ULTRACAM DESIGN REVIEW
UKATC, 2001 May 23

Procurement, mounting and coating of the ULTRACAM optics

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This document is concerned with the procurement, mounting and coating of the ULTRACAM optics, including the lenses, dichroics, filters and windows. In order to use Tully Peacocke's time as efficiently as possible, the responsibility for these operations fell with VSD. Note that I do not discuss the Aristarchos collimator in this document, as its design has yet to be finalised. Our intention is, however, for the Aristarchos collimator to be procured at the same time as the WHT collimator and the three cameras, thereby saving considerable amounts of money in the coating process.

1 Lenses

1.1 Procurement

Tender documents were sent out to the following companies on 21/12/2000 for the manufacture of the 22 lenses in the ULTRACAM optical design.

- ICOS. Very interested in the work, and quoted £41 221+VAT to do it (including the coating and mounting of the optics).
- Optical Surfaces. Not interested in the work.
- Specac. Very interested in the work, and quoted £25 264+VAT (including the coating and mounting of the optics and 6 windows – see section 4).
- Spanoptic. Very interested in the work, and quoted £10 480+VAT for the lenses. They were not interested in the coating or mounting work, which would add approximately £12 000+VAT to the quotation (and the associated risk of using multiple contractors).
- Sinden Optical. Not interested in the work.

Given the above response, the track record of each company and the technical risk of using multiple contractors, it was clear that Specac offered the best value for money and a contract was signed with them on 08/03/2001 with an expected delivery date at the end of August 2001. Details of the lenses to be provided by Specac are given in table 1 and drawings of the individual lenses (together with tolerances) are given in appendix B. Additional details (e.g. ray-traces, spot diagrams, etc) can be found in Tully Peacocke's optical design document.

1.2 Coating

Approximately 4% of the incident light at a typical air/glass interface will be reflected (the exact figure is given by $[(n-1)/(n+1)]^2$, where n is the refractive index of the glass). The 18 lens surfaces in the blue arm of ULTRACAM, for example, reduce the throughput to only ∼48% (and this is without taking into account the degradation in throughput due to the windows, filters, dichroics and CCDs). Anti-reflection (AR) coating is hence a necessity for ULTRACAM.

Ideally, we would like a broadband AR coating on the collimator elements and then a blue, green and red-optimised AR coating for each of the arms of ULTRACAM. Unfortunately, such an option

Ultracam and the WHT collimator: the full system (06/03/01)
SURFACE DATA SUMMARY for collimator and dichroics:

