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TITLE: SILICON SUBSYSTEM MECHANICAL ENGINEERING CLOSEOUT REPORT
FOR THE SOLENOIDAL DETECTOR COLLABORATION

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SUBMITTED TO: This is a report detailing work contracted to do for the
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**SILICON SUBSYSTEM
MECHANICAL ENGINEERING
CLOSEOUT REPORT
FOR THE
SOLENOIDAL DETECTOR
COLLABORATION**

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Los Alamos National Laboratory

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1.0 INTRODUCTION---GOALS

Our group at Los Alamos National Laboratory was responsible for the mechanical engineering of the silicon tracking system of the Solenoidal Detector Collaboration (SDC) experiment of the Superconducting Super Collider (SSC) project. The responsibility included the overall design of the system from the mechanical point of view, development and integration of the cooling system, which was required to remove the heat generated by the front-end electronics, assembly of the system to extremely tight tolerances, and verification that the construction and operational stability and alignment tolerances would be met. A detailed description of the concepts we developed and the work we performed can be found in a report titled "Silicon Subsystem Mechanical Engineering Work for the Solenoidal Detector Collaboration" which we submitted to the SSC Laboratory. In addition to the mechanical engineering work, we also performed activation, background, and shielding studies for the SSC program. Much of the work we performed was potentially useful for other future high energy physics (HEP) projects. When the SSC project was voted down by Congress in October 1993, some funds were made available to allow the completion of key elements of the SSC work that was caught at a critical developmental stage and which would be useful for other HEP projects. This report describes the close-out work that was performed for the Los Alamos SDC project. Four major tasks were identified for completion:

- 1) Integration of the semi-automated assembly station being developed and construction of a precision part to demonstrate solutions to important general assembly problems (the station was designed to build precision silicon tracker subassemblies);
- 2) Build a state-of-the-art TV holography (TVH) system to use for detector assembly stability tests;
- 3) Design, build, and test a water based cooling system for a full silicon shell prototype; and
- 4) Complete and document the activation, background, and shielding studies, which is covered in a separate report.

This effort started in May 94. The technical work was completed in October 94, and the final report was finished in December 94. A summary of the results for the first three tasks is given in the next section, which is followed by a detailed discussion of the work..

By the time we received funding, late in FY 94 (May), almost everyone from the original Los Alamos SSC team had been assigned to other projects. To complete the close-out tasks, we rebuilt a small team consisting of: Jack Hanlon, Wynn Christensen, D.C. Jones and Bill Wilds, all of whom were members of the original design team; Steve Yeamans gave up work in his private business for a few months to contribute very capable optical/mechanical help; Greg Hayman, a graduate research assistant, helped with TVH testing and considerable TVH software development; Richard Ross, an undergraduate electrical engineering summer student, became an expert LabVIEW¹ programmer and helped with many LabVIEW software tasks; Andrea Palounek, was responsible for the background and activation calculation effort; Hans Ziock, as the local chief physicist on the project, kept us on track, guided and encouraged our work, and edited this report; Bill Miller, our former group and team leader, and Tim Thompson, our new group leader, added welcome encouragement, support, and ideas. We very much appreciated the support from Abe Seiden and Gil Gilchriese in convincing the SSC close-out committee to fund the LANL effort.

The close-out team worked well together, enjoyed the work, and is proud of what we accomplished. We hope this report will be useful to other researchers in the high energy physics community.

2.0 SUMMARY---RESULTS

With the close-out money provided we completed the Los Alamos engineering contribution to the Solenoidal Detector Collaboration (SDC) silicon subsystem. The close-out efforts concentrated on completing tasks that would be of interest to researchers in the HEP community. The main tasks were to integrate an automated assembly station and build a precision prototype part, built a state-of-the-art TV holography system, and to construct and test a water cooled system concept on a complete silicon shell.

Integrating the automated assembly station and building a precision silicon detector prototype subassembly was the most difficult and time consuming close-out task. We were able to demonstrate, for the first time, that large silicon structures could be built to the very difficult ± 5 micron azimuthal tolerance on ladder location specified for the SDC silicon tracker. We accomplished the precision with the automated assembly equipment, by precisely locating silicon ladders in space relative to stable optical reference systems and filling in the difference between the precise ladder locations and the imprecise support structure with adhesive. Considerable effort went into designing and building a stable optical reference system to use for an assembly axis, and into defining, building and testing optical equipment to locate a pair of reference microscopes off of the reference axis to precisely locate the silicon ladders. At the heart of the automated assembly station is a sophisticated control system, built with LabVIEW software, to supervise the automated assembly operations. With this system we moved ladders into position, automatically compensated for runout in the goniometers that held the support rings, located the fiducials on the ladders, found round fiducial centroids, and with closed loop feedback control, maneuvered the ladders into the desired precise location and bonded them to the support rings. Three closed loop feedback systems used information from 3 CCD cameras coupled to PC based image processing software, to direct the motions of four stepper motors and three piezoelectric drives to precisely place the ladders. The main accomplishment was to build a precision part with uniform adhesive joints using an automated assembly station. The details of the integration techniques and control system are described in Section 3.1. Results of measurements on the precision part are summarized in Section 3.1.8.

During the close-out work we improved our TV holography system. We originally built our systems from surplus parts, and although the original system was functional, we were able to improve it in many ways. The first improvement was a 200 milliwatt, diode pumped solid state laser that is frequency doubled to provide green light. This is extremely useful, because it allowed us to make TV holography set ups without carefully matching the lengths of the two beam paths of the interferometer. Also, with the increased power we could now look at larger parts, up to about a meter diameter, with TV holography. The laser saved us significant setup time during the water cooling system tests. We also greatly improved our image processing algorithms for processing fringe data into surface shape change maps. Our original algorithm was time consuming and not very robust. We now have a very robust algorithm and complete image processing capability using a program from Interactive Data Language (IDL)². IDL is an interactive data language designed for remote sensing image processing applications. The program is very useful, because the language allows development of an interactive user interface with pull down menu's and fast image processing. With IDL we implemented the most recent and robust algorithms available for unwrapping TV holography data. Examples of the results of this algorithm development are spread throughout Section 3.2.5 and Section 3.3.2. Finally, we improved the TV holography hardware to display shape changes at TV frame rates. We farmed this task out to Ryszard Pryputniewicz at Worcester Polytechnic Institute (WPI), because he had worked with these systems before, and we had worked closely with him during the SSC program. With all these improvements, we now have a state of the art TV holography system for future silicon detector system work.

Cooling system design continues to be one of the most challenging problems facing future large silicon tracking systems designers. This is a complicated problem, and we had only partial success, but we did learn a considerable amount about assembly techniques and water cooling systems. During close-out we built and tested a water cooling system concept for a silicon detector, which we implemented on a full 360 degree silicon shell. We tried to design a system that would give relevant data for the planned CERN Large Hadron Collider (LHC) detectors, ATLAS and CMS. The concept was built around the following idea: glue the silicon ladders to low thermal coefficient of expansion graphite epoxy support rings for mechanical stability, and use thermal grease to transfer the heat, from the silicon through a metal cooling fin to a metal cooling channel that was glued to the support ring in only one place. Since the cooling channel is attached in only one place, it should slide on the grease joints without effecting the mechanical shape of the detector when the temperature changes. The construction details for the shell, the cooling system, thermal imaging camera pictures of the shell under full power operation, and TV holography results that evaluate the mechanical stability of the design concept are detailed in Section 3.3. The shell was instrumented with thermal couples, and flow meters. With full power applied to the shell (260 Watts) and the water cooling system in operation, we first examined the shell with a thermal imaging camera. For the most part, the shell appeared to be very uniformly cooled, which meant that construction details such as uniform adhesive bonding surfaces and thermal grease joints were also uniform. Detailed tests using TV holography, however, showed that the mechanical stability of the shell was not as good as we had hoped for. When the coolant in the cooling system changed temperature by only a fraction of a degree Fahrenheit, the shell changed shape. We were able to determine that the shape changes the position of the ladders in the critical azimuthal dimension. At a stable operating temperature part shape was stable within a fraction of a micron over a 30 minute period. We could have spent much more time testing this part, but we believe time would be better spent finding a different, improved design.

In summary, for the close-out work, we performed the following tasks:

- 1) We built and integrated an automated assembly station, and used it to assemble a prototype of a silicon shell to a precision suitable for an SSC type silicon detector.
- 2) We demonstrated automated assembly with uniform adhesive joints and 5 micron placement accuracy in the critical azimuthal dimension.
- 3) We demonstrated we could meet all the difficult assembly specifications for an SSC silicon subassembly with an automated assembly station.
- 4) We built a state-of-the-art TV holography system, and programmed robust algorithms to change TV holography fringe data into shape change surface plots.
- 5) We tested a water cooling concept on a 360 degree silicon shell that demonstrated uniform thermal cooling.
- 6) We measured the mechanical stability of the water cooled silicon shell using TV holography.

3.0 TECHNICAL DISCUSSION

Figure 3.1.1-1 A cutaway of the SDC silicon detector array and space frame support showing the cylindrical central region and the disks forming the forward planar arrays.

3.1 Semi-Automated Assembly Station Integration

3.1.1 Introduction

The goals of this part of the close-out effort were to finish integrating a semi-automated assembly station, build a precision part, and as a result, demonstrate solutions to many practical problems associated with automated precision assembly of large structures for silicon tracking systems. The central region of many silicon detector designs is comprised of cylindrical shells as shown in Figure 3.1.1-1. Typically, the silicon detector ladders on each shell must be placed with high precision. The SSC requirements, which are representative, were for the ladder placement to be within $\pm 80 \mu\text{m}$ in the radial (R) direction, within $\pm 250 \mu\text{m}$ in the axial (Z) direction, and within $\pm 5 \mu\text{m}$ in the azimuthal ($R\phi$) direction. Obviously, all these requirements, except perhaps the axial tolerance, are very difficult to achieve. The total azimuthal alignment requirement for the fully assembled silicon tracker was $\pm 25 \mu\text{m}$, but in order to allow for tolerance build-up in the many steps required to reach the fully assembled state, a $\pm 5 \mu\text{m}$ goal was placed on subassemblies.

Little progress was made in the precision work until we were able to establish excellent temperature control for our precision assembly equipment. A cost effective temperature controlled assembly space is absolutely essential to build large precision parts. Good temperature control is needed because commercial assembly equipment is made of materials with aluminum-like temperature expansion coefficients ($\sim 20 \text{ ppm}/^\circ\text{C}$). In a typical air conditioned laboratory thermally driven problems easily squander the entire assembly error budget. To control thermally driven problems, a $\pm 0.05^\circ\text{C}$ temperature control is

needed. Large commercial rooms with this capability are usually clean rooms with humidity control and are very expensive. We therefore opted to build our own inexpensive temperature controlled rooms using the approach described in the Appendix 4.1. The rooms performed very well and additional rooms for other projects have been built using our design.

In our temperature controlled work spaces, we integrated mechanical parts with precision optical metrology instrumentation. Most of the assembly station's commercial and custom mechanical hardware and the temperature controlled space were designed and built during the SSC program. For the close-out work we:

- 1) defined an optical technique to establish a stable line of sight to serve as a primary assembly reference axis;
- 2) built closed loop feedback control systems to remove the radial run-out of the goniometer (rotation) stages which would potentially move the support rings off of the reference axis;
- 3) defined a technique and built hardware to set up reference telescopes which viewed fiducials on prototype ladders as the ladders were positioned to be glued to the support rings, and which had to be perpendicularly offset from the line of sight;
- 4) measured the long term stability of the reference telescopes;
- 5) developed a technique to attach and precision position the ladder support rings onto the goniometer/optical axis;
- 6) learned how to measure and shim the support ring landings so ladder-support ring bond joints would be within reasonable thickness;
- 7) finished the LabVIEW software development to automate the assembly process as much as possible;
- 8) set up an automatic glue dispensing head and investigated its performance; and
- 9) built a precision prototype part with glass slides and Plexiglas support rings to demonstrate our solutions of the precision assembly problems.

Figure 3.1.1-2 Schematic of the semi-automated assembly equipment arrangement for construction of the central region subassemblies.

Figure 3.1.1-3 Schematic of the semi-automated assembly equipment arrangement for construction of the forward region subassemblies.

All mechanical equipment for the automated assembly station was mounted on a 6 ft X 14 ft optical table that was inside a temperature controlled space, with $\pm 0.05^\circ\text{C}$ temperature control. The optical table had a doubler on one end, which was intended to allow joining it to another 6 ft X 14 ft table that would have been required to assemble the entire SSC silicon tracker on one continuous optical platform. The mechanical equipment could be configured to build either the cylindrical shells for the central region or the planar arrays for the forward region detectors. However, to make the change, the large assembly hardware had to be repositioned and realigned to build the different structure type. Figures 3.1.1-2 and 3.1.1-3 show schematic equipment arrangements for both types of silicon structures. For the close-out work, we concentrated our effort on proving the techniques for the central region.

