectively covered the entire reflector main surface.

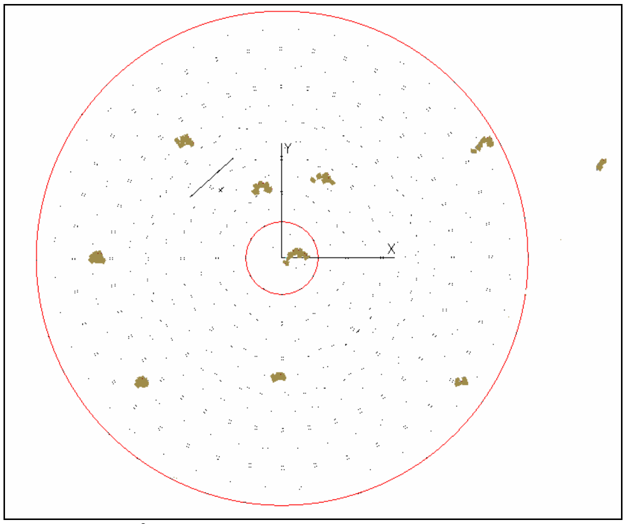
The two measurements are summarized below. As we can see, the accuracy estimates for the second measurement are about 50% worse than for the first measurement. This is due to the larger RMS of measurement and the worse geometry for the measurement.

Case	# of pictures	# of points	RMS of measurement	Accuracy Estimates X Y Z
45˚s – Before adjusting	132	938	0.23µm	0.0018" 0.0020" 0.0029"
45˚s – After adjusting	126	936	0.29µm	0.0030" 0.0029" 0.0045"

In fact, after reviewing the second layout it was clear the geometry for both cases was less than desired. Top views of the camera layout for the two measurements are shown below.



45˚ measurement 1 camera layout



45˚ measurement 2 camera layout

Notice not only how poor the camera geometry is for the second measurement compared to the first but also how much poorer the geometry is for both measurements than for the 90˚ measurement shown earlier. The cameras were only rarely positioned outside the edge of the antenna as desired. Nor are they well arranged at 45˚ spacing around the antenna. Although the top locations were hard to get to because of crane height limitations, even the pictures at the bottom were not taken from good locations. As it turned out, it was difficult to estimate the camera locations from the crane, and not enough attention or effort was made to get the best possible locations for the camera. Instead, too much of a “scattershot” approach was used where pictures were taken from wherever was convenient. In retrospect this was a mistake.

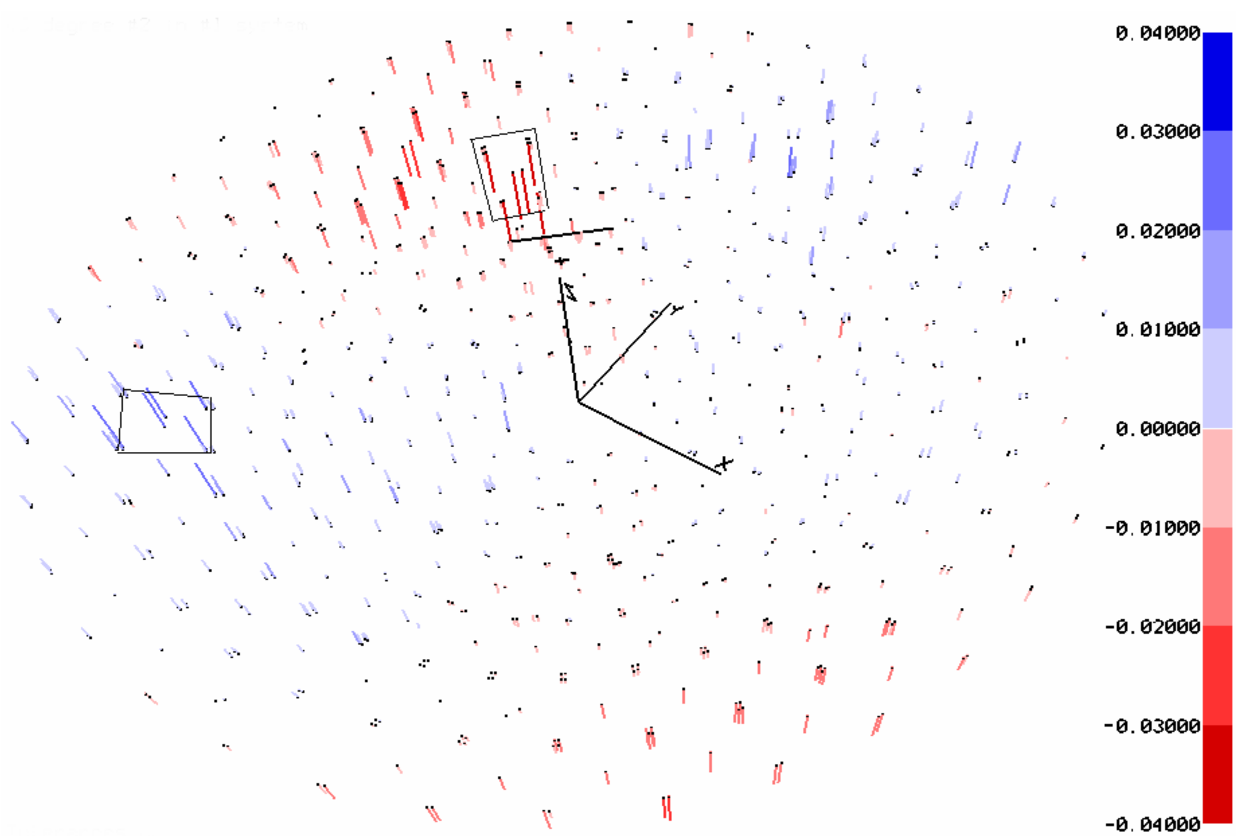
The two measurements were compared to each other and the results are shown below.