Surf	Type	Comment	Radius	Thickness	Glass	Diameter	Conic
Telescope:							
OBJ	STANDARD		Infinity	Infinity		0	0
1	STANDARD		Infinity	7994		4196.456	0
STO	STANDARD		Infinity	105.9		4180	0
3	STANDARD	PRIMARY	-20879	-8034.961	MIRROR	4180.003	-1
4	STANDARD	SECONDARY	-6231.38	9969.75	MIRROR	981.7574	-2.53287
5	STANDARD		Infinity	565		141.7655	0
Ultracam starts here:							
6	STANDARD	TELESCOPE FP.	Infinity	189.4		94.34637	0
7	STANDARD	COLLIMATOR LENS 1	220.05	12	N-PSK3	113.7975	0
8	STANDARD		340	88.93		112.6269	0
9	STANDARD	COLLIMATOR LENS 2	99.64	15	CAF2	111.4181	0
10	STANDARD		151.5	56.42		108.2404	0
11	STANDARD	COLLIMATOR LENS 3	192.5	7	LLF1	95.35354	0
12	STANDARD		82.55	59.67		90.44141	0
13	STANDARD	COLIIMATOR LENS 4	135.7	15.35	CAF2	100.5328	0
14	STANDARD		-571.51	60		100.1218	0
Dichroic section:							
16	STANDARD	DICHROIC 1	Infinity	10	F_SILICA	114.0082	0
17	STANDARD		Infinity	0		103.2933	0
18	COORDBRK		-	100		-	-
19	COORDBRK		-	0		-	-
20	STANDARD	DICHROIC 2	Infinity	10	F_SILICA	90.6975	0
21	STANDARD		Infinity	0		79.5608	0
g' band camera:							
22	COORDBRK		-	-34.5 from dichroic			
24	STANDARD		-50.5	-6.3	N-LAK10	49.5341	0
25	STANDARD		-110	-15.02656		48.05969	0
26	STANDARD		-27.15	-8	N-LAK10	34.78777	0
27	STANDARD		-94.8	-2.5	SF2	31.54592	0
28	STANDARD		-17.47	-12.33266		24.60229	0
29	STANDARD	PUPIL IMAGE	Infinity	-11.68591		20.23071	0
30	STANDARD		19.6	-2.5	SF2	21.8694	0
31	STANDARD		-2304	-7.5	N-LAK10	25.86956	0
32	STANDARD		24.68	-12.00045		27.91988	0
33	STANDARD		-62.188	-6	N-LAK10	31.16941	0
34	STANDARD		180	-16.3158		30.76735	0
35	STANDARD		Infinity	-5	F_SILICA	24.94951	0
36	STANDARD		Infinity	-5		23.79206	0
37	STANDARD		Infinity	-6.25	F_SILICA	22.07835	0
38	STANDARD		Infinity	-6		20.63155	0
IMA	STANDARD		Infinity			18.57509	0
R' and I' camera:							
22	COORDBRK		-	58.98881 For red camera (straight through)			
24	STANDARD		45	6.002615	N-LAK22	43.11535	0
25	STANDARD		126.9	8.131806		41.85542	0
26	STANDARD		23.1	8	N-LAK22	32.5246	0
27	STANDARD		52	2.5	N-SF1	28.88557	0
28	STANDARD		16.5	8.414048		23.28097	0
29	STANDARD	PUPIL IMAGE	Infinity	15.13583		21.31166	0
30	STANDARD		-19.2	2.5	N-SF1	22.85309	0
31	STANDARD		-49.5	6.8	N-LAK22	26.04743	0
32	STANDARD		-23.5	5.133866		28.66146	0
33	STANDARD		61	5.4	N-LAK22	31.59627	0
34	STANDARD		-100.3	19.39821		31.45469	0
35	STANDARD		Infinity	5	F_SILICA	24.68365	0
36	STANDARD		Infinity	5		23.56774	0
37	STANDARD		Infinity	6.25	F_SILICA	21.92752	0
38	STANDARD		Infinity	6		20.53273	0
IMA	STANDARD		Infinity			18.56466	0
U' camera:							
22	COORDBRK		-	-71.27613			
		-	-				
23	COORDBRK		-	0		-	-
24	STANDARD		-40	-6	N-SK16	40.44543	0
25	STANDARD		-87	-6.769136		38.85048	0
26	STANDARD		-27.15	-8	N-SK16	32.60326	0
27	STANDARD		-195.62	-2.5	LLF1	29.73712	0
28	STANDARD		-17.37	-4.892894		23.50989	0
29	STANDARD	PUPIL IMAGE	Infinity	-17.15984		23.34132	0
30	STANDARD		19.2	-2.5	LLF1	23.85496	0
31	STANDARD		-88.5	-8	N-SK16	28.99746	0
32	STANDARD		25.4	-13.04095		30.13387	0
33	STANDARD		-57.82	-6	N-SK16	32.36682	0
34	STANDARD		216.48	-16.32716		31.85916	0
35	STANDARD		Infinity	-5	F_SILICA	25.5191	0
36	STANDARD		Infinity	-5		24.26517	0
37	STANDARD		Infinity	-6.26	F_SILICA	22.39097	0
38	STANDARD		Infinity	-6		20.82105	0
IMA	STANDARD		Infinity			18.58412	0

Table 1: Lens specifications.

would be prohibitively expensive due to the large number of coating runs required, even for a simple quarter-wave coating of magnesium flouride (which in any case would be inferior in performance to a good broadband coating). The most cost-effective option is to pay for a high-quality broadband AR coating and apply this to every element. Even this approach requires 6 separate coating runs, as the two sides of the lenses need to be coated separately and different substrates (with different refractive indices) need to be coated with different layers.

