ING LA PALMA TECHNICAL NOTE NO.96

Update on Filter Characteristics for ING Telescopes

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Filters

This document summarises the filters available for use with the ING telescopes. Table 2 lists the filters available for CCD imaging. All of these are 50 mm square, except where otherwise noted, and can be used at all the imaging instruments: JKT Cass, INT Prime, WHT Prime and WHT AUX port. Apart from the filter characteristics we also give some telescope specific information. At the end of this note we list in Table 2 the larger, circular, filters available for imaging and for Fabry-Perot spectroscopy with TAURUS-2 on the WHT. The information in this document comes from various sources: the La Palma Technical Notes 45, 73, 75 and 90, the INT Prime Focus manual, and a List of Optical Components compiled by Chris Benn. All the information (filter curves and tables as far as available) can be found on the La Palma xmosaic server under *filters*.

1 Imaging filters

Our collection consists of broad band and narrow band filters. For broad band imaging we have several sets of BVRI filters, which are not meant to leave their telescope. Our set of narrow band filters at the moment is still rather limited, except for (redshifted) Hα filters, of which we have more than 15. All filters are square, and have a length and width of more or less 50mm. Some of the larger filters do not fit into every filterwheel. There are however filterwheels to accomodate each filter.

1.1 Broad band filters - the Kitt Peak Interference Filters (BVRI)

These were purchased from Kitt Peak, as originally specified by J Mould. They have flat-topped profiles and are intended for use with CCD detectors (unlike earlier filter systems). Figure 1 shows details of these filters. Three sets exist; one for the INT, one for the JKT and a spare set at Herstmonceux. The original specifications are given below:

All filters to be 5cm × 5cm, 3mm thick, blocked to 1.1 micron, better than 75% peak transmission (except B 70%), MgF_2 coated, no pinholes, optical quality glass.

R: *Filter 7200Å= short-pass hard-coated on 3mm OG590, blocked to 1.1 micron, 75% or better peak transmission, MgF_2 coated on glass side.*

I: *Filter 9000Å= Short-pass hard-coated on 3mm RG-M9, blocked 1.1 micron, 75% or better peak transmission, MgF_2 coated on glass side.*

V: Filter 6000Å= Short-pass hard-coated on 3mm GG 495 blocked to 1.1 micron, 75% or better peak transmission, MgF_2 coated on glass side. (Sent back did not come up to specification, 1/6/81)

B: Filter 4900Å= Short-pass, hard-coated on the glass substrate indicated below, blocked to 1.1 micron, 65% or better peak transmission, MgF2 Coated on glass side. Glass substrate to be cemented combination of Schott GG 385 and either Hoya GM-500 or Hoya C-500 (whichever will adequately suppress the red leak). Total thickness to be 3mm as with the other items.

1.2 Broad band filters - The RGO Glass Broad Band Filters (UBVRIZ)

These filters have been made at RGO from various cemented combinations of Schott glass. R W Argyle specified the combinations which are similar to those in use at the AAT, SAAO and elsewhere. Table 1 shows details of these filters. Three sets exist; one for the INT, one for the JKT and one at Herstmonceux. These filters are on the Johnson system. Nowadays, this system (for R and I) is not used very often any more, possibly because of the large sky background. At La Palma the RGO R and I are seldom used. The U,B and V filters however are not very different from U, B and V filters on other systems.

Table 1: **RGO Glass Filters**

Filter	Materials
U	1mm UG1 + 5mm $CuSO_4$ (Solid)
B	1mm GG385 +1mm BG12 + 1mm BG18 + 2mm KG3 + 2mm WG280
V	2mm GG495 + 2mm BG 18 + 2mm KG3 +1mm WG280
R	2mm KG3 + 2mm OG570 + 3mm WG280
I	3mm RG9 + 4mm WG280
Z	4mm RG850 + 3mm WG280

The WG280 is used to give uniform thickness of all filters (except U). For Z, and to some extent I, the longwave cutoff is determined by the CCD response.

1.3 Broadband filters - the Harris set

To replace a deteriorating set of Kitt Peak filters, 3 sets of large BVR glass colour filters were purchased in 1990 for CCD imaging.
The filters consist of cemented stacks of Schott glass, following the following recipe (see also NOAO newsletter 11,12 and 14:
B: 2mm BG12 + 2mm BG39
V: 2mm OG570 + 2mm KG3
R: 1mm BG12 + 2mm BG39 + 1mm GG385

It is thought that

- When the filter response curves are convolved with a typical CCD response, the glass filters provide a closer match to the standard Johnson B and V and the Kron-Cousins R bandpass.
- The transmission of the glass filters is comparable to that of the interference filters, and does not deteriorate with time.
- Glass filters are significantly cheaper than interference filters of the same size.

Harris filters are very often used at La Palma, just like Kitt Peak filters, probably because both are on the Kron-Cousins system. Note that the transmission in B is significantly (about 30%) lower than in Kitt Peak B.

1.4 Narrow band filters

At present, we have 31 narrow band filters, mostly of 50Å bandwidth, comprising a set of emission line filters and a set of redshifted Hα redshifted filters. Only one set exists and therefore the filters are shared between the INT and JKT. These filters were specified for a focal ratio of 4.5 which explains the difference in wavelength between the actual peak wavelength and the required peak wavelength. The original specification for the emission line filters is given below:
Unless otherwise specified the effects of an f/4.5 converging beam of light has been taken into account and the central wavelength duly reddened. A correction of +2 Angstroms has also been made to correct the central wavelength for operation at +10 degrees Celsius on the assumption that the filters will be made, tested and specified at +20 degrees Celsius.
In all cases the thickness of the filter including blocking filters should not exceed 9mm and should be the same for all filters wherever possible. The effective refractive index should be near 2.1. Blocking in all cases should be 3000-12000 Angstroms and the tolerance on the central wavelength should be ± 3 Angstroms. The tolerance on the dimensions of each filter should be ±

0.5mm. Filters should be free from pinholes greater than 0.03mm diameter in the central 25mm diameter circle and free from pinholes greater than 0.1mm diameter elsewhere.

1.5 General Remarks

The filters marked with an asterisc in Table 2 have been scanned in October, 1994. No lightleaks were found, except for the [OI] λ 6306 filter (see Fig. 1). We plan to scan the rest of the interference filters in the first half of 1995. Many filters are already old, which means that especially their edges are not as smooth as they could possibly be. To prevent stray light coming in through the edges, especially on INT-PF, some blocking off of the edges before observing is advisable.

We have also included into this note the transmission curves of the CCDs available on the mountain. Remember than what you measure is the transmission of the filter multiplied by the transmission of the CCD. These are given in Fig. 2

Table 2: **Summary of filters for CCD imaging**

Type	Central wavelength (nm)	Bandpass (nm)	Peak transmission (per cent)	Thickness (mm)	#	Focus Offset INT	Comments
Kitt Peak broad-band glass/interference filters:							
B	440	110	80	3	3	0.90	
V	547	94	80	3	2	0.90	
V	547*	94	80	5	1	1.50	
R	646*	126	87	3	3	0.90	
I	809*	184	85	3	3	0.90	also for WHT-PF
U-band filters:							
U	360*	62	60	7	1	2.10	25mm square
U	360*	62	60	7	1	2.10	38mm square
U	360*	62	60	6	4	1.80	50mm square 1 damaged
U	360	62	~ 30	?	1	?	for WHT-PF
Glass broad-band filters (Harris set):							
B	436*	107	67	4	3	1.20	also for WHT-PF
V	545*	105	88	4	3	1.20	also for WHT-PF
R	659*	149	84	4	3	1.20	also for WHT-PF
Glass broad-band filters (RGO set):							
B	435	106	52	7.3	2	2.19	
V	535	94	70	7.2	2	2.13	
R	645	150	81	7.2	2	2.13	
I	~840	~200	94	7.0	2	2.10	
Z	~930	~150	80	7.1	3	2.13	
Emission line interference filters:							
[OII]	373.1*	5.2	43	9	1	2.70	
[SII]	407.5	3.0	33	9	1	2.70	
HeII	469.1*	4.9	61	9	1	2.70	
Hβ	486.6*	5.1	60	9	1	2.70	
[OIII]	501.2*	5.0	61	9	1	2.70	
HeII	588.1	4.6	62	9	1	2.70	
[OI]	630.6*	5.3	70	9	1	2.70	Red leak
Hα	655.6*	6.0	70	8.2	1	2.46	Ghost
[NII]	659.0*	1.6	60	9	1	2.70	
[SII]	673.0	4.8	68	9	1	2.70	
[OII]	733.1	4.6	67	9	1	2.70	
[SIII]	907.5*	5.4	74	9	1	2.70	
[SIII]	953.9*	5.2	74	9	1	2.70	
HeII	1083.7*	11.4	52	9	1	2.70	

Table 2: Summary of filters for CCD imaging (continued)