Repeatability Case	**# of points**	**RMS of Differences**		
		X	**Y**	**Z**
45˚s – First night , before vs after adjusting (#1 vs #2)	930	0.0058”	0.0045”	0.0070”

The differences are considerably worse than for the 90˚ measurement. Some of this can be attributed to the poorer measurement accuracies for the second measurement. By computing the RSS of the individual accuracy estimates we can again get the expected accuracies of the comparison which should be:

Estimated RMS of differences in X = $\sqrt{(0.0018^2 + 0.0030^2)} = 0.0035$”
Estimated RMS of differences in Y = $\sqrt{(0.0020^2 + 0.0029^2)} = 0.0035$”
Estimated RMS of differences in Z = $\sqrt{(0.0029^2 + 0.0045^2)} = 0.0054$”

The computation shows us the results are still considerably worse than expected. The differences can also be displayed graphically and are shown below.



The differences are very systematic in nature. Only two panels appear to have moved. They are outlined above. They stand out as being significantly different from the surrounding points and from the first measurement. The tables below list the amount the points on the panels moved as well as the average movement.

25th panel clockwise from the top, on the second outermost set of panels.

Point	R4_49	R4_50	R5_25	R6_49	R6_50	Average
Difference	+0.029”	+0.019”	+0.025”	+0.021”	+0.020”	+0.025”

35th panel clockwise from the top on the third outermost set of panels.

Point	R7_69	R7_70	R8_35	R9_69	R9_70	Average
Difference	-0.031”	-0.032”	-0.036”	-0.035”	-0.031”	-0.035”

The results were somewhat worse than expected and also worse than the differences between the 90˚ measurements.

Measurements #5 – 0˚s First night

For the final measurement on First night, the reflector was measured in the 0˚ position. The results are summarized below.

