Assembly, alignment, and testing of the DECam wide field corrector optics

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ABSTRACT

The DES project is a 5 year imaging survey of the southern sky using the 4m Blanco Telescope at the Cerro Tololo International Observatory in Chile. A new wide field camera with a 2.2 degree diameter field of view has been built to undertake this survey. The alignment of the large lenses for this camera poses a significant challenge as they have to be aligned to a tolerance of ±50 micrometers. This paper presents the assembly and alignment process of the full optical system along with the test results. Also included is the predicted imaging performance from the as-built system.

Keywords: wide field corrector, alignment, dark energy

1. INTRODUCTION

The Dark Energy Survey Project (DES)[1] is a 525 night multi-band photometric imaging survey of 5000 square degrees of the southern sky using the 3.8m Blanco Telescope at the Cerro Tololo International Observatory in Chile. As part of this project a new wide field camera, the Dark Energy Camera (DECam)[2,3] has been built and is being installed at the telescope with a first light date scheduled for September 2012. DES will use four different probes to investigate Dark Energy, they are type 1a Supernovae, baryon acoustic oscillations, galaxy clusters and weak lensing. The last method in particular puts stringent conditions on the optical performance of the camera and hence on the alignment of the camera optics. Figure 1 shows a schematic of the camera.

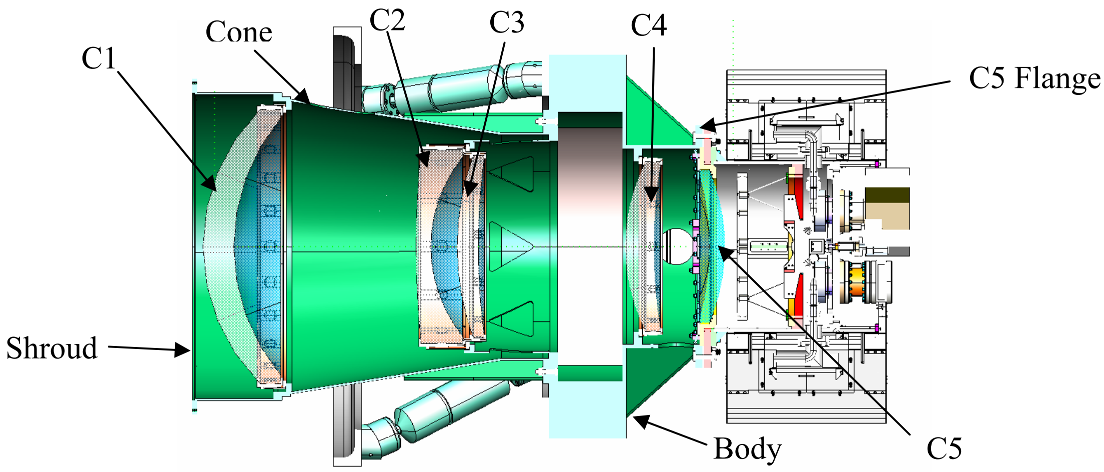

Figure 1. Schematic cut through of the DECam camera with lenses highlighted (C1-C5)

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1.1 Alignment Strategy

The five lenses of the DECam require mounting into their respective lens cells and then into the main barrel of the camera. The lenses in the camera have to be mounted and held to a high precision and maintain this position over a wide temperature range (-5 to 27^{o}C) and differing gravity vector. The description of optical design and the mechanical design of the lens cells are given in previous papers.[4, 5] There are two aspheric surfaces in the design, these the concave side of C2 and the convex side of C4.

To define the required tolerances a full tolerance analysis of the optical system was undertaken using the ZEMAX optical design software. The results given in the following table.

Table 1. De-centre and alignment assembly tolerance (±)

Lens	De-centre Tolerance µm	Tilt Tolerance on diameter arcseconds (µm)	Axial Position Tolerance µm
C1	100	10 (48)	50
C2	50	17 (56)	50
C3	100	20 (63)	50
C4	100	20 (58)	50
C5	200	40 (105)	200

The above analysis was based on rms image size. A further tolerance analysis was performed that looked more closely into the effect of misalignment on image shape. This generally confirmed the above tolerances but also showed the particular importance of keeping the tilt of the aspheric surfaces small. To that end the decision was made to aim to get these surfaces perpendicular to the optical axis (i.e. if there was a wedge on the lens this was expressed on the spherical surface face).

The alignment technique adopted was to use precision metrology of the components to position them to the required accuracy. The metrology methods used were co-ordinate measuring machines, a Faro gauge arm, and digital dial gauges coupled with a precision rotary table. A check on the position of the lenses was made using a pencil beam laser system.

1.2 Cell positioning in barrel

Fermilab were responsible for the design and construction of the camera barrel. The barrel consists of 3 separate pieces termed the body, the cone and the shroud. C2, C3, C4 and C5 connect to the body whilst C1 connects to the cone. At Fermilab the barrel elements and the lens cells produced by UCL were measured using a long reach co-ordinate measuring machine. The C5 flange was used as a datum and the position and flatness of the cell interface flanges were measured. The flange positions were with ±5µm of the design position and the flatness of the flanges was better than ±12µm. Using the data derived from the measurements the cells were set at their optimal position for centring the lenses. The cells were drilled and doweled to facilitate their removal and subsequent replacement after the lenses were mounted in them. The cells were aligned to an accuracy of ±20µm to a common axis and the accuracy of centring and realignment on the dowels was in the order of ±10µm.

Accurate alignment between the cone and body was achieved at Fermilab using a co-ordinate measuring machine to locate the two sections. Once the parts were aligned then square keys slots were machined across the mating joint. Accurately fitting keys were manufactured to key the parts together. The realignment accuracy of the two sections was measured to be ±10µm.

2. LENS-CELL ALIGNMENT

2.1 Lenses into cells

The cells and barrel were then shipped to UCL where the first stage was to install the lenses into the cells. The axial support pads were first attached to the cells. To ensure that all the axial pads were the same thickness, moulds were used

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to produce the pads and the pads were attached with a custom tool to ensure a uniform pad height. After the pads were glued in position the heights were checked using a Micro-Epsilon optical displacement sensor with the cell mounted true to its Fermilab defined centre on the rotary table. The target was to get the axial pads surfaces within ±25µm, if a pad was found to be outside this range the pad was removed and a new pad glued in position and re-measured. Once this was completed the lens could be mounted into the cell. Figure 2 shows the alignment system used for the lens to cell alignment. Support for the lens is given by a nine point whiffletree system for lenses C2 to C5 and an eighteen point system for C1. Tip and tilt of the lens is controlled with precision screw jacks incorporated into the whiffletree. The lens/whiffletree structure can be centred using translation stages with the aid of sprung adjustment screws. This system gave very good control of the optic surfaces allowing for micrometer accuracy. The whiffletree plate support legs, made from PTFE, were manufactured to conform to the optical surface curvature on a CNC lathe and have 1 mm thick Viton pads adhered to them. Care was taken to space the support points of the whiffletree system so that the lens did not distort. Both top and bottom surfaces of the lens were clocked to check for run out and adjustments made to compensate for any wedge between the surfaces, with the clock stylus running at the edge of the optical surface, outside of the clear aperture of the lens. Figure 3 shows the rollers and X-Y adjusting screws used to facilitate alignment of the cell. The very final stage of aligning the lenses and cells together was done using the precision screw jacks. They gave very tight control of how the surfaces of the pads and glass mated together.

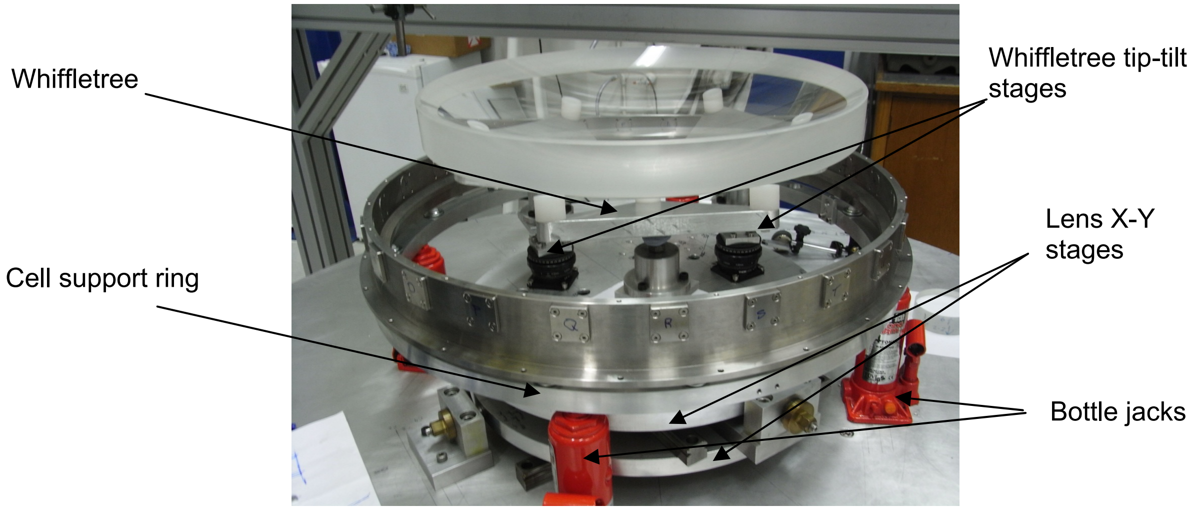

Figure 2. Basic set up for lens and cell alignment

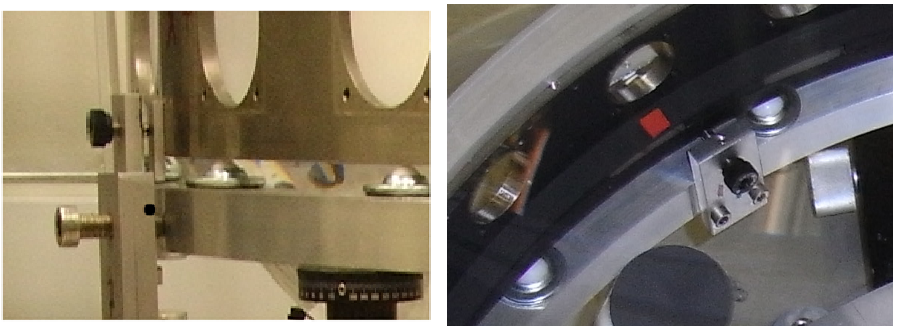

Figure 3. Cell support ring showing roller supports and X-Y adjustment screws

Once the lens was aligned in position the cell was carefully jacked up towards the lens using four hydraulic bottle jacks. Each jack was pumped in turn to keep the cell level and even as it approached the lens. When the cell was within 2 mm of the lens the jacks were replaced with aluminium posts and precision screw jacks. The cell was then clocked and adjusted in tip-tilt using the screw jacks and centred using the X-Y adjustment screws. When this was completed each screw jack was raised in turn a small amount (~100µm), until the RTV axial pads were within 200µm of touching. The

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lens and cell were then rechecked for position. The final 200μm movement was in 50μm increments until the RTV pads were contacted. The cell and lens was then re-measured to establish their positions. If the position was not within specification the cell was backed off and realigned. Contact of the RTV pad and glass could clearly be seen through the glass and gave a very good indication of the match between the cell and lens.

After each cell and lenses were deemed to be at the required position the radial pads on their inserts are put in place. The procedure to do this is as follows. Paper sheets of the exact thickness of the RTV glue gap required were placed between the glass and the pads and the inserts were screwed into place locking the structure together. Figure 4 (left) shows the C2 lens and cell combined and clamped in place by the inserts and paper. An insert with RTV pad attached is shown in figure 4 (right). Opposite pairs of insert were removed and the glass primed with SS 4155 glass primer. Figure 5 (left) shows the primer being applied with the aid of a mask. The primer was allowed to dry for 1 hour. The inserts were coated with RTV and bladed to the desired thickness plus around 100μm of extra RTV to ensure complete coverage. The inserts were then screwed into position with dial gauges placed to indicate if the system was moving during attachment. The inserts at 90º to the last were glued in next. After that inserts at 60º and 30º each side of the origin were glued in attempting to keep the inserts as balanced around the periphery as possible. Figure 5 (right) shows the lens and cell of C2 attached by the radial inserts. This process was repeated for all of the lens and cells except C5.

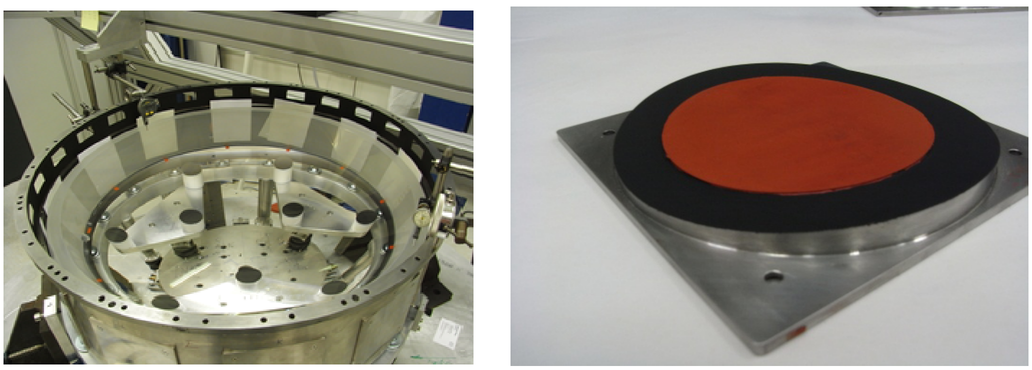

Figure 4. C2 lens and cell with papers in place (left), radial insert with RTV pad attached (right)

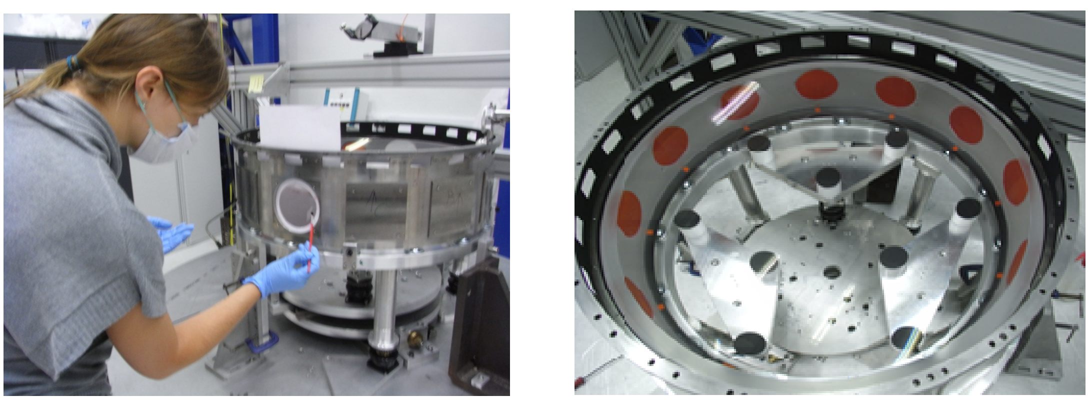

Figure 5. Application of primer (left), pads glued in place (right).

A safety retaining ring with RTV pads was fixed in position at the rear of each lens. In order that the lens is not over constrained the RTV pads on the retaining ring do not touch the glass but are held ~50μm from the surface.

The C5 lens which is the Dewar window for the CCD camera is held in the C5 cell manufactured from stainless steel by Argonne National Laboratory. The lens does not require RTV pads but sits on a Viton "O" ring making the vacuum seal. There is also a 50μm thick and 5mm wide Mylar ring, mounted on the cell at the edge of the optical surface of the lens, preventing the glass from contacting the metal cell when the vacuum is applied. Nylon guides around the periphery hold

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the lens and maintain positional control when not under vacuum. Four of the guides have screw adjustment giving lateral control of the lens when aligning.

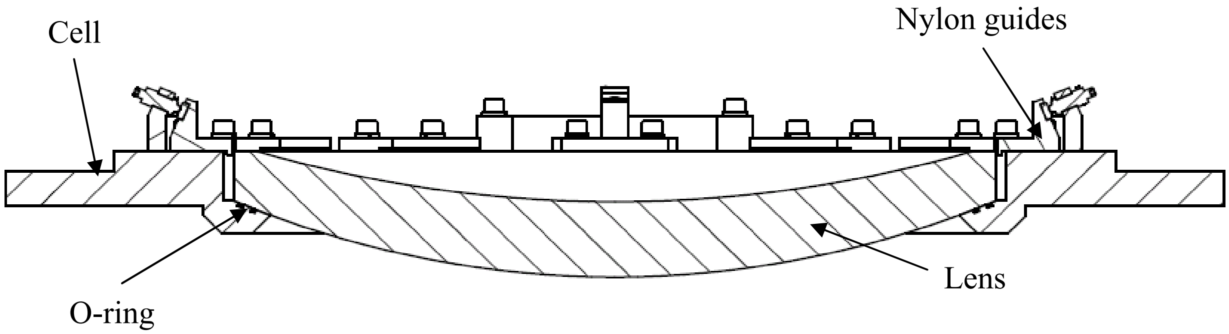

Figure 6. Schematic of the C5 lens and cell[6]

The C5 lens was placed in position in its cell in a similar way to C1-C4. Once in contact with the O-ring the Nylon guides were screwed into contact with the lens to maintain its lateral position and Nylon retaining pads attached to the top of the lens. The lens then underwent vacuum testing to validate its performance (see figure 7.). The "O" ring was measured to compress by 650µm and the lens deformed by 37µm under vacuum, which were close to FEA simulation predictions. The distance from the C5 cell flange and the centre of the concave surface of the lens was measured with the Faro gauge arm and found to be within specification.

Figure 7. C5 under vacuum test

The C5 lens and cell were aligned to the barrel with two 12mm adjustable dowels. There is an electrical insulating spacer between the barrel and the cell.

2.2 Alignment of C2 and C3

The C2 and C3 lenses are a close pair and sit in mount with a single interface to the barrel. After lens C2 had been aligned with its cell and the radial inserts mounted. Careful measurements were made using the FARO Gage measuring arm to obtain the distance from the sag of the lens to the mounting shoulder for C3 cell. The lens was removed from the rotary table and stored in its delivery crate. C3 lens and cell were then aligned together and the distance from the mating face that connects to the C2 cell and the crown of the glass were measured using the Faro Gage. The lens was removed from the cell and the cell was ground on a rotary surface grinder to the correct spacing. C3 was then realigned with its cell and the radial inserts attached. The C2 lens and cell combination was then mounted and centred on the rotary table and the C3 lens and cell were careful lowered into place using a crane. Blocks with a M8 treaded holes were positioned at 90º to each other and bolted to the base ring of C2. M8 screws were inserted and used to push the C3 cell into the correct optical position on cell C2. The base ring of C2 was checked for true along with the optical and base ring surfaces of C3. When all was adjusted to within specification the cells were bolted together.

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3. LENS AND CELL TO BARREL ALIGNMENT

The C2/C3 doublet support by four screw jacks and the cell support ring were mounted on the rotary table. The support ring allowed the doublet to be rotated under the body of the camera to align the dowel and screw holes and the side adjustment screws gave a few millimetres translation. After the C2/C3 doublet had been positioned centrally on the rotary table the body of the corrector was lower into position with a small gap (approximately 4 mm) left between the faces of the cell and the body. A set of spacers were placed in the gap between the cell and body. The 8mm removable dowels, trade name "Metaligner" manufactured by S. B. Whistler & Son Inc, were inserted. The lens and cell were then jacked up to make contact with the body and the bolts were inserted. The distance between the C5 flange and the sag of the C3 lens was measured using a Mitutoya internal bore micrometer. The spacers were removed and surface ground to the desired dimension and refitted between the cell and body. The dowels and bolts were refitted and the distance from the C5 flange and the lens checked for the correct distance. A flexure test was then performed by tilting the body assembly by 30 degrees and measuring the deflection of the C2/C3 cell. This was measured as 6μm, which is within specification.

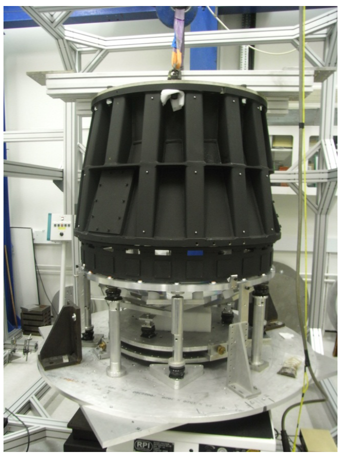
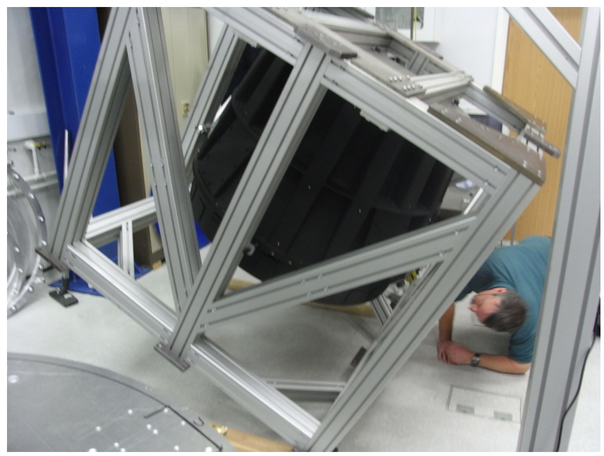

Figure 8. C1 lens and cell being mounted to the cone (left), and C1 lens under tilt flexure testing (right)

The C1 lens and cell, figure 8 (left) were installed onto the cone of the barrel in a similar way to that of C2/C3 to the body. A flexure test was also performed as shown in figure 8 (right), and the deflection at ~30 degrees was measured as a few micrometers which was within specifications.

For C4 lifting claws were constructed to enable the C4 cell and lens to be lifted into position on the body. The claws had threaded rods attached that went through a lifting plate and was raised and lowered by the crane. Figure 9 (left) shows the C4 lens being lifting into position using the claws and rods.

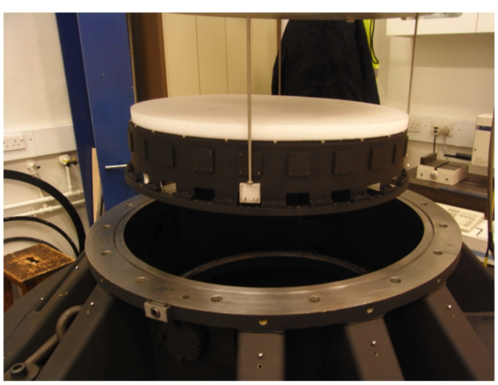
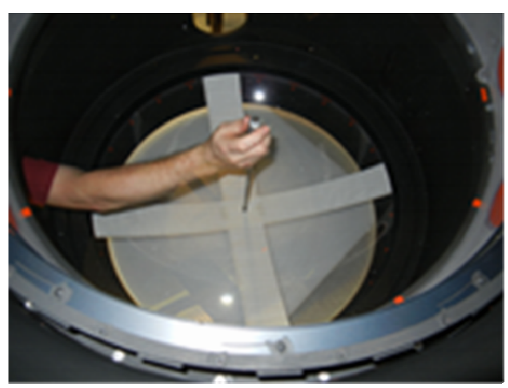

Figure 9. Positioning C4 into the body (left) and measuring the spacing of C3 and C4 (right).

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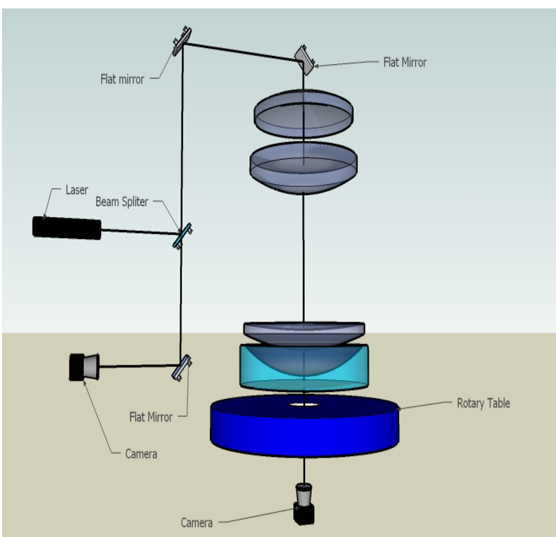
Over sized spacers were positioned on the mating flange for C4 and the cell and lens were lowered into place within the body and the dowels and bolts aligned and tightened. The distance between the C3 and C4 lenses was measured using the internal bore micrometer as shown in figure 9 (right). The C4 lens and cell were then removed and the spacers machined to the correct thickness and the C4 lens and cell re-installed.

3.1 Cone to body alignment

The cone and shroud were removed and placed on a flat floor surface in the lab with a 20mm thick piece of stiff foam in between. The body was removed from its support frame and aligned above the cone with the use of the crane. Oversized spacers were installed on the top of the cone. The body was lowered carefully into the cone section leaving a 2mm gap between the two connecting faces. The four alignment keys were inserted and bolted in place to the cone. Next the M20 bolts were inserted and the two sections of the corrector drawn together with the bolts and they were tightened to the correct torque of 120 foot lbs. Using the internal bore micrometer the distance from the sag of lens C1 and the crown of C2 was measured. The body and cone were then separated and the spacers removed. The spacers were then ground down to the required thickness and reinstalled on the cone and the body reconnected using the previous method. The distance between C1 and C2 as then re-measured as a check.

4. LASER ALIGNMENT TESTS

To optically check that the surfaces of the lenses were running a true laser alignment system was built. Figure 10 (left) shows a schematic of the optical setup. The system measured the tip/tilt and decentres of the optical surfaces by centrioding of the reflected and through beams. Software was written in Labview to display the laser spot images and give the centroid of the image obtained



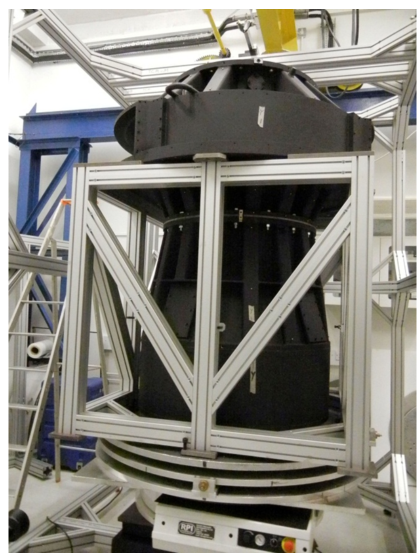


Figure 10. Laser alignment system schematic (left) and corrector under test (right).

Laser alignment checks were preformed at each stage of the installation of the lenses into the body. A test was also preformed on the whole corrector when assembled. The procedure was to first align the laser system then to mount the body (or full corrector) onto the rotary table in an alignment test framework on an X-Y translation stage and tip-tilt bolt system. Figure 10 (right) shows the full corrector mounted on the rotary table and test frame. Using dial gauges on the C5 flange the corrector was adjusted to run true, using the tip tilt bolts and the x, y translation stage to control the position. The through and reflected beams of the laser alignment system were then examined and measured. The alignment of the lenses in the body and the full corrector were rechecked at the telescope.

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5. ALIGNMENT RESULTS

The distance of the lenses from their nominal position along the optical axis were measured to be the +1µm, -69µm, +40µm, +60µm and -80µm for C1, C2, C3, C4 and C5 respectively (a positive error is away from the focal plane).