The ULTRACAM AR coatings will be provided by CVI Technical Optics of the Isle of Man. They are multilayer broadband AR coatings (composed of 16 layers). Figure 1 shows the predicted performance curve of the ULTRACAM AR coatings. Given our desire for high performance in the blue, we have asked CVI to push the coating as blue as possible – they have informed us that they cannot go any bluer than the curves shown in figure 1, as the individual layers become too thin to control during manufacture. With these coatings we can increase the throughput of the ULTRACAM lenses from approximately 48% to 76%.

Note that the contract we have signed with Specac includes the cost of the coating runs with CVI. This means that Specac take the responsibility for any mishaps during the coating process (and the associated shipping of the substrates).

1.3 Mounting

One of the main reasons we selected Specac over Spanoptic for the manufacture of the ULTRACAM lenses is Specac's ability to mount the lenses in barrels for us (at a reasonable cost). The assembly drawings for the ULTRACAM collimator barrel and the three ULTRACAM camera barrels are shown in appendix A. It can be seen that the lenses will be mounted using the tangent-mount method in barrels which can, in principle, be taken apart (i.e. no adhesives will be used, apart from in the doublets). The barrels will be black-anodised by Specac and textured on the inside to reduce scattered light. The designs of the outsides of the barrels have been specified by Mark Stevenson in order to be compatible with the rest of the mechanical design and are also shown in appendix A.

There are two design features of note in the barrels, both due to the fact that some of our lenses have knife-edges and are hence difficult to manufacture. The first is element BC5, which is cemented to BC4 and is not in direct contact with the barrel. Specac assure us that the cement is more than strong enough to hold the lens firmly in place. The second feature of note is the final collimator element (C4), which is mounted via a thinned spacer in order to keep the outer diameter of the lens at a minimum and hence maximise the thickness of the lens at its edge.

2 Dichroics

Tender documents were sent out to the following companies in November 2000 for the manufacture of the 2 ULTRACAM dichroic beamsplitters.

- CVI Technical Optics. Very interested in the work, and quoted £5352+VAT for the substrates and the coatings.
- Barr Associates. Clearly not interested in the work – they quoted £28 117+VAT for the subtrates and coatings!
- Siltint Industries. Interested in the work – they quoted £4200+VAT for the coatings only. The substrates would add approximately £1900+VAT to this quotation.

None of the three companies listed above were able to meet our (over-demanding) specifications, but CVI Technical Optics came the closest by quite a way. Given that they also gave the lowest quote and have a strong track record in this area (they were responsible, for example, for the latest set of

Figure 1: AR coating performance (predicted).

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Dichroic 1:
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Cut point at 390nm
Coated aperture: 140mm x 100mm
Substrate dimensions: 155mm x 115mm x 10mm

Coating side 1: >98% reflectivity (average) at 300-390nm and
>90% transmission (average) at 440-1100nm.

Coating side 2: <2.5% reflectivity (average) at 300-1100nm

Dichroic 2:
-----------
Cut point at 545nm
Coated aperture: 105mm x 75mm
Substrate dimensions: 115mm x 85mm x 10mm

Coating side 1: >98% reflectivity (average) at 370-545nm and
>90% transmission (average) at 595-1100nm.

Coating side 2: <2.5% reflectivity (average) at 300-1100nm

- Durability: ultra-hard oxide-based coatings, which meet our temperature
  specifications of -10 to +30 degrees C and humidity specifications of
  0% to 100%.
- Polarization: assumes randomly polarized light
- AOI: 45 degrees
- Substrate material: UV grade fused silica
- Scratch-dig: 10-5
- Wedge: <5 arcminutes
- Chamfered edges
- Surface figure: lambda/4 over whole surface, lambda/10 over
  a beam footprint diameter (approximately 20mm)
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Table 2: Dichroic specifications.

ISIS dichroics), we have decided to go with them. CVI have said they can deliver within 8–10 weeks. The dichroic specifications are given in table 2 and their predicted performance curves are given in figure 2.

There are some important design issues to consider in the specifications of the ULTRACAM dichroics.

- **Throughput**. High throughput is our priority for ULTRACAM, and hence we require long-wave pass (LWP) dichroics (i.e. transmit wavelengths longer than the cut and reflect all those shorter). This is because there is generally less passband "ringing" and fewer problems with harmonic effects with LWP dichroics. We also require dichroics which cut as sharply as possible, and which have cut-points that lie on the crossover points between the filter bandpasses (as shown in figure 6) and which have a broadband AR coating on their undersides to minimise ghosting (see below).

- **Ghosting**. The dichroics in ULTRACAM will produce ghost images, as shown schematically in figure 3. The u' ghost is not too bad (0.0006%), but it can be seen that the g' ghost will be

Figure 2: Dichroic performance (predicted).

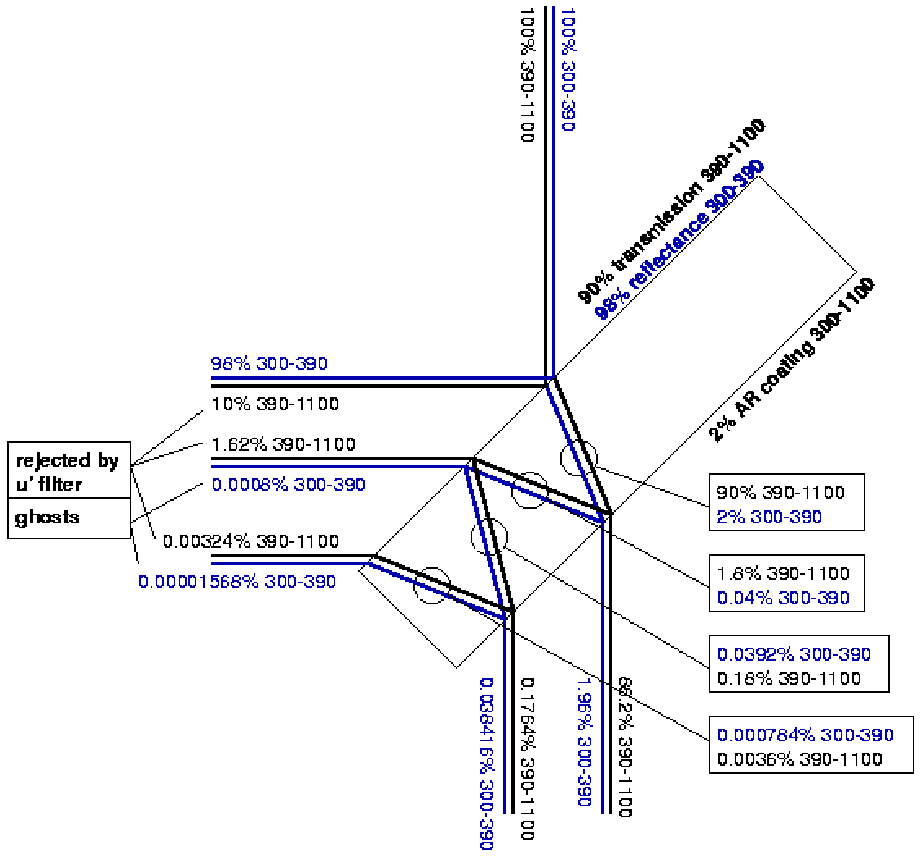

Figure 3: Schematic of the ghosting in the dichroics.

significantly worse (0.1764%). A similar thing applies to the r' arm, which I have not drawn here. Tully Peacocke has modelled the effect – the resulting ghost spot diagram is shown in figure 4. It can be seen that the ghosts are indeed as strong as indicated figure 3, but they are formed in a collimated beam. This means that they will fall on top of the main image at the CCD and will be in focus, so we will not notice them. This is not quite true at the extreme corners of the field (see figure 4). There, the ghosts will be severely chromatically aberrated and spread over a disc $\sim$8 times the radius of the main image (and approximately centred on it). Because of this, it is unlikely we will notice the ghost. The edges of the field (not the corners) will, however, be fine.

- **Polarization**. Another problem is polarization. The dichroics are designed to work for random incident polarization. If the light is 100% linearly polarized in a plane perpendicular to the long axis of the dichroic, then the dichroic cut point will move by $\sim$ 20 nm compared to incident light polarized in the orthogonal direction. The strength of the effect in the ULTRACAM dichroics can be seen from the theoretical curves in figure 5, which have been supplied by CVI. This phenomenon means means that if we are observing polarized objects, the dichroic cut will move around, giving us variable flux in the bandpasses. There is not much we can do about this when observing polarized objects apart from: 1. using narrower-band filters which lie completely above/below the (moving) cut-point; 2. putting a rotating half-wave plate in the beam, which is possible on the WHT. Note that the short exposure times we will be using means that the HWP will have to be spinning very rapidly and will also have to complete an integral number of revolutions per exposure time; 3. performing some sort of crude correction, where one looks at the anti-correlation in the flux between two adjacent pass-bands (on the assumption that the instrinsic flux variations in the different wave-bands are not themselves anti-correlated). The only other solution is to avoid observing polarized objects!

Figure 4: Spot diagram of the ULTRACAM ghosts.

Details of the dichroic mountings are given by Mark Stevenson in his mechanical design document.

3 Filters

We have decided to use the Sloan Digital Sky Survey (SDSS) filter set for ULTRACAM. The thinking behind the design of these filters – of which there are five ($u'g'r'i'z'$) – has been described by Fukugita et al. (1996, AJ, 111, 1748). There are three main reasons we have adopted these filters for ULTRACAM. First, the SDSS system is likely to become the dominant photometric system of the future. Second, the overlaps between the $u'g'r'i'z'$ bandpasses are minimal compared to the overlaps in the $UBVRIZ$ filter-set, which will minimize the problems associated with using dichroics to split the light between the filters. Third, the SDSS r' filter has a curtailed red wing compared to the Cousins R filter, which means that fringing with the thinned ULTRACAM CCD chips will be non-existent in r'.

The specifications of the ULTRACAM SDSS filter set are given in table 3 and their bandpasses are shown in figure 6 (together with the dichroic cut-points, the ULTRACAM CCD QE curves and a representative atmospheric extinction curve).

To procure these filters for the lowest possible price, I submitted a joint tender document with the ING (who were interested in buying several sets of SDSS filters). Unfortunately, I found out last week that the ING have decided to pull out of this agreement due to new budget restrictions. This means that we will have to pay a much higher price for our filters (Liverpool John Moores University tell

Figure 5: The effect of polarization on dichroic performance.

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NOTE:

* Basically, color glass defines the response at the short-wavelength side and coating defines the long-wavelength side.
* (1) is specification for glass, defining the name and thickness of colour glass. (2) is for coating.
* The specifications for coating are the 'standard' ones which were adopted for the original SDSS filters. We can ask for
  better/worse specifications depending on the cost.
--------------------------------------------------------------------

* T = transmission
* R = reflectivity
* Cutoff width is defined as
  wavelength(T=90%) - wavelength(T=10%)
  around T(cutoff)
* Amplitude of ripples is defined as
  T(top of the largest ripple) - T(bottom of the largest ripple)

1. u' band

  (1) UG11 (1mm thickness) + BG38 (1mm thickness) + 3mm Quartz
  (2) coating
      (for main part)
        T(330-420 nm)               > 90% (average)
        T(320-330 nm)               > 80%
        amp. of ripples             < 10%
      (for red leak)
        T(665 nm)                   < 1%
        T(720 nm)                   < 0.01%
        T(800 nm)                   < 1%
      anti-reflection coating on the other side
                  R<1% over the bandpass range
2. g' band

  (1) GG400 (2mm) + BG38 (3mm)
  (2) coating
        T(400-530 nm)               > 94% (average)
        T(600-750 nm)               < 0.1%
        cutoff (T=50%) wavelength   545 +- 5 nm
        T(558 nm)                   < 10%
        cutoff width                < 20 nm
        amp. of ripples             < 5%
      anti-reflection coating on the other side
                  R<1% over the bandpass range
3. r' band

  (1) OG550 (4mm) + BK7 (or equivalent glass) (1mm)
  (2) coating
        T(530-675 nm)               > 94% (average)
        T(750-1080 nm)              < 0.1%
        T(1080-1100 nm)             < 0.3%
        cutoff (T=50%) wavelength   700 +- 5 nm
        cutoff width                < 20 nm
        amp. of ripples             < 5%
      anti-reflection coating on the other side
                  R<1% over the bandpass range
4. i' band

  (1) RG695 (4mm) + BK7 (or equivalent glass) (1mm)
  (2) coating
        T(680-832 nm)               > 94% (average)
        T(900-1100 nm)              < 0.1%
        cutoff (T=50%) wavelength   850 +- 5 nm
        cutoff width                < 20 nm
        amp. of ripples             < 5%
      anti-reflection coating on the other side
                  R<1% over the bandpass range
5. z' band

  (1) RG830 (4mm) + BK7 (or equivalent glass) (1mm)
  (2) coating
        R(830-1100 nm)              < 0.5%
      anti-reflection coating on the other side
                  R<1% over the bandpass range

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Additional information:

filter    CWL (Angstroms)    FWHM (Angstroms)    Comments

  u'      3560+/-36          600+/-30            4500A+blocker
  g'      4825+/-48          1380+/-69           cut-off at 5500A
  r'      6261+/-63          1382+/-69           cut-off at 7000A
  i'      7672+/-77          1535+/-77           cut-off at 8500A
  z'      9097+/-91          1370+/-69

- Central Wavelength (CWL) and Full Width Half-Maximum (FWHM) specified in Angstroms.
- CWL specified to 1% at 0 degress C.
- FWHM specified to 5% at 0 degrees C.
- Circular filters of diameter 50mm.
- Filters to work in f/2.3 beam of ULTRACAM cameras.
- Filter thickness 5mm+-0.5mm.
- Blocking should be 1 part in 10000 in visual 300nm to 1200nm.
- Flatness lamda/4 at 633nm over whole surface and lambda/10 over a beam footprint diameter (approximately 20mm).
- S/D: 10-5.
- AOI: 45 degrees.
- Polarization: Assume randomly polarized light.
- Wedge: < 30 arcseconds.
- Edges chamfered.
- Operating conditions: temperatures from -10 degrees C to +30 degrees C. Humidity of 0% to 100%.
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Table 3: SDSS filter specifications.