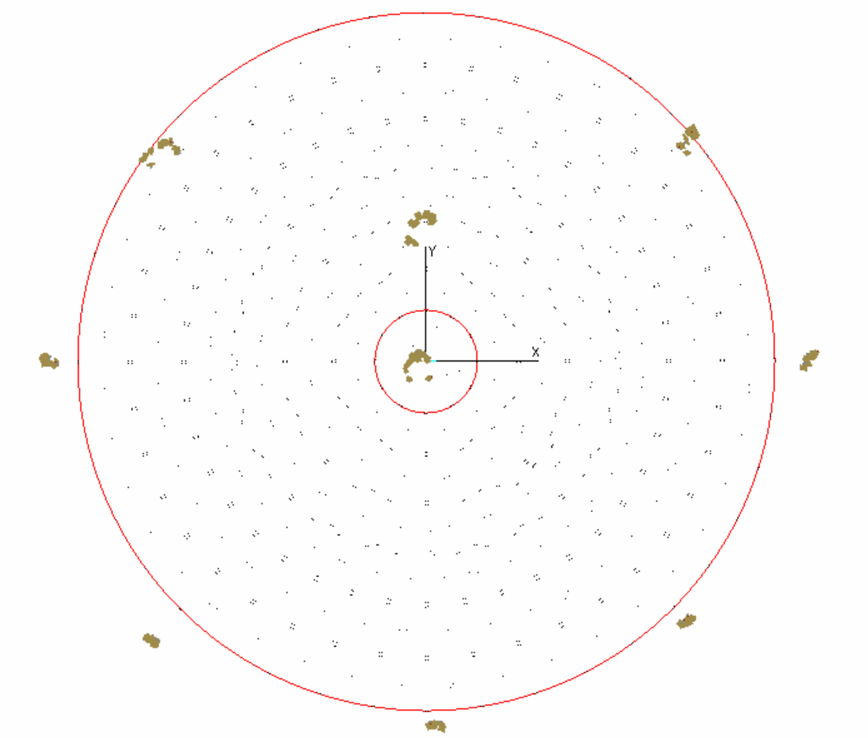
Case	# of pictures	# of points	RMS of measurement	Accuracy Estimates X Y Z
0˚s –	118	934	0.41µm	0.0030” 0.0030” 0.0040”

The RMS of measurement is somewhat worse than expected, and worse than the other cases. The cause for this is unknown but could be due to movement of the reflector.

Measurements #6 and #7 – 45˚s Second day (same time and conditions)

Because the differences between the two 45˚ measurements were worse than expected we decided to stay another day and do some more measurements to try and find the cause. Since we had the time, we decided to attempt the 45˚ measurement during daytime. Measuring outside in daylight on white surfaces is possible, but the lens must have a neutral density filter attached to reduce the amount of ambient light. Then the strobe power is increased proportionately to compensate for the filter loss. Given this limitation, I could only use a 25% neutral density filter. This did not reduce the ambient light as much as desired but the pictures were measurable so we decided to try anyway.

To improve the geometry, greater care was taken in positioning the camera. Certain features of the reflector were used as “alignment marks” to ensure we were in the proper position. Also, we decided to move the crane to two different positions so we could reach more of the desired locations around the antenna. These steps improved the geometry considerably. A typical layout of the camera stations for all the remaining measurements is shown below.



Although we could not reach the desired location for the three highest camera positions, the two outer ones are very close to the desired positions. We were only unable to get close to the topmost camera position.

The unanswered question regarding the previous night's measurements was whether the larger than expected systematic differences were due to the measurement system or a change in the antenna. The antenna was not measured under exactly the same conditions each time. There was more than an hour between the two measurements, and the antenna was moved to the 90˚ position between the measurements so the selected panels could be adjusted. Then it was moved back to the 45˚ position.

To try and determine the cause of the differences, we decided to make two independent measurements of the reflector under the same conditions. At each position of the crane, two duplicate sets of pictures were taken (first one set, then the other) that each collectively covered the entire surface of the reflector. Thus, there were two independent sets of pictures that were interleaved in time. The plan was to use these two measurements as a baseline to compare to the adjustment measurement that followed.

The results of the two "identical" daytime measurements are summarized below.

Case	**# of pictures**	**# of points**	**RMS of measurement**	**Accuracy Estimates X**	**Y**	**Z**
45˚s – Daytime, first group of pictures (#3A)	101	935	0.44µm	0.0039"	0.0040"	0.0054"
45˚s – Daytime, second group of pictures (#3B)	101	935	0.45µm	0.0040"	.00040"	0.0055"

Unfortunately, though the two measurements were successful, the higher than expected RMS of measurements indicated the measurement quality was poor. We attributed the poor measurement quality to two possible factors. First, the background exposure was higher than desired because of the high ambient light level. A high background level lowers the "signal to noise" ratio of the image processing, and can reduce the measurement quality. Second, there could be significant thermal deformations of the reflector during the 90 minutes or so required for the photography.

Despite the poor measurement quality, we computed the differences between the two measurements. They are summarized below.