Type	Central wavelength (nm)	Bandpass (nm)	Peak transmission (per cent)	Thickness (mm)	#	Focus Offset INT	Comments
Redshifted Hα interference filters: - old set							
	656.3	5.3	50	6.0	1	1.80	
	660.7	5.3	54	6.0	1	1.80	
	665.2	4.9	55	7.5	1	2.25	
	670.0	5.3	58	7.5	1	2.25	
	674.2	4.7	54	7.5	1	2.25	
	678.9	5.3	60	7.5	1	2.25	
	683.5	5.0	55	6.0	1	1.80	
	687.7	5.3	58	6.0	1	1.80	
	692.5	5.0	59	6.5	1	1.95	
	697.0	5.1	57	6.0	1	1.80	
Redshifted Hα interference filters: - new set							
	656.5	4.5	56	6.6	1	2.00	
	656.5	6.0	53	8.6	1	2.58	
	659.5	4.5	51	6.7	1	2.00	
	662.5	4.5	56	6.6	1	2.00	
	665.5	4.5	56	6.8	1	2.04	
	668.5	4.5	56	6.5	1	1.95	
	671.5	4.5	56	6.5	1	1.95	

1.6 The Prime Focus Camera on the INT

1.6.1 Mounting the CCD filters

The filter cut-out is designed to take 2.0 inch square filters (in a 51 mm square hole); a 47 mm clear aperture is provided.
In addition, filters up to 56 mm diameter can be accommodated, although in this case light can "leak" around four corners unless a mask is fitted.
Any smaller filters should be mounted within a 2.0 inch square frame which is then readily fitted to the wheel.
The maximum thickness of filter allowed is 12 mm; filters of thickness ≤ 3 mm will require packing material to stop them moving about within the 3 mm deep cut-out hole.
Each filter is held in position by three adjustable clamps, each of which consists of three parts: a flat-headed screw, which holds a threaded brass post to the filter wheel under pressure from a coil spring, and the main clamp body which screws on to the threaded brass post.
When mounting a filter in the filter wheel, there should be no need to touch the central screw on each clamp. To mount the filter, turn the clamps anti-clockwise on the threaded brass posts (which winds the clamps away from the filter wheel) until the clamps will just clear the filter mounted in the recess. The threaded brass posts should not themselves turn. When the filter is in position, wind the clamps clockwise until they just clamp the filter under light pressure from the springs.
Problems may be experienced with extra thick (>10mm thick) filters. In this case, do not slacken the central screw, but consult one of the La Palma-based support astronomers.
The telescope focus is automatically compensated for filter thickness. Relevant focus offsets for all of the filters in this note are given in Table 2.
Also, the filter wheel for the Prime Focus should be fairly well balanced. i.e., if a heavier filter is used in one position, it should be matched by a heavy one in the opposite position if possible. This will help to avoid reluctance to move from one filter position to another, or even filter movement during exposures.

1.6.2 Calculating of Focus Offsets

Focus offsets for a filter of thickness t can be calculated as follows:
Consider the light from a converging beam falling on a translucent plate of thickness t and refractive index n as shown in Figure 4.

Now the change in focus $OO' = PP' = AP - AP' = AP(1 - \frac{1}{n}) = t(1 - \frac{1}{n})$
For the glass broad-band filters, the refractive index is 1.6, so the focus offset $= 0.38\,t$