Figure 3.1.1-4 shows the actual assembly station equipment configured for building the cylindrical silicon shells. The reference telescopes are in position to view ladders as they are bonded to the support rings. The telescopes, which are really changed into long working distance microscopes by adding a focusing lens, are mounted on precision movable stages to allow them to be easily repositioned for attaching ladders to either the inside or the outside of support rings. The end effector, on the primary compound stage, has a vacuum chuck that holds the ladders as they are moved into position in front of the reference telescopes. The end effector is a custom three axis flexure mechanism driven with piezoelectric actuators for precision positioning of the ladders.

The essence of the assembly technique is to view the round $30\ \mu\text{m}$ diameter ladder fiducials with the telescopes, find the fiducial centroids, and then with closed loop feedback control, precisely position the ladders so the fiducials are aligned to the reference telescopes. At that time the ladders are adhesively bonded to the support rings. The key issues in implementing the assembly approach are to: create and maintain a straight and stable optical reference line; define techniques to achieve precision placement and long term

opto-mechanical stability of the reference telescope assemblies; sense the ladder fiducials and, with closed loop feedback control, move the ladders to the telescope reference points; and bond ladders to support structures with uniform bond joints and good adhesion in acceptable times.

Figure 3.1.1-4 The actual assembly station equipment configured for building the cylindrical silicon shells.

3.1.2 The Optical Reference System

As is shown in Figure 3.1.2-1, establishing the optical reference system involves centering the two support rings on the two rotation stages, establishing a stable optical reference line between the rotation stage centers, and precisely positioning the two reference telescopes at 90° to the optical reference axis, so that they can view fiducials as the ladders are bonded to the support rings. The objective of the alignment procedure is to establish a reference line between the centers of ladder fiducials which is precisely parallel to a reference line between rotation stage centers.

There are two reference systems: the optical reference axis and that of the reference telescopes. The optical reference line of sight is built using a three point alignment method that utilizes a light source, a lens and a detector. This technique is well known in the HEP community, and, for instance, was used effectively as an alignment method for the muon chambers for the L3 detector at CERN. We found it to be a simple and effective method for the reference line of sight. The telescopes are placed in their reference position off axis using a novel optical afocal system, which is described in detail in Appendix 4.2.

Figure 3.1.2-1 A schematic of the optical reference system.

3.1.2.1 Optical Reference Axis System Set-Up

During the initial alignment, all the stages and drives, on which the goniometers were mounted, are set approximately to their center of travel, and roughly aligned parallel or perpendicular to the initial reference axis, which we defined as the Z axis. We used conventional optical tooling to establish the optical reference axis. With an alignment telescope, we established a line of sight which passed through center of the large goniometer and was perpendicular to the goniometer's plane of rotation (XY plane). Then, we mechanically positioned the center of the small goniometer onto the telescope line of sight. This procedure provides only a rough alignment because the telescope's optical axis wobbles as the focus is racked from the center of the large goniometer to the center of the small goniometer.

The precise optical reference axis needs to be defined independent of the flatness of the optical table and straightness of the mechanical slides. For this and several other precise alignment procedures, we used an autocollimation technique in which we autocollimated light from an electronic autocollimator off of a precision ball. Although the electronic autocollimator is designed to measure angles, it can be converted to a position measurement device by mounting a short focal length acromatic lens on the autocollimator output to focus the light onto a tooling ball. There are two ways to get a useful return from the ball; focus on the ball's surface or focus at its center. If the focus is at the center of the ball, the angle of the returned beam is linearly related to the ball displacement as shown in Figure 3.1.2-2. The technique is extremely sensitive. Using a 25 mm lens on the telescope, the last digit on the electronic readout for our instrument corresponded to 40 nanometers of motion, at least 10 times better than we needed.

To use this technique for precision set up, we mounted a tooling ball on a small XY translation stage, which was in turn mounted on the small goniometer's rotation stage and positioned such that the center of the tooling ball was near the center of the small goniometer's rotation axis. With a short focal length lens on the end of the alignment telescope we centered the tooling ball within the small goniometer's radial run-out by moving the ball and the telescope until the autocollimated return traced out a minimum area when the goniometer was rotated 360°. We then removed the ball, centered a 50 μm fiber at the telescope focus, and directed the fiber light approximately parallel to the initial line of sight. The center of the fiber light source is one point on the optical reference axis.

Figure 3.1.2-2 The dependence of the angle of the returned beam on the ball displacement obtained using a 25 mm lens.

Next, a 250 mm focal length lens is mounted near the center of the large goniometer. This lens receives light from the fiber source mentioned above and forms an image on a CCD camera, which is positioned about 190 cm away in the Z direction. The CCD camera is mounted in place on an Invar post. The 250 mm lens is mounted in a small XYZ stage. The Z motion supplied by the lens mount is used to set lengths for placing the two 90° reference telescopes off axis in a later alignment step. The XY lens mount motions center the lens on the large goniometer's rotation axis, which is accomplished by rotating the stage and observing the light spot movement on the CCD camera monitor. The image spot moves even when the lens is centered in the goniometer, because the goniometer has runout. The amount of motion of the spot is however minimized when the lens is centered. A point is picked on the CCD camera's image plane which is within the runout circle. That point is defined as the goniometer center. The center of the fiber in the small goniometer, the position of the lens center in the large goniometer and the light spot center on the CCD camera, define 3 points on the reference line of sight. Once the reference line of sight is established, any motion of the spot on the CCD is assigned to the large goniometer lens moving off of the reference axis due to runout. The large goniometer runout can be removed with high precision, because the lens position changes are magnified by the image-object conjugate ratio, which in our case is about a factor of six, so sensing and compensating for the runout is relatively easy. An added advantage of the technique described above is that it also automatically compensates for most (67%) of the small goniometer's runout. Since the small goniometer's runout is already small, the small goniometer's runout is a non-issue in the alignment error budget.

During initial set-up, we had a few mechanical problems, which we worked around. For example, we originally planned to have the lens in the large goniometer move in and out, so ladders could be bonded to the inside of support rings through the center clearance hole in the goniometer. However, we found that the mechanical mechanism to move the lens in and out did not repeat well enough and needed to be redesigned. The redesign is relatively minor but was judged to be too time consuming and costly for the close-out task. Since we planned to only bond ladders to the outside of the support ring in our first prototype part anyway, we rigidly fixed the XYZ lens mount in position on the large goniometer's axis of rotation.

3.1.2.2 Stability Measurements

Long term stability of the reference line of sight is key to our assembly concept. We knew that long term stability measurements involved difficult issues which we had to face before we could build precision parts. We started by monitoring the reference line of sight image spot centroid on the CCD camera over a weekend, expecting the spot would not move very much because the equipment was in a temperature controlled room, and the CCD camera was mounted on an Invar post. The results are shown in Figure 3.1.2-3. As far as stability tests were concerned, the test appeared to be successful. After an initial settling, the drift over the weekend was less than one half of a CCD pixel in both directions, which is about a 5 μm box, and we get to divide this by the optical magnification factor of six in assigning the error to motion of the critical parts. At first, we were satisfied, but when we looked closely at the data we could see that the image spot area on the CCD was changing with time and influencing the XY data. These results made us question the accuracy of the methods and our position sensing equipment.

We therefore decided to try to determine the causes of the observed drift. Our first attempt was to stabilize the area of the image spot on the CCD camera. Several methods were available. We could stabilize the current driving the fiber light source, or use a software threshold control to stabilize the area of the spot we used to calculate the spot centroid. The software method was much easier. Figure 3.1.2-4, shows the same data going to two programs, one with, and the other without, spot size area control using the threshold control technique. As is evident, threshold control significantly improved the results. With the threshold control technique, we monitored the optical reference line of sight stability over a four day period. The results shown in Figure 3.1.2-5 indicate an underlying problem remained in the form of a day-night cycle. Since the optical reference system was in a temperature controlled room, the observed behavior was hard to explain. Initially we expected that the light source was the cause of the observed behavior, so we built an ultra stable light source, made with an LED and an integrating sphere for the next test. That however turned out not to be source of the trouble, which we eventually traced to a temperature dependence of the video processing system, which we had not placed in the temperature controlled room. When we moved the video processing equipment into the temperature controlled space, used the ultra stable light source, and used the threshold control routine, we obtained the results shown in Figure 3.1.2-6. The data show stability within 0.25 μm over a 4 day test period. We believe this is about the limit of the present video processing equipment, which easily satisfies our requirements for this project.

Figure 3.1.2-3 Our initial result for the stability of the reference line of sight.

Figure 3.1.2-4 The stability results obtained for the line of sight, both with and without the software threshold control.

Figure 3.1.2-5 The stability result over a four day period obtained for the line of sight using the software threshold control method. Note the day-night cycle evident.

Figure 3.1.2-6 The final stability result over a four day period obtained for the line of sight using all the improvements made. Note the factor of three enhancement in the vertical scale compared to Figure 3.1.2-5.

3.1.3 Telescope Reference System

The two 90° reference telescopes (microscopes) form the second reference system required to build a precision shell. The telescopes must be precisely positioned as they define the points in space to which the fiducials on the silicon ladders are aligned as they are being bonded to the support rings to build a silicon shell. These telescopes must be aligned such that an imaginary line joining the telescope image points is parallel to the optical reference axis, which was established as explained in the previous section.

3.1.3.1 Telescope Reference System Design and Set-up

The reference telescope positioning procedure involves several critical alignment steps and includes both a coarse and a precision alignment sequence. For coarse alignment, we set the telescopes up mechanically. First the telescopes' focusing lenses were removed, and then by shimming, we positioned the axes of both telescopes to the same height above the optical table and perpendicular to a reference flat. Then, we replaced the focusing lenses. After centering, clocking, and shimming the support rings on the rotation stages as discussed in the goniometer section of this report, we were ready to proceed with the final step in the coarse alignment process: a ladder with fiducials was positioned in approximately the proper position against support ring landings, and the telescope mount spacing was slightly adjusted so the telescopes were aligned to the ladder fiducials.

The concept we used to precision position the telescopes, which determines the azimuthal accuracy of the final parts, is shown in Figure 3.1.3-1. The alignment fixture uses two optical systems on a common 5-axis mount attached to a movable cart. The two systems possess several interesting optical properties. Both systems are afocal, giving them unique focusing properties. For example, the object and image distances do not change when the optical system is moved along its primary axis. The systems are however sensitive to movement (tilt or displacement) with respect to their primary optical axis. One system is sensitive to tilt, but not displacement, while the other is sensitive to displacement, but not tilt. A description of the design and alignment details for these optical systems is given in the Appendix 4.2.

Figure 3.1.3-1 The concept used to position the 90° reference telescopes.

For the precision telescope alignment process, the single lens in the center of the large goniometer was removed, which still left the fiber source and the CCD camera to define the optical reference axis. Next, the afocal alignment fixture was positioned on the reference line, and the displacement sensitive afocal system was moved around until the image of the line of sight fiber source was back in the proper position on the CCD camera. The angular orientation of the moveable cart was then recorded by saving the position of the centroid of the fiber image on a second CCD camera, which viewed the output of the tilt sensitive afocal system. Then, the light from a second fiber source was directed perpendicular to the line of sight and adjusted to go through a ladder fiducial and into the first reference telescope. When the cart was then moved to position the second reference telescope, it was again placed on the optical line of sight and angularly oriented exactly like when the first telescope was positioned and aligned. That was accomplished by adjusting the cart's position and angle until the image spots were back to the proper points on the CCD cameras. The second reference telescope was then aligned to the image of the perpendicularly directed fiber source. After repeating the procedure several times, and waiting in between for thermal and mechanical drift to settle out, the telescopes were in the proper position. This procedure aligns the telescopes using only the optical reference line of sight. It is independent of the flatness of the optical table and the straightness of the mechanical slides. The remaining question concerned the long term stability of the set-up: namely do the telescopes point at the same position over a time span long enough to build a precision full silicon shell?

3.1.3.2 Reference Telescope Stability Measurements

We measured the long term stability of the reference telescope mechanical system by mounting a tooling ball on an Invar post in front of each telescope. Invar posts make good reference systems in the temperature controlled room. By autocollimating off the tooling balls with the telescopes, we could monitor motions over several day periods and assign the drift to the telescope mechanical support system. We had learned from previous long

term stability tests to move the electronics inside the temperature controlled room; however, because we now needed to monitor 3 spots simultaneously (the optical line of sight spot, and a spot from each of the two reference telescopes), we purchased an electronic quad box to combine the video from four cameras into one video frame. With this system we set out to do our first test. The results are shown in Figure 3.1.3-2. As is clearly seen, systematic problems had reappeared. After several days of looking we found a camera synchronization problem associated with the use of the quad box. After fixing that problem, the square waves previously seen disappeared and we produced the data shown in Figure 3.1.3-3. Although we still measured some motion for both of the telescopes, most of the motion was identical for both telescopes and hence inconsequential. The important error to look at is the difference in the vertical motions of the telescopes, which would show up as azimuthal error in building a part. The result of subtracting the Y-motions of the two telescopes is shown in Figure 3.1.3-4. Over a 3 day period, approximately the time required to build a full 360° shell, the azimuthal error that would be built into a part due to mechanical drift should be less than $\pm 1.0 \mu\text{m}$. In reality, we certainly expect a somewhat larger error during an actual shell assembly procedure, because there is more activity in the room than there was during the stability test. The resulting temperature disturbances are however largely compensated for by the room temperature control feature, and further ameliorated by the relatively large thermal mass of all the equipment, which greatly dampens short term variations. Given the excellent stability achieved during the stability test, coupled with the small size of thermal effects that are likely to be produced by people moving in the room, the construction of precision parts within the allowed error tolerances seemed possible.

Figure 3.1.3-2 The initial stability results obtained when all 3 spots were monitored simultaneously using the quad box.

Figure 3.1.3-3 The stability results obtained after fixing the synchronization problem.

Figure 3.1.3-4 The stability results obtained when the Y-motion of the two 90° reference telescopes were subtracted from each other.

Figure 3.1.4-1 The precision XY translation interface plate built on the front of the large goniometer to remove the radial runout problem.

3.1.4 Goniometers

Goniometers are the rotation stages we used to rotate the cylindrically symmetric shell during its assembly. By using the rotation stages, we were able to assure that the ladders were all aligned to each other as the alignment points were fixed in space, being defined by the 90° reference telescopes that remained stationary. That simplified many aspects of the assembly process, but in turn dictated a number of requirements for the goniometers.

3.1.4.1 Goniometer Requirements

The goniometers had to meet a number of requirements. These included a hole in the center large enough for the detector placement arm to enter and position the ladders on the inner surface of the silicon shell support rings, sufficient weight handling capacity, good mechanical stability, and minimal runout. Goniometer runout error is the major cause for the complexity of the automated assembly station design. Runout is the displacement of the center of rotation, in both the radial and axial direction, as the goniometer is rotated 360°. We purchased the best commercial goniometers available at the time the assembly station was being designed. The best rotation stages we could find were built by Huber. They satisfied all the requirements except the radial runout, which was thought to be about 10 μm , based on specifications given by the manufacturer. This runout would build an azimuthal error into the silicon shells that was larger than our tolerance; hence, the complications. As shown in Figure 3.1.4-1, a precision XY translation interface plate was built on the front of the goniometer to remove the radial runout. The XY stage was driven by a pair of piezo electric transducer (PZT) inchworms from Burleigh. PZT inchworms were chosen for their large range of precision travel, which reduced the requirements for a

large mechanical advantage. The runout had to be sensed and corrected, hence the requirement for a stable optical line of sight, a three point alignment system and a feedback control system to remove the runout in a precise way. The solutions to the initial complications produced their own set of complications. For example, we found that the inchworms tended to burn out if left on for extended periods of time. That unfortunately was discovered after 3 weeks of delicate precision alignment work.

In the years since we started the design work on the semi-automated assembly equipment, better rotation stages have become available. If we were to start over again now, we would carefully consider using air bearing rotation stages like the one recently built at Los Alamos, which has a radial runout of less than 1 micron.

3.1.4.2 Huber Goniometers Runout Measurements

We determined the radial runout of the Huber goniometers using the procedure described in Section 3.1.2.1. We monitored a precision tooling ball that was mounted on an XY translation stage near the center of rotation of the goniometer. Our results are shown in Figure 3.1.4-2. We averaged the data from several runs to produce the results. The radial runout for the large goniometer is about 10 μm , and for the small goniometer it is about 6 μm .

Figure 3.1.4-2 The radial runout results obtained for the goniometers.

3.1.5 Attaching Ladder Support Rings to the Goniometers

It is difficult to find the center of an object whose shape is as complex as that of the support ring. We realized, in fact, that there is no absolute center, and that what is important is to define a center and accurately relocate it later. We had to attach the support rings to mounting fixtures and then mount and center the support ring-mounting fixture subassembly onto the goniometer rotation axis. For that purpose we designed and

fabricated a precision Invar tooling plate. Locating pins and rods in the plate aided in precision locating the ladder support ring relative to the goniometer interface ring while support posts were precisely glued to the support ring. Our prototype support rings were made of Plexiglas, which is not a stable material. However, since this exercise was only a demonstration of the technique, and was carried out in a temperature controlled room, Plexiglas was judged to be adequate. Actually, we learned a lot using Plexiglas, because the rings were not perfectly round. The two Plexiglas support plates were machined together and holes were drilled through the rings every 90°. We glued small precision ball bearings into the holes to help center the subassembly onto the goniometer axis of rotation. Next the support ring subassembly was mounted on the goniometers and centered, with precision dial indicators working against the tooling balls. The assembly was shimmed to be perpendicular to the axis of rotation by working off of the front of the 4 orthogonal alignment balls in the support rings. Then it was centered radially by working off of the sides of the alignment balls. Then, the support rings were clocked using the precision dial indicator and a height gauge. The dial indicator is able to indicate 2.5 μm , but of course there are thermal effects from handling the indicator and the flatness of the optical table effects the precision, but the squaring procedure was only needed to get close. Precision ladder placement was done optically in the subsequent steps described earlier.

3.1.6 Glue and Glue Dispensing

The adhesive to use for the assembly process must be carefully chosen. The adhesive had to meet many requirements including, radiation hardness, electronics compatibility, short curing time, and a curing method and temperature that was compatible with the assembly procedure and the stability requirements. We needed a room temperature curing adhesive whose curing time was no more than a few minutes. We discarded adhesives that only cure with UV light or heat because it is impossible to get UV light through the silicon to the bond joint, and elevated temperature curing is nearly impossible given our assembly tolerances. The only acceptable solution was a room temperature adhesive curing with the aid of an activator. We settled on Dymax 991, a modified urethane, multi-cure, aluminum oxide filled, thermally conductive adhesive. This adhesive can be room temperature cured with an activator (Dymax 535). (It turned out that the adhesive could also be cured with UV light, or by heat.) We successfully tested the adhesive for radiation hardness and shear strength, but more testing is necessary before this adhesive could be used with complete confidence. The most important test remaining is the electronic compatibility test. We found that the Dymax adhesive bonded parts together after a couple of minutes. However, at the micron precision level, we found that if we removed the holding fixtures after that short time, the bond joint would move. We therefore settled on curing times of at least 15 minutes, although a somewhat shorter time would probably have been adequate.

We originally thought automated glue dispensing systems would be required to make uniform bond joints between the silicon ladders and the support rings, but when we set up and tested the automated glue dispensing system, we were disappointed with the results. The bond joints we produced with the automated dispensing system were neither consistent nor uniform. We decided after a few weeks of work, that if automated glue dispensing were required later, it could probably be made to work. However, given the compressed schedule we faced, we didn't have the required time, so we investigated manual methods. We found that by making a mask and buttering the glue onto the glass slide, we obtained good and uniform results. The activator was also applied by hand, which meant a person had to be on to optical table to apply the activator to the support rings. Clearly this was not the optimum technique for a production job, but was adequate for constructing a prototype and producing bond joints that looked nearly perfect. After some experimenting, we were able to bring the ladders into position for bonding and make final maneuvers to align the ladders before the adhesive set. After about 15 minutes we could remove the holding fixture without the alignment being disturbed.

Figure 3.1.7-1 A block diagram of the pick and place control system.

3.1.7 Pick and Place Control Hardware and Software

The control system for the pick and place equipment formed a major part of the semi-automated assembly work station. It consisted of a number of different elements that had to be integrated to make the overall system functional. The different components of that system are described in the following subsections.

3.1.7.1 Master Controller

A block diagram of the pick and place control system is shown in Figure 3.1.7-1. The master controller for the system is a 486 PC computer running programs written in LabVIEW, a graphical programming language. The master controller performs the following functions, it: 1) provides a user interface to the system; 2) closes the feedback loop for the line-of-sight and wafer alignment, and 3) orchestrates the tasks required to glue the wafer to the cooling ring. Programs written in LabVIEW are called virtual instruments (VI's). The front panel for the main VI is shown in Figure 3.1.7-2. The main VI brings up several sub VI's that gave an indication of how the operation is proceeding. A flow diagram of the shell assembly software is shown in Figure 3.1.7-3.

Communication to the hardware controllers is done with RS232 communication lines. Since we required more serial ports than are typically available on standard PCs, we used a LabVIEW compatible CONTROL eight channel serial port card. Through standard RS232 communication lines the master controller controls the quad centroid computer, the Anorad motion controllers, the Burleigh inchworms, and the Physik piezoelectric actuators. Each of these items are described in more detail below.

Com Port		FUNCTION	
4		INITIALIZE SYSTEM	
PRESENT ACTION		WAFER POSITION
<div>0</div> <div>0</div>	
Anorad Command		FINE ADJUSTMENT
<div>Xsetpoint</div> <div>Ysetpoint</div> <div>160.00</div> <div>308.80</div>	
		GLASS NUMBER BEING GLUED	
		<div></div>	

Figure 3.1.7-2 The front panel for the main virtual instrument.

Figure 3.1.7-3 A flow diagram of the shell assembly software.

3.1.7.2 Quad Centroid Computer

There are two alignment processes used in the shell construction: 1) the alignment of the line-of-sight (LOS) axis, which compensates for goniometer runout; and 2) the wafer alignment in the final gluing position. Both these alignments use video cameras to sense position and video processing to find the centroid of a circular spot.

The LOS alignment camera receives a focused image of the fiber optic source in the small goniometer on the shell central axis. If the imaged spot is not in the calibrated center line position, the lens position in the large goniometer is adjusted by translating the movable interface plate to the correct position with Burleigh inchworms. Since the optical system magnification is 6, the LOS scale factor is 1.6 microns/pixel.

Wafer alignment is accomplished by reflecting light off two 30 μm circular fiducials that are vapor deposited on the glass wafers in precision located positions. The reflected light from the fiducials is magnified through the two reference telescopes and imaged onto two video cameras. The resulting spot size on the two cameras is approximately 30 pixels in diameter, so the wafer scale factor is approximately 1 micron/pixel.

The alignment spot centroids are measured with a centroid algorithm which can find centroid position with sub-pixel resolution. The video signals from the three cameras (one for the line of sight, one for each of the reference telescopes) are combined in a video quad box that allows the video from four separate cameras to be combined into one video frame; a frame from each camera taking up one quadrant of the video picture. The resultant video is fed to an ITI 150 video processor system where the video information is digitized and prepared for computer processing. A 386 PC is used for computer video processing. The processing consists of continuously determining the pixel address of the centroid of each of the three spots. When interrogated by the master computer, the location of the three spot centroids are returned to the master computer over the RS232 lines. The video processing program is written in the C programming language. The program basically consists of a protocol for talking to the master computer over the RS232 port and an algorithm for determining the centroid of the spots. This function is performed by a separate computer instead of using the master computer because it is a time consuming operation.

3.1.7.3 Anorad Motion Controllers

The Anorad I-Serv2 controllers are two axis servo motor controllers manufactured by Anorad, the company that built the slides used in the pick and place system. Seven axes of linear motion and two axes of rotational motion are controlled by these drivers. The I-Serv2 controllers have stand alone operation and have 16 kilobytes of non-volatile user memory that can be programmed using the Anorad ACSPL language. There are also 16 uncommitted digital inputs and 16 uncommitted digital outputs available for user utilization. The controller includes an addressable RS232 port from which the user may program the device or issue it commands in real-time. When coupled with a times 50 encoder multiplier, the linear motion slides have 162,560 steps/inch, or a resolution of 0.156 microns/step. For the pick and place application, a state-machine architecture is employed so that synchronous motion between the five I-Serv2 controllers can be achieved without overburdening the master controller. The five controllers have been given RS232 addresses 0 through 4. Controller 0 communicates with the master controller and sets the machine states. Four of the digital output lines of controller 0 are fed in parallel to four of the digital input lines of each of the other four controllers. The four controller 0 output lines form a four bit word which has 16 different possible values. The particular value chosen indicates to the other four controllers the current operating state. Two additional lines are used as handshake lines. One handshake line notifies the other controllers when the machine state lines are valid and triggers an interrupt in the other controllers to begin any operation that needs to be done during that state. The other handshake line is a *done* flag that is *ANDed* with the *done* lines of the other controllers so the master controller will know when all of the operations that are to occur during that machine state have been

completed. Of these 16 possible machine values, nine are used for pick and place operations. Instead of having the master computer command each of the I-Serv2 controllers, the pick and place operation is divided into groups of motions that involve one or more of the controllers. The master computer can initiate any one of these groups of motions by telling controller 0 to execute the appropriate routine programmed into its memory. Controller 0 then sets the machine state and each of the other controllers carries out the procedure that is programmed for that particular state. When the task is completed, controller 0 notifies the master computer by sending a special character back over the RS232 line. This methodology considerably decreases computer programming and timing related problems.