Repeatability Case	# of points	RMS of Differences		
		X	Y	Z
45˚s – Second daytime, same time and conditions (#3A vs #3B)	933	0.0052"	0.0053"	0.0042"

Although the differences are larger than for the 90˚ measurement, they are comparable to the previous night's measurements in the X and Y coordinates, and considerably better (0.0042" vs 0.0070") in the most important Z coordinate. They are also consistent with the accuracy estimates.

The daytime measurements were not of the best quality. Since we were looking for the best measurement we decided to wait until nighttime to try again rather than proceed with the adjustment measurement.

Measurements #8 and #9 – 45˚s Second night (same time and conditions)

The two 45˚ baseline measurements were repeated Second night beginning at about 7PM. Other than being done at night they were practically identical to the two daytime measurements. Again, two independent sets of measurements were interleaved in time so that as nearly as possible they were taken during the same period of time and under the same conditions. The results are summarized below.

Measurement Description	# of pictures	# of points	RMS of measurement	Accuracy Estimates		
				X	Y	Z
45˚s – Second night, first group of pictures (#4A)	111	935	0.29µm	0.0024"	0.0025"	0.0034"
45˚s – Second night, second group of pictures (#4B)	112	935	0.27µm	0.0022"	0.0024"	0.0032"

The differences between the two measurements were computed and are summarized below.

Repeatability Case	# of points	RMS of Differences		
		X	Y	Z
45˚s – Second night , same time and conditions (#4A vs #4B)	935	0.0033"	0.0032"	0.0027"

The repeatability is the best obtained so far by far.

Measurements #10 – 45˚s Second night (first measurement after adjustment)

After the baseline measurements, the antenna was moved to the 90˚ orientation so some of the antenna panels could be adjusted. Then, the antenna was returned to the 45˚ orientation and measured. The measurement results are summarized below.

Measurement Description	# of pictures	# of points	RMS of measurement	Accuracy Estimates X	Y	Z
45˚s – Second night, first measurement after adjustment (#5)	114	935	0.30 µm	0.0024”	0.0025”	0.0035”

The differences between this measurement and the two measurements before adjustment were computed and are summarized below.

Repeatability Case	# of points	RMS of Differences X	Y	Z
45˚s – #4A vs #5, Second night, before vs after adjustment	926	0.0061”	0.0072”	0.0058”
45˚s – #4B vs #5, Second night , before vs after adjustment	926	0.0068”	0.0062”	0.0049”

We would expect differences in line with those of the differences between the baseline measurements. Instead, the differences are much larger than for the baseline case. This result still did not completely answer the question of whether the differences are due to a deformation of the reflector, or a problem with the measurement system. We decided to do one more measurement of the reflector to try and settle the issue.

Measurements #11 – 45˚s Second night (second measurement after adjustment)

Measurement Description	# of pictures	# of points	RMS of measurement	Accuracy Estimates X	Y	Z
45˚s – Second night, second measurement after adjustment (#6)	119	935	0.28 µm	0.0022”	0.0024”	0.0032”

The differences between this measurement and the previous one were computed and are summarized below.

Repeatability Case	# of points	RMS of Differences X	Y	Z
45˚s – #5 vs #6, first vs second measurement after adjustment	933	0.0073”	0.0046”	0.0030”

These results are puzzling. The X differences are more than double the baseline differences, but the Z differences are nearly as good as the baseline’s Z differences.

