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Assembly of the Dark Energy Survey CCD Imager

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ABSTRACT

The Dark Energy Camera (DECam) is the new wide field prime-focus imager for the Blanco 4m telescope at CTIO. This instrument is a 2.2 sq. deg. camera with a 45 cm diameter focal plane consisting of 62 2k x 4k CCDs and 12 2k x 2k CCDs and was developed for the Dark Energy Survey that will start operations at CTIO in 2011. DECam includes the vessel shell, the optical window cell, the CCDs with their readout electronics and vacuum interface, the focal plane support plate and its mounts, and the cooling system and thermal controls. Assembly of the imager, alignment of the focal plane and installation of the CCDs are described. During DECam development a full scale prototype was used for multi-CCD readout tests. This test vessel went through several stages as the CCDs and related hardware progressed from early prototypes to final production designs.

Keywords: CCD, camera, Blanco, CTIO

1. INTRODUCTION

The Dark Energy Survey (DES)[1] is building a CCD imager for the 4 m Blanco telescope at the Cerro-Tololo International Observatory (CTIO). This 2.2 sq. deg. camera utilizes 62 2k x 4k 0.250mm-thick CCDs[2] and 12 2k x 2k CCDs for guiding and focus control, totaling 0.57 Gpixels. The CCD modules[3] are packaged at the Fermi National Accelerator Laboratory using CCDs developed by the Lawrence Berkeley National Laboratory. The CCDs are mounted to an aluminum focal plane support plate (FPSP). This plate is supported on four sets of titanium bipods. These supports suspend the plate in place while allowing radial thermal shrinkage as the plate is cooled. The FPSP is connected via ten copper braids located near its outer rim to a liquid nitrogen heat exchanger. These braids each contain built-in thermal controls to maintain the average temperature of the CCDs in the array to -100 degC. The heat exchanger is a loop of 26.7 mm diameter stainless steel tubing through which liquid nitrogen is pumped and is part of the imager's cooling system[4]. Flexible Kapton cables with integrated JFET and pre-amp boards at each end connect the CCD modules to one of two vacuum interface boards (VIBs)[5]. These boards are mounted into vacuum flanges such that one section of each board is inside the vacuum within the imager vessel while the other side is on the outside of the vessel, where cables connect the VIBs to the three MONSOON front end electronics crates[5] which are mounted on the outside of the imager vessel, where there is also a fourth crate for the instrument control system. A turbo pump is mounted to the rear cover of the imager and it is used for initial pump-down of the system, after which it is isolated by a gate valve. While the imager is running, pumping is provided by an ion pump also mounted to the rear cover. Both of these pumps have been electrically isolated from the shell of the imager vessel. The front of the imager vessel is covered by the cell that houses the C5 optical element that also acts as the camera's vacuum window. This cell acts as an interface flange, bolting between the imager vessel and the barrel containing the four other lens elements as well as the shutter and filter assemblies. The imager is currently being assembled and is shown in Figure 1.

A multi-CCD test vessel was built early in the project on the same scale as the expected size of the final imager design. In addition to using it to gain experience in the operation of an array of CCD modules with a low-noise readout system, it has been used to test cooling performance, focal plane flatness measurement, CCD handling issues, vacuum system operation, and several other aspects useful towards the final design of the imager.

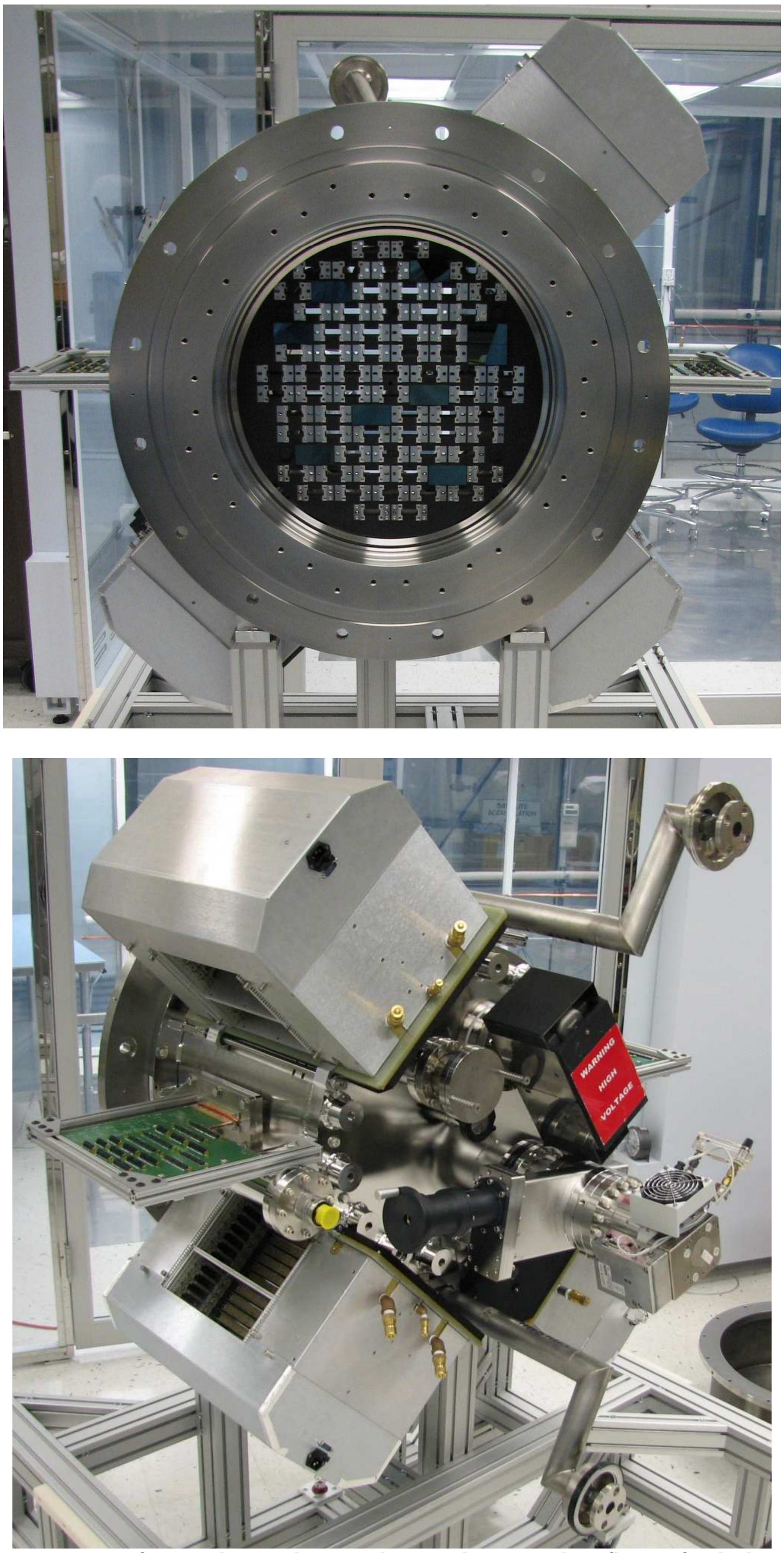

Figure 1. The DES imager front and rear, showing the vessel, C5 window flange, focal plane support plate, vacuum interface boards, readout crates, vacuum pumps, and liquid nitrogen ports.

2. FOCAL PLANE ARRAY

2.1 CCD Packages

The Dark Energy Survey utilizes fully-depleted high-resistivity CCDs developed by Lawrence Berkeley National Laboratory[2]. These devices are 0.250 mm thick for greatly-improved efficiency at 800-1100 nm. Reference 3 describes the prototype CCD module design that was developed at the Fermi National Accelerator Laboratory for use with these sensors. The design of the Invar foot and mounting pins was updated for the production module and is shown in Figure 2. The gold-plated Invar foot has two mounting pins that engage the FPSP. One pin has a 5 mm diameter while the other is 6 mm, thus ensuring that the module can only be mounted in one orientation. The pins are machined with their precision diameters over only a portion of their length such that the full diameter extends about 4 mm beyond the face of the foot and into the mating features in the FPSP. Beyond this point the pins have a slightly smaller diameter. The added length helps provide accurate guiding during module installation into the 4-side-buttable array but provides a loose enough fit to prevent binding. The end of each pin has a threaded hole for the mounting screw used to hold the module on the FPSP or in its storage box. The foot is also equipped with four additional threaded holes that are used with a set of handling rods. These rods are temporarily threaded into the foot and used to handle the module during installation or removal on the FPSP or into and out of their storage boxes. Although four threaded holes are provided, only two handling rods are used in practice. The additional threaded holes are included to provide flexibility during use, allowing the installer to select the two most convenient rod holes, for the rear side of the FPSP is partially-shadowed by the VIBs so use of the holes furthest from the obstruction provides better installation clearance.