3.1.7.4 Inchworm Controller

The Burleigh inchworms are controlled by a Burleigh 7000 series controller. This controller provides the high voltage sequencing required to actuate the inchworms. The Burleigh inchworm is chosen for the LOS position control because of its small size, its 4 nm resolution, and its two inch travel. The 7000 series controller has many capabilities; however, most of them only apply when the inchworm is used with an encoder. For our purposes the addition of an encoder made the mechanical package too large, so the encoder was not included. Instead, we used feedback from a linear pot, or the position of the LOS spot itself to position the inchworms. The basic capabilities of the 7000 series controller for an inchworm without an encoder, includes the speed, direction, and an on/off control. Therefore to move the inchworm a given number of steps, it is necessary to set the speed, turn the inchworm on and then turn it off again after enough time has passed to move the given number of steps. This type of control is too CPU intensive to be useful. The 7000 series controller will, however, allow step and direction movement if the step and direction signals are fed to the controller via a connector on the back of the controller. The step pulses must be precisely 50-50 duty cycle pulses. An RS232 controlled stepper motor controller with step and direction outputs that met this criteria is used to add "smarts" to the inchworm controller. With the stepper motor controller, a command can be given to move a given number of steps, and the controller will move that many steps without further intervention. The stepper motor controller is a Centent model CN0170. A LabVIEW VI had been previously written for this device, so its integration into the system was fairly straight forward. The Centent controller also had capabilities for digitizing the position of the linear pot connected to the inchworm. This permitted position measurement and position control from the same device.

3.1.7.5 Physik Piezo Controller

Three axes of very fine piezoelectric positional control are incorporated in the end effector. They are tip, tilt and rotation. We actuate the three piezos with a three axes Physik R27730 controller with an RS232 interface. It receives positional commands over the RS232 port and converts them to voltages from 0 to 1000V with a resolution of 0.25 Volts that is applied to the piezos to set their positions. The tip and tilt axes are set during initial system alignment and are not changed. The rotational axis is positioned as required by the closed-loop wafer positioning system.

3.1.8 The First Prototype Part

The previous subsections describe the subsystems needed to build a precision prototype part. In this section we describe how the subsystems work together. For the assembly of the shell prototype, we used glass ladders instead of silicon ladders, because glass ladders with fiducials are considerably less expensive than silicon ladders with fiducials. With glass ladders, we were also able to visually inspect the bond joints by looking through the slides.

3.1.8.1 Assembly Procedure

The glass slides we used in the prototype had round 30 micron fiducials deposited near their ends. The fiducials were deposited while the glass ladders were held in a 3 pin positioning jig in a coating chamber. A similar 3 pin support was used on the vacuum end effector, so the ladder fiducials always appeared within the small field of view of the reference telescopes. Every ladder was placed according to the following procedure:

- 1) Rotate the goniometers to the first position.
- 2) Check the line of sight. If the LOS CCD spot is not centered, translate the interface plate on the large goniometer, which holds the alignment lens, until the three point line of sight is in the reference position.
- 3) Place a glass ladder on the vacuum end effector.
- 4) Prealign the glass ladder by moving it into position and aligning the ladder using closed loop feedback according to the reference telescope images of the alignment fiducials. Store the settings for the motors and PZT voltages.
- 5) Bring the ladder back to the start position. Remove the ladder and apply the adhesive by hand through a mask. The mask has a 3 point positioning jig to hold the glass while the adhesive is applied. The mask is machined so the proper amount of adhesive is put in the proper place to make uniform bond lines when the adhesive is squeezed out to make the bond joint.
- 6) Put the glass ladder with the adhesive on it back onto the end effector and position it against the 3 point alignment pins.
- 7) Apply adhesive activator to the support ring landing.
- 8) Move the glass ladder back to the position defined by prealignment (step 4).
- 9) Fine position the ladder the final time, with closed loop feedback control, using the alignment fiducial images from the reference telescopes.
- 10) Wait until the adhesive is set (about 10 to 15 minutes).
- 11) Release the vacuum and move the end effector away and back to the start position.
- 12) Check that the ladder is still aligned after the end effector has moved away.
- 13) Rotate the goniometer into position for mounting the next ladder.
- 14) Repeat steps 2) through 13) for the next ladder.

With the current procedure, we estimate 3 ladders per hour could be bonded in place; therefore, it would take about a week to assemble ladders on the inside and the outside of 0.5 meter diameter support rings.

3.1.8.2 Results

The partially finished shell prototype is shown in Figure 3.1.8-1. Close up pictures of typical adhesive joints are shown in Figure 3.1.8-2. We placed 37 of the 42 ladders allowing a few positions to be open for demonstration and show and tell at a later time. The sawtooth pattern of the support rings allowed all but the last ladder to be moved radially inward and be directly bonded without problem. However, placing the last ladder would have required a special procedure due to the circumferential overlap of the ladders. We did not work out the special procedure required in full detail, but most likely it would have involved the following steps. First the ladder would have been moved inward toward the support ring along a line shifted, but parallel to the desired radial line. This motion would have been stopped when the ladder was radially inside the overhanging edge of the neighboring ladder, but not yet touching the support ring. At that time the ladder would have been moved tangentially to the support ring until it was underneath the overhanging edge and tangentially in the correct position. Then it would have been moved the final step radially inward. The procedure would have also entailed placing the ladder in an offset position on the vacuum chuck so that the chuck itself would not bump into the overhanging edge of the neighboring ladder.

Figure 3.1.8-1 The partially finished shell prototype.

Figure 3.1.8-2 Close up pictures of typical adhesive joints on the assembly.

Figure 3.1.8-3 Measured placement accuracy of the ladders. The ΔX and ΔY measurements refer to the left fiducials. The YL-YR values are the difference of the vertical locations of the left and right ladder fiducials and hence give the tilt of the ladders.

The assembly of the shell took nearly 3 weeks after initial alignment, because there were the usual first time delays needed to fix equipment and software, and to alter and gain confidence in the procedures. After the part was assembled we checked the placement ladder by ladder, which took about 30 minutes in total. The results are shown in Figure 3.1.8-3. We took several runs to demonstrate the measurement repeatability.

In retrospect, many of the procedures used could be improved, but overall the ladders were placed very precisely, especially considering that this was our first attempt. Most of the "poorly" placed ladders can be explained. The offset seen for the first ladder resulted from our allowing only 2 minutes for the glue to set before releasing it from the end effector. Although the glue appeared to have set, in reality it was still soft enough to allow motion on the micron scale. Between ladders 2 and 18, things went smoothly and the ladders are well within the $\pm 5 \mu\text{m}$ specification. Around the placement of ladder 18, a spring on the transverse interface plate adjustment broke and we could not get the part out without a complete disassembly. We patched the parts together to allow us to finish the assembly, but the placement was not as consistent after that, especially on ladders 26, 28 and 30. Between the completion of the support ring alignment and the start of the shell assembly, one of the Burleigh inchworms burned out. We could not replace the failed part without completely disassembling the critically aligned parts. We therefore opted to build in a manual adjustment. It was however often difficult to reach without bumping the reference system equipment. Consequently, we could not take out goniometer runout in one direction prior to placing some of the ladders.

3.1.9 Summary and Conclusions

The basic concept we developed proved to be sound. We were able to demonstrate on the first prototype shell that we built using the semi-automated assembly workstation, that we could bond most of the ladders within the tolerances we were given. Those tolerances were $\pm 5 \mu\text{m}$ in $R\phi$, $80 \mu\text{m}$ radially, and $250 \mu\text{m}$ in Z. The more poorly placed ladders can largely be traced to hardware failure in the assembly machinery. We learned a great deal from the construction of the first prototype, a lot of which is in the form of small

details that only first hand experience can provide. There is still work to do to completely finish the automated assembly station before precision silicon assemblies can be made with complete confidence. Mostly the work involves fixing small mechanical hardware, making parts accessible for repair or replacement if they break during assembly, and practicing alignment and assembly procedures. The automated glue dispensing equipment also still needs to be debugged and incorporated into the overall system before one can enter a true production mode. We did however prove that off the shelf hardware can be used to build precision assemblies if the temperature of the assembly space is controlled. We learned that temperature controlled assembly areas are absolutely essential to build precision assemblies. We built three large inexpensive temperature controlled assembly rooms and demonstrated that they could easily be operated within a $\pm 0.05^{\circ}\text{C}$ temperature range. We proved that commercially available optical equipment can be adapted to make the precision alignment measurements needed to assemble large precise silicon subassemblies. Hopefully this record of our experiences will save someone else considerable time and anguish.

A large investment was made in the development of the semi-automated assembly workstation. As is typically the case, the hardware costs were relatively small compared to the cost of personnel. Approximately a 12 man year effort was required from the development of the initial concepts to the production of the first prototype shell. This work was accomplished over a four year period. We believe that reducing that time period by a factor of two would have been close to impossible even with the use of a considerably larger team.

Before anyone embarks on a different assembly procedure for constructing large, high precision silicon structures, they should very carefully evaluate what potential advantages such a procedure would confer over what we have developed given the cost and time required to turn the concept into hardware. That is especially true when an existing concept has already been developed and essentially proven.

3.2 TV Holography Measurement System

3.2.1 Introduction

One of our SSC close out tasks was to upgrade the TV Holography (TVH) system. We had developed the system to assess the stability of silicon detector parts, assemblies, and subsystems. Our first TVH system was built with spare parts we had on hand, and although it had all the necessary features, the system was cumbersome to use and slow compared to state of the art systems. The goal of the upgrade was to produce a compact TVH system with 30Hz "real-time" image processing capability, with enough laser power to view the larger size silicon system subassemblies, and greatly improved ease of operation. The upgrade involved acquiring a higher power, single frequency laser, better image processing hardware for the on-line data acquisition system, and improving the post-processing software, which was used to provide a quantitative rather than a qualitative interpretation of the measurements.

We purchased the laser and built a small movable unit to use for stability measurements in the full shell water cooling tests discussed later. Part of the upgrade and integration work of the on-line image processing hardware and software was farmed out to Ryszard Pryputniewicz of Worcester Polytech Institute (WPI). We had previously worked very closely with Ryszard in the development of our original TVH system. Ryszard had already developed similar hardware and software for high speed operation of his own TVH systems, and we were confident that he could put the units together easier than we could. At the same time, we started work on the development of improved post-processing software needed to turn the fringe patterns produced by the upgraded image processing package into surface shape information.

To make this chapter self contained, we incorporate herein several sections from our earlier TVH write-up that formed part of our FY 93 final report which we had already submitted to the SSC Laboratory.

Early in the silicon tracker design process we realized that shape stability of structures would be an important detector issue. After a search for a sensitive stability measurement technique, we decided on TV holography, which proved to be a useful tool to verify the mechanical stability and dynamic characteristics of many prototype structures. TVH is a noncontact, full field-of-view interferometric method for measuring shape changes of parts caused by a variety of effects, including thermal heating and mechanical stress. Interesting dynamic characteristics of mechanical systems, such as mode shapes and mode frequencies, are also determined by TVH. Often, a stated goal of stability testing is to compare predictions from finite element models (FEM) used for design, with the properties of mechanical prototypes. TVH provides full field-of-view, "real time" (TV frame rate) measurements with submicron sensitivity, and it often shows features that were not predicted by the FEM. The differences between models and test results lead to better understanding, ideas for improved designs, and better modeling techniques.

TVH systems have been researched since the 1970's, but faster, smaller computers and a phase shifting technique for directly evaluating speckle intensity patterns, make TVH in the 1990's, a very useful measurement tool for many applications. The present trend in TVH system development is to build smaller systems for use outside of controlled laboratory environments, and to develop more robust algorithms to quickly calculate and display surface shape changes. The newest systems use fiber optics and laser diodes. They measure 3D shape changes, in-plane or out-of-plane shape change components, as well as, absolute shape, stress profiles and dynamic characteristics. The original system we used for the SSC program was adequate to answer many questions about silicon tracker design and stability, but it had only a modest capability compared to the more modern systems. Since future detectors for high energy physics experiments will likely have difficult stability requirements, improved TVH systems could play a useful role in determining if the stability requirements are indeed met, and in helping to identify satisfactory detector designs.

Figure 3.2.2-1 A typical TVH system layout.

3.2.2 Basic Principles

A typical TVH system layout is shown in Figure 3.2.2-1. In our first system we used a 25 mW He/Ne laser that is split into 2 beams. One beam, called the reference beam, is reflected from a mirror mounted on a piezoelectric pusher and then expanded and directed toward the CCD camera. The other beam is expanded and directed toward the object, which scatters light into the CCD camera. The zoom lens on the CCD camera images the object. A measurement typically involves collecting and processing 8 frames of camera data. Four frames are gathered from the object in an initial or "start" state. The other 4 frames are collected after the object is deformed. In each state, 4 frames are gathered sequentially. Between each frame in the 4 frame set, the piezoelectric pusher in the reference beam is moved to change the path length by a quarter wavelength of light. This is called phase stepping. Processed information is sent to the TV monitor, which displays fringes representing the shape change caused by the load. The fringe pattern is superimposed over the image of the object. Modern image processors can process and display the data at the TV frame rate. Shape changes that are slow compared to TV frame rates are observed in "real time".

For the object "start" state, the i^{th} frame intensity at each CCD camera pixel location is described by the equation for two beam interference:

$$I_i(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r].$$

The o and r subscripts refer to the object and reference beams, and the pair (x_p, y_p) refers to the location of pixel p . The optical phases ϕ_o and ϕ_r are proportional to the path lengths of the object and reference beams from the first beam splitter to the CCD camera. After the part deforms, the pixel intensity for the j^{th} frame is given by:

$$I_j'(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[(\phi_o + \Omega) - \phi_r].$$

The phase shift Ω is related to the optical path length change caused by part deformation; Ω contains the shape change information. The phase Ω is separated from the 3 other unknowns, I_o , I_r , and $[\phi_o - \phi_r]$, by phase stepping the piezoelectric pusher in the reference beam between each frame, with phase steps of $0, \pi/2, \pi$, and $3\pi/2$. The 4 frame intensities for the "start" state are given by:

$$I_1(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r].$$

$$I_2(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r - \pi/2]$$

$$I_3(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r - \pi]$$

$$I_4(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r - 3\pi/2]$$

After the object moves, the 4 frame intensities are:

$$I_1'(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r + \Omega]$$

$$I_2'(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r + \Omega - \pi/2]$$

$$I_3'(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r + \Omega - \pi]$$

$$I_4'(x_p, y_p) = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r + \Omega - 3\pi/2]$$

If $D_1 = (I_1 - I_3) + (I_1' - I_3')$ and $D_2 = (I_2 - I_4) + (I_2' - I_4')$, then the monitor display:

$$D_1^2 + D_2^2 = 32I_o I_r (1 + \cos[\Omega]),$$

shows fringes draped over the object. More frame grabber arithmetic leads to an expression for Ω . The arithmetic is easy. Let

$$N_1 = (I_1 - I_3) + (I_2' - I_4')$$

$$N_2 = (I_2 - I_4) - (I_1' - I_3')$$

$$N_3 = (I_1 - I_3) - (I_2' - I_4')$$

$$N_4 = (I_2 - I_4) + (I_1' - I_3')$$

$$D_1 = (I_1 - I_3) + (I_1' - I_3')$$

$$D_2 = (I_2 - I_4) + (I_2' - I_4')$$

$$D_3 = (I_1 - I_3) - (I_1' - I_3')$$

$$D_4 = (I_2 - I_4) - (I_2' - I_4')$$

and let

$$N = (N_1^2 + N_2^2) - (N_3^2 + N_4^2) = 64 I_o I_r \sin[\Omega]$$

$$D = (D_1^2 + D_2^2) - (D_3^2 + D_4^2) = 64 I_o I_r \cos[\Omega]$$

then,

$$\Omega = \text{atan}[N/D]$$

Once Ω is known, the shape change between the deformed and the reference state of the object is calculated. The arctangent calculation of Ω provides information modulo 2π , which is called phase wrapped data. Finding and taking out the 2π phase jumps is called phase unwrapping. Unwrapping would be simple if the data were clean, but scattered laser light has speckle noise, which makes unwrapping difficult; however, recently developed unwrapping algorithms have quite good noise immunity.

3.2.3 Examples

3.2.3.1 Static Measurements

Figure 3.2.3-1 shows the mechanical fixture used to test prototype silicon ladder assemblies. The ladders were made from 4 pieces of engineering grade silicon 34 mm wide. The four 60-mm long silicon pieces are butt-bonded together to make a ladder 240 mm long by 34 mm wide and 300 μm thick. Down the length of each side of the ladder, 4 mm wide by 200 μm thick graphite epoxy strips are bonded to the silicon to

Figure 3.2.3-1 Mechanical fixture used to test prototype silicon ladder assemblies.

stiffen the part. For one of our tests, a ladder is bonded to the top and bottom sides of two graphite blocks, and this assembly is mounted to precision rotation and translation stages. With this mechanical arrangement the ladder assembly was bent, positively and negatively twisted, and hand heated. The results are shown in Figure 3.2.3-2. Each fringe spacing

corresponds to approximately $\lambda/2 = 0.32 \mu\text{m}$ of shape change. We say approximately, because there are small angle cosine effects that we did not consider. An important aspect of the technique is that large shape changes can be measured by bootstrapping; that is, the shape shown is saved, fringes are cleared and the old deformed state is made the new "start" state, then the part is further deformed until a similar number of new fringes again appear. At the end of any number of these bootstrapping steps, the total displacement is determined by adding the fringes from all the different deformation steps. In principle, the number of new "start" states can be arbitrarily large, corresponding to arbitrarily large shape changes.

One conclusion of our measurements is that in static and dynamic tests, ladders behave as one continuous piece of silicon, even though they are constructed of smaller silicon pieces bonded together with adhesive. We have not seen any fringe discontinuity at the bond joints in any of our testing.

Figure 3.2.3-2 Results showing the effects of twisting, buckling, and hand heating a silicon ladder assembly.

Figure 3.2.3-3 Fringe patterns mode shapes for a vibrating silicon ladder.

3.2.3.2 Dynamic Measurements

A technique called time average holography is used to display mode shapes of vibrating parts. Four phase shifted frames of data are needed to display mode shapes on the TV monitor. In time average holography, the phase Ω , which contains the mode shape information, is a function of time and position. For example, for a cantilever beam vibrating at a frequency ω ,

$$\Omega[x,t] = 2kD[x]\cos[\omega t],$$

where $D[x]$ is the maximum displacement amplitude at position x , from the cantilever base. At each CCD pixel the intensity is given by:

$$I[x,t] = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r + 2kD[x]\cos[\omega t]]$$

If the camera frame time is much longer than the cantilever oscillation period, a camera frame records a time average of the intensity which is given by:

$$\langle I[x,t] \rangle = I_o + I_r + 2\sqrt{I_o I_r} \cos[\phi_o - \phi_r] J_0^2[2kD[x]] = I_j$$

where J_0 is the 0-order Bessel function. Four phase shifted frames (I_j) are collected and processed according to:

$$(I_1 - I_3)^2 + (I_2 - I_4)^2 = 16I_o I_r J_0^2[2kD[x]]$$

When the processed information is displayed on the TV monitor, the fringes shown are a contour map of the mode shape for the vibrating part. Fringe pattern mode shapes for a vibrating silicon ladder, supported near both ends are shown in Figure 3.2.3-3.

It is interesting to see the effect of stiffening strips on the sides of silicon wafers. In the time average holograms, absence of fringes indicate a node in the mode pattern. Figure 3.2.3-4 shows mode shapes of silicon ladders with and without graphite stiffening strips along the side. The node along the sides of the ladder with the stiffening rib clearly shows how ribs improve the rigidity of the part.

Figure 3.2.3-4 Mode shapes of silicon ladders with and without graphite stiffening strips along the side.

3.2.4 Hardware Improvements

3.2.4.1 The Laser

For the SSC close-out effort we purchased a new laser, which significantly improved the TVH system performance and ease of operation. The 200 mW laser is a doubled, diode pumped solid state laser from Coherent Laser Inc., which operates at a single frequency in the green. Single frequency operation is very desirable for TVH systems as it means that the reference beam and object beam path lengths no longer have to be matched. This allows all the optical equipment to be put on a small 2 ft X 2 ft optical table, which can easily be moved around, with only minor realignment, to change the point of viewing or the image size. Since the laser power is nearly 10 times greater than our original 20 mW HeNe laser we are able to look at structures up to about 0.50 meter in diameter with relative ease. For larger objects, there are now 750 mW, single frequency lasers on the market that operate in the infrared at 990 nm. Figure 3.2.4-1 shows the new optical system.

3.2.4.1 The Data Cube Processor

The image processing system is to be upgraded from a PC base to a MaxTD development system from Datacube³. The MaxTD system contains a stand alone computer system with a pipeline processor to achieve state-of-the-art 30 Hz operation. The system has a high level programming interface that allows quick evaluation of different image processing algorithms and parameters. We farmed out the processor work to WPI, because we were short handed, and WPI had already implemented several Datacube systems. We received the system just as we were finishing this report, and our initial tests indicate excellent performance.

Figure 3.2.4-1 The new bread board based TV Holography optical system.

3.2.5 TV Holography Post-Processing Software

3.2.5.1 Introduction

Although the fringe pattern as viewed on the TV screen is often sufficient to obtain a qualitative understanding of the test part performance, sometimes it is important to obtain quantitative information. TV holography provides the information needed to make plots of surface shape change from the fringe data, but the required algorithms are difficult to implement because the data are typically quite noisy. Before the close-out work we had only the simplest software to go from fringes to surface plots. As part of the close out work, we developed a robust software package to interpret and present TV holography data. The software was written in IDL² (Interactive Data Language) and implemented on a PC platform. We chose IDL for its robust, fast image processing characteristics and its unique programming language, which made it possible to create user oriented software.

3.2.5.2 Software Description

We structured the software so that the data processing is interactive. The user directs the course of the processing and visualization through a menu driven interface. As we learned, this proved invaluable because a predetermined processing sequence does not consistently produce valid and meaningful results.

The typical processing steps are: 1) read in the data, 2) create an intensity-based interferogram and a phase-based interferogram, 3) filter the phase-based interferogram, 4) unwrap the phase-based interferogram, 5) create visual displays of the unwrapped phase-based interferogram, and 6) store the results.

The holography data is stored in sets of four frames (files) of video information corresponding to the four pathlength phase steps of $\pi/2$. To produce an interferogram, two data sets (primed and unprimed) of 4 files each must be loaded into the processing software. The user selects the names of the two data sets of interest for viewing. The software then reads these files into IDL from the hard disk drive.

Once the holography data is read into the software, the program calculates both the intensity and phase interferograms. The intensity interferogram is found using:

$$I = \sqrt{((I_1 - I_3) + (I_2 - I_4))^2 + ((I_1' - I_3') + (I_2' - I_4'))^2}$$

where, I_x is from the first data set, I_x' is from the second data set, and the subscript refers to the x^{th} file (1→4) of a file set. I_x and I_x' are defined in Section 3.2.2. The phase interferogram is determined from:

$$\Omega = \tan^{-1}\left(\frac{I_4' - I_2'}{I_1' - I_3'}\right) - \tan^{-1}\left(\frac{I_4 - I_2}{I_1 - I_3}\right)$$

The phase information corresponds directly to the object deformation. Unfortunately, the phase data obtained from the preceding equation is ambiguous because of the multi-valued nature of the arctangent function. To obtain accurate deformations the phase data must be unwrapped^{4,5}, eliminating the modulo 2π effect of the arctangent function.

In most cases, the phase data must be filtered prior to unwrapping. Filtering reduces the effects of noise on the unwrapping algorithm. Filters can also be used to select sub-regions in the data, which is useful when only a portion of the interferogram must be unwrapped. Our software includes the following filters: smooth, median, sine/cosine average, low intensity, background separation, saturation, and local discontinuity.

Phase information is unwrapped using a fluid flow algorithm. A starting location for the phase unwrapping is chosen interactively by the user. The algorithm then proceeds to unwrap the phase by producing an expanding wave front whose origin is the user-selected point. Along the wave front a criteria is used to locate the phase discontinuities which resulted from the arctangent function. Based on this criteria, the algorithm adds 2π , subtracts 2π , or leaves the phase unchanged. The algorithm has the ability to "flow" around noise or other bad data points. After the unwrapping is complete, the bad points are determined by assigning them a phase value equal to the average of the neighboring, unwrapped, points.

After successfully unwrapping the phase data, the user can visualize the results. The software includes two basic display features -- a 3-D shaded surface plot and a contour plot. With the surface plot, the user can change the viewing angle, which provides the user with a full field of view. The contour plot indicates deformation with shaded contour regions or simple line contours, with the value of each contour line given. These results give an immediate understanding of the deformations which is not possible when looking at the numerical results on paper.

The results can be saved in several forms. All of the images produced during processing may be sent to a printer at any time. In addition, the unwrapped phase data can be stored in an ASCII file. The data is then easily transferred to a spreadsheet program for further data processing. Also, the entire processing session may be saved so that future processing can begin where the last session ended.

3.2.5.2 Processing Example

We will illustrate typical program operation by analyzing the cantilever plate shown in Figure 3.2.5-1. The raw intensity and phase interferograms are shown in Figures 3.2.5-2a and 3.2.5-2b respectively. Figure 3.2.5-2c shows the phase interferogram after sine/cosine filtering. Next, we typically use a background filter to separate the plate from the background. The result is shown in Figure 3.2.5-2d. Then, the phase data are unwrapped and displayed using both a 3-D surface plot and a contour plot as is shown in Figure 3.2.5-3.

Figure 3.2.5-1 Cantilevered plate used in the processing example.

Figure 3.2.5-2a

Figure 3.2.5-2b

Figure 3.2.5-2c

Figure 3.2.5-2d

Figure 3.2.5-2 The interferograms at various stages of processing. Figure 3.2.5-2a is the raw intensity interferogram. Figure 3.2.5-2b is the phase interferogram. Figure 3.2.5-3c is the phase interferogram after sine/cosine filtering and Figure 3.2.5-2d shows the result of using a background filter to separate the plate from the background.

Figure 3.2.5-3 The unwrapped phase data are displayed using a 3-D surface plot on the left and using a shaded contour plot on the right .

3.2.6 Summary and Conclusion

TV holography is a sensitive, full field of view testing method that provides essential information about precision assembly shape stability in realistic test configurations. TVH is capable of providing answers to detector stability questions that have never been experimentally answered and cannot be answered by FEM modeling alone. TVH results are also important for developing assembly techniques that preserve the high precision built into individual parts. State of the art TVH systems update at 30 Hertz, and can be small if single frequency lasers are used for illuminating the object. The software to unwrap fringes and produce quantitative 3-D surface shape change plots is now quite robust. Future designs will likely move the TVH systems off of the optical table to the shop floor. Because future silicon detector systems for high energy physics experiments will have to meet difficult stability requirements, TVH systems should play an important role in future tracking detector subsystem development.

3.3 Water Based Cooling System and Tests

3.3.1 Water Cooling Concept

Cooling system design continues to be one of the most challenging problems facing designers of future large silicon tracking systems. During the past few years, Los Alamos developed and tested several butane based evaporative cooling systems concepts with some success, but safety concerns and unforeseen operational requirements led us to begin exploring water based systems. At the end of the SSC program we were just beginning to test water based cooling system concepts. As part of the close-out work, we were funded to continue those efforts.

Figure 3.3.1-1 Cooling system concept.

Figure 3.3.1-2 Cooling test hardware (end view).

Figure 3.3.1-3 Cooling test hardware (front view).

The development of a cooling system design is a particularly difficult task. For the SDC silicon system, the cooling system had to be capable of removing approximately 20 kW of heat and keep the silicon detector ladders at a temperature of about 0°C. The electronic heat sources were to be at the ends of the silicon ladders. The several thousand ladders in the SDC system were to be dispersed throughout a cylindrical volume about 1 m in diameter and 5 m long. The system temperature had to be uniform to prevent thermally induced mechanical distortions. Further requirements were that the cooling performance had to be attained with a very low mass system which did not introduce mechanical strains of its own into the silicon structure. There are important questions concerning mechanical stability, thermal resistance, construction difficulties, and uniformity. We developed a concept which tried to address these issues, and by constructing a prototype, we gained first hand knowledge of the remaining problems. The concept we built and tested is shown in Figure 3.3.1-1, and the hardware is shown in Figure 3.3.1-2 and Figure 3.3.1-3

The concept is to mount a metal cooling channel on a graphite epoxy support ring, glue right angle fins to the graphite ring and transfer heat from the electronics, along the silicon ladders, through the fins, and then finally into the cooling channel through a heat conducting grease film. The silicon ladders assemblies are bonded directly to the top of the cooling fin. The graphite epoxy support rings, which have a low thermal expansion coefficient, provide the mechanical stability. The aluminum cooling channels carry the circulating antifreeze which removes the heat. The aluminum cooling channels were bonded to the graphite rings in only one spot, and as such, were free to slide on the graphite ring and thermal grease joints when the aluminum contracted as the system was lowered to its operational temperature. In theory, the grease joints provide thermal paths without upsetting the mechanical stability of the rest of the structure. Our cooling channels are made of aluminum, but beryllium, or carbon-carbon is the material of choice. However, both were too expensive and required too large a lead time to obtain for our proof of concept tests.

3.3.2 Silicon Shell Construction Details

Constructing this assembly was time consuming and messy. In fact, the construction process would be difficult with valuable parts because it would be difficult to keep them clean. Given that we weren't using valuable detector parts in the construction of the prototype, we could be somewhat "messy" and come back at later times and clean things up. Even so, it seemed that thermal grease oozed out of every joint when one wasn't looking.

The procedure followed to build the water cooled shell was as follows: First we obtained enough ladders to build the full shell. Some of the ladders came from prototype shell arc segments that we had previously constructed. This turned out to be facilitated by the Dymax 991 adhesive we had selected to attach ladders. The adhesive could be softened by moderate heat allowing the easy removal and replacement of ladders should any have been found to be defective during the final assembly. We were able to remove the ladders from the old prototypes without breaking them.

The next step was to solve a problem concerning the gluing of the aluminum fins to the support rings. We found that the graphite foam core of our new support rings crumbled easily and the glue used to attach parts there tended to push into the foam yielding poor bond joints. That made it difficult to glue the cooling fins to the graphite and make them lie flat. Therefore, an epoxy filler was used to smooth and seal the landing on the steps of the support rings. Having solved that problem, we now had to deal with the grease. A layer of thermal grease was put on the side of the aluminum cooling channel that was to be in contact with the graphite support ring. That was done around the entire circumference, except for the one spot where glue was used to bond the aluminum ring to the graphite ring. The adhesive used was the Dymax 991, and the one spot was about a 0.5 inch long. This procedure was used to address the large coefficient of thermal expansion (CTE) mismatch between the aluminum ring (CTE ~ 20 ppm/ $^{\circ}\text{C}$) and the graphite ring (CTE ~ 0). With such a mismatch, an aluminum ring 40 cm in diameter would shrink by 200 μm when cooled from assembly temperature to operational temperature ($\Delta T \sim 25^{\circ}\text{C}$). That is outside the allowed radial error budget, and in addition would have introduced a severe strain on the carbon support ring. By bonding the rings together at only one spot, the aluminum ring was supported by the graphite ring, but still free to contract by sliding on the grease around the remainder of its circumference and thus not induce a load into the graphite ring.

Having sealed the edges of the support ring and having bonded the cooling channel to the side of the support ring at a single point, we were ready to start bonding the right angle cooling fins in place. Dymax 991 was applied to one face of a right angle fin and thermal grease to the orthogonal face. The fin was placed with the glue face down on the support ring landing while pushing the grease face hard against the aluminum channel to force out as much grease as possible. That was done to keep the grease film both uniform and as thin as possible, at most several thousandths of an inch thick. That was required as the term "thermally conductive grease" is somewhat of a misnomer. We had used Dow Corning 304 heat sink compound, one of the better greases. Nevertheless, its thermal conductivity was only about 0.5 W/m $^{\circ}\text{C}$, implying a temperature drop of 0.5°C for each mil of thickness for a heat load of 1 W/cm 2 . Although the whole process was not too difficult, it was extremely messy and humbling, and something that should encourage all cooling system designers to search for new concepts.

The aluminum cooling channel walls were about 1/32 inch thick. We tried to make them thinner, but without success given the limited time available. We made the cooling channels by laser welding two face plates to the inside and outside side walls. That seemed to work, but the rings became slightly warped in the process, and they could not be ground flat because the walls were too thin. The finished cooling channels were 2 mm high and 17 mm wide. The cooling fins were also made from 1/32 inch Aluminum stock.

Next, we set the now completed support rings, equipped with cooling channels, in a fixture and hand bonded the silicon directly onto the right angle cooling fins. As the final step, electrical heaters were bonded directly to the silicon to simulate typical electronic heat loads.

3.3.3 Cooling Test Description

A series of tests were conducted to study both the thermal behavior of the water based cooling system and the mechanical behavior of the silicon shell. The temperature response of the cooling system and shell was determined using a series of thermocouples and a thermal imaging camera. The mechanical behavior of the shell was determined using the TV holography system. The shell was mounted on a 3-point kinematic support inside a large "sealed" thick walled cylindrical aluminum chamber. The chamber was actively cooled using a series of copper pipes bonded to the exterior wall of the chamber. Coolant was circulated through the copper pipes. The coolant was supplied by the same system that supplied the silicon shell, although a separate flow loop was used. For insulation purposes the cylinder was wrapped in fiberglass on all sides except for a 60 cm diameter window used to view the silicon shell. The 3-point kinematic support consisted of 3 Invar posts mounted on an Invar table. The posts were each topped by a spherical ball. The balls were accepted by a V-grooves bonded to the silicon shell. One end of the shell had two V-grooves which were oriented tangent to the shell to allow for circumferential expansion or contraction, while the other end of the shell had a single V-groove that was oriented parallel to the axis of the shell to allow for lengthwise expansion or contraction of the shell.

3.3.3.1 Results From The Thermal Imaging Camera

We used a thermal imaging camera to examine how uniformly the cooling system removed the simulated electronic heat load from the silicon shell. For this set of tests, the front end of the chamber was removed in order to get better quality thermal images. Therefore, the test was run with the coolant temperature only a few degrees below ambient temperature. The parameters for the tests are summarized in Table 3.3.3-1. The ladder temperatures given in the table came from thermocouples on one ladder which was located near the center of the backside of the shell and which is not visible in the images discussed below. The left and right thermocouples are located inboard of the electronic heaters, directly above the support rings. As such, the thermocouples did not give the maximum temperature of the ladders. Rather, the maximum temperature was at the location of the heaters, which got as hot as 105°F (~40°F above the coolant temperature) for the case of the maximum heat load. Typical thermal imaging pictures are shown in Figures 3.3.3-1, 3.3.3-2 and 3.3.3-3. When comparing the different images which represent different power levels and coolant flow directions, be aware that the camera temperature range setting was changed between pictures. In some cases saturation was reached, so the camera only gave a lower limit for the maximum temperature.

For the images shown on the left hand side of Figures 3.3.3-1 and 3.3.3-2, the coolant entered the cooling channel at the bottom of the shell, flowed up the front side and then down the back side, finally exiting at the bottom of the back side. In other words, for the left side images the flow was from bottom to top. In another test, we reversed the flow direction in the cooling channel so that the outlet side faced toward the camera, and the flow direction on the side viewed was from top to bottom. Those results were very similar and are shown on the right hand side of Figures 3.3.3-1 and 3.3.3-2. Nearly uniform operation around the circumference is seen at all operating temperatures up to a full load of 258 Watts total input heater power. However, a small and variable temperature gradient did exist, both from the top to the bottom of the shell, and in the inboard region of the

Figure 3.3.3-1 Thermal imaging camera results for several input power values. The coolant flow is from bottom to top (top to bottom) for the right (left) side images.

Figure 3.3.3-2 More thermal imaging camera results for several input power values. The coolant flow is from bottom to top (top to bottom) for the right (left) side images.

Table 3.3.3-1 Operational parameters used to obtain the thermal imaging results.

Power (W)	Time	T (°F) Left	T (°F) Center	T (°F) Right	T (°F) Inlet 1	T (°F) Out 1	T (°F) Inlet 2	T (°F) Out 2	ΔP #1 (psi)	ΔP #2 (psi)	Flow (g/s)
FLOW: BOTTOM to TOP											
0.0	15:16:02	65.82	67.33	65.32	65.78	66.74	65.61	66.41	1.19	1.20	15.58
38.4	15:22:29	68.33	69.12	67.80	65.98	67.76	65.87	67.26	1.17	1.18	15.50
78.6	15:31:43	70.88	70.78	70.31	65.82	69.11	65.70	68.34	1.20	1.22	15.68
153.7	16:30:13	75.32	73.65	74.73	65.80	70.77	65.58	69.56	1.10	1.13	16.36
195.0	15:53:27	78.69	75.70	77.86	66.07	72.99	65.86	71.73	1.06	1.08	14.53
234.2	16:03:15	81.21	77.26	80.25	66.02	74.38	65.83	72.98	1.05	1.06	14.48
258.2	16:10:04	82.88	78.32	81.87	66.12	75.25	65.88	73.73	1.04	1.06	14.48
FLOW: TOP to BOTTOM											
0.0	17:06:59	66.17	68.20	65.61	66.27	67.70	66.16	67.19	1.23	1.24	17.28
39.9	17:13:20	68.07	69.36	67.37	65.99	68.24	65.86	67.57	1.21	1.21	16.98
81.8	17:19:02	70.32	70.62	69.44	66.11	69.49	65.96	67.90	1.03	1.04	14.76
157.4	17:28:39	73.84	72.94	72.62	65.97	71.04	65.77	69.77	1.50	1.49	21.03
195.0	17:33:26	75.76	74.11	74.41	65.94	71.65	65.70	70.29	1.39	1.39	20.08
258.4	17:36:15	78.83	75.84	77.28	65.95	73.04	65.71	71.38	1.15	1.15	17.14
FLOW: CLOCKWISE											
262.1	11:55:26	80.16	75.88	78.47	66.57	75.03	66.48	73.66	1.06	1.01	14.94
262.1	12:01:32	80.59	76.47	78.92	66.84	75.49	66.75	74.17	1.06	1.02	14.75

shell. Since each of the 78 ladders had a heater at each of its ends, the full power load that we used corresponded to 1.65 Watts of electronic heat on each ladder end. For the SDC silicon system, a single ladder was to have 1280 electronics channels (half on the upper and half on the lower surface) at each end of the ladder. The 1.65 Watts per ladder end corresponds to 1.3 mW/channel, a little below the 1.5 mW/channel that the SDC front end electronics system seemed to be converging on.

Except for one ladder near the center of the field of view, the shell appears to be cooled nearly uniformly in the circumferential direction. We examined the ladder in question after the test, but could not find any unusual visual sign to account for the higher temperature near its one end. We speculate that it probably had to do with the adhesive joint between the silicon and aluminum fin or the grease joint between the aluminum fin and the aluminum coolant channel. One should note that along the right hand side of the images a small sliver of the inner surface of the back side of the shell can be seen, which includes the heater area of some of the inside ladders..

The small nonuniform response around the circumference can be attributed to a couple of effects. First, as the coolant flows around the shell, it picks up additional heat from each ladder it encounters. Therefore, the coolant and ladder temperature should increase as one proceeds around the circumference of the shell from the coolant entrance point to the exit point. For the full power case, and a coolant mass flow rate of 16 g/sec (1/2 at each end of the shell), the temperature rise should be ~5°C (9°F), given a heat capacity of 3.18 J/g-°K for the coolant. That result is confirmed by the experimentally determined values given in Table 3.3.3-1. The second effect has to do with the stratification of the air temperature inside the chamber. Given that cold air is denser than warm air, one expects that the air at the bottom of the chamber to be colder than the air at the top of the chamber. Some heat is necessarily transferred between the ladders and the air by convection. Part of that heat is in turn removed by conduction down the length of the ladders. However, since the ladders are so thin, heat conduction down their length is quite

poor. As a result, the heat the ladders pick up from the air produces the greatest heating at the center of the ladders, the points furthest away from the coolant channels, as seen in Figure 3.3.3-1. Furthermore, the temperature rise is directly proportional to the temperature difference between the air and the ladder, and hence is greatest at the top of the shell where the air is the warmest. Since the tests were run at slightly below room temperature, one expects, at least for the low power cases, for the ladders to be warmed by the air. However, as the power level applied to the heaters is increased still further, the ladders become warmer than the ambient air temperature. Therefore, the ladders begin to transfer heat to the air, and one expects, and indeed observes, that the centers of the ladders are cooler than their parts near the support rings, as seen in Figure 3.3.3-2.

In Figure 3.3.3-1, one clearly notices that at low power levels, the bottom of the shell is colder than the top of the shell, regardless of the direction of the coolant flow. Part of that behavior can be attributed to the sinking and gathering of the colder air near the bottom of the tank. An additional contributing factor probably has to do with changes in the heat transfer effectiveness from the coolant channel wall to the coolant. The coolant enters and exits the coolant channel at a right angle to the direction of flow in the channel itself. Also the entrance and exit ports of the channel represent a narrowing of the fluid path cross section, and hence a higher velocity flow and better heat transfer. Those effects combine to produce a very effective heat transfer to the fluid near the channel entrance and exit points. In between those points, a boundary layer begins to become established in the fluid, resulting in a reduction of the efficiency of heat transfer into the fluid. The thermal conductivity of the metal cooling channel also helps to reduce the temperature of the coolant on the exit side as the channel walls are continuous in that region, and only a thin metal barrier physically separates the entrance and exit regions.

At higher power levels, as the coolant begins to be warmed substantially on its way around the circumference, one expects to the result of the above mentioned effects to become less apparent. That is clearly seen in Figure 3.3.3.2 (higher power levels), where the direction of the coolant flow becomes evident. One notices that there is a larger temperature gradient from the top of the shell to the bottom when the flow is also in that direction (right side pictures).

When the power level was increased in a series of steps to the full power value, the ladders quickly came to equilibrium at every new operating condition, typically in less than 5 minutes. Even with the low coolant flow rate that was used, ~16 grams/sec, we could always remove all the heat and achieve a stable result, although there was a significant increase in the temperature of the ladders, especially at the electronics ends for the higher power levels.

Figure 3.3.3-3 is an end view of the shell showing the cooling channel and fins, and in the case of the left side picture some of the ladders on the inside of the shell. (A small bit of the inside ladders can also be seen near the top of the right side picture.) The views were obtained using a mirror, which unfortunately was not big enough to capture the full end at once. The right side picture shows all of the "front" side of the shell, whereas the left side picture shows the bottom part of the back side of the shell. The bad ladder mentioned earlier is clearly visible in the right side picture. As its cooling fin, as well as its partner's cooling fin on the inside of the shell, appear to be warmer than any of the other fins, one can conclude that the defect is most likely poor thermal grease joints between the fins and the cooling channel, rather than bad adhesive joints between the ladders and the cooling fins. One also sees that the direction of the fluid flow (clockwise) is not very apparent from the images, which can be attributed to the effects discussed earlier.

To better understand the cooling system operation, we estimated the temperature drops along the paths from the heaters to the water/glycol channel that carries away the heat. By assuming adhesive joint and grease film thickness, we can compare calculated results with experimental temperatures taken from the thermal camera images. Figure 3.3.3-4 is a schematic of the heat flow path. Table 3.3.3-2 summarizes the thermal resistance and the temperature drop calculations along the thermal path.

Figure 3.3.3-3 Thermal imaging camera results showing an end view of the shell. The flow direction is clockwise. The power applied to the shell was 262 Watts.

The two largest temperature drops are through the silicon, from the heaters to the silicon cooling fin adhesive joint, and through the aluminum fin, from the silicon adhesive joint to the grease film that thermally connects the fin to the water channel. The total calculated temperature drop from the heaters to the water channel is 16.3°C. Over one half the drop, 11.65°C, is in the silicon; the rest, 4.65°C, occurs along the rest of the path, from the silicon, through the cooling fin, to the water channel.

Using the thermal imaging color chart in Figure 3.3.3-2, one sees that the silicon temperature over the top of the adhesive joint between the silicon and the aluminum fin (dark blue) is about 27°C for the full power case. From the thermocouple data, the average water temperature is 21°C. The 6°C difference compares reasonably well with the calculated 4.5°C difference; especially, since we don't know grease and adhesive joint thicknesses accurately, and we used average values for the lengths and water temperature.

Figure 3.3.3-4 A schematic of the heat flow path and temperature drops.

Table 3.3.3-2 The thermal resistance and temperature drops for the heat flow path.

#	Material	σ [W/m°C]	L_{AVE} [in.]	A [in. ²]	$R = \frac{L}{\sigma A} \left[\frac{^\circ\text{C}}{\text{W}} \right]$	$\Delta T [^\circ\text{C}] = RQ$
R_{g1}	Glue	0.5	0.001	0.5 x 0.75 (0.375)	0.21	0.34
R_s	Silicon	237.0	0.500	0.012 x 1.0 (0.012)	6.92	11.35
R_{g2}	Glue	0.5	0.004	1.0 x 0.5 (0.5)	0.63	1.03
R_{a1}	Al	237.0	0.031	1.0 x 0.5 (0.5)	0.01	0.02
R_{a2}	Al	237.0	0.625	0.0625 x 1.0 (0.0625)	1.66	2.72
R_{a3}	Al	237.0	0.031	(0.313)	0.02	0.03
R_{a3}	Grease	0.5	0.002	(0.313)	0.50	0.82
R_{a4}	Al	237.0	0.031	(0.313)	0.02	0.03
				TOTALS	9.97	16.34

We estimated the experimental temperature drop across the grease joint by looking at Figure 3.3.3-3, the end view of the cooling channel and cooling fin. The center of the cooling channel is 23.8°C (dark blue), and the fins are 24.8°C (light blue). The difference, 1°C, is close to the calculated value for a .002 inch thick grease joint (0.82°C); either the grease joint is a little thinner than assumed, or the conductivity is a little larger than the vendor quoted value, 0.5 W/g°C. Actually the thermal conductivity of the same grease was measured to be closer to 1W/g°C last year at LANL, but it seems the small differences are not worth quibbling about at this stage.

Some of the large temperature drops and the high local temperatures can be attributed to various compromises that were made during the construction of the shell. The ladders used to build the shell did not have beryllium ground planes as the real ladders would possess. Furthermore, the real ladders would have had electronics on both their upper and lower surface, whereas for this test, we had the resistive heaters on only the outer surface of the ladders, and hence ran them at twice the heat load expected to be generated by the chip set on one surface of the ladder. The purpose of the ground planes was two fold: first to isolate the strips from any electrical noise generated by the electronics, preventing pickup and possible feedback; and secondly to provide a significant increase in the thermal conductivity along the ladder (and ground plane) from the electronics to the right angle fin. Assuming a 300 μm thick beryllium ground plane on each surface of the ladder in the region of the electronics to the inboard end of the right angle fin, the temperature drop along the ladder would have decreased by over a factor of four to 2.6°C from its value of 11.65°C for the full power case, given the effective tripling of the conductor thickness available, and the 1.75 times higher thermal conductivity of beryllium compared to silicon.

In summary, the thermal imaging camera results show that there are no unexpected gross problems with water cooling approach. With the exception of one ladder end, the part seems to be uniformly cooled, even with manually made grease and adhesive joints; the temperature drops are about what is expected based on reasonable assumptions, and the flow rate is adequate to keep the silicon stable, although a higher flow rate is easily possible. We found that secondary heat transfer mechanisms, such as convection, have a noticeable impact on the final temperature distributions. The exact benefit of convection is however hard to predict for the final system since that system was to be enclosed in a sealed chamber, and with a system as complicated as the SDC tracker, convection flow

would be hard to predict and undoubtedly be highly variable. From our point of view, the main problem with the water cooling approach we used is implementation. The grease is messy to work with; the metal channel and cooling fins, even if they are made with beryllium, have too much material, and the fin joints, both grease and glue, would be hard to assemble to assure controlled thickness joints. In addition, as we will show in the next section, the mechanical stability of the arrangement is unpredictable. Even so, we had considerable success, and based on what we learned, we expect that a more careful design and a better construction technique would solve or at least mitigate the remaining problems. If we were to start again, we would also investigate building the water cooling channel directly into the support ring. Recently a metalized carbon foam that is durable, easy to machine and highly conductive has become available. A cooling channel could be machined into this foam and sealed to make a water tight channel in the support ring. This was a design concept early in the SSC project, but it fell by the way side because of material problems. One can speculate that the new foam has promise for a very nice cooling ring design.

Mechanical Stability Test Results For the TV holography tests of the prototype shell, we placed the part into the cooling tank and carefully supported it, as described at the beginning of Section 3.3.3. This was done to insure that thermally induced motion of the support structure would not couple into the shell. For the initial test, we worked with the tank evacuated to avoid potential problems with convection and other secondary effects. During the tests, we determined these effects were indeed very small, and vacuum operation was not needed to obtain consistent results.

In the first test we evaluated the shell stability with the coolant near room temperature. The coolant was flowing through both the shell and the cooling tank walls, but the heaters were turned off. The operating parameters for the test are given in Table 3.3.3-3. After all the operating conditions reached equilibrium we watched the part with TV holography to see if the shell changed shape with time. The results are shown in Figure 3.3.3-5 to Figure 3.3.3-8. The first set of two pictures shows the shape change during a 7 minute test and the second set of pictures shows the accumulated shape change when the test interval was increased to 28 minutes. Since fringes indicate shape change, no fringes is a desired result. From the intensity pictures, Figures 3.3.3-5 and 3.3.3-7, one concludes that the shape is very stable with these operating conditions. Off line image processing using the phase image data brings out more detail. From the phase images, Figure 3.3.3-6 and Figure 3.3.3-8, we obtain higher resolution information for the motion with each color indicating a small additional increment in phase, between $-\pi$ and π . As a phase change of 2π (one fringe in the intensity pictures) corresponds to a motion of $1/2$ wavelength ($0.27 \mu\text{m}$), each color change in the phase image represents an even smaller motion. From the results, one concludes that when the system is near room temperature, with the heaters off and when the operating temperatures are kept stable to within about 0.05°C , the whole part is stable to a small fraction of a micron.

Table 3.3.3-3 Operating parameters for the test in Figure 3.3.3-5,6 and 3.3.3-7,8

File name	Time	ΔT ($^\circ\text{F}$) South	T ($^\circ\text{F}$) Center	T ($^\circ\text{F}$) North	T ($^\circ\text{F}$) Tank	T ($^\circ\text{F}$) Inlet 1	T ($^\circ\text{F}$) Out 1	T ($^\circ\text{F}$) Inlet 2	T ($^\circ\text{F}$) Out 2	ΔP #1 (psi)	ΔP #2 (psi)	Flow Rate (g/s)
T0	16:34	56.79	56.86	56.70	53.99	59.16	59.31	58.67	59.01	1.38	1.40	15.74
T7	16:40	56.84	56.86	56.70	54.02	59.20	59.35	58.72	59.06	1.42	1.42	15.49
T28	17:01	56.92	56.95	56.85	54.15	59.34	59.50	58.83	59.17	1.39	1.44	15.53
TVH Figure		ΔT ($^\circ\text{F}$) South	ΔT ($^\circ\text{F}$) Center	ΔT ($^\circ\text{F}$) North	ΔT ($^\circ\text{F}$) Tank	ΔT ($^\circ\text{F}$) Inlet 1	ΔT ($^\circ\text{F}$) Out 1	ΔT ($^\circ\text{F}$) Inlet 2	ΔT ($^\circ\text{F}$) Out 2	$\Delta(\Delta P1)$ (psi)	$\Delta(\Delta P2)$ (psi)	$\Delta\text{Flow Rate}$ (g/s)
3.3.3-5,6		0.05	0.00	0.00	0.03	0.04	0.04	0.05	0.05	0.03	0.02	-0.25
3.3.3-7,8		0.13	0.09	0.15	0.16	0.19	0.19	0.16	0.16	0.01	0.04	-0.21

For the second test we returned the chamber to ambient pressure and again let the shell and tank come to equilibrium. As before, coolant was flowing through the shell, and the heaters were off. Then, we watched with TV holography while evacuating the tank. The results are shown in Figure 3.3.3-9. For the small temperature change associated with the pressure change, the shape changes are non-zero, but are uniform over the full pressure change. Every ladder bows about the same amount. Even for this simple case it is difficult to understand how the support constraints act to buckle the ladders, but we had seen this behavior before, during pump down for Butane cooling tests on another shell.

Figure 3.3.3-5 Intensity image for the 7 minute stability test.

Figure 3.3.3-6 Phase image for the 7 minute stability test.

Figure 3.3.3-7 Intensity image for the 28 minute stability test.

Figure 3.3.3-8 Phase image for the 28 minute stability test.

The next set of tests involved shape change during cool down from room temperature to a lower operating temperature by dropping the temperature of the coolant flowing in the part and the tank. Typical results are shown in Figure 3.3.3-10. For this picture, the temperature change is only 0.33°C over a 2 minute period. It appears that the part is not changing shape symmetrically, as for example in Figure 3.3.3-9. The part is twisting, which, although difficult to understand, seems to be initiated on the side with the double

Figure 3.3.3-9 Pump down test results. The left side pictures are image intensity results and the right side pictures are phase image results. The top set gives the shape change between 0 and 1 minute, and the bottom set gives the shape change between 1 and 1.5 minutes. Each fringe corresponds to approximately $0.27\text{ }\mu\text{m}$ of motion.

Figure 3.3.3-10 Typical shape change results for cool down tests. The left side pictures are image intensity results and the right side pictures are phase image results. The top set gives the shape change for a ΔT of -0.22°C , and the bottom set gives the shape change for a ΔT of -0.33°C . Each fringe corresponds to approximately $0.27\text{ }\mu\text{m}$ of motion.

kinematic supports, which are at the lower right hand corner of the picture. There are not many fringes, since the temperature change is only 0.33°C . A typical ladder near the center of the part is isolated and shown in Figure 3.3.3-11. The twist is obvious in the unwrapped picture of the ladder. This must be induced by twisting of the ends relative to each other, most likely from an interaction between the support rings and the kinematic supports. If that is indeed the case, then for the current prototype, a ΔT of -20°C from room to operating temperature (approximately 60 times that shown in the figures) would

introduce a very significant twist in the critical ϕ dimension. This behavior is different than we observed on the part built for Butane tests described in our previous report. For that part the cool down test showed symmetrical results, like the pictures in Figure 3.3.3-9. A possible explanation is that the grooves in the kinematic support in the current prototype are not exactly lined up, and as a result, induce a torque into the part as it cools. It also illustrates the need for a truly kinematic support mechanism, even for low CTE parts.

Figure 3.3.3-11 Unwrapped surface change for the ladder near the center of the part in the top images of Figure 3.3.3-10. The maximum differential motion is 1.2 μm .

Figure 3.3.3-12 Fringes showing the shape change due to apparent stiction

The shape changes shown in Figure 3.3.3.-10, are typical, but occasionally a different type of shape change also occurs. Its character is shown in Figure 3.3.3.-12. The shape change looks like a twist, which could be caused if the cooling ring did not slide uniformly on the graphite support ring and cooling fins as the parts cooled down. During the cool down, we observed the shape would move from that shown in Figure 3.3.3.-10, through the shape change shown in Figure 3.3.3.-12 and back again to Figure 3.3.3.-10. We took this to be indicative of stiction. We conclude that the shape change of the part on cool down is complex and unpredictable, and that the concept of a graphite support ring providing the mechanical stability, with the aluminum cooling channel sliding freely between the graphite ring and cooling fins, although perhaps not flawed in principle, was not fully achieved in practice. Part of the problem is no doubt due to our attempt to keep the grease film as thin as possible, which could have led to local stiction problems.

In the last tests we tried to evaluate the stability of the part at a reduced temperature with full power and cooling. The results are very similar to the results shown in Figure 3.3.3-5 to Figure 3.3.3-8. If the operating conditions are stable the shape is stable, but small temperature changes effect the shell shape. During these tests we had problems with air entering the cooling system. We could see the cooling efficiency drop by monitoring the consequent part shape change that simultaneously occurred. Much more testing would be possible, but we believe the time would be better spent finding, building, and evaluating a better design based on the information we have already gathered from the tests.

4.0 APPENDICES

4.1 Temperature Controlled Work Spaces

Early on, as the work began, it became apparent that to assemble anything with micron precision would require a temperature controlled work space. A survey of commercially available temperature controlled spaces revealed that precision temperature controlled rooms were very costly. We investigated some relatively small, but inexpensive temperature controlled spaces that Lawrence Livermore National Laboratory had designed, which used air blown through banks of light bulbs to control their spaces to 0.05°C . We decided that this technology would fit nicely with our needs. We designed a small prototype for a small space in our building and found that it worked very well, controlling the temperature to within 0.05°C . With that encouragement, we constructed three additional 20 x 12 foot rooms that would eventually house the three main experiments, TV holography, the automated assembly equipment and the tank for the cooling tests. As shown in Figure 4.1-1 the work space consists of an aluminum frame covered with 12 mil plastic. The frame includes a plenum area where the air conditioned room air is blown across the light bulb banks. The heated air in the plenum is blown through two layers of filter material into the work space below. The filter material makes the air flow more laminar and also helps keep the light from the light bulb bank from getting into the work space. Six 750 cfm blowers, three on each end, provide the air movement. This arrangement provides between one and two air exchanges per minute. A four inch gap along the bottom of the aluminum frame allows the air to escape. The plenum was broken into three removable sections so large equipment could be dropped into the chamber with an overhead crane. The temperature control system consists of 1) the temperature sensors, 2) the data acquisition and control computer, and 3) the light bulb control electronics.

4.1.1 Temperature Sensors

Seven temperature sensors are strategically located to provide feedback and temperature monitoring. Four sensors are evenly distributed inside the work space itself, two sensors are located in the plenum as part of the feedback control loop, and one sensor monitors the outside room air. Integrated Circuit sensors were initially used to determine the temperature, but were later replaced by thermistors, which eliminated a problem we had with a periodic jump in the temperature readings.

Figure 4.1-1 The temperature controlled work space.

Figure 4.1.2-1 The two loop cascaded control loop used.

4.1.2 Computer System and Software

The computer control is provided by a STD Bus based 286 AT computer with a Sensoray Model 7418 board and a Burr-Brown ST4305 D/A card. The Sensoray board digitizes the output of the seven temperature sensors. The D/A card provides command input to the light bulb control electronics. The control program was written in the "C" language, and provides a visual display of the temperature history for the previous 20 hours. The control loop is a two loop cascaded control system as shown in Figure 4.1.2.-1. The slower outside loop, sensed by the thermistor in the work space, sets the temperature setpoint for the faster inner loop. The inner loop sensor is located in the plenum and controls the level of power that is fed to the light bulbs. The room is long enough that we can control the temperature on each side of the room with little interference. So there are actually two control loops running simultaneously.

4.1.3 Light Bulb Brightness Control Electronics

The heart of the linear light bulb control electronics is a Douglas Randall LC70 B-10 linear proportional controller that is similar to a basic household light dimmer except that it has a 70 Amp capability and it takes a 0 to 10V input signal to control it. Other electronics are included for safety considerations.

4.1.4 Caveats About Temperature Controlled Work Spaces

4.1.4.1 Power Availability

In our 12 ft x 20 ft workspace we are using 56, 150W light bulbs to heat the incoming air. Although, in normal situations the bulbs are running at 30 to 60% of the full 8.4KW, there are still times when the power will be at maximum. In our smallest work space, which is 7 ft x 12 ft, we are using 28, 150 W bulbs or 4.2 kW. The smaller

workspace runs at about 30% of full power under stabilized conditions. The power required of course varies depending upon the difference between the outside room temperature and the setpoint temperature, as discussed below.

4.1.4.2 Air Conditioning System

The workspace temperature setting is typically one to two degrees Centigrade above the outside room temperature. The air conditioning system should be able to handle the extra heat load. If it can't, a bootstrapping effect will occur with the work space heating up the outside space and a stable temperature will not be achievable. Also, the outside room temperature must be regulated well enough that there are no wild fluctuations in its temperature that would be outside the bandwidth of the control system. If there are such fluctuations the ability to hold the work space temperature will be reduced.

4.1.4.3 Work Space Centers

We found that the control point temperatures can be controlled under normal conditions to within 0.05°C . In the large chambers, we have banks of light bulbs on both sides of the room. The localized temperature variations in the room, due to heat given off by equipment or people, are large enough to require the use of multiple independent control systems. We regulated the temperature at two points, one on each end of the chamber, to within 0.05°C . Other areas within the work space were not regulated to that extent. It is important to have the controlling temperature probe (and there is a choice of five) be as close as possible to the area where temperature control is critical.

4.1.4.4 Light Intensity Fluctuations

Light bulbs are used for warming the incoming air because light bulbs have a fast response. This allows a higher control bandwidth than would otherwise be possible. However, the light could potentially adversely effect light sensitive measurement equipment in the room. The filter material in the plenum performs two functions. It distributes the air flow and also blocks most of the light. Nevertheless, some variations in light intensity remain inside the work area and any highly light sensitive equipment needs to be shielded.

4.2 Afocal Alignment Fixture Design & Alignment

The afocal optical systems were used to position the 90° reference telescopes in their proper location. Those telescopes are offset from the optical reference axis in order to view the ladder fiducials. The afocal optical systems are interesting objects in their own right, and may be useful for other applications. The idea for their design is discussed on page 39 in reference 6, which contains many examples of useful and current optical metrology techniques. Afocal optical systems are not often discussed in optics texts, and their properties are therefore not well known. These two afocal optical systems are particularly interesting.

Afocal systems have an interesting imaging property: the overall object to image distances does not change when the optical system is moved along the axis between the object and the image. In addition, one of the systems we built is sensitive to tilt, but not displacement, while the other is sensitive to displacement, but not tilt.

In the simplest setup, the afocal property is easy to understand. Figure 4.2-1 shows the displacement sensitive system, and Figure 4.2-2 shows the tilt sensitive system. The figures show their behavior for both a collimated beam input and for an object at a finite distance.

Figure 4.2-1 A displacement sensitive afocal optical system.

Figure 4.2-2 A tilt sensitive system afocal optical system.

For the case of collimated beams, it is easy to see that the system geometric performance is independent of the position along the beam axis. For finite objects it is not so easy to show, but certainly true, that the distance between object and image is given by $L = 4F + F^2/f$ for the displacement sensitive system, and by $L = 4(F+f) + F^2/f$ for the tilt sensitive system, independent of the optical system position along the optical axis. Since f , the focal length of the center lens, can be small compared to F , the focal length of the end lenses, the object-image separation, L , can be large compared to the length of the lens system. For the displacement sensitive system, the object and the image are inverted: a transverse movement of the source point produces an equal and opposite transverse movement of the image; it follows that a transverse movement of the unit at any axial

position produces a doubled movement of the image. This behavior is similar to the three-point optical system used for the reference line of sight, and like a single lens, the system is not sensitive to tilt. For the tilt sensitive system, a lateral displacement of the source produces an identical lateral movement of the image, and it follows that the image position is not sensitive to lateral displacement of the optical system, but image position is sensitive to the optical system tilt.

DISPLACEMENT SENSITIVE SYSTEM

TILT SENSITIVE SYSTEM

Figure 4.2-3 Practical afocal alignment systems.

Once the system operation is understood, the design is straight forward. We used the off-the-shelf components shown in Figure 4.2.-3, but instead of a single lens in the center, we used 2 lenses and adjusted their separation to get the proper object image spacing L .

Originally we thought we would combine the systems with beam splitters, but we soon discovered it was easier to use a separate source and camera for each system than to precisely set the distance L to be the same for each system. With this arrangement L can be slightly different for each system, and the camera positions are adjusted to get sharp images. The hardware is shown in Figure 4.2-4.

For initial setup of the afocal systems, we used a laser and a shearing plate. The tilt sensitive system was the easiest to align. The key is that a collimated laser beam into that system produces a collimated beam in the space between the two inside lenses. We set up each side independently, by placing a flat mirror after its inside lens. When the system is set up properly, a collimated beam into the system should be reflected by the inside mirror and return toward the source collimated. The collimation of the input and return beam were checked with a beam splitter and a shearing plate; the spacing between the lenses was adjusted until the return beam was collimated. Once both sides are set up independently, the spacing between the sides is adjusted to give the proper object-image distance L .

The displacement sensitive system is more difficult to set up, because a collimated beam into the system does not produce a collimated beam in the space between the inside lenses. After several attempts, we discovered, partly by accident, that we could use a 3/8 inch tooling ball between the lenses to set up each side independently. Without the negative

lens in place we first autocollimated off of the ball surface. Then the negative lens was put in place and we autocollimated off the ball center. The radius of the ball was almost exactly equal to the distance the focal spot needed to move when the negative lens was inserted and the spacing is properly adjusted. When both sides were set up this way and placed in series, collimated light into the system gave collimated light out the other side as expected, and for a finite object, the object-image distance was only slightly off, it was close enough to be easily adjusted for by moving the camera. Both light sources were located in the center of the small goniometer and both cameras were located on the same Invar post for stability.

Figure 4.2-4 The hardware used in our afocal alignment systems.

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