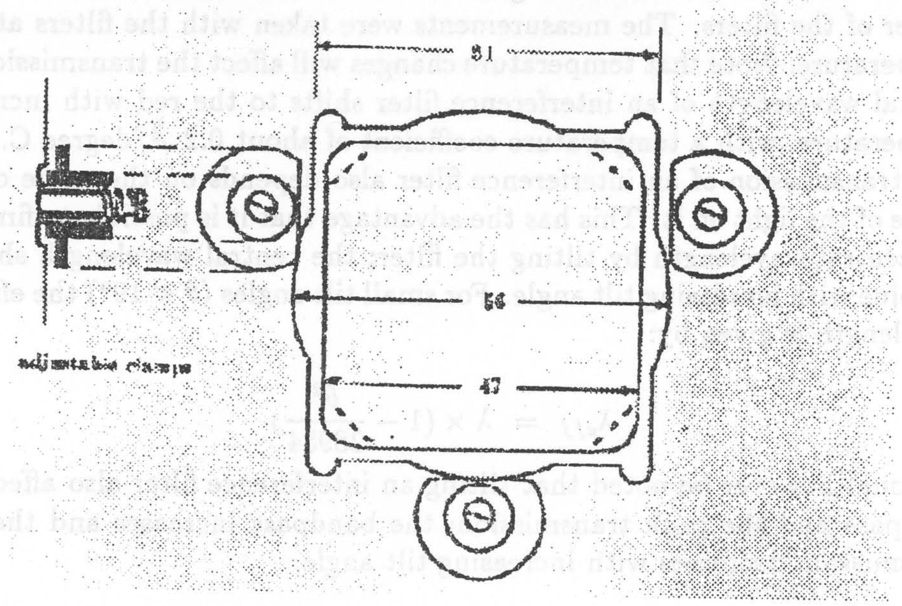

Figure 3: Standard CCD filter mounting layout - INT Prime, JKT and WHT-AUX

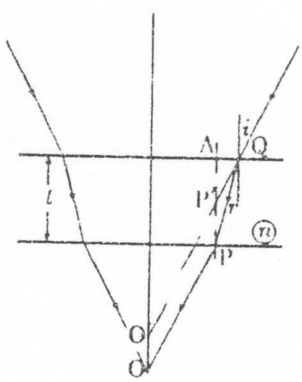

Figure 1:

The angle $\widehat{APQ}$ is the angle of refraction r,

$$\text{so } \sin r = \frac{AQ}{PQ}$$

The angle $\widehat{AP'Q}$ is the angle of incidence i.

$$\text{so } \sin i = \frac{AQ}{P'Q}$$

$$\text{herefore } n = \frac{AQ}{P'Q} / \frac{PQ}{AQ} = \frac{PQ}{P'Q}$$

If i, r are small,

$$n = AP/AP'$$

Figure 4: The light path of the INT-PF near the filter

The filters have been scanned using the Guildford Spectrometer at RGO. The measurements covered a region of about 5mm in diameter close to the center of the filters. The measurements were taken with the filters at room temperature. Note that temperature changes will affect the transmission; the central wavelength of an interference filter shifts to the red with increasing temperature, with a temperature coefficient of about 0.2 Å/degree C.
The transmission of an interference filter also depends on the angle of incidence of the light on it. This has the advantage that it is possible to fine-tune the central wavelength by tilting the filter; the central wavelength shifts to the blue with increasing tilt angle. For small tilt angles ($\theta < 10°$) the effective wavelength is given by:

$$\lambda_{eff} = \lambda \times (1 - \frac{\theta^2}{28954})$$

It should however be noted that tilting an interference filter also affects the bandpass and the peak transmission; the bandpass increases and the peak transmission decreases with increasing tilt angle.

Emilios Harlaftis has pointed out that a second correction is needed. It is due to the corrector lens. In practise you have to multiply the correction calulated above by $(f/f')^2$, where f is the focal length without corrector lens, and f' the focal length of the whole system, resp. 2.94 and 3.29. The final change in focus now is $t \times (1 - \frac{1}{n}) \times 0.799$.

For the interference filters, the values for the refractive indices are approximately 1.45 for the OII(3727Å), SII(4070Å), HeII, Hβ, OIII, HeI(5876Å), OI and NII filters, and 1.48 for the Hα, SII(6724Å), OII(7325Å), SIII(9069Åand 9532Å) and HeI(10830Å) filters. (N.B. Do not use the refractive index of the substrate, which, although of large refractive index (~2.1), is thin and enclosed in thick glass.

1.6.3 Calculation of Central Wavelength

When interference filters are used at angles other than normal incidence, the optical path difference between the direct transmitted beam and the multiple order reflections within the cavity decreases, causing a corresponding decrease in the wavelength of peak transmission. Changes in the bandwidth and transmission characteristics are generally small (for the relatively wide passbands used here).

For angular tilts of less than 30°, the central wavelength can be calculated from the expression

$$\lambda_\theta = \frac{\lambda_0 \sqrt{n^2 - sin^2\theta}}{n}$$

where λ_0 = Central wavelength at normal incidence

λ_θ = Central wavelength at the off-normal angle, θ

and n = Effective refractive index of the total filter.

1.6.4 Change due to uncollimated light

Utilising the filter in uncollimated (i.e. convergent or divergent) light involves slightly more complex considerations. Here, light enters the filter at a range of angles, so that different rays undergo unequal wavelength shifts. This results in not only a central wavelength shift, but a broadening of the bandwidth and lower peak transmission.

As a rough approximation, relatively uniform beams (with full cone angles less than 20°) will undergo peak shifts of aproximately one half of that which would be predicted for a collimated beam at the maximum angle of incidence of the cone.

$$\text{Therefore, } \lambda_\theta - \lambda_0 = \frac{\lambda_0}{2}\left(\frac{\sqrt{n^2 - sin^2\theta}}{n} - 1\right)$$

The filters were specified for a focal ratio of 4.5, having a maximum angle of incidence of the cone of 6°.34, and of effective refractive index 1.6. Substituting these values in the equation,

$$\lambda_\theta - \lambda_0 = -0.0012\lambda_0$$

The focal ratio of the INT prime focus is 3.29, which gives a maximum angle of incidence of the cone of 8°.64, so, substituting again into the equation,

$$\lambda_\theta - \lambda_0 = -0.0013\lambda_0$$

Therefore, at the INT prime focus, the central wavelength (i.e. the wavelength of peak transmission) is shifted towards shorter wavelengths by 0.06% from the specified central wavelengths. For example, for an H_α filter with specified central wavelength 6560Å, the effective central wavelength will be 6556.1Å.

1.6.5 Change due to temperature

Temperature changes affect a filter's performance due to thermal expansion and contraction of the materials used to construct them. Most filters are designed and specified for operating at 23°C, and deviations from this value in the range of -60°C to +60°C will produce peak wavelength shifts approximately linear with temperature. The exact shift coefficient will depend on the particular design wavelength of the filter, and, typically, ranges between 0.2Å and 0.3Å per °C at 4000Å and 6500Å respectively. Bandwidth and peak transmission changes observed are relatively minor, of the order of 0.01Å per °C and 0.013Å per °C respectively.
The interference filters were specified for working at 10°C, so temperatures significantly different from this will affect the effective central wavelength of the filters.
For example, at an ambient temperature of 0°C, an $H\alpha$ filter with specified central wavelength 6556Åwill have an effective central wavelength of 6553Å.

Special Purpose Filters

Table 2 presents a list of interference filters for use at the WHT, either for narrow-band imaging, or as order-sorting filters for instruments such as TAURUS or UES.

Table 2: **TAURUS-2 filters**

Central wavelength (Å)	Bandpass (Å)	Diameter (mm)	Thickness of filter (mm)	Thickness of cell (mm)	Comments
3721	28	76			
3737	50	50	8.5		
3742	40	76			
3760	34	76			
3769	30	76			
3770	15	50	9.0		
4550	100	76.2	4.0		
4550	300	63.5	6.1	7.0	
4770	320	63.5	5.9	7.0	
4868	15	63.5	6.1		
4880	100	76.2	10.5		
4883	15	63.5	7.0		
4898	15	63.5	7.0		
4912	15	63.5	6.1		
4962	15	76.2	6.1	6.7	
4974	15	76.2	6.0	7.0	
5000	350	63.5	7.0		
5009	15	76.2	13.0		
5010	100	76.2	10.0		
5012	20	50.7	9.1	10.0	
5021	15	76.2	13.0		
5032	20	50.8	9.2	10.1	
5033	15	76.2	13.0		
5046	15	76.2	12.2		(Missing)
5052	20	50.8	9.2	10.1	
5065	15	76.2	7.0		
5072	20	50.7	10.0		
5092	20	50	10.6		(Missing)
5108	16	76			
5124	16	76			
5145	15	76.2	6.1	7.0	
5164	16	76			
5175	15	76.2	5.9	7.0	
5194	16	76			
5216	16	76			
5220	380	63.5	6.0	7.0	
5232	16	76			
5247	17	76			
5267	15	76			
5340	15	76.2	5.1	7.0	
5450	410	63.5	6.1	7.0	(Broken)

Table 2: **TAURUS-2 filters (continued)**

Central wavelength (Å)	Bandpass (Å)	Diameter (mm)	Thickness of filter (mm)	Thickness of cell (mm)	Comments
5700	450	63.5	6.0		
5905	10	76.2	7.0		
5960	490	63.5	6.1	7.0	
6240	540	63.5	5.9	7.0	
6303	15	63.5	10.0		
6345	18	50.7	6.0		
6565	15	76.2	13.0		
6568	17	50.7	6.0		
6577	15	76.2	13.0		
6589	15	76.2	14.0		
6589	16	50.8	5.1	6.0	
6590	130	76.2	10.3		
6601	15	76.2	13.0		
6610	16	50.7	6.0		
6613	15	76.2	13.0		
6631	17	50.8	7.0		
6639	18	76			
6652	17	50.8	7.0		
6667	15	76			
6673	17	50.8	7.0		
6676	15	76			
6689	15	63.5	6.1	7.0	
6692	18	76			
6702	17	76			
6714	18	76			
6726	18	76			
6730	50	50.8	6.1	7.0	
6741	19	76			
6754	19	76			
6765	18	76			
6770	50	50.8	6.1	7.0	
6778	18	76			
6792	18	76			
6803	19	76			
6816	18	76			
6826	17	76			
6838	17	76			
6851	19	76			
6859	16	76			
6872	16	76			
6884	18	76			