How Narrow is Too Narrow? - Rev 1

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Test Report – June 21st, 2023

Revised text noted in blue.

Introduction:
For many years now I have been promoting the idea that for emission nebulae, the narrower your filter's pass bands are, the better. Time and again my test results have demonstrated this relationship to be true; that object contrast and signal-to-noise-ratio (SNR) increase as the pass band width decreases. Recently however a question occurred to me: is there no limit to this relationship, or is there a practical limit on how narrow a filter's pass bands should be? The purpose of this test report is to document my investigation of this question of "How narrow is too narrow?"

Objective:
The objective of this test report is to evaluate the performance of a selection of H-α filters, ranging in bandwidth from >100nm down to 0.4nm. Use of the term "bandwidth" in this report refers specifically to the filter's full width half maximum (FWHM), the wavelength range over which the filter's transmissivity is more than 50% of it's maximum. I had a long list of H-α filters to choose from for this project, either in physical form or just as a measured spectrum data set. The list of filter configurations considered in this test report is summarized in Table 1 (costs are for 2" version). Indicated in the table is the source used for each filter's spectrum data, either a measurement made by myself (JT), the well known amateur astronomer André Knöfel (AK), or by the manufacturer in the case of some Chroma brand filters (C). The values of FWHM quoted in the table are as I have calculated from each filter's measured spectrum data. Also indicated in the table is whether or not I own a sample of the filter, and if I used it to collect image data as part of this test. Take note of the filter numbering in Table 1 as it will be used throughout the report.

If theory is born out in the test results, there should be an observable improvement in deepsky object contrast as I move down the list of filters since they have progressively narrower pass bands. You will note that there is also an increase in filter cost as the pass bands get narrower. Whether or not the increase in performance is worth the increase in cost is yet another question that will hopefully be answered during this test. Filter performance is evaluated during this test based on the increase in contrast between the observed object and the background, which is a measurable quantity. It was evaluated quantitatively using the measured filter spectra combined with the spectrum of a typical H-α rich emission nebula, and by direct measurement from images captured using each filter and a monochrome camera. The spectra and image data were also used to evaluate the SNR achieved using each filter.

Method:
Testing consisted of data collection from the following sources:

- Spectral transmissivity data, from near-UV to near-IR, measured using an Ocean Optics USB4000 spectrometer; and

- Image data, collected using the following camera and telescope: a ZWO ASI183MM Pro (bin 2x2) monochrome camera, and a William Optics ZS66 ED doublet refractor (f/5.9).

No.	Filter or Filter Combo	FWHM [nm]	Cost [USD]	Have Sample [Y/N]	Spectra By [JT/AK]	Image Data [Y/N]
0	No Filter (for reference)	n.a.	0	Y	n.a.	Y
1	Optolong Nightsky H-α	140	119	Y	JT	Y
2	Optolong NS H-α + Astronomik UV/IR Blocker	67.0	(119+99) 218	Y	JT	Y
3	Omega XMV660/40	43.6	180	Y	JT	Y
4	IDAS NB-1 + Optolong NS H-α	22.0	(199+119) 318	Y	JT	Y
5	Omega 650BP10	11.3	220	Y	JT	Y
6	Omega 8nm H-α	7.7	180	Y	JT	N
7	Optolong 7nm H-α	6.4	259	Y	JT	N
8	IDAS 6.8nm H-α	6.7	379	Y	JT	Y
9	IDAS 6.8nm H-α + Omega 650BP10	5.0	(379+220) 599	Y	JT	Y
10	Optolong 3nm H-α	3.1	439	Y	JT	Y
11	Chroma 3nm H-α	2.7	1300	N	JT	N
12	Omega 1.5nm H-α (1")	1.5	480	Y	JT	Y
13	Andover 1nm H-α (1")	1.2	563	Y	JT	Y
14	Baader Planetarium 35nm H-α	35.9	220	N	AK	N
15	Astronomik 13nm H-α	19.1	287	N	AK	N
16	Chroma 8nm H-α	7.7	830	N	C	N
17	Baader Planetarium 7nm H-α	6.9	279	N	AK	N
18	Astronomik 6nm H-α	6.3	470	N	AK	N
19	Chroma 5nm H-α	5.1	975	N	C	N
20	Custom Scientific 4nm H-α	5.0	1200	N	AK	N
21	Ideal 2nm H-α	2.0	?	N	JT	N
22	Ideal 1nm H-α	1.0	?	N	JT	N
23	Ideal 0.4nm H-α	0.4	?	N	JT	N

Table 1 List of Filters Considered in Test

The spectrometer data was collected in my basement workshop with the USB4000 and a broad spectrum light source. Filter spectrums were measured for a range of filter angles relative to the light path, from 0° (perpendicular) to 20° off-axis. The spectrometer was recently upgraded, replacing the entrance slit and diffraction grating, to give a wavelength resolution of 0.5nm.

The image data was collected from my backyard in central Ottawa, Canada where the naked eye limiting magnitude (NELM) due to light pollution is +2.9 on average, which translates to Bortle 9+. I switched filter configurations using a ZWO 2" filter drawer. Each time I changed filters I refocused on a conveniently located bright star using a Bahtinov mask. Images with the various filters under test were collected on two separate evenings: Feb. 6th (Flame & Horsehead Nebulae), and Feb. 8th (Rosette Nebula). These objects were selected because they were well placed high in the sky for the duration of the image captures.

Nebula Reference Spectrum:

The filter performance prediction method that I use relies on a reference emission spectrum for the deepsky object the filter is being evaluated against. Sources for such reference spectra are readily available online. In particular I have up to now used spectra for NGC7000 (North American) and M27 (Dumbbell) as the reference in my calculations. Something that I overlooked in the first revision of this report is how the resolution of the spectrometer used to capture the reference spectra impacts the outcome of my analysis. For the filter performance predictions I have performed previously the impact has been neglidgible, but for this test report the impact is significant due to the unusually narrow filter pass bands being considered. The impact of spectrum resolution is illustrated in Figure 1. The plot has the portion of an emission nebula's spectrum from two different sources plotted around the H-α emission band. The red curve is respresetative of the reference spectrum data I had been using up to now. It was captured by a well known amateur astronomer Christian Buil using a spectrometer with reported spectral resolving power of R=800. That translates to a wavelength resolution of 0.8nm in the H-α part of the spectrum. As a result of this instrument's wavelength resolution, the emission lines of the nebula are artificially broadened. The blue curve is taken from a scientific paper where the authors used data gathered by the VLT UVES echelle spectrograph at the European Southern Observatory (ESO) in Chile. That instrument has a spectral resolving power of R=8800, giving a wavelength resolution of 0.07nm. That instrument is able to resolve the actual width of the nebula emission lines, and in fact uses this information to determine things like how fast the gas is moving or its temperature. The impact of the emission nebula spectrum resolution on my calculations is made evident by overlaying the transmissivity spectra for the three "ideal" filters I have considered in my study. If the low resolution nebula spectrum were to be used, filters with FWHM less than 2nm are not able to pass all of the H-α emission unhindered. This explains why in the first revision of this report I was predicting that the theoretical maximum SNR is achieved for bandwidths around 1 to 2nm. If the high resolution nebula spectrum is used for my predictions, the filter bandwidth would need to be below 0.2nm before the filter performance is noticeably impacted by all of the nebula emission not being passed.

Results – Spectrum Measurements:

Using the test method mentioned above the spectral transmissivity for each filter that I have a sample of was measured for a range of filter angles relative to the light path. Figures 2 to 4 present plots of the resulting spectral transmissivity data for the case of the filter perpendicular to the light path. All the filters have their pass bands well positioned around 656nm, apart from a few exceptions. It is evident from the measured spectra that both the Baader 35nm H-α and Omega 650BP10 filters are not optimized for Halpha as their center wavelength (CWL) is shifted significantly to the left, a property that would make them both sensitive to band-shift. Similarly, my sample of the Optolong 7nm and Omega 1.5nm filters are also not properly centered on 656nm, being shifted significantly off-band to the right, which would actually mean these two filters should perform better at faster f-ratios.

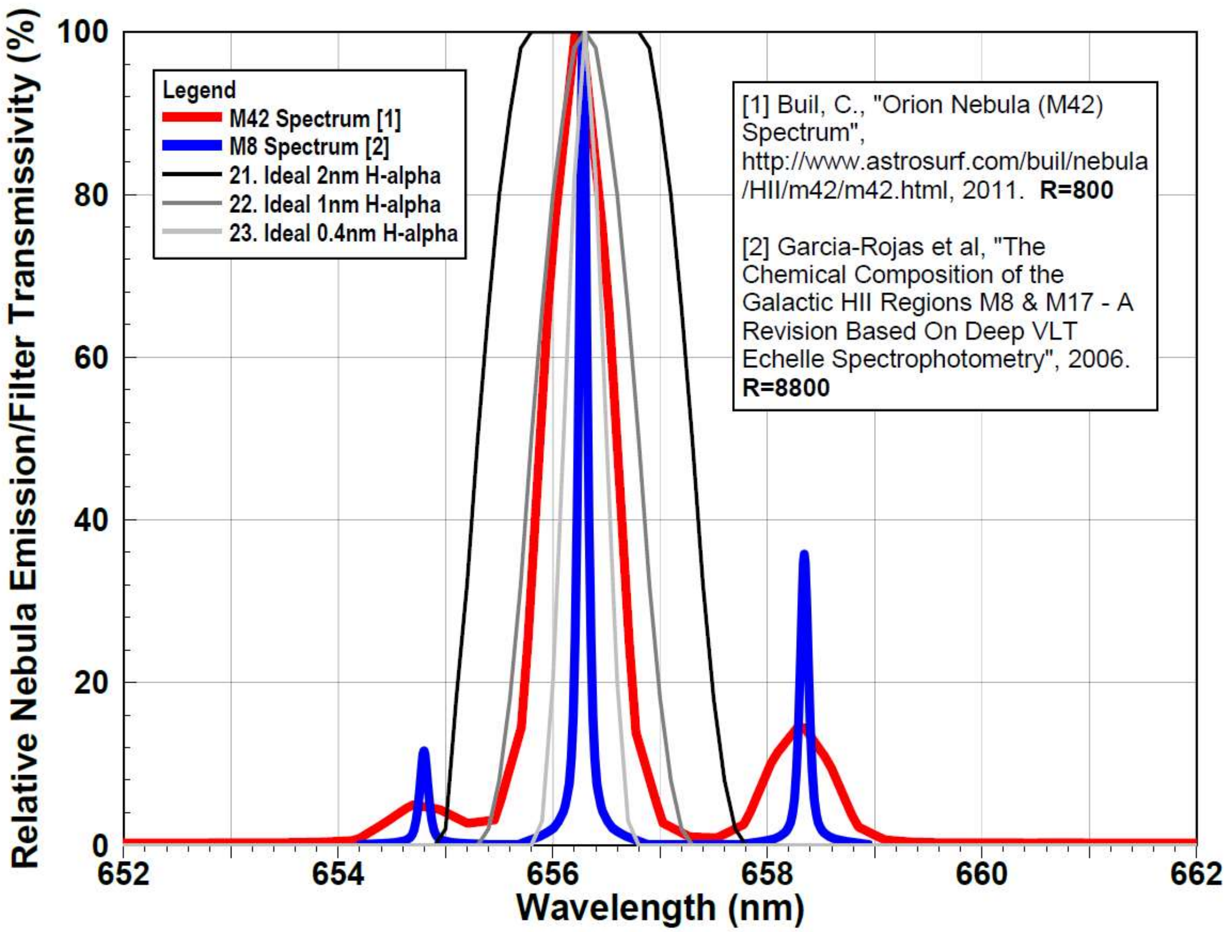


Figure 1 Measured Nebula Emission Spectra @ Different Spectral Resolving Powers

The impact of angle on transmission for each of the filters for which I have a sample is shown in Figures 5 and 6. As expected, filters with wide pass bands were less sensitive to angle than filters with narrow pass bands, with the most sensitive filters to angle being the two sub-2nm samples. The Omega 650BP10 has almost the same sensitivity to angle as the 3nm filters because of its CWL being shifted to the left of 656nm. Similarly the Optolong 7nm filter has performance that peaks at faster f-ratios because its CWL is shifted to the right.

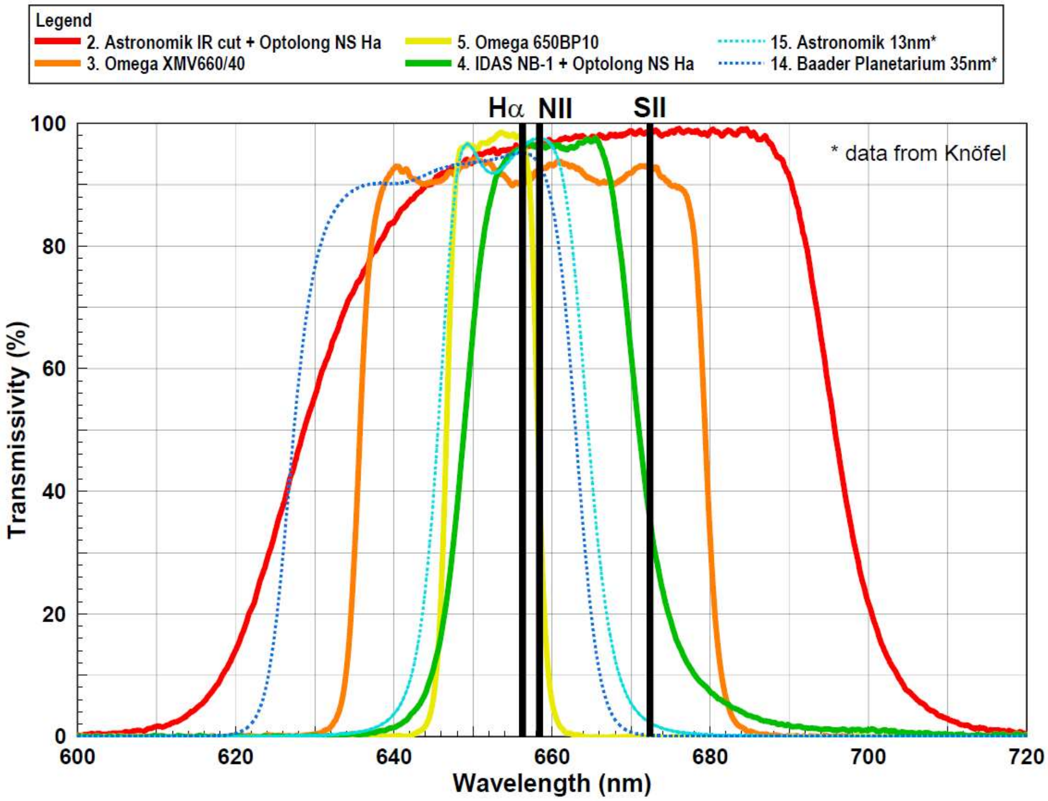


Figure 2 Measured Filter Spectra – Filter Perpendicular to Light Path, FWHM >10nm

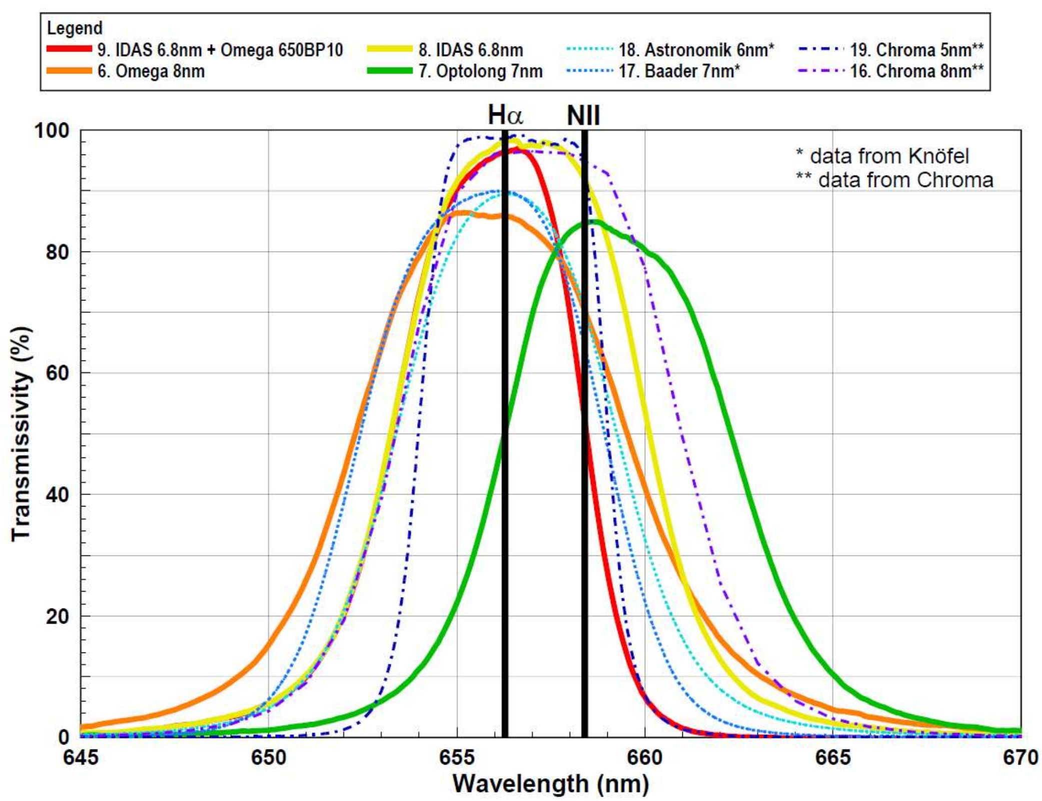


Figure 3 Measured Filter Spectra – Filter Perpendicular to Light Path, 10nm > FWHM >5nm

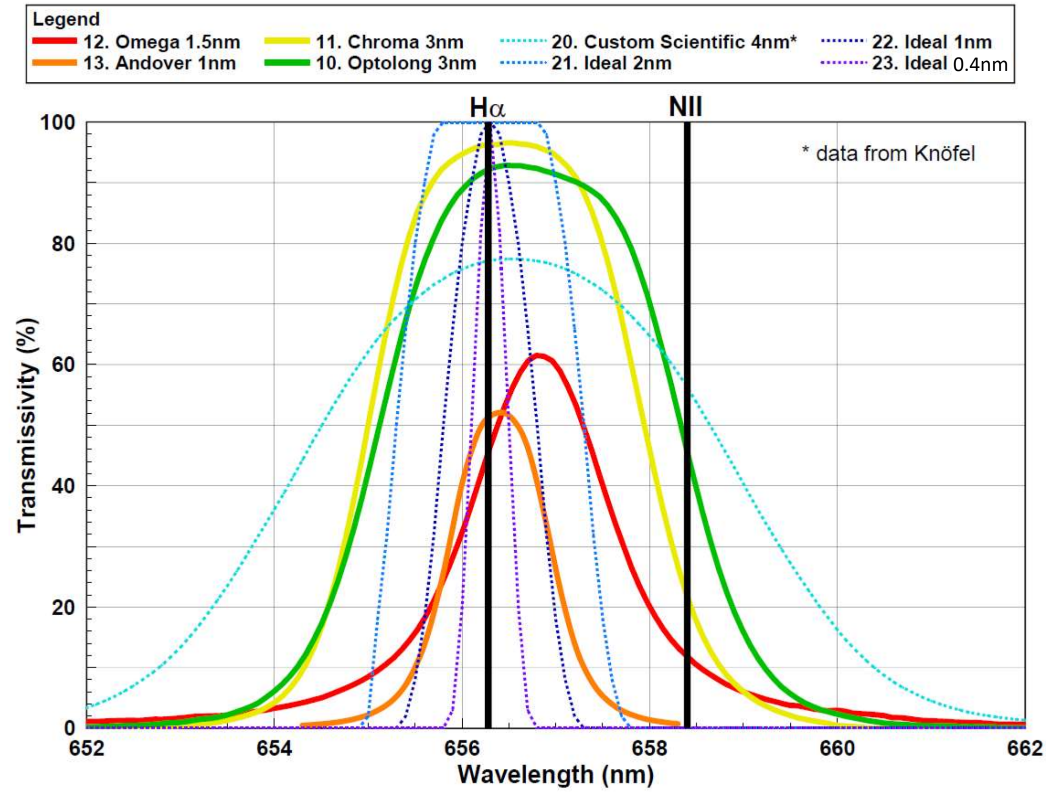


Figure 4 Measured Filter Spectra – Filter Perpendicular to Light Path, FWHM <5nm

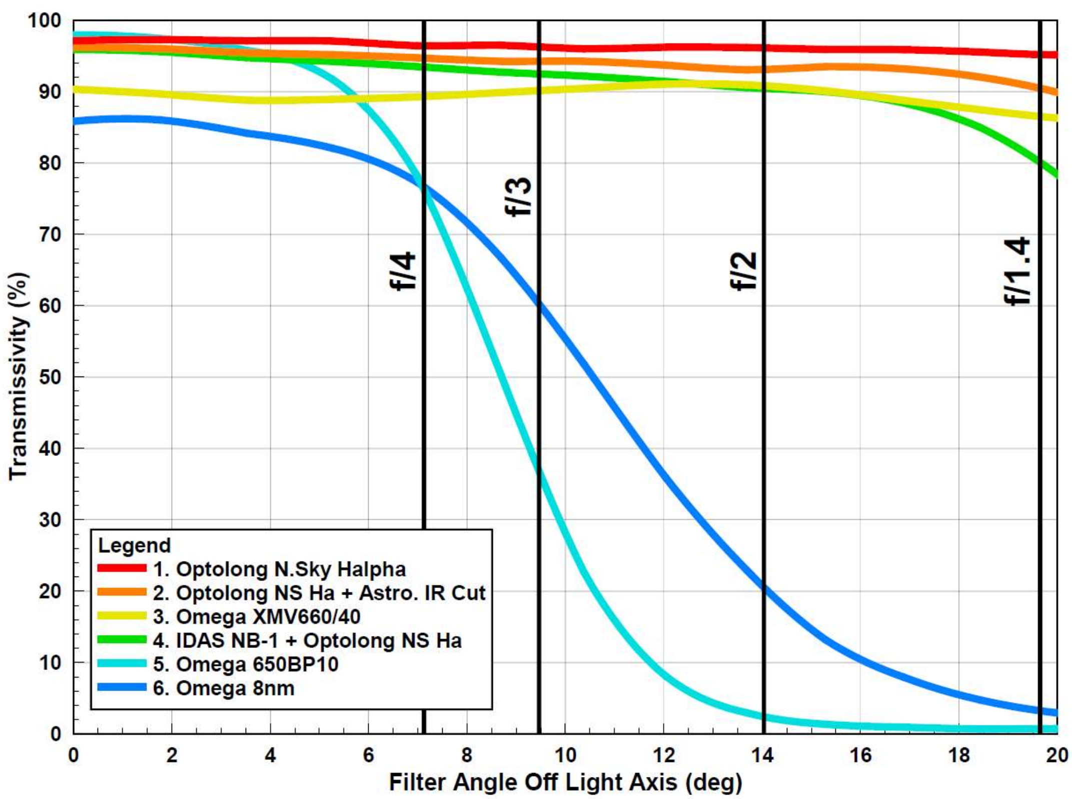


Figure 5 Measured Impact of Angle on Filter Response, FWHM >8nm

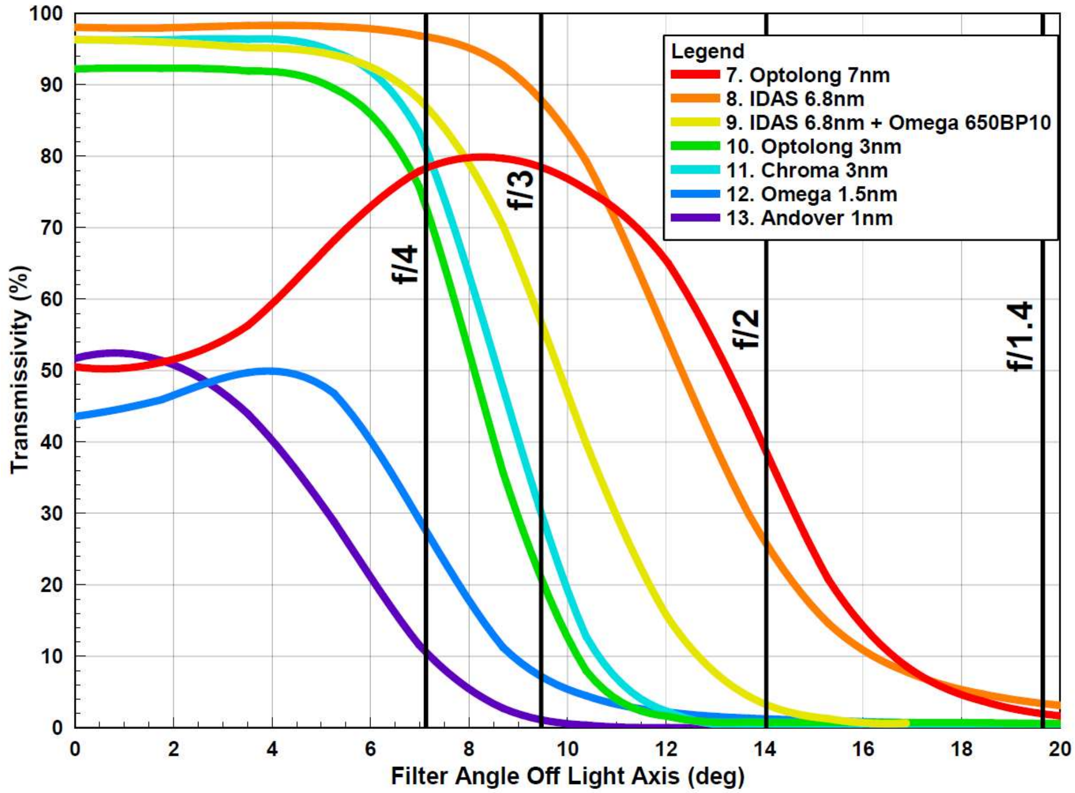


Figure 6 **Measured Impact of Angle on Filter Response, FWHM <8nm**

Figures 5 and 6 also have black vertical lines corresponding to different optics f-ratios. These lines are positioned at the angle values corresponding to light coming from the outer edge of the scope's aperture for the noted f-ratio. The net performance of a filter on any particular speed of optics is an area weighted average of the filter's performance, for light angles from perpendicular out to the angle at the outer edge of the aperture. As your scope optics get faster, the extent of the filter transmission curves from Figure 5 and 6 that you integrate over is larger, and thus your net filter transmission for the wavelength of interest goes down. Another way to look at the impact of using a narrowband filter on fast optics is it is like adding an aperture mask to your telescope. The narrower the filter, or the faster the optics, the smaller the effective aperture mask. This relationship is illustrated in Figure 7 for a range of generic filter bandwidths and optics f-ratios. Scopes with a central obstruction are especially affected since they have a larger percentage of their light cone at an angle away from perpendicular. Note that the plots in Figure 7 are from one of my previously released technical reports: "Narrowband Filters & Fast Optics", November 2020.

With the filter spectra in hand, it was possible to extract overall performance related statistics for each filter, such as transmission values at key wavelengths of interest and pass band widths. These filter statistics are provided in Table 2, including a calculated value for percent Luminous Transmissivity (%LT), a single number that describes generally how much light is getting through the filter. The calculated value of %LT depends on the spectral response of the detector, which in this case is assumed to be a modern back illuminated monochrome CMOS sensor. For the filters that I measured myself, I have included transmission measurements in the table for a range of telescope f-ratios, from f/∞ (perfectly parallel & perpendicular light) down to f/2.

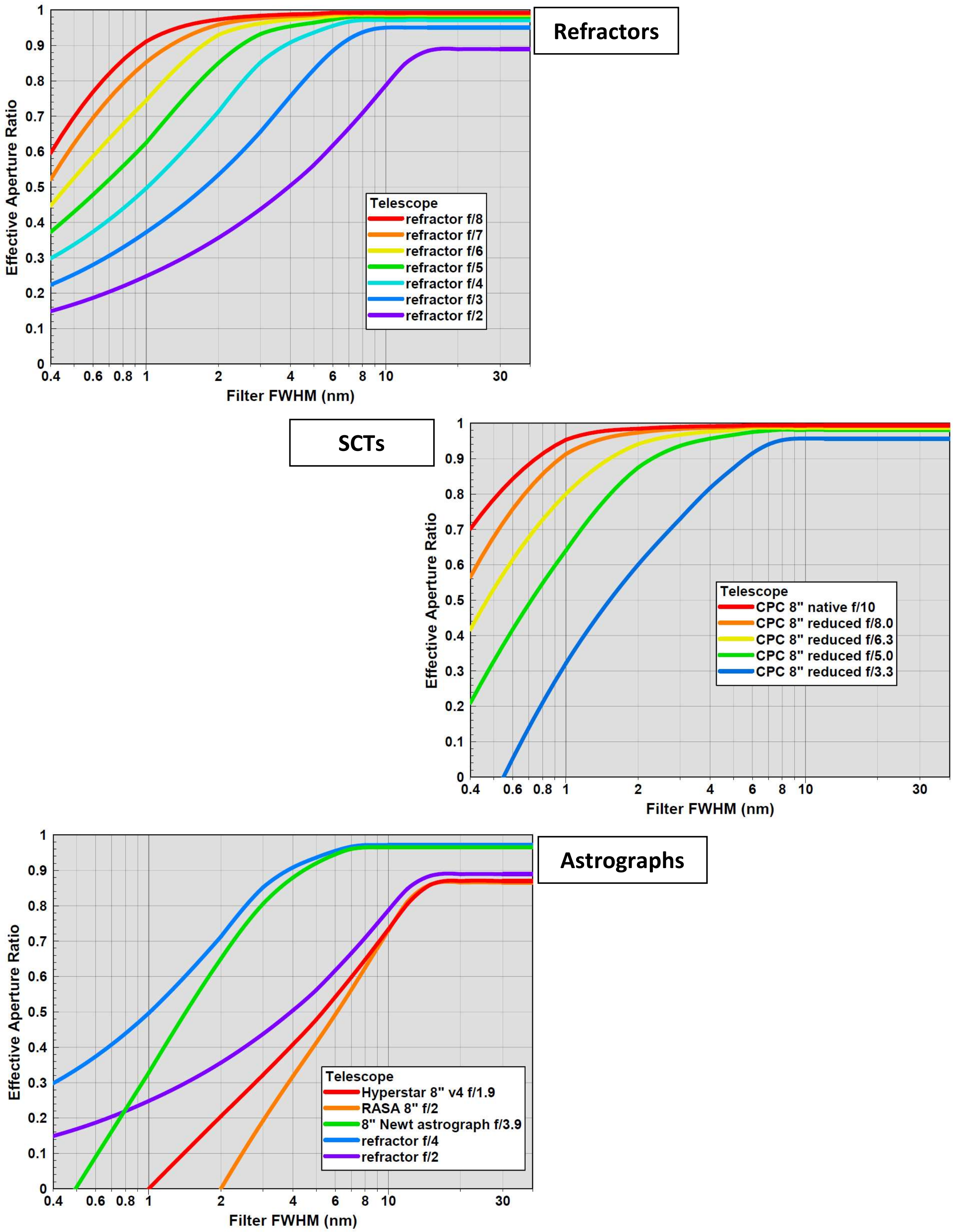


Figure 7 Predicted Effect of Filter Band Shift in Terms of Effective Aperture for Various Scope Types

No.	Filter	Scope Optics	%LT*	Halpha Pass Band			
				FWHM	Halpha (656.3)	N-II (658.4)	S-II (672.4)
1	Optolong Night Sky H-α	f/∞	37.9%	~140nm (high pass filter)	97.1%	97.8%	99.5%
		f/6.3**			97.2%	97.4%	99.3%
		f/4.9**			97.1%	97.4%	99.2%
		f/3.0**			96.7%	97.0%	98.8%
		f/2***			96.3%	96.7%	98.6%
2	Optolong NS H-α + Astronomik UV/IR Blocker	f/∞	13.1%	67.0nm	96.2%	96.9%	98.5%
		f/6.3			95.6%	96.0%	97.9%
		f/4.9			95.4%	95.6%	97.8%
		f/3.0			94.9%	95.1%	97.2%
		f/2			94.1%	94.3%	96.3%
3	Omega XMV660/40	f/∞	8.29%	43.6nm	90.3%	92.1%	92.5%
		f/6.3			89.1%	90.7%	91.1%
		f/4.9			89.0%	90.7%	90.7%
		f/3.0			89.4%	90.8%	89.4%
		f/2			90.2%	90.2%	84.6%
4	IDAS NB-1 + Optolong NS H-α	f/∞	4.96%	22.0nm	95.9%	96.7%	35.3%
		f/6.3			95.0%	95.6%	30.2%
		f/4.9			94.7%	95.2%	28.1%
		f/3.0			93.7%	94.2%	22.7%
		f/2			92.2%	92.8%	15.3%
5	Omega 650BP10	f/∞	2.64%	11.3nm	98.0%	42.1%	0.0%
		f/6.3			96.1%	30.6%	0.0%
		f/4.9			94.4%	25.2%	0.0%
		f/3.0			76.0%	13.7%	0.0%
		f/2			35.7%	4.4%	0.0%
6	Omega 8nm H-α	f/∞	1.67%	7.7nm	85.8%	70.4%	0.5%
		f/6.3			84.7%	64.1%	0.4%
		f/4.9			83.6%	59.8%	0.4%
		f/3.0			76.5%	45.5%	0.4%
		f/2			52.9%	25.2%	0.3%
7	Optolong 7nm	f/∞	1.13%	6.4nm	50.5%	84.8%	0.0%
		f/6.3			55.3%	82.1%	0.0%
		f/4.9			60.4%	81.0%	0.0%
		f/3.0			71.5%	75.2%	0.0%
		f/2			68.6%	49.6%	0.0%
8	IDAS 6.8nm	f/∞	1.49%	6.7nm	98.0%	91.9%	0.0%
		f/6.3			98.2%	85.3%	0.0%
		f/4.9			98.1%	80.9%	0.0%
		f/3.0			96.1%	61.1%	0.0%
		f/2			72.6%	30.9%	0.0%
9	IDAS 6.8nm H-α + Omega 650BP10	f/∞	1.20%	5.0nm	96.3%	52.5%	0.0%
		f/6.3			95.4%	44.5%	0.0%
		f/4.9			94.9%	37.7%	0.0%
		f/3.0			85.2%	21.4%	0.0%
		f/2			46.1%	6.7%	0.0%
10	Optolong 3nm	f/∞	0.68%	3.1nm	92.2%	45.8%	0.0%
		f/6.3			91.9%	28.8%	0.0%
		f/4.9			90.9%	21.4%	0.0%
		f/3.0			69.3%	9.6%	0.0%
		f/2			27.8%	2.0%	0.0%
11	Chroma 3nm	f/∞	0.66%	2.7nm	96.3%	21.9%	0.0%
		f/6.3			96.2%	13.9%	0.0%
		f/4.9			95.6%	10.5%	0.0%
		f/3.0			77.0%	4.8%	0.0%
		f/2			32.5%	0.9%	0.0%
		f/∞			43.5%	11.3%	0.0%

12	Omega 1.5nm H-α	f/6.3	0.28%	1.5nm	48.1%	7.5%	0.0%
		f/4.9			47.6%	6.2%	0.0%
		f/3.0			31.1%	3.7%	0.0%
		f/2			12.4%	1.5%	0.0%
13	Andover 1nm H-α	f/∞	0.13%	1.2nm	51.7%	0.6%	0.0%
		f/6.3			45.5%	0.2%	0.0%
		f/4.9			38.9%	0.0%	0.0%
		f/3.0			19.7%	0.0%	0.0%
		f/2			5.0%	0.0%	0.0%
14	Baader Planetarium 35nm H-α	f/∞	7.34%	35.9nm	95.2%	93.3%	0.2%
15	Astronomik 13nm H-α	f/∞	5.08%	19.1nm	96.7%	97.5%	2.2%
16	Chroma 8nm H-α	f/∞	1.63%	7.7nm	96.0%	96.2%	0.1%
17	Baader Planetarium 7nm H-α	f/∞	1.40%	6.9nm	89.9%	64.3%	0.0%
18	Astronomik 6nm H-α	f/∞	2.33%	6.3nm	89.4%	70.4%	0.1%
19	Chroma 5nm H-α	f/∞	1.10%	5.1nm	99.1%	93.1%	0.0%
20	Custom Scientific 4nm H-α	f/∞	0.83%	5.0nm	77.1%	56.3%	0.0%
21	Ideal 2nm H-α	f/∞	0.40%	2.0nm	100%	0.0%	0.0%
22	Ideal 1nm H-α	f/∞	0.20%	1.0nm	100%	0.0%	0.0%
23	Ideal 0.4nm H-α	f/∞	0.08%	0.4nm	100%	0.0%	0.0%

* calculated assuming spectral QE curve for IMX174M with no UV/IR blocking filter; ** refractor; *** C14 w/Hyperstar

Table 2 Measured Filter Performance Summary

Knowing the measured spectral response of the sample filters also allowed me to predict the theoretical relative performance of each filter when observing or imaging a faint emission nebula. To do this I used the method I developed back in 2012 which uses the spectral response of the filter and sensor combined with the spectral emission from the deepsky object and background light polluted sky to estimate the apparent luminance observed. To help visualize the results of this analysis I have plotted the predicted % increase in contrast for each filter versus the filter's FWHM. Figure 8 shows the resulting plot corresponding to filter performance when using a monochrome CMOS camera under heavily light polluted skies complete with local LED street lights (i.e. my backyard). Note that these are theoretical predictions of the increase in visible contrast between the object and the background. The absolute values of my predictions may not reflect what a user will experience with their own setup, but the predicted relative performance of one filter to another should be representative. In general, the desired performance for a filter is high contrast increase and high %LT (i.e. low exposure time), so the higher and more to the right a filter's performance is in the plot the better. Each filter's performance is plotted as a short line to show how the performance is predicted to change depending on the f-ratio of the telescope you are using the filter with. Slow f-ratio optics are at the upper-most end of the line, and f/3 is at the lower-most end of the line. I have plotted predicted filter performance assuming the target is a typical faint H-α rich nebula, in this case NGC7000 the North American Nebula.

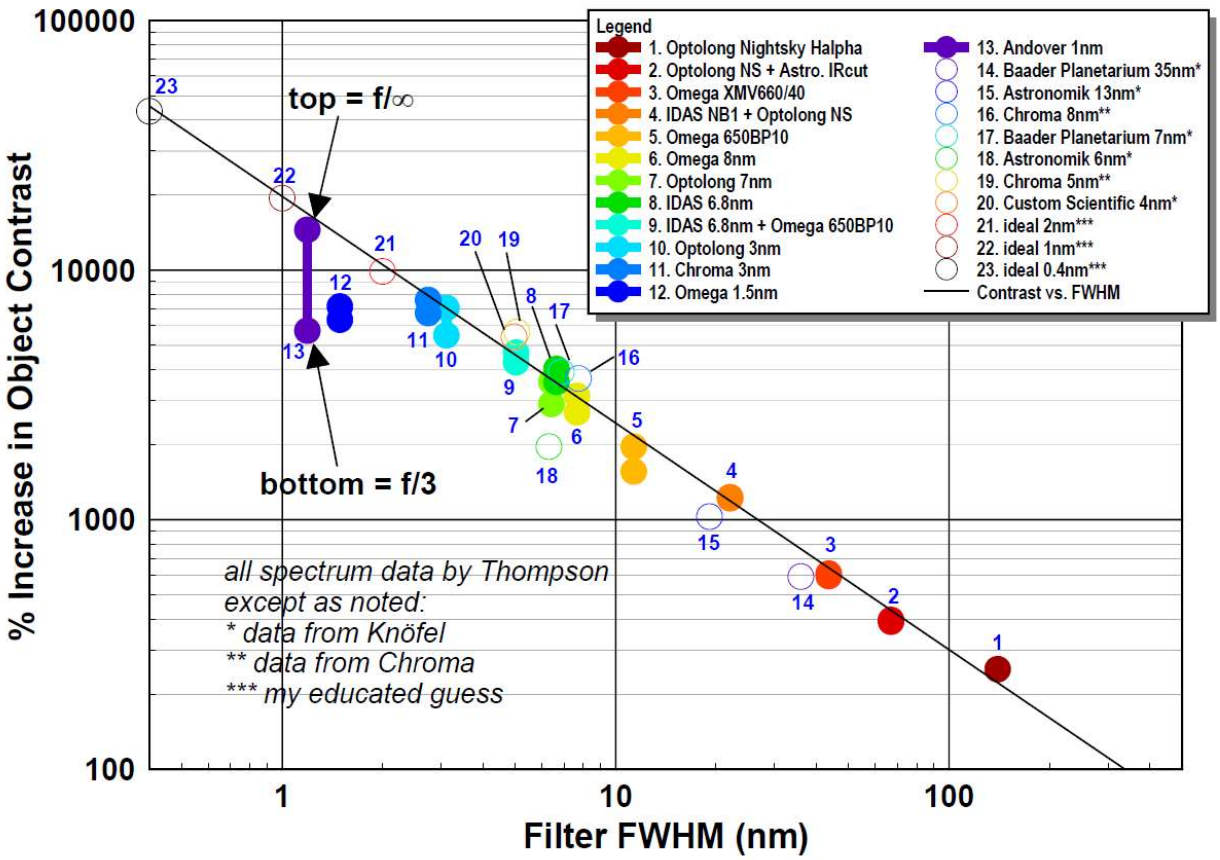


Figure 8 Predicted Contrast Increase: Back Illuminated Monochrome CMOS, LP w/LED (NELM+2.9)

As expected, the predictions indicate that the narrower the filter's pass band, the larger the contrast increase. In fact there appears to be a well behaved relationship between FWHM and contrast increