Southern African Large Telescope
SALTICAM
Preliminary Design Review

Document Number 3310AE0001:
Optical Design Document

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1 Scope

This document is the Optical Design Document for the preliminary design review of SALTICAM, the verification instrument, acquisition camera, and scientific imager for the Southern African Large Telescope (SALT). The approach to the design is discussed, including materials used, and the route to the current design described. Optical specifications for each optical element, opto-mechanical considerations, and a fabrication plan are also outlined.

2 Optical Design

2.1 Requirements

The optics are required to re-image the 8 arcmin diameter science field of view (FoV) of SALT on to CCD detectors (which turn out to be a 2 x 1 mosaic of 2k x 4k x 15 micron pixel CCDs) over the design wavelength range of 320 to 950 nm. In addition, the SALT Project team requested that as much as possible of the 10 arcmin diameter guide star FoV be included. As usual, throughput should be as large as possible. The first optical elements should be placed "downstream" of the telescope exit pupil and fed by a fold mirror: the Prime Focus Imaging Spectrograph was designated to be placed at the unfolded focal station.

Image quality degradation of no more than 0.3 arcsec (EE50) is allowed. This figure contains the design residual, and all causes of image degradation due to manufacturing, mounting or operations. It does not contain any component of the telescope error budget.

SALTICAM will be used for long exposures (up to 1 hour) during which closed loop guiding of the telescope is required. Picking off guide stars from the guide star field of view is a difficult issue, which will be discussed further later. A shutter and filter unit must also be fitted in, so space constraints are tight.

SALT and its associated instrumentation are intended to operate to specification without degradation over the temperature range 0 to 20 degrees Celsius; to operate with up to 10 per cent performance degradation allowed over the temperature range -10 to 25 degrees Celsius; and to survive in the temperature range -20 to 45 degrees Celsius. Occasional exposure to condensing conditions may be experienced.

The camera will be located on the Payload which rides the Tracker on the top hexagon of the telescope structure. However, it is planned to seal the Payload to enable clean dry air with positive pressure to be fed through it. Light entering the Payload will **not** pass through a sealing window. Thus, while the camera will not be nakedly exposed to dome air, some dust and moisture must inevitably find its way to the immediate environs of the camera.

The Payload will be tipped with respect to the vertical by 28.5 to 45.5 degrees (as the Tracker follows a specific celestial target). The optics will be mounted perpendicular to the Tracker axis. In addition, the Payload contains a rotational stage to rotate part of the Payload (including the camera) about the Payload axis by up to 240 degrees. Thus the angle between the optical axis of the camera and the vertical will vary over the range 44.5 to 90.0 degrees.

2.2 Design Approach

Some trial designs using a mirror to provide the bulk of the power were tried but none of these were found to be practicable: as usual the problem with reflective optics in a fast

beam is central obscuration. By the time the beam leaves the telescope exit pupil, is folded and clears the light path to the unfolded focal station, it is only 130 mm in diameter. None of the reflective designs tried yielded anywhere near satisfactory throughput. It was therefore concluded that a refractive solution was required.

2.3 Materials Used

The very short lower wavelength limit (320 nm) for the instrument imposes strong constraints on the materials used: no ordinary optical glass has high transmission at 320 nm. Thus UV transmitting crystals were considered. Following Harland Epps' popularization of NaCl in a number of modern instruments (e.g. the Goodman Spectrograph for the SOAR telescope which is optimized for UV efficiency), some initial refractive designs used NaCl for colour correction. Inquiries revealed that although some optical shops were experienced and therefore sanguine about working with this material (e.g. Lick Observatory), most were not. Dr. Ken Nordsieck (U. of Wisconsin) kindly drew our attention to the value of BaF_2 as a suitable material and we found that designs with BaF_2 in performed as well as those with NaCl (after re-optimization). Thus, the preliminary optical design makes use of fused silica (which we shall often refer to as "silica"), CaF_2 and BaF2. CaF_2 and especially BaF_2 are fragile materials and vulnerable to mechanical and thermal shock as well as moisture (though far less vulnerable than NaCl). Staining and scratching are also sources of concern. So care was taken in the optical design to protect the materials as far as possible.

The thermal expansion coefficients of CaF_2 and BaF_2 are similar and substantially larger than that of fused silica. Thus usage of these materials implies sophisticated coupling and mounting schemes which will be described later.

2.4 The Preliminary Optical Design

2k x 4k x 15 micron pixel CCDS are readily available from commercial vendors (e.g. Marconi Applied Technologies or SITe). The requirement to image 8 arcmin on to such devices which are ~60 mm on their longest side implies speeding up the f-ratio emerging from the spherical aberration corrector from f/4.2 to f/2.2. Imaging almost 10 arcmin can be achieved with f/2.0. It was found that further increases in speed with the refractive optical designs to be described below led to rapid deterioration in image quality. Thus the f-ratio was set to be f/2.0.

The initial starting point for the design was constructed from general optical design principles: one or more components must provide the power required, other components should provide correction of spherical aberration and spherochromatism; near the focal plane there should be field flattening components. The first design tried therefore had three groups comprising a CaF_2/silica doublet for power, a CaF_2/NaCl/silica triplet for correction and a CaF_2/silica doublet field lens.

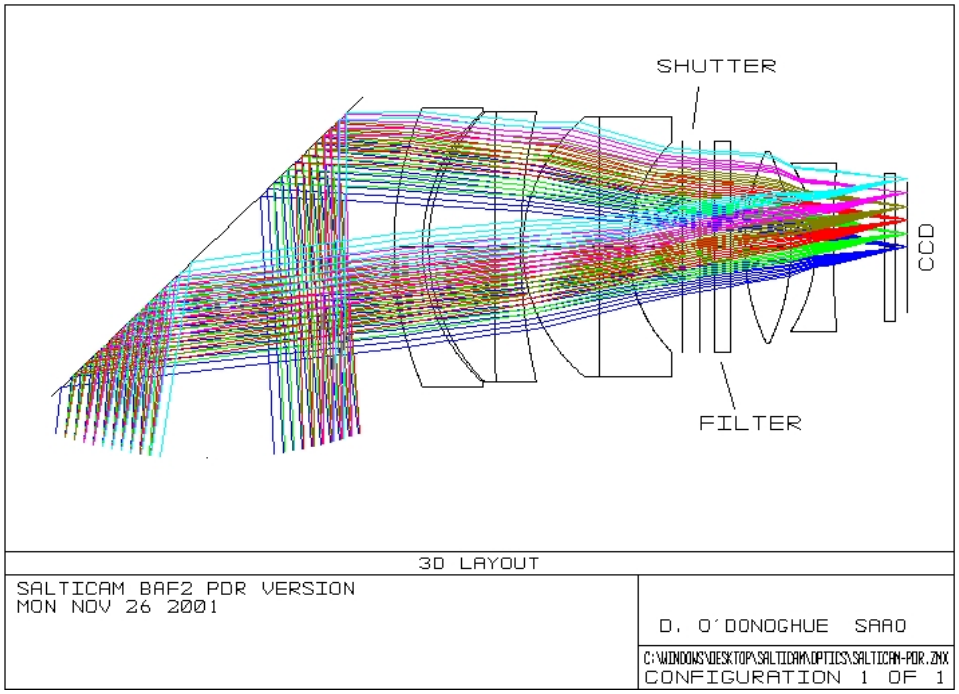


Figure 1. SALTICAM optical layout in Acquisition Camera and Scientific Imager mode. The exit pupil is shown at lower left. Immediately above it is the folding flat mirror feeding light into the optical re-imaging system. Filter, shutter and CCD detectors are marked.