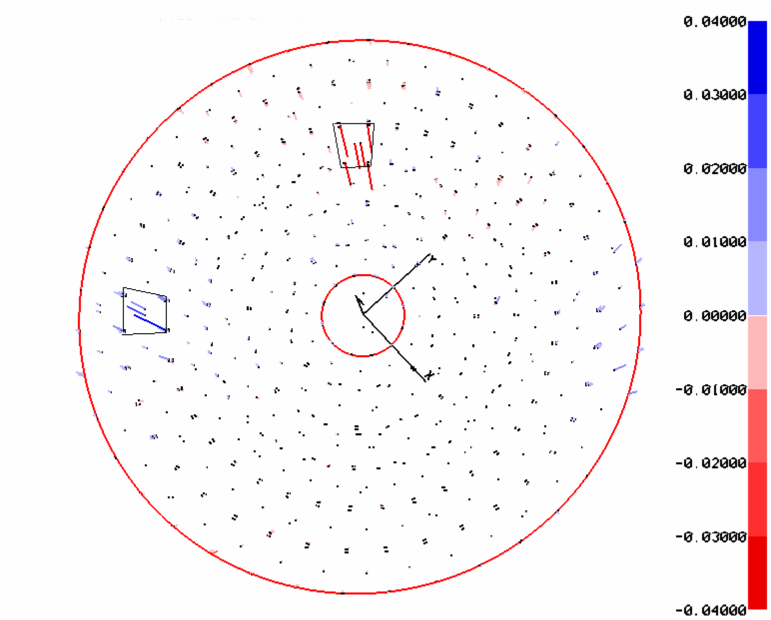
Some meaningful comparisons

To try and get more insight into what might be happening several comparisons between different 45˚ measurements were made. These are summarized below. Some of the previous comparisons are included for convenience. Most of the comparisons are to measurement #4B.

Case	**RMS of Differences** X	Y	Z
4B vs 4A (Second night, same time and conditions)	0.0033”	0.0032”	0.0027”
4B vs 5 (First measurement after adjusting)	0.0068”	0.0062”	0.0049”
4B vs 6 (Second measurement after adjusting)	0.0042”	0.0045”	0.0037”
5 vs 6 (First vs second measurement after adjusting)	0.0073”	0.0046”	0.0030”
1 vs 2 (First night, before vs after adjusting)	0.0058”	0.0045”	0.0070”
4B vs 1 (Second night vs First night before adjusting)	0.0041”	0.0042”	0.0043”
4B vs 2 (Second night vs First night after adjusting)	0.0064”	0.0062”	0.0074”
3A vs 3B (Second daytime, same time and conditions)	0.0052”	0.0053”	0.0042”

If we use 4B vs 4A as the standard of comparison (because they were taken at the same time and under the same conditions), we can see 4B agrees better with 6 than 5 does with 6. It is as if the antenna needs some time to settle when it is returned to 45˚s. This seems to be confirmed by the good agreement between 4B and 1. Both are with the antenna at 45˚s for some time, but they are on different nights, and the antenna was turned up to 90˚s at least twice between these measurements. Notice 1 vs 2 and 4B vs 2 do not agree nearly as well as 4B vs 1. Also, notice the RMS of Z, the most critical coordinate, is under .005" in all cases except the comparison to measurement 2. Keep in mind the geometry for measurements 1 and 2 was not very good and is one of the reasons we decided to stay the second day and try again.

By looking at the differences between measurement #4B before adjustment and measurement #6 after adjustment, it appears the same two panels have been moved. The differences between the two measurements are shown graphically below.



The differences are again very systematic in nature. The two panels that appear to have moved are outlined above. They stand out as being significantly different from the surrounding points and from the measurement before adjustment. The tables below list the amount the points on the panels moved as well as the average movement.

25th panel clockwise from the top, on the second outermost set of panels.

Point	R4_49	R4_50	R5_25	R6_49	R6_50	Average
Difference	+0.014”	+0.007”	+0.021”	+0.039”	+0.010”	+0.023”

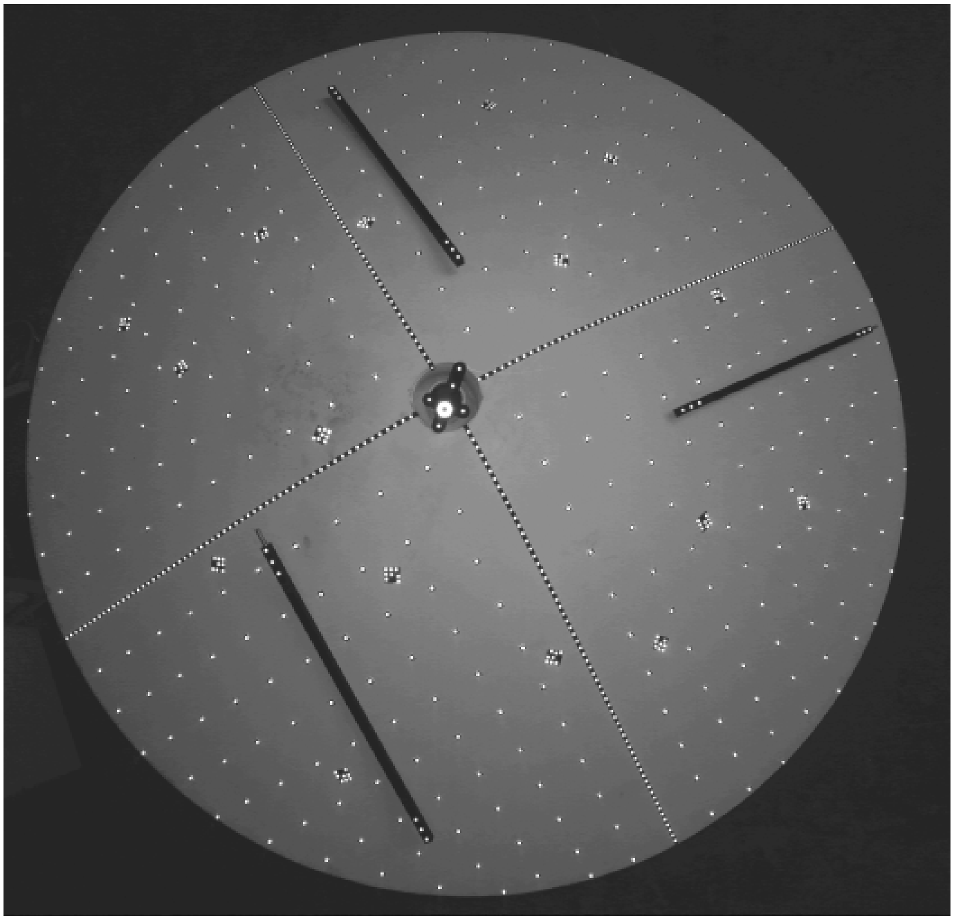
35th panel clockwise from the top on the third outermost set of panels.

Point	R7_69	R7_70	R8_35	R9_69	R9_70	Average
Difference	-0.038”	-0.034”	-0.034”	-0.031”	-0.041”	-0.036”

Point R6_49 is not consistent with the other points on the panel. If we remove it, the average is +0.013” not +0.023”. It is unclear why there is such a large discrepancy. If the target is still on the antenna, it would be worthwhile to inspect it to see if it is damaged.

VLBA Subreflector Surface Measurements

A VLBA subreflector mounted in a holding fixture located inside the barn was measured on First afternoon. Prior to photography, approximately 600 retro-reflective targets were applied to the surface. Four strips of “target tape” were applied that went radially from the center of the subreflector out to the edge. Target tape has targets at regularly spaced intervals (in this case 1” spacing). Individual stick on targets were applied elsewhere on the surface. In addition, three one meter scale bars were attached to the antenna to provide scale for the measurement. A small reference bar with five known points (called the AutoBar) was also placed on the reflector. Finally, about 15 special targets, called coded targets, were applied to the surface of the antenna. Each coded target is surrounded by a unique pattern of retro-reflective squares so it can be automatically identified. With the AutoBar and the coded targets, the pictures can be processed completely automatically. Targeting time took about one hour. A picture of the targeted VLBA subreflector is shown below.



The subreflector was measured three times. Each measurement of the subreflector used about 30 photographs taken from various locations and heights all around the subreflector. The different camera locations were needed to ensure all points on the object were seen from enough geometrically diverse locations to get good intersection angles for triangulation. For the first two measurements, the camera was moved around the stationary object with the help of the on-site crane. For the third measurement, the subreflector was rotated in the fixture while the camera remained fixed. The third measurement demonstrated the ability to measure the object by rotating it (a sometimes very useful property of photogrammetry), and was used to determine if rotating the object in the fixture maintained its shape.

The photography time varied depending on the number of pictures and whether the object was stationary or rotated. For the first two measurements, photography took ten to fifteen minutes. For the third measurement photography took six minutes. The processing time also varied depending on whether the measurement was an initial or a repeat measurement. In a repeat measurement, the processing time is about half since the approximate locations of the targets are already known. Processing time varied from about 5 to 10 minutes.

Each measured point is assigned a label to help identify it. The prefix of the label identifies what kind of point it is. The following labeling scheme was adopted.

- L#_# – Points on the “lines” of target tape points. The first number of the label represents the line number (1 to 4). The second number represents the point's location on the line. The innermost point on a line is #1, and the numbers increase as the point’s progress outward towards the edge. For example,L3_12 is the 12th point outward from the center on the third line of targets.

- QUAD#_# - Individual target points on the surface. The first number of the label indicates which quadrant of the surface the points lies on. The second number indicates which target the point is within the quadrant.
- CODE – Special coded targets used to automate the measurement
- AUTOBAR – Points on the reference bar used to initialize the first measurement
- A – Points on the "A" scale bar

The photogrammetric measurements produced results in an arbitrary working coordinate system defined by the AutoBar reference bar. We decided to leave the coordinates in this system since no preferred coordinate system was specified.

Case	**# of pictures**	**# of points**	**RMS of measurement**	**Accuracy Estimates**		
				X	**Y**	**Z**
Measurement 1 – Camera moved	34	644	0.22µm	0.0005"	0.0005"	0.0008"
Measurement 2 – Camera moved	37	642	0.30µm	0.0007"	0.0007"	0.0009"
Measurement 3 – Object moved	31	644	0.29 µm	0.0007"	0.0007"	0.0010"

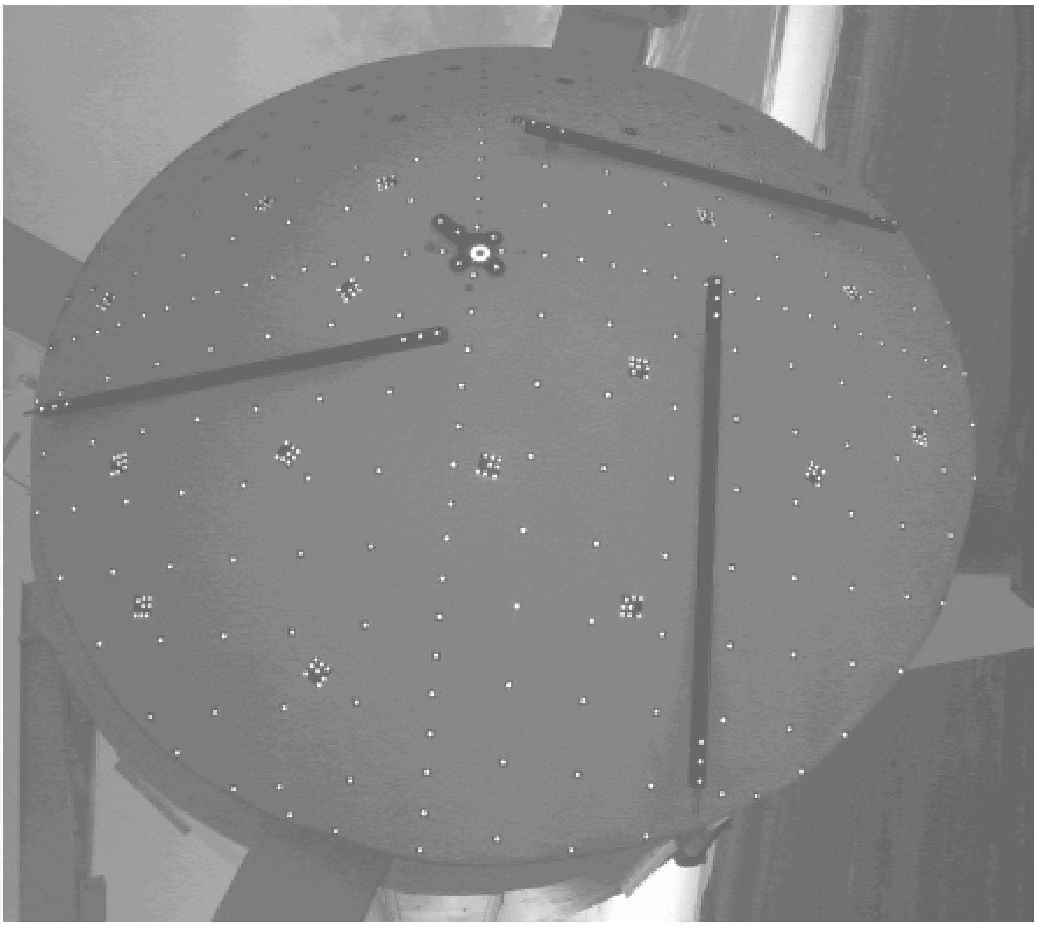
Again, the RMS of measurements is a quality indicator, and .30 microns is typical. The actual differences between the three measurements were computed, and the RMS of those differences is shown in the table below.

Repeatability Case	**RMS of Differences**		
	X	**Y**	**Z**
Measurement 1 vs 2	0.0007"	0.0008"	0.0009"
Measurement 1 vs 3	0.0007"	0.0007"	0.0009"
Measurement 2 vs 3	0.0010"	0.0009"	0.0010"

The analysis above shows that the repeatability is very consistent with the estimated accuracies provided by the bundle adjustment.

VLA Subreflector Surface Measurements

The VLA antenna's subreflector was also measured on First afternoon. Prior to photography, 260 retro-reflective targets were applied to the surface. Individual stick on targets were applied in a regular pattern on the surface. In addition, three one meter scale bars were attached to the antenna to provide scale for the measurement. A small reference bar with five known points (called the AutoBar) was also placed on the reflector. Finally, about 15 special targets, called coded targets, were applied to the surface of the antenna. Each coded target is surrounded by a unique pattern of retro-reflective squares so it can be automatically identified. With the AutoBar and the coded targets, the pictures can be processed completely automatically. Targeting time is unknown since the targets were applied by NRAO personnel prior to my arrival for photography. A picture of the targeted VLA subreflector is shown below.



The subreflector was measured three times. Each measurement of the subreflector used about 40 photographs taken from various locations and heights all around the subreflector. The different camera locations were needed to ensure all points on the object were seen from enough geometrically diverse locations to get good intersection angles for triangulation. The crane was used to position the camera in front of the subreflector. For both measurements, the subreflector was rotated continuously while pictures were taken from the crane. A set of inner and outer pictures were taken by moving along the basket of the crane. Photography time was very fast taking only four to five minutes per measurement. Processing time took less than ten minutes.

Each measured point is assigned a label to help identify it. The prefix of the label identifies what kind of point it is. The following labeling scheme was adopted.

- L#_# – Points on the "lines" of target points. The first number of the label represents the line number (1 to 4). The second number represents the point's location on the line. The innermost point on a line is #1, and the numbers increase as the point's progress outward towards the edge. For example,L3_12 is the 12th point outward from the center on the third line of targets.
- QUAD#_# - Individual target points on the surface. The first number of the label indicates which quadrant of the surface the points lies on. The second number indicates which target the point is within the quadrant.
- CODE – Special coded targets used to automate the measurement
- AUTOBAR – Points on the reference bar used to initialize the first measurement
- A – Points on the "A" scale bar

The photogrammetric measurements produced results in an arbitrary working coordinate system defined by the AutoBar reference bar. We decided to leave the coordinates in this system since no preferred coordinate system was specified.

Case	# of pictures	# of points	RMS of measurement	Accuracy Estimates X Y Z
Measurement 1	37	308	0.20μm	0.0004" 0.0004" 0.0006"
Measurement 2	42	308	0.19μm s	0.0004" 0.0004" 0.0006"

Again, the RMS of measurements is a quality indicator, and .30 microns is typical. The actual differences between the three measurements were computed, and the RMS of those differences is shown in the table below.

Repeatability Case	RMS of Differences X Y Z
Measurement 1 vs 2	0.0003" 0.0003" 0.0004"

The analysis above shows that the repeatability is somewhat better than that expected from the accuracy estimates provided by the bundle adjustment.

Conclusion:

As our demonstration shows, the V-STARS system provides a broad and powerful range of capabilities for meeting the demanding requirements for industrial measurement at NRAO. These include:

1. Measurement in unstable environments, or from unstable platforms.
2. Non-contact measurement so the reflector is not deformed.
3. Minimal interference with production resulting in low downtime.
4. Ability to work in a wide variety of environmental conditions.
5. High portability.
6. Fast setup with little warm-up time and no pre-calibration required.
7. Fast, automatic measurement and very efficient repeat measurements.
8. High accuracy and repeatability.
9. Operation from a notebook computer.

10. Fully integrated transformation and analysis capabilities.

We thank NRAO for the opportunity to demonstrate our system and its capabilities to you. We believe there are many applications at NRAO that are well suited to photogrammetric measurement. Please contact us at any time to discuss possible applications.