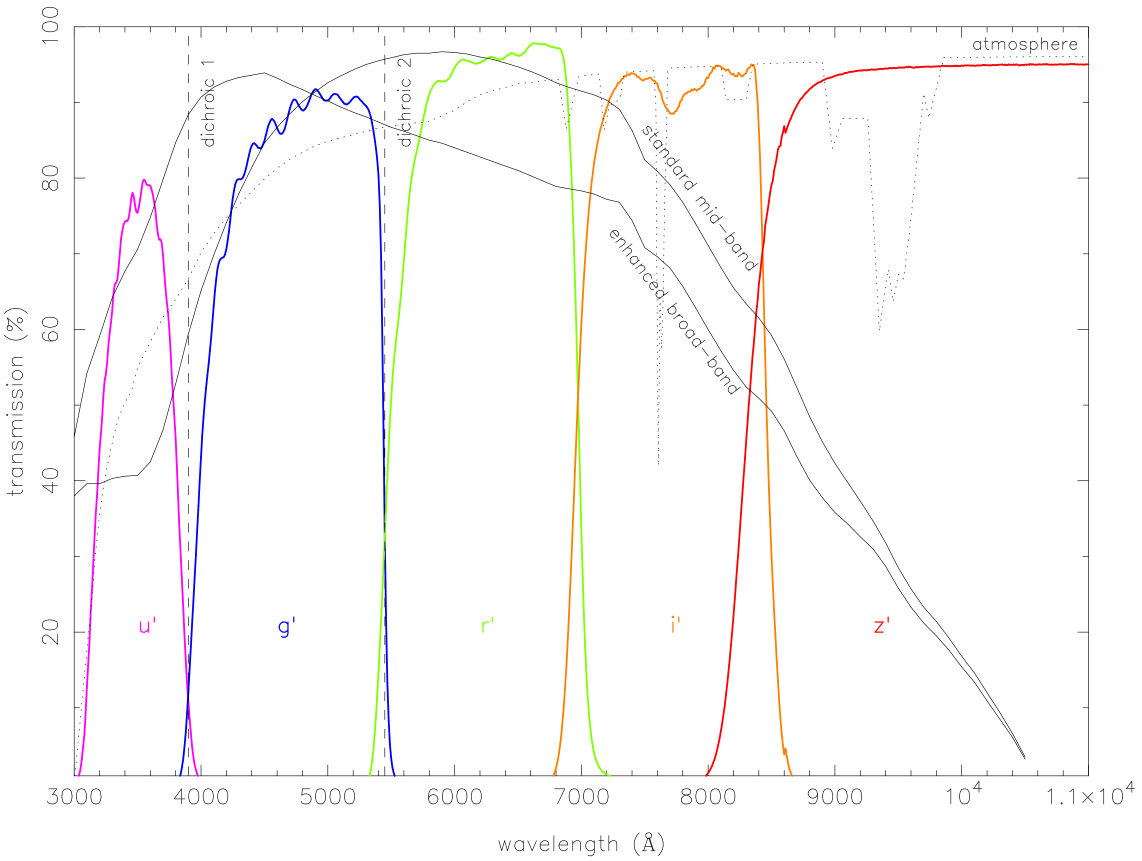

Figure 6: SDSS filter bandpasses.

me that their 50mm SDSS filter-set cost \$7500 from Barr Associates). This week, I therefore sent a new tender document to three companies: CVI Technical Optics, Barr Associates and Asahi Spectra (the latter provided the original SDSS filter set). I have yet to receive a quotation from any of these companies.

If we are unable to afford a full SDSS filter set, we can either procure just 3 ($u'g'r'$) or borrow a set from the ING during commissioning and observing on the WHT. Note that if we do have to pay a one-off price for the SDSS filters, it might instead by worth designing our own modified SDSS filter set which have slightly narrower bandpasses and so avoid the problem of the moving dichroic cut-point when observing polarized objects.

Details of the filter mountings are given by Mark Stevenson in his mechanical design document.

4 Windows

The CCD head will require a window to allow light through to the chip whilst retaining the vacuum seal of the camera head. Because the window is so close the focal plane, the surface flatness and parellelism of the substrate is not as important as the surface roughness (characterised by the S/D number). We were about to order these windows from CVI Laser corporation (product code: PW1-2025-UV), via their UK distributors Elliot Scientific. The cost of three such uncoated windows is £357+VAT (uncoated). However, Specac offered us *six* such windows as part of our lens contract at no extra cost. The specifications of the Specac windows are slightly lower – as listed in table 4 – but they are still acceptable and they are free, so we have decided to go with them. The advantage of having three spare windows is that we can use them in place of the filters to obtain the highest throughput to each of the arms, without having to refocus the instrument.

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- Material: UV grade fused silica.
- Dimensions: 50.0mm (+0.0mm,-0.2mm) diameter, 5.0mm (+0.0,-0.2mm) thickness.
- Clear aperture: exceeds central 90% of diameter.
- Flatness: lambda/4 at 633nm.
- Parallelism: <1 arcminute.
- Surface quality: 20-10.
- Chamfer: 0.35mm at 45 degrees typical.
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Table 4: Window specifications.

The internal transmission of UV-grade fused silica is greater than 99.9% across the entire region 300–1100nm. These losses are in addition to reflection losses, of course, which we will minimize by coating the windows with the broadband AR coating shown in figure 1 at the same time as the rest of our optics (CVI are happy to do this).

Using the window as part of a vacuum seal means that the window will flex slightly due to the difference in pressure on its two sides. This flexure effectively turns the window into a meniscus lens. We have calculated the flexure under these conditions and find it is 0.5 microns for a 5mm thick window of diameter 50mm. We have calculated that such an enormous radius of curvature gives a negligible change in the effective focal length of the camera and hence will have a negligible effect on the image quality.

Details of the window mountings are given by Mark Stevenson in his mechanical design document.

A Assembly drawings of the collimator and camera barrels

B Specifications of the ULTRACAM lenses