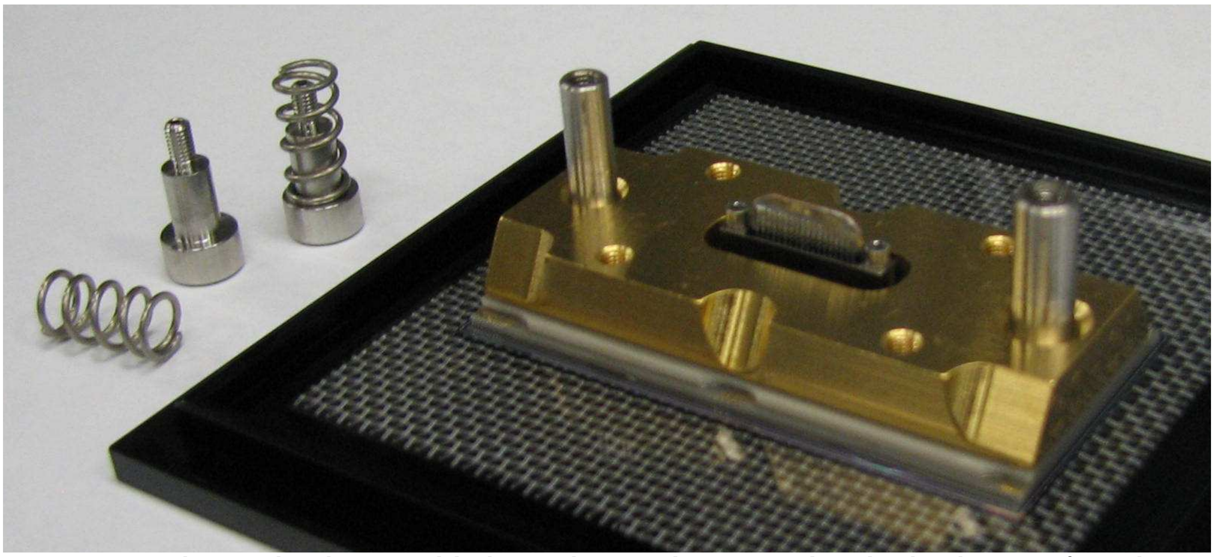

Figure 2. The DES 2k x 4k CCD module showing the CCD, aluminum nitride readout board, its Invar foot and mounting pins, and its mounting screws and springs. A shorting plug, with all its leads connected together, is plugged into the module's connector.

The same assembly techniques developed for the prototype modules[3] were utilized with the new foot design as well. Maintaining thickness uniformity module-to-module is an important component of achieving focal plane flatness, and module thicknesses are inspected with an optical coordinate measuring machine (CMM) during production. The average thickness of the modules has been found to be within one micron of nominal, as shown in Figure 3. The locations of the silicon edges are also inspected during production and are found to be within 40 microns of nominal for production devices. It is important to keep the sensor well-centered on the module due to the 0.500 mm gaps between adjacent modules in the four-side-buttable array.

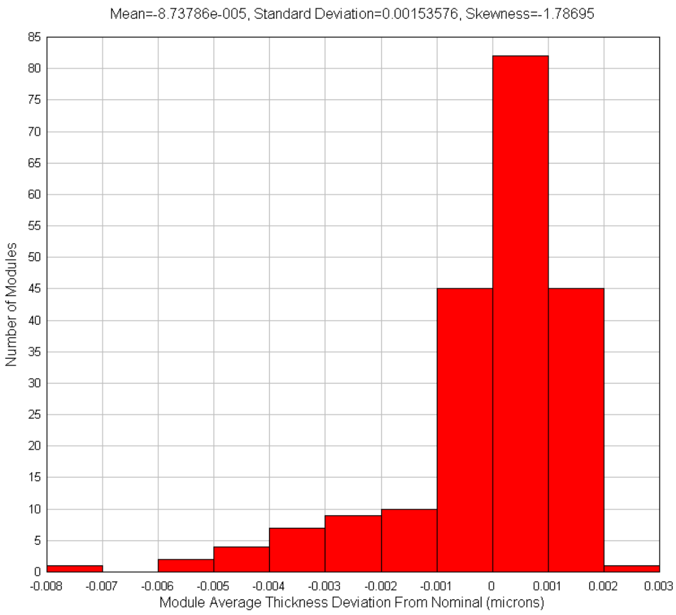

Figure 3. Measured average 2k x 4k CCD module thickness

The 2k x 2k CCD modules used for guiding and focus control are mechanically similar to the 2k x 4k modules with several exceptions. The Invar foot is 1.5 mm thinner but features are added to accommodate the addition of precision-thickness aluminum-nitride ceramic spacers. The module can therefore be configured as needed with three different thicknesses. The middle thickness corresponds to the same thickness as the 2k x 4k modules, and modules so configured are used for guiding, with their sensors co-planar with the science array. The other 2k x 2k modules thicknesses are set either 1.500 mm above or below the remainder of the focal plane and are used for focus / alignment control. The mounting footprint is shared between the 2k x 4k and the 2k x 2k designs, thus making the basic FPSP cell design uniform for all module types. Additional clearance cutouts in the FPSP are necessary, however, in order to accommodate the heads of the fasteners used to hold the height shims to the Invar foot. In order to make up for the smaller size of the 2k x 2k sensor, an additional piece of silicon is used to cover the extra surface of the aluminum nitride readout board and to allow module assembly techniques similar to those used for the 2k x 4k devices. This additional silicon piece is cut from a non-functional 2k x 4k CCD to take advantage of its anti-reflective coating and its identical thickness.

2.2 Focal Plane Support Plate (FPSP)

The array of CCD modules is mounted onto the 36mm-thick aluminum FPSP, which is shown in Figure 4. Each module cell has several features. The first is an elevated mounting surface to which the CCD surface mates. These pads, two per module, have been precision-lapped and are coplanar across the entire plate to about 5 microns. The remainder of the front surface is slightly recessed and has been painted with Aeroglaze Z306 anti-reflective black polyurethane paint in order minimize the effect of light reflecting from between modules or from beyond the outside extent of the array. Holes and slots in the pads accept the mounting pins from the CCD modules. These features were machined by wire-EDM (electro-discharge machining) and are sized, as mentioned above, so that each module can be installed only in one orientation.

Pockets machined from the rear of the plate are centered on the holes and slots. The depths of these pockets are sized such that the module's Invar mounting pins protrude slightly into this space. Here, shoulder screws are installed into the threaded hole in the end of each CCD module mounting pin and tightened against their faces. Springs installed on the screws are compressed between the shoulder screw heads and the bottom of the pockets in the FPSP. This force pulls on the module's Invar mounting pins and seats the module foot against the FPSP mounting pads, as shown in Figure 5. Stainless steel liners, 0.1 mm thick, are tacked with epoxy to the bottom of each pocket to protect the softer aluminum from the harder spring ends.

The FPSP also has clearance holes for the module handling rods and a cutout through which the Kapton cable attaches to the CCD module from the rear of the camera. The rear side of the plate also has ten sets of threaded holes to which the copper cooling braids are attached.

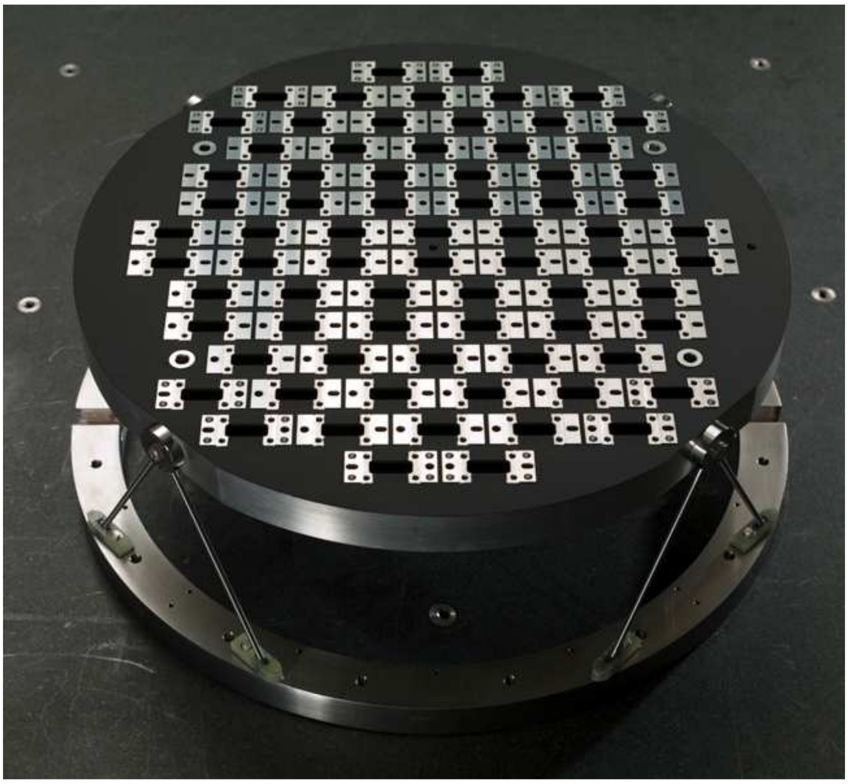

Figure 4. The aluminum focal plane support plate (FPSP). Anti-reflective black paint minimizes reflected light from the small gaps between modules and from the plate beyond the extent of the CCD array.