The results from the contact metrology for the lens into the cells gave the results given in table 2. The uncertainty on the measurements is a few micrometers. It should be noted that C1 has spherical surfaces and the decentre and tilt cancel to give a surface run out of ~40µm.

Table 2. Position of lenses relative to cell centres after installation ton the cells

Lens	Cell decentre X,Y (µm)	Tilt over diameter X,Y (µm)
C1	0, -33	0, -74
C2	0, 0	0, 8
C3	-43,0	0, -23
C4	0, 25	26, 0
C5	0, 53	0

Using the laser pencil beam test system the position of the lenses after installation into the barrel were measured. Dial gauge measurements were also made on the concave surfaces of C3 and C4. The calculated positions of the lenses are given in table 3.

Table 3. Calculated positions of the lenses in the barrel

Lens	Cell decentre X,Y (µm)	Tilt over diameter X,Y (µm)
C2	-20,-45	-2,-15
C3	-63,-45	-2,-46
C4	20, 45	10, 8

The position of C1 is not shown as the laser alignment system is very insensitive to the C1 decentre (C5 was not measured). However a visual measure of the position of C1 can be made by looking at the return beam from all the surfaces in the corrector. An image taken is shown below (note: small white square in corner of central image is an artefact of the display software). The image shows a good symmetry giving a general indication that the lenses are in alignment though no quantitive information can be obtained.

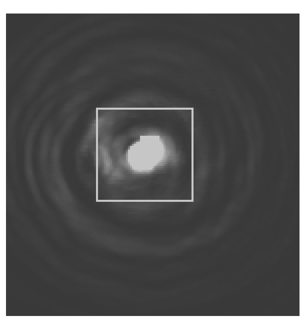

Figure 11. Image of reflected beams from C1-C4 lenses

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The calculated values of the tilts and decentres along with the measured spacing and wedges of the lenses can be input in an optical model of the system, and the imaging performance compared to the original predicted performance. Figure 12 (left) shows the "perfect" image quality (I-band) and the "as built" image quality (right).

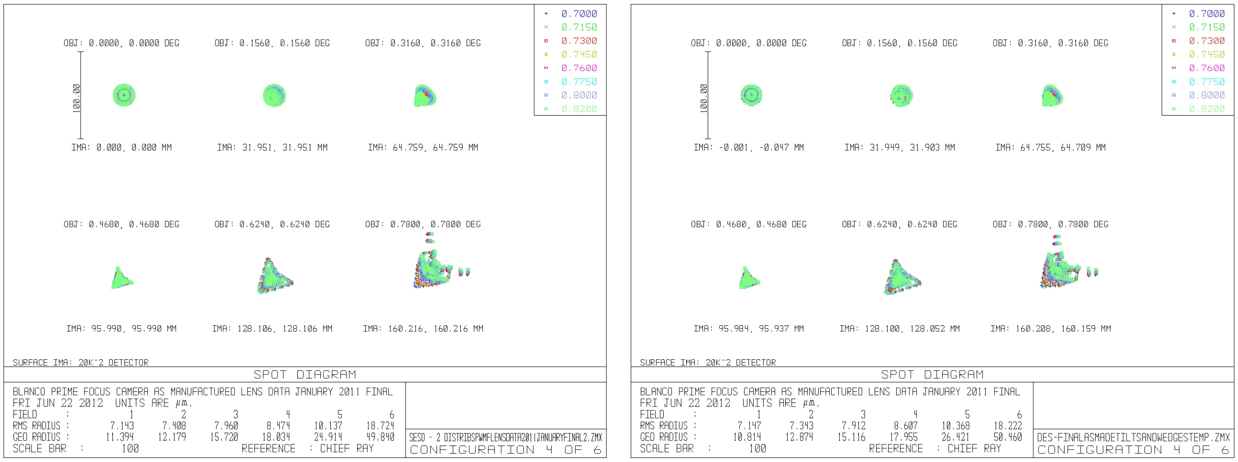

Figure 12. Spot diagrams for the "perfect" corrector (left) and the "as built" corrector (right)

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