A significant complication is the need to provide closed loop guiding. Light from a guide star has to be "picked off" by a mirror which must be located as close to the focal plane as possible: with an f/2.0 final focal ratio, separation of the field angles sufficient to enable the pick-off mirror to avoid unacceptable vignetting of the rest of the science field is only possible close to the focal plane. On the other hand, the pick-off mirror cannot be located inside the cryostat. Thus, the pick-off mirror must be insertable between the cryostat window and the field flattener and the standard scheme of using the entrance window into the cryostat as the field flattener cannot be used in this design. Field-flattening lenses perform best if located as close to the focal plane as possible, so pushing the field lens forward to make room for the pick-off mirror “stressed” the design and is a limiting factor in the image quality delivered. As a result, the field flattener in the initialdesign, which was a CaF_2/silica doublet, had to be split into two singlets. By this stage of the development, the optical design comprised a CaF_2/silica doublet, a CaF_2/NaCl/silica triplet and two rear singlets of CaF_2 and silica. The spacings are such that the shutter and filter unit would be inserted in the space between the front five elements and the two rear singlets. Indeed, it appeared that a barrel containing the front five elements and another containing the two rear singlets would be an advantageous way of mounting the optics.

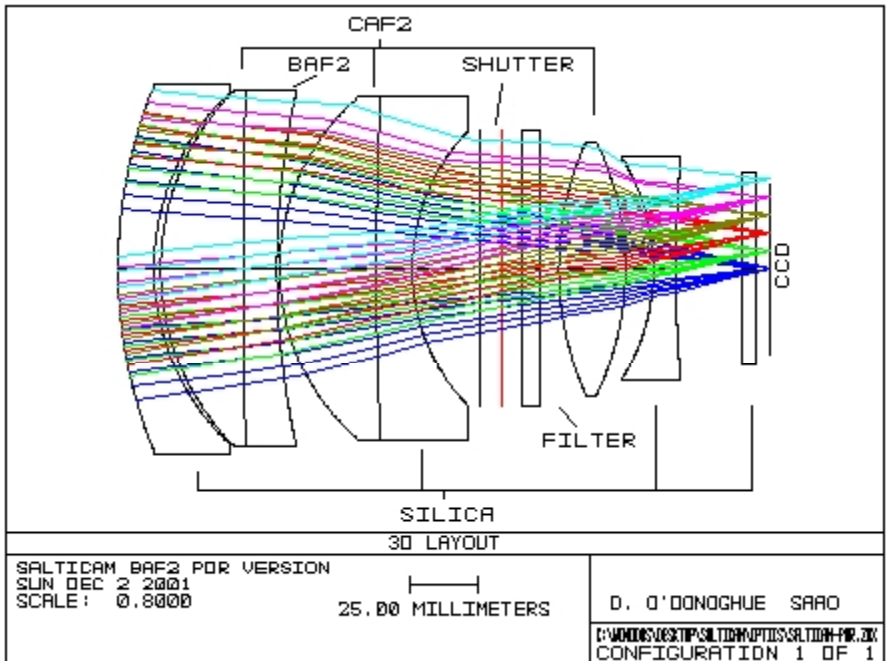


Figure 2. SALTICAM optical layout in more detail. The optical materials are marked.

At this stage we became aware of the potential of BaF_2 and experiments quickly showed that replacing NaCl in the triplet with BaF_2/CaF_2/silica yielded equivalent optical performance, although the front BaF_2 element was strongly curved almost to the point of being hemispherical. Another source of concern was the fact that the front element of the entire lens system is CaF_2, which would be maximally exposed to any sudden temperature changes. It was deemed highly desirable to avoid, if at all possible, positioning the fragile materials (CaF_2 and BaF_2) in the first five elements at the front or rear of the chain. Consequently, the design was then constrained to have fused silica as the first and fifth elements. Re-optimization yielded an unacceptable degradation of performance with field angle. This problem was circumvented by splitting the front doublet and a little more work resulted in an arrangement comprising a front silica singlet, a CaF_2/BaF_2 doublet, a CaF_2/silica doublet for the front five elements, with the two rear singlets of CaF_2 and silica remaining as before. This design is shown in Fig. 1.

Fig. 2 shows the optical materials used for each element. There is a very small spacing between the front singlet and the first doublet. Note also that the interfaces in both doublets is almost flat, as well as the fact that the curvatures of each face of the first rear singlet are similar. Experiments were conducted in which the doublet interfaces were constrained to be plano, and the curvatures of the first rear singlet were constrained to be equal. Equivalent optical performance was achieved after re-optimization. It is therefore likely that the final design will have these constraints introduced but for the present the additional freedom is retained.

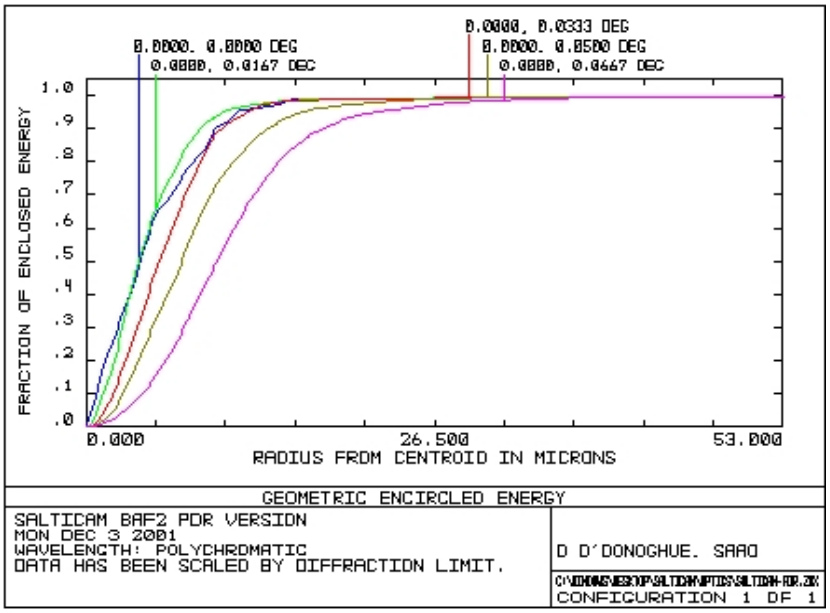


Figure 3. SALTICAM optical performance. Encircled energy is shown as a function of radius from the spot centroid. The horizontal axis spans a radius of half an arcsec on the sky.

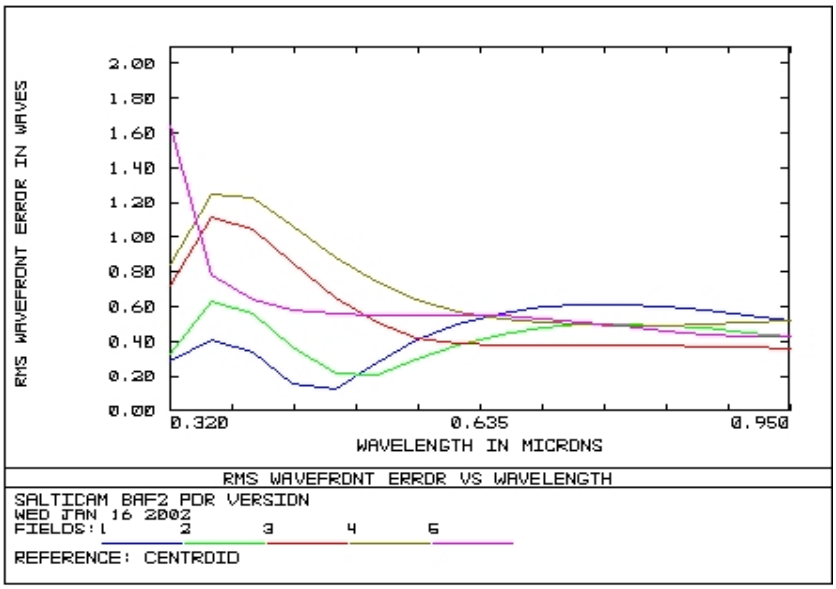


Figure 4. SALTICAM optical performance versus wavelength.

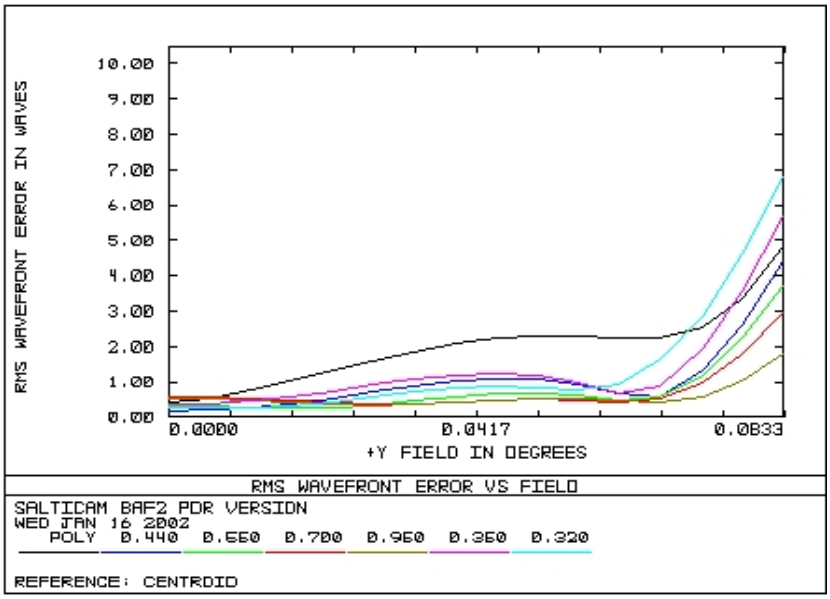


Figure 5. SALTICAM optical performance versus field angle. The science field extends to 80 per cent of the horizontal axis.

Numerical data (radii of curvature, element thickness', spacings and clear apertures) and element drawings for the preliminary optical design are available in the Appendix: 3310AE0002 optical spec.pdf, which also contains a specification for procurement of the material for manufacturing the elements. This was sent out to a number of potential material suppliers in December 2001.

It is planned that focusing will be achieved by moving the barrel containing the two rear singlets.

2.5 Optical Performance of the Preliminary Optical Design

Fig. 3 shows the optical performance of the design as measured by a polychromatic encircled energy plot. The horizontal axis spans a radius of 0.5 arcsec. The design residual has EE50 of 0.08 arcsec on axis and 0.19 arcsec at the edge of the science FoV. Weighting the field angles by 0.5 (on-axis) and 0.25 (2 and 4 arcmin off axis) leads to a weighted image quality of 0.12 arcsec.

Fig. 4 shows the performance as a function of wavelength and Fig. 5 shows the performance as a function of field angle. The sudden decline in performance in the guide star field shown in Fig. 5 is mostly due to field curvature: image quality can be improved considerably by refocusing which, in practice, will be possible as the guide stars will be accessed by a pick-off mirror with independent focusing capability.

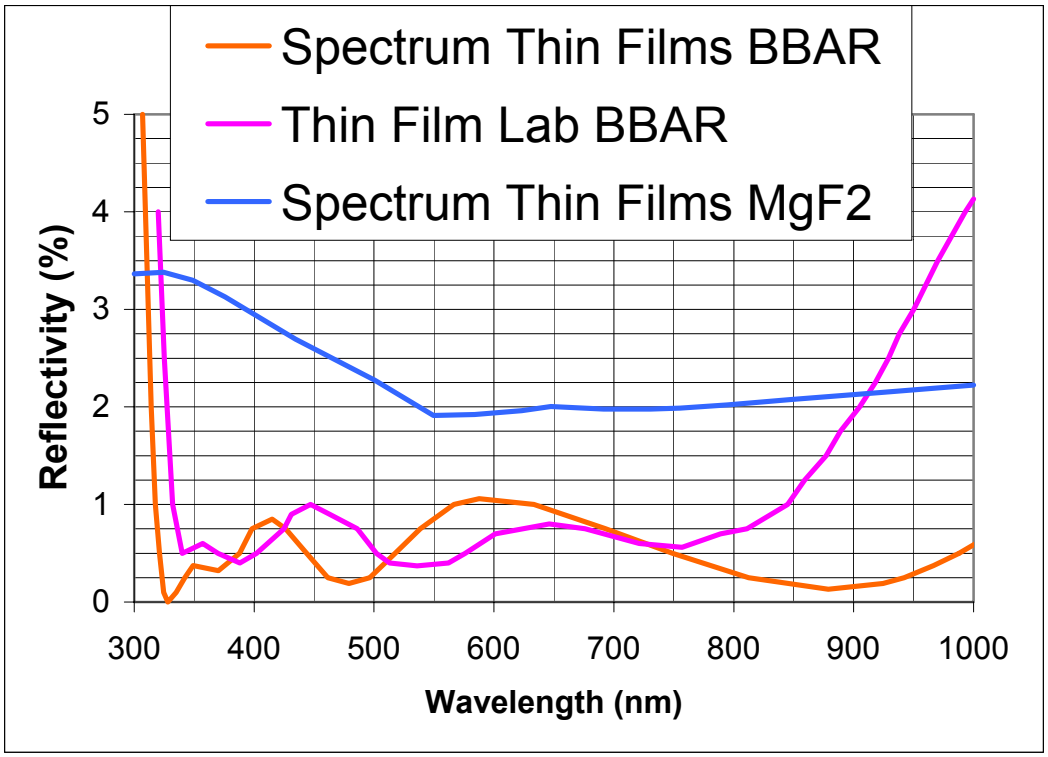


Figure 6. Coating options. The blue line indicates a single layer MgF2 coating from Spectrum Thin Films. The red line indicates a multilayer broad band anti-reflection (BBAR) coating from the same company. The purple line indicates a multilayer BBAR coating from Thin Film Lab. The angle of incidence is 0° for all three curves.

Is the design shown in Figs. 1 and 2 optimal? It is, of course, impossible to say. Following an inquiry from one of the external reviewers as to whether BaF_2 is necessary, an experiment was conducted in which this material was replaced by fused silica and the design re-optimized. RMS spot radii were about a factor 2.5 worse than in the design presented above.

3 Coating

The fragility (especially thermal sensitivity) of the UV crystals (CaF_2, BaF_2) rules out "hot" anti-reflection coatings. Ideally, pulsed ion beam technology, which is capable of applying coatings at room temperature, should be used. Quotations for Broad Band Anti-Reflection (BBAR) coatings were obtained from Spectrum Thin Films (100-E Knickerbocker Avenue, Bohemia, NY 11716, USA) and from Thin Film Lab (112 Sawkill Rd, Milford, PA 18337, USA). Spectrum Thin Films' coating is "Cold": a room emperature coating applied by pulsed ion beam technology. They also provided a

quotation for a single layer of MgF_2. The coating from Thin Film Lab is a "warm" coating with "the proper ramping". The performance is shown in Fig. 6. It is clear that the "Cold" coating from Spectrum Thin Films has the best performance: it has 1 per cent or less reflectivity across the 320-950 nm bandpass of the instrument. It is also less risky than the "warm" coating of Thin Film Lab. There is a price to pay: the cost difference is substantial as shown in Table 1. Delivery is 6 weeks and 2 weeks for Spectrum Thin Films and Thin Film Lab respectively. Our recommendation is for the cold coating if it can be afforded.

Table 1: Prices On Coating Of SALTICAM Optics

Supplier:	Coating Type	Price
Spectrum Thin Films	"Cold" BBAR on CaF_2 & BaF_2	$23725
	"Cold" BBAR on fused silica	$11775
	"Cold" SL MgF_2 on CaF_2 & BaF_2	$16125
	"Cold" SL MgF_2 on fused silica	$8375
Thin Film Lab	"Warm" BBAR on all optics	$3600

4 Tolerance Analysis

4.1 Manufacturing Tolerances

A preliminary tolerance analysis for manufacture was carried out using "reasonable" optical shop tolerances as listed in Table 2. The air spacings between the lens groups were used as compensators in the analysis so that the design will have to be re-optimized after the lenses are fabricated.

Table 2: Tolerance On Manufacture Of SALTICAM Optics

Tolerance On:	Tolerance
Radius of Curvature	0.1 per cent
Element Thickness	0.1 mm
Wedge	30 arcseconds
Surface Irregularity	¼ wave P-V
Scratch/dig	60/40

Sensitivity analysis revealed little detectable degradation in image quality over the design residual for any specific tolerance. The most sensitive surfaces are the entrance surface of the doublets. Refractive indices of the glasses need to be known to a precision of at least 0.0001, and Abbe numbers to a precision of 0.5.

Table 3: Tolerance On Mounting Of SALTICAM Optics

Tolerance On:	**Tolerance**	**Relative Sensitivity**
All Air Spacings	100 micron	~0.050
Decentre on:	(micron)	
Complete System	100	0.000
Front Barrel	100	0.020
Rear Barrel	100	0.021
Doublet 1	30	0.118
Doublet 2	50	0.020
Element 1	30	0.151
Element 2	30	0.116
Element 3	50	0.001
Element 4	50	0.044
Element 5	50	0.011
Element 6	40	0.045
Element 7	40	0.061
Tip/Tilt of:	(degrees)	
Complete System	0.044	0.006
Front Barrel	0.044	0.055
Rear Barrel	0.064	0.048
Doublet 1	0.013	0.061
Doublet 2	0.024	0.006
Element 1	0.013	0.088
Element 2	0.013	0.062
Element 3	0.022	0.013
Element 4	0.024	0.031
Element 5	0.024	0.012
Element 6	0.025	0.036
Element 7	0.025	0.039

Fifty Monte Carlo simulations using these tolerances showed that ninety per cent of manufactured systems (assuming perfect mountings) will have image quality of better

than 0.15 arcsec (including the design residual). This is only slightly worse than the design residual of 0.12 arcsec, and substantially less than the image quality goal of 0.3 arcsec. Assuming the design residual and the manufacturing errors sum in quadrature implies that the component due to the manufacturing residuals is 0.09 arcsec (EE50).

4.2 Mounting Tolerances

Mounting tolerances are of greater significance. Bearing in mind that it is difficult to center elements in cells to better than 25 microns, and that 100 microns is comparatively straightforward, a set of tolerances for mounting was derived as shown in Table 3. Tolerances on air spacings, decentre and tip/tilt were allowed for. Movement of the rear barrel only was allowed as a compensator. The tip/tilt tolerances, listed in degrees, were set such that one edge of the element is tipped with respect to its diametrically opposite edge by an amount equal to the corresponding decentre tolerance. Sensitivities are also listed in Table 3. These are related to the degradation in RMS spot

size resulting from perturbing the system by the corresponding tolerance: a total perturbation of about 0.6 in this figure degrades the image quality from nominal to 0.2 arcsec (EE50).

The most sensitive mounting error is decentration of the first and second elements and the first doublet. Fifty Monte Carlo simulations using these tolerances showed that ninety per cent of manufactured systems (assuming perfect manufacture) will have image quality of better than 0.20 arcsec (including the design residual). Assuming again that the mounting errors and design residual sum in quadrature yields 0.16 arcsec (EE50) for the component due to mounting errors.

4.3 Error Budget

The results of the previous sections can be assembled into an image quality error budget for the instrument:

Table 4: Image Quality Error Budget For SALTICAM Optics

Component	Contribution (EE50 arcsec)
Design residual	0.12
Manufacturing	0.09
Mounting	0.16
Operations	0.20
Total:	0.30

The 0.20 arcsec contribution from “Operations” is to allow for image quality degradation from causes yet to be defined.

5 Optical Testing

Some thought has been given to optical testing. All SALTICAM surfaces are spherical so standard testing during fabrication followed by metrology will be part of the fabrication contract. As described below, the lenses will then be mounted in cells which themselves will be placed in barrels within the tolerances derived above. A system test for the final assembly is therefore required.

Tests involving mounting the lens assembly on an existing SAAO telescope were considered. It was found that mounting the system at the Cassegrain foci would require extensive test fore-optics as the Cassegrain foci of SAAO telescopes is slower than f/12. Mounting at the Newtonian focus of the 1.9-m was also considered (there the focal ratio is f/4.8 and there is a Newtonian flat). Indeed, a simple doublet about the size of the front

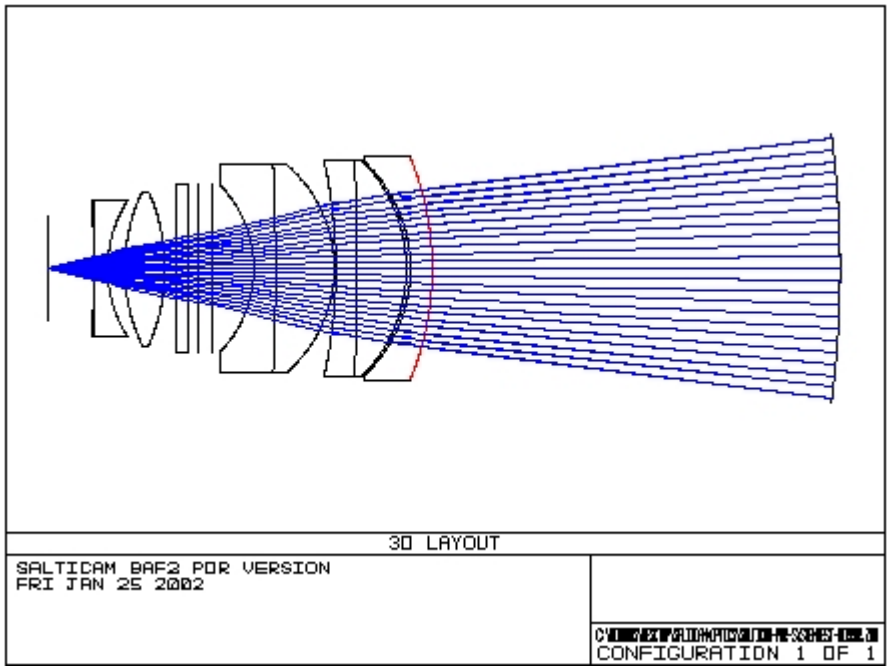


Figure 7. System optical test.

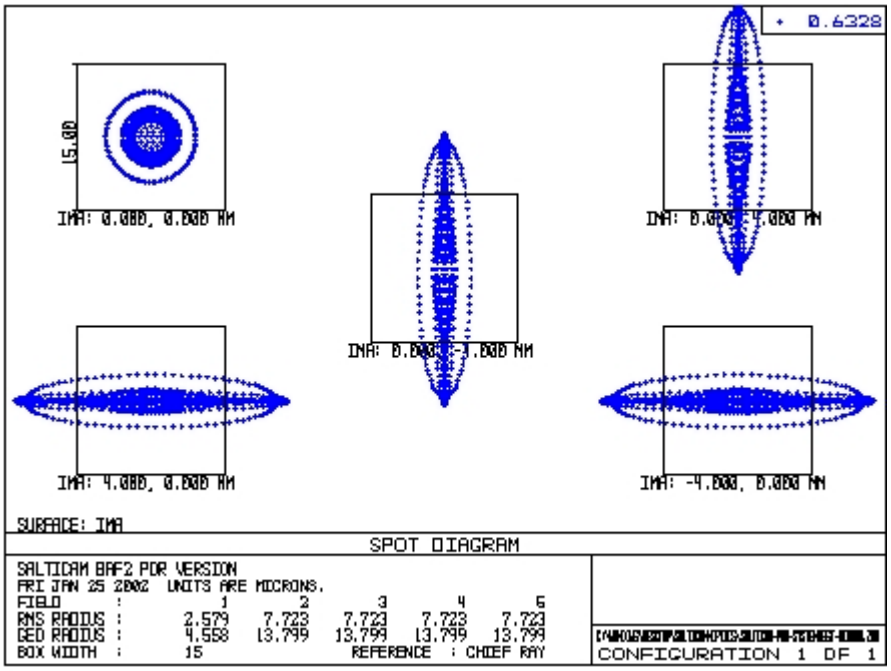


Figure 8. Performance of the system optical test. The boxes are 15 microns on a side, the size of a typical CCD pixel.

element in SALTICAM would produce diffraction limited imagery on axis. However, off-axis the normal substantial coma of a parabolic mirror operated at prime focus is not corrected by SALTICAM. If anything, it is made worse.

Accordingly, a system optical null test using a 160 mm diameter mirror as shown in Fig. 7 was adopted. The test has less than a wavelength of spherical aberration (and this could be reduced) and could be used as a classical null test with an interferometer. However, interferometers of the kind needed for such a null test cost in excess of US$ 50,000 and seem hardly justified for an acceptance test. Instead, it is proposed to use the above layout with a beam splitter to image an object (a pinhole) on to a simple CCD. Spot diagrams for a field of +/- 4 mm are shown in Fig. 8 and, off axis, are dominated by the astigmatism of the mirror. Nevertheless, perpendicular to the primary astigmatism there is good image quality so this setup could be used not only to verify performance on axis but limited off axis performance too. Tolerancing of this test will be investigated for the Final Design Review.

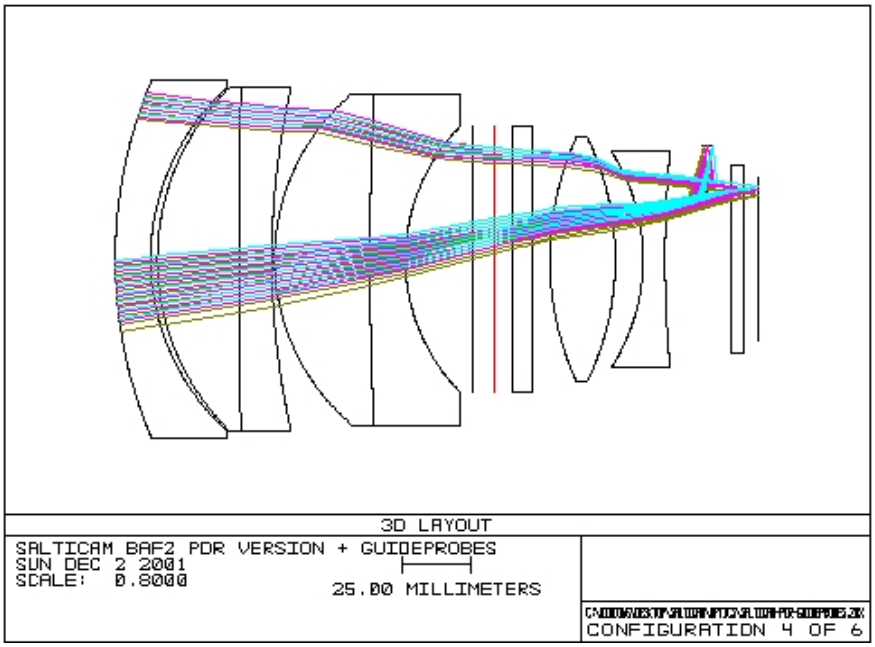


Figure 9. SALTICAM optical layout with the pickoff mirror for the guide probe illustrated.

6 Preliminary Opto-Mechanical Design

SALTICAM has to survive a considerable temperature range: -20 to +45 Celsius. The coefficients of thermal expansion (CTE) of CaF_2 and BaF_2 are similar but dissimilar to that of fused silica (Table 5). Thus contacting of the elements, especially in the second doublet, will require special care, as discussed below.

Table 5: Lens material Coefficients of Thermal Expansion (CTE)

Lens material	CTE (ppm/C)
CaF2	18.85
BaF2	18.1
Fused Silica	0.52

Space is also tightly constrained and as already indicated, a filter unit and shutter will have to operate between the fifth and sixth elements in the optical train. In addition, a guide star probe will be inserted between the last lens element and the cryostat window. This is illustrated in Fig. 9.

6.1 Multiplet Coupling

There are a variety of choices for optically contacting lenses in multiplets. The simplest method is usually to rigidly bond the lenses with an appropriately transmitting adhesive or epoxy. However, due to the large operating and survival temperature ranges, and the varying CTE in the materials found in the SALTICAM doublets, this option was considered suspect. A second option is to couple with optical grease or oil, but optical greases have been seen to degrade over time, and coupling oils require oil-sealed lens cells, substantially complicating the mechanical design, fabrication, and assembly. A third option is to bond multiplets with a transmitting room temperature vulcanizing (RTV) elastomer. This option is appealing because of it simplicity, both in terms of the bonded coupling itself, and in terms of the mounting of the resulting multiplet. The desire to elastomerically bond the doublets led to an investigation of the expected thermal stresses over the survival temperature range. Finite Element Analysis (FEA) was used to quantify the stresses under different bonding conditions.

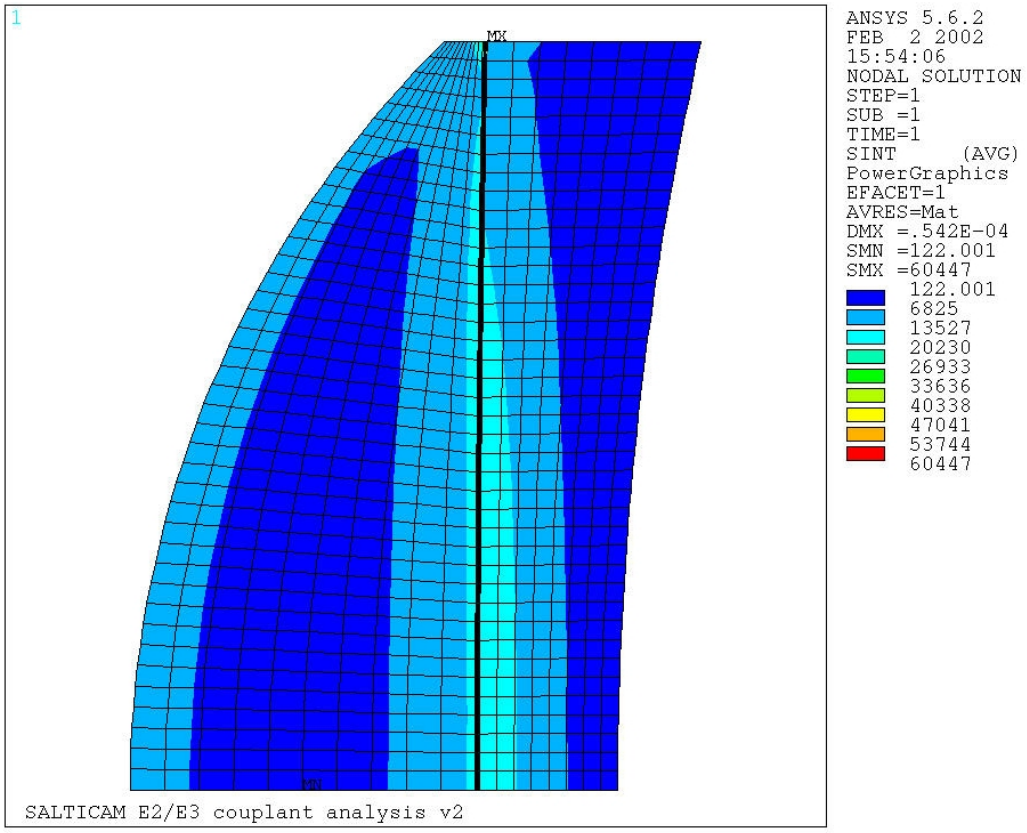


Figure 10. Stresses (MPa) in doublet D1 for a 0.4 mm layer of RTV elastomer.

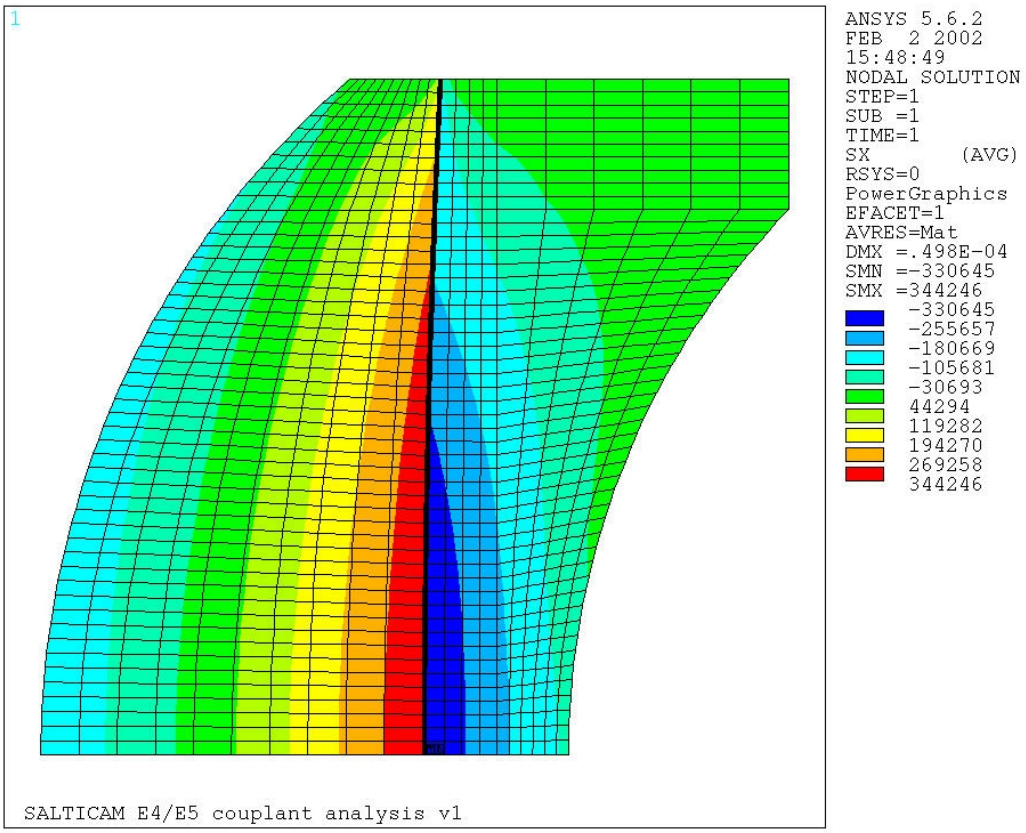


Figure 11. Stresses (MPa) in doublet D2 for a 0.4 mm layer of RTV elastomer. It is interesting to note that, as expected, the stresses are of opposite sign (see legend) along the interface between the two materials.

The two doublets, here designated D1 and D2, are composed of CaF2 / BaF2 (lens elements 2 and 3), and CaF2 / fused silica (lens elements 4 and 5). In the FEA of the doublets, axi-symmetric elements and models were used. The models for D1 and D2 used 880 and 1200 elements respectively. Parameters were used to describe the geometry, material properties, and finite element mesh characteristics in both models, so that the models could be changed easily to examine a variety of cases. The lens geometry and final mesh density for the two doublets can be seen in Figs. 10 and 11.

Initially, both doublet models were analyzed assuming that they had been bonded with a rigid adhesive. In the case of D1, the stresses were found to be low, as expected by the small differences between the CTE of CaF2 and BaF2. Thus, in principal, D1 could be rigidly bonded. However, in the case of D2, the stresses were found to exceed the elastic limit of CaF2 (36.5 MPa), and rigid bonding is not an option.

For D2, a UV-transmitting, room temperature vulcanizing (RTV) elastomer, Dow-Corning Sylgard 184, was then analyzed as a couplant in the FE models. The resulting stresses in the E4 CaF2 element, as a function of bond thickness, are shown in Table 6.

Table 6: Stresses as a function of RTV bond thickness in E4.

RTV bond thickness, mm	CaF2 Stress, MPa	CaF2 Stress, PSI
0.0	48.0	7000
0.1	1.3	188
0.2	0.67	97
0.3	0.45	65
0.4	0.34	49
0.5	0.27	39
0.6	0.23	33

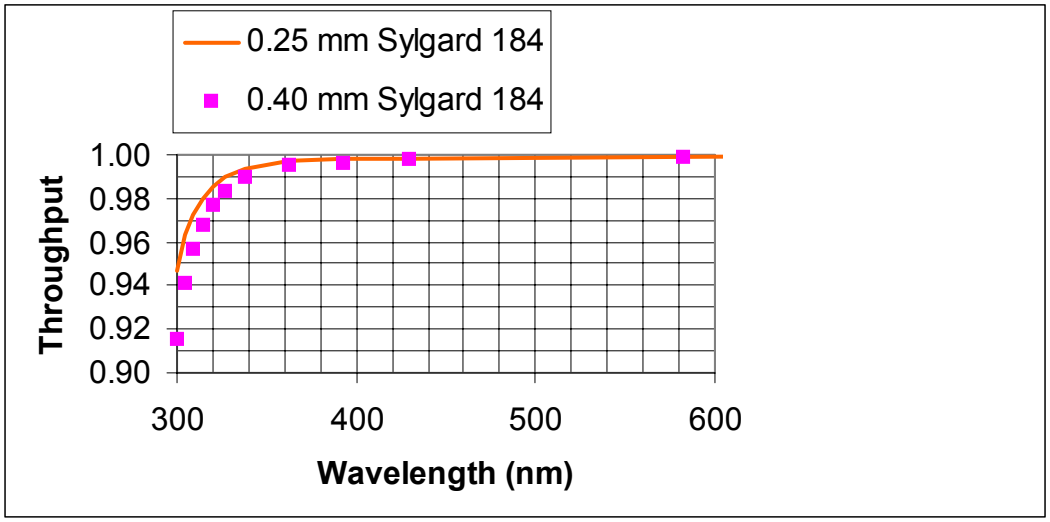


Figure 12. Throughput as a function of wavelength for Sylgard 184.

In this case, the stresses increase linearly with decreasing thickness of the bond layer. Optimization of the bond thickness is thus a trade-off between absorption losses in the RTV, and peak stresses in the CaF2. It is suggested that for ease of assembly and low stress, a bond layer of at least 0.2 mm be used, and 0.4 mm (0.016") is recommended. For simplicity and economy of bonding materials, it is recommended that D1 also be bonded with the same thickness and RTV as D2. Note that in Figs. 10 and 11, the stresses shown are for a bond thickness of 0.4mm. Fig. 12 shows the throughput of

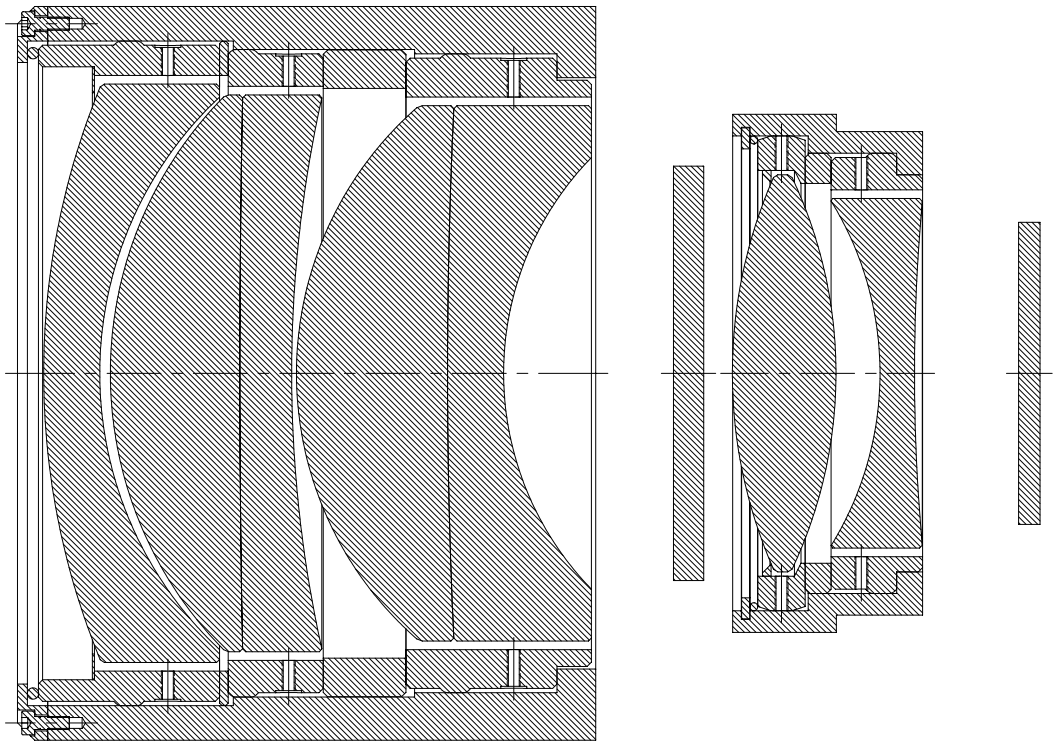


Figure 13. SALTICAM preliminary lens / cell / barrel interface design.

Sylgard 184 as a function of wavelength, using measurements made by Dr Steve Shectman of Carnegie Observatories using a spectrometer on a 10 mm sample of Sylgard 184 in a pyrex cell. At 320 nm, a 0.40 mm layer absorbs a little over 2 per cent.

6.2 Opto-mechanical Design

There are a variety of constraints imposed on the opto-mechanical design for SALTICAM. The most stringent requirement is the large survival temperature range – the lens mountings must allow for the expansion and contraction of the lenses as temperature changes, while simultaneously maintaining the positions of the lenses in the camera within the allowed tolerances. There are tight space constraints imposed by inclusion of the camera shutter and filter insertion between lens elements 5 and 6. Similarly, space must be provided for a guiding pick-off mirror between element 7 and the dewar window.

As with optical coupling, there are a variety of methods for athermal mounting of lenses. Among the options are rigid bonding of lenses to cells, mechanical suspension, location by thermally compensating elements (usually plastic), and flexible bonding.

In order to meet the thermal, spatial, and positional requirements for SALTICAM, elastomeric mountings were proposed. By careful selection of the elastomer (for elastic modulus and CTE), and proper design of the elastomeric bond itself (location on the lens, bond width, and bond thickness), elastomeric mountings can be optimized to compensate for differential thermal expansion, while at the same time maintaining the positions of the lenses within the allowed tolerances. Additionally, elastomeric mountings effectively insulate the lenses from deformation by flexure or deformation of the cells. In a properly designed cell, the lens will move as a rigid body within its elastomeric ring if the cell is distorted by gravity or other external forces. Fig. 13 shows the lenses and cells with partial versions of the barrels. Further discussion of the barrels can be found in 3320AE0001 mechanical.pdf.

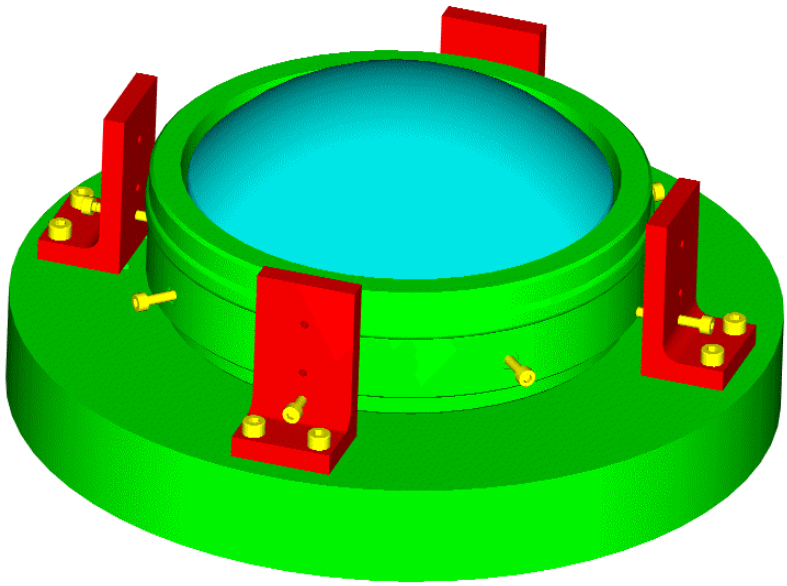


Figure 14. E4/E5 Doublet with bonding tooling

Several design elements are common to each of the lens/cell units. First, each lens is elastomerically bonded to its cell in a fixture that allows the lens to be located in the cell (radially, axially, and tilts) to better than 25 microns. A typical bonding tooling

arrangement can be seen in Fig. 14. There is no adjustment of radial position for any of the cells in the barrels - each cell is manufactured such that the remainder of the position allowance (10-40 microns) is used in the fits between the cells and barrels. Note from Fig. 13, that tight fabrication tolerances will only be held for small regions where the cells and barrels interface. The majority of the cell and barrel surfaces require only low precision machining. Note also that aperture stops are present in front of the front silica element, and in front of the CaF2 singlet. These stops are intended to help minimize stray light, but are not necessarily sufficient to provide baffling for the entire camera.

One end of each barrel provides the local reference position. The stacks of cells and spacers are loaded into the barrel and held in place from the opposite end by a retainer. The thickness of the spacers will be adjusted at assembly to provide the correct final spacings between each lens group. Each cell has four threaded radial holes, which are used for centering the lens during bonding. The lens cells and barrels will be fabricated from 7075-T6 aerospace-grade aluminum, primarily for its stability and ease of machining, and then black-anodized for corrosion resistance. Selection of the mounting elastomer and detailed design of the bond section for each lens group will be completed in the final design phase.

6.3 Coupling, Alignment and Bonding

A typical set-up for bonding a lens into its cell is shown in Fig. 14. This tooling will also be used to bond the elements in the multiplets. One base plate and mounting bracket set will be used for alignment and lens/cell bonding for all the five SALTICAM lens groups. The alignment and lens/cell bonding operations are as follows:

1. Clean and apply primer to lens and cell bonding surfaces
2. Align cell to base plate, using a dial indicator and base jacking screws
3. Align lens in cell, using dial indicator and cell jacking screws
4. Insert temporary bonding forms, dams, etc.
5. Apply first batch of elastomer to seal forms and dams
6. Apply second batch of elastomer, not to exceed 10-15 mm bond depth
7. Apply additional batches of elastomer to finish bond if necessary
8. Remove lens/cell from tooling, then dams/forms from cell
9. Apply final batch of elastomer to fill dam/form volumes as necessary

Provided that the fabrication tolerances for the lenses and cells have been properly specified, this method can easily result in lens/cell centration errors of less than 25 microns, and with somewhat greater effort, to a quarter of that value, or 6-7 microns.

7 Fabrication Plan

In June 2001, a preliminary opto-mechanical specification for SALTICAM's optics was prepared and sent out to a list of reputable vendors gleaned from various sources. The specification called for interested parties to provide budgetary prices and delivery times for the lens fabrication, coating and opto-mechanical mounting, either as a complete job to provide a turnkey system, or any sub-component of the work. The design being considered at that stage was not the same as that shown above and instead comprised a front doublet of CaF2/silica, a triplet of CaF2/NaCl/silica and two rear singlets similar to those shown in Fig. 2. The replies were assessed in terms of price, schedule, technical experience and risk.

Only one company expressed interest in providing a complete system: Specac in the UK provided a budgetary price of 50000 pounds sterling (approximately $75000). Nevertheless, this company had not manufactured any optics requiring the sophisticated mounting described above.

A number of optical shops provided quotation on fabrication of lenses only as shown in Table 7. Procurement of the blank material (and replacement in case of damage or breakage) was the responsibility of the vendor in each case.

Broadly speaking, these quotes were similar (including the Crystran quote which was for only 4 of the 7 elements).

Table 7: SALTICAM Optics Fabrication Quotes (Material procurement included)

Optical Shop	Price (US Dollars)	Comment
Lick Observatory	$82534	
Janos Technology	$60000	
Coastal Optics	$70500	BaF_2 design (declined NaCl design)
Crystran	$36200	3 x CaF_2 and NaCl only

At that time, quotations from optomechanical engineers with experience in this kind of optics were sought. The scope of work was the design and assembly of cells similar to those described above. Two quotations of about $40000 were received from one of the authors (BB) and J. Alan Schier of the Pilot Group. The net result of this was that optical fabrication and mounting would easily exceed $100k.

On the basis of his own experience and opinion at Carnegie, BB suggested that these price estimates were high and advocated contacting optical shops with whom he has had experience: Harold Johnson Optical Labs and the Tucson Optical Research Corporation.

Table 8: SALTICAM Optics Fabrication Quotes (Material procurement excluded)

Optical Shop	Price (US Dollars)	Comment
Harold Johnson Optical Laboratories	$7308	BaF_2 excluded
Tucson Optical Research Corporation	$11000	
Industrial Optics Unlimited	$13550	

(Both of these had been contacted by DOD but declined to bid (HJOL) or failed to respond (TORC)). Quotes for fabrication only (i.e. the customer supplies the blank material) were obtained from these two companies as well as a third known to BB. The results are shown in Table 8.

David Hilyard of Lick Observatory Optical Shop had been kind enough to provide a breakdown of labour and material in the Lick quote. The material costs were about $26k.

Table 9: SALTICAM Blank Material Quotes

Potential Supplier	Element 1: silica	Element 2: CaF_2	Element 3: BaF_2	Element 4: CaF_2	Element 5: silica	Element 6: CaF_2	Element 7: silica
Korth Kristalle		$5600	$4600	$5900		$2800	
Saint Gobain		$10950		$11575		$4025	
GB Crystalsland	$1133	$3620		$3460	$830	$1260	$273
ISP Optics	$1750	$6520	$8485	$6650	$1720	$2400	$1150
Oken	$2000	$2600		$2700	$1400	$1600	$450
Canon (Canada)	$1750	$2180	$2480	$2430	$1680	$850	$460
Schott (Labotec)	$1071	$3098	$2380	$3257	$754	$1201	$310

Table 9 continued: Summary of SALTICAM Blank Material Quotes

Potential Supplier	Total Price: Elements 1-7	Delivery	Comment
Korth Kristalle	$18900	6 weeks	For 4 elements only
Saint Gobain	$26550	12 weeks	For 3 elements only
GB Crystalsland	$10576	8 weeks	BaF_2 excluded
ISP Optics	$28675	25 weeks	
Oken	$10750	Negot-iable	
Canon (Canada)	$11830	12 weeks	
Schott (Labotec)	$12071	6 weeks	

The above results then suggested that **substantial** savings might be possible from management of blank material procurement and fabrication separately. Blank material quotations were then sought from a number of recommended companies. The results are shown in Table 9.

On the basis of the above information and estimation of the risk, a fabrication plan was deduced on the following grounds:

- It is our judgement that one of the most significant risks associated with the instrument is the mounting of the optics: the materials to be used are thermally and mechanically fragile and vulnerable to scratching and staining. Their mounting as discussed in Section 6 requires sophisticated treatment. Only one supplier offered a complete turnkey system. Discussions with Specac in the UK revealed that they had no experience of mounting of optics of this kind. On these grounds, we judged that *solid experience of optomechanical mounting of lens elements was indispensable.* Consequently, Specac was eliminated from consideration in the fabrication plan.
- It is clear that in the choice between having a set of lenses delivered with material procurement and all risk assumed by the optical fabricator (Table 7), and managing the material procurement and supplying it (at the customer's risk) to the

optical fabricator (Tables 9 and 8), that considerable savings are achievable from the latter course of action. Of course, some insurance against lens breakage will have to be provided (this could be in the form of waiting to see what gets broken if there is sufficient time, or by purchasing extra blank material if there isn't).

The fabrication plan can be summarized then as:

1) Procure blank material, probably from Schott: their price is competitive, delivery time is amongst the best (thereby reducing schedule risk in the event of breakage), and they have South African agents (Labotec) so management of the procurement may be easier (contact with them so far suggests they are efficient and interested in the business).

2) The lenses will be fabricated by the Tucson Optical Research Corporation

3) The lenses will be coated by Spectrum Thin Films

4) The lenses will be mounted in cells by BB

5) The cells will be integrated into barrels by DOD and JOC

6) A final system test will be conducted as described earlier

Table 10: SALTICAM Optics Fabrication Plan

Process	Price (US Dollars)	Schedule	Comment
Optical material procurement	$19100	6 weeks	1 extra blank of silica, CaF_2 and BaF_2
Fabrication: Tucson Optical Research Corporation	$11000	15 weeks	Contract management by BB
Coating: Spectrum Thin Films	$35500	6 weeks	
Fabrication management and opto-mechanical mounting: BB	$15000	4 weeks	
Shipping	$200	2 weeks	
TOTAL:	**$80800**	33 weeks	

A summary of price and schedule for the fabrication plan is shown in Table 10.

8 Filters

It seems useful to conclude with a brief word on filters. Johnson-Kron-Cousins UBVRI filters will be supplied as standard, along with a fused silica plano-plano element (for when no filter is required). A neutral density filter for flat-field measurements will also be supplied. It is assumed that the SALT Project will supply the fold mirror, pellicle for autoguiding, and dichroic for parasitic observations (if approved), the mounting slide for these elements and their control. Additional narrow band filters which may be needed during VI usage for telescope verification, or any other scientific filters will be the responsibility of the SALT Project, Project Scientist or scientific investigator.

Appendix: SALTICAM Optical Design And Optical Material Specification

This document was prepared in LaTeX under Unix so could not easily be integrated with this document which originated in MS Word. Accordingly, it appears in PDF format only and is called 3310AE0002 optical spec.pdf. Clicking on it from MS Word should open the document in the Adobe Acrobat Reader if you have that installed.