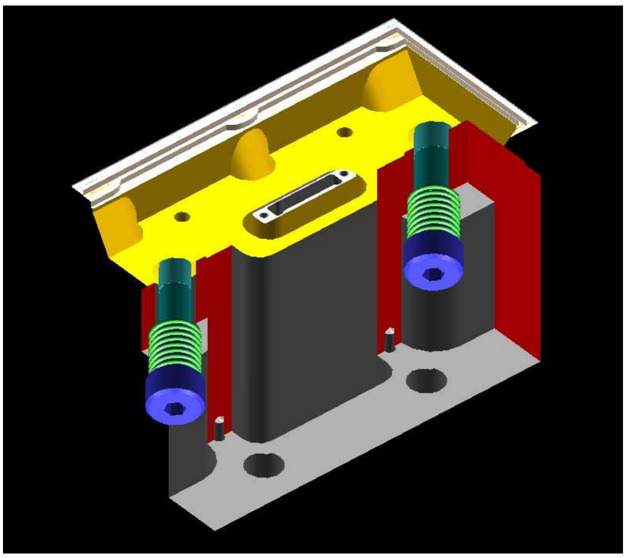

Figure 5. Cross-section image of a CCD module mounted into a cell of the FPSP. Compression springs push on the screws fastened to the ends of the mounting pins, thus pulling the CCD module against the FPSP surface.

2.3 FPSP Support & Alignment

As shown in Figure 4, the FPSP is mounted with four sets of bipods to the bipod base ring. Each bipod is a set of two titanium rods designed to rigidly support the FPSP while allowing the plate to contract radially when cooled and while providing a thermally-restrictive path to minimize heat leaks. In addition, the ends of the rods closest to the base ring are electrically isolated from the ring by use of G10 feet into which the rods are epoxied and then drilled and pinned. When installing the bipod legs between the FPSP and the base ring, this joint was made up last after establishing the height and parallelism of the FPSP to the base ring using a coordinate measuring machine. This electrical isolation can be jumpered with a low-thermal-conductivity stainless steel braid at each bipod location, allowing control of the grounding within the vessel. These jumpers can be installed/removed during testing as electrical grounding options are evaluated.

Integration of the FPSP assembly into the imager vessel requires that the FPSP be aligned parallel to the barrel mating surface of the C5 optical window cell. This is achieved by use of a set of 16 shims mounted between the bipod base ring and the surface of the mounting ring that is part of the vessel shell. The system was first assembled and inspected on a CMM and the shim modifications necessary to achieve parallelism were calculated. The serial-numbered shims were then removed and ground and lapped to the specified thicknesses. The system was then reassembled and reinspected. Steps were taken to minimize deviations during the initial fabrication and assembly of each of the components involved such that the as-assembled tilt achieved was 46 microns over the 89 cm diameter of the flange. After reworking and reinstalling the shims the parallelism was found to be approximately 19 microns, as shown in Figure 6, and is primarily dominated by the flange's flatness.

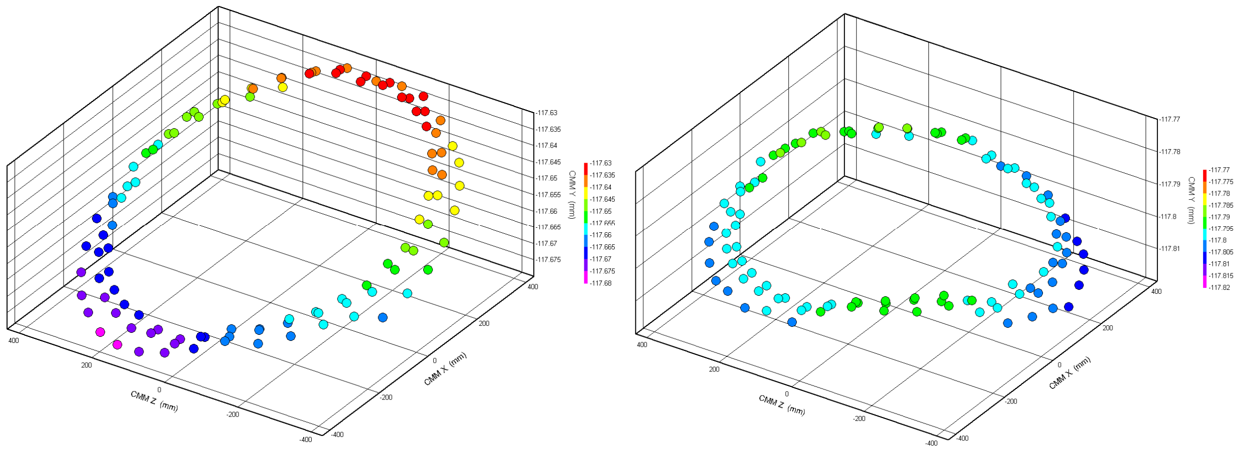

Figure 6. Parallelism measurements of the C5 cell mounting surface relative to the FPSP before and after bipod base ring shim thickness modification.

2.4 CCD Installation onto the FPSP

CCD modules are installed while the imager is positioned on its side and is performed with one person feeding the module from the front, or window-side of the vessel, while the other works from the rear of the vessel. Module position numbers engraved in the FPSP help facilitate communication when working from both ends. The handling rods that attach to the Invar foot of the module are fed by hand into the loading rod holes in the front of the FPSP. After the ends pass all the way though the FPSP they are pulled by the person in the rear. The module mounting pins then engage the FPSP holes & slots and the module is pulled in further until it is fully seated. With the imager positioned on its side, this operation can be safely stopped at any moment. After placing a locking collar on one of the handling rods to hold it in place, the shoulder screws with their compression spring are fastened to the threaded holes in the end of the module mounting pins, as shown in Figure 5. The handling rods are then removed and the Kapton flex cable is installed. A slotted restraint is then attached to the rear face of the FPSP that constrains the flex cable's transverse motion but allows freedom along its length when the system is cooled. CCD removal from the array is done as the reverse of this process.

2.4 Optical Measurements of CCD Surfaces

The flatness of the CCD array will be scanned through a flat window using a confocal chromatic displacement measurement system[3] from Micro-Epsilon Corp. This system uses light from a halogen light source and focuses it through a lens such that light of different frequencies is focused at different distances from the instrument. The frequency of the light reflected from the focus spot is sensed by the system and is used to determine the distance between the instrument and the surveyed point. The instrument is mounted on a set of automated precision stages that allow surveying of a section of the focal plane. The 30 x 30 cm range of the stages precludes coverage of the entire array at once due to its 45 cm optical diameter, so the full array will have to be surveyed using overlapping fields.

In the multi-CCD test vessel, a section of the array with mechanical- and electrical-grade (not science-grade) CCD modules mounted on the test plate was surveyed, as shown in Figure 7. Points were taken on a 2 mm x 2 mm grid. Measurement variations can be seen in the points taken at the edges of the silicon, including at the gaps between modules, or near the upper-left region where the window flange partially blocks the array. This is not believed to accurately represent the silicon surface in these areas due to irregularities in the reflected instrument light.

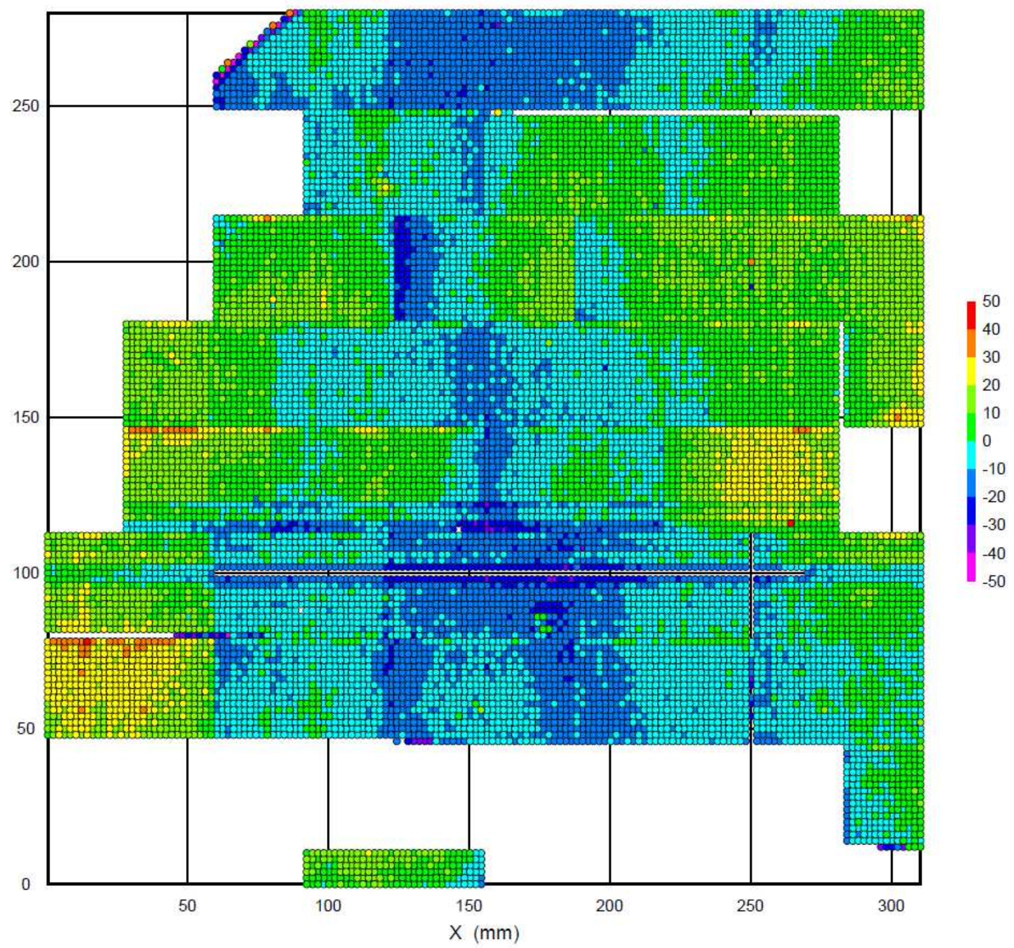

Figure 7. -150 degC flatness survey results, in microns, of a section of the test vessel CCD array taken through a flat window using the Micro-Epsilon confocal chromatic displacement system.

3. CCD READOUT

3.1 Kapton Flex Cables

These flex cables connect each module to its corresponding connector on one of the two VIBs. The Airborn connectors that join the cable to the CCD module have captive connecting screws that are used to either tighten or separate this joint for reliable mating. Attachment is done from the rear after module installation since the pre-amp board integrated into the VIB-end of the cable is too wide to fit through the focal plane support plate.

3.2 Vacuum Interface Boards

These two boards each have one half inside the vessel vacuum and one half outside the imager for connection to the front end electronics crates. Each board is first partially assembled and then the unpopulated vacuum-side is passed through a narrow slot EDM-machined in a mounting flange and epoxied in place. The remaining components are then assembled onto the boards. Edge reinforcements on the vacuum side of the boards bridge across the gap between the two opposing boards, thus providing a self-reinforcing stiffening effect to limit deflection during Kapton cable handling. These reinforcements are slotted in a way that allows relative motion between the boards in the direction along their length in order to allow for assembly variation and thermal expansion changes. A temporary brace can also be used during cabling to help constrain the boards.

On the air side of the board, an aluminum frame acts as a bumper to protect the board edges. Bars attached to this frame mate to several points on the board in order to minimize deflections from board-to-crate cable handling. Copper foil soldered around the air-side perimeter of the board is part of the board's grounding scheme but also acts to prevent light from leaking into the imager through the edges of these multi-layered boards.

3.3 Electronics Crates Mounted on the Imager

Three MONSOON crates and an additional crate for the imager controls are mounted onto the exterior of the vessel shell. They are positioned such that boards can be slid out of their slots with the crates still in place on the imager. Each crate is mounted to an electrically-insulating G10 plate. Bearing blocks fastened to each plate mate to sets of rails installed on the exterior of the imager vessel. With the imager mounted on the telescope, bolt-on rail extensions can be fastened to the rear cover of the imager vessel to help facilitate sliding the crates off the camera to the end of the telescope's prime focus cage for potential in-situ replacement.

The crates are to have insulating shells to minimize heat leakage within this region and are cooled with a separate water-glycol system. The coolant is to be supplied at a constant 15 degC and a dry gas purge is used to maintain low humidity within the crates.

4. VACUUM & COOLING

4.1 Vacuum System

The CCD module array is designed to operate at a temperature of -100 degC, so the imager vessel is evacuated to insulate the cold mass. For cooldown and warmup operations, a turbo pump is used to achieve the necessary level of vacuum. During imager operation, the turbo pump is isolated by means of a vacuum gate valve, its pumping station is removed and pumping is then provided by two other means. The surface of the heat exchanger mounted inside the rear of the imager, being full of liquid nitrogen, acts as a cryopump to remove water vapor from the vacuum. An ion pump then provides pumping of other gases in the system in order to maintain the vessel vacuum level.

Prior to introducing the nitrogen coolant into the heat exchanger, vacuum in the vessel is reduced to at least 2×10^{-4} Torr. During operation, the vacuum is required to be 10^{-5} Torr or less, and operational experience with the multi-CCD test vessel indicates that 5×10^{-6} Torr is common during cold operation. If the ion pump were to fail during operation, testing performed with the multi-CCD test vessel using a representative amount of board and flex cable material indicates that it takes just over an hour for the vacuum to rise to 2×10^{-4} Torr. During this period the telescope is to be driven to the maintenance position and the turbo pump started.

4.2 Cooling the CCD Modules

Ten copper braids are used to thermally connect the FPSP to the liquid nitrogen heat exchanger. The block at one end of the braid is bolted to the rear of the FPSP and is equipped with an RTD temperature sensor, an electric heater, and a bimetallic thermal safety switch that cuts off heater power if the temperature were to rise above 55 degC. This end of the braid also includes an epoxied joint designed to provide electrical isolation so that FPSP grounding can be controlled. The other end of the copper braid ends in a clamp that attaches to the liquid nitrogen heat exchanger tubing. The cap of the clamp has been brazed to the heat exchanger tubing, ensuring good thermal contact. The braids and their connection to the FPSP and the heat exchanger tube can be shown in the Figure 8 photo.

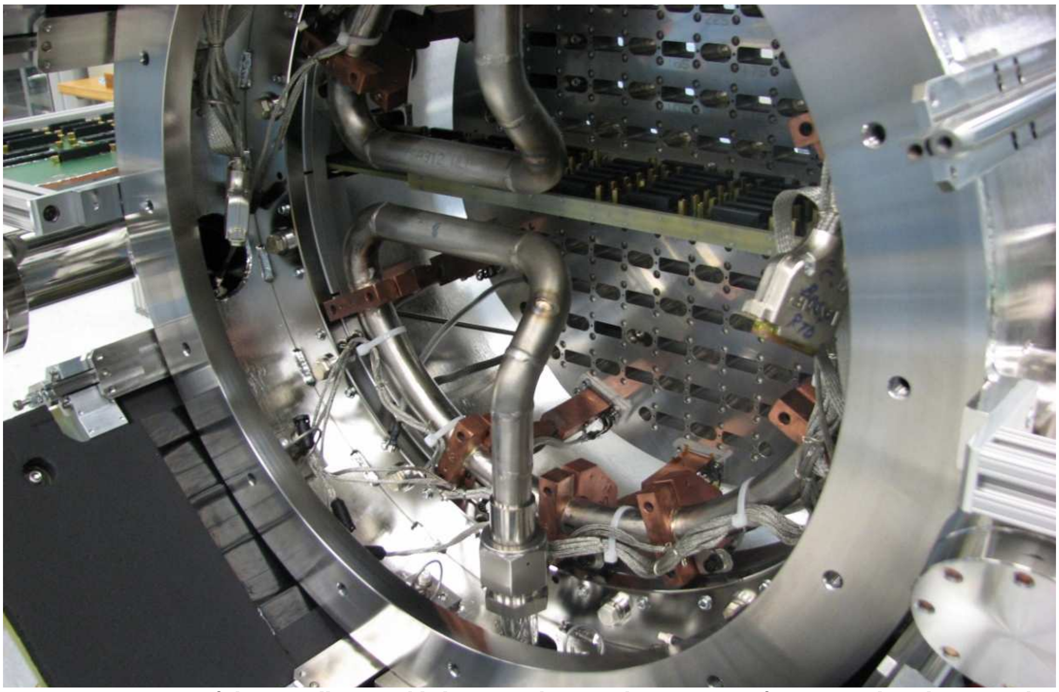

Figure 8. Rear view of the partially-assembled imager showing the FPSP rear face, VIBs, liquid nitrogen heat exchanger, and copper braids.

The RTDs on the braids, as well as four mounted on the FPSP, provide input into the temperature control system, which regulates heater power to control FPSP temperature. When the test focal plane plate in the multi-CCD test vessel was instrumented with 28 CCDs, a 20 degC variation in the temperature of the detectors was initially measured. After some investigation that included studies in the single CCD module testing stations it was confirmed that this temperature variation could be attributed to the strength of the springs pushing the modules against the FPSP. The spring constant used originally was 0.5 N/mm and it was decided to change to a stiffer spring with 6 N/mm. The stiffer springs reduced the temperature variation to 10 degC between CCDs (Figure 9), which satisfies the technical requirements for DECam. The spring force measured at a given compression height for a sample of springs showed < ±3% variation and it was concluded that the remaining temperature difference between the detectors was not coming from the springs. The highest temperature was seen at the center of the focal plane, where the electronics heat load was concentrated in the partially-assembled prototype. We expect better performance on the production DECam imager because of a more evenly distributed heat load from the electronics and a more uniform contact surface between the CCDs and the focal plane.

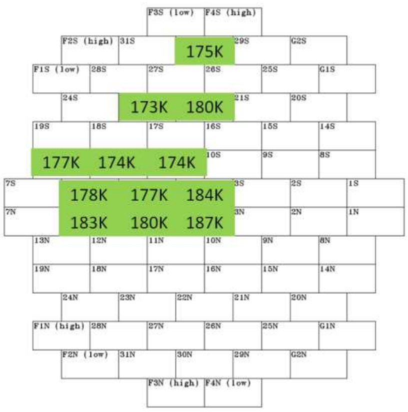

Figure 9. CCD module RTD temperatures on a partially assembled focal plane in the multi-CCD test vessel.

5. CONCLUSION

The imager design has been developed and provides a suitable platform for the DES CCD array. Imager assembly continues with delivery scheduled in 2011. A prototype of the imager vessel for multi-CCD readout testing was constructed early in the project and has proved to be a useful tool for testing various elements developed for the final imager design. Operating requirements for handling the CCDs, achieving focal plane flatness, maintaining thermal conditions, and preserving vacuum have been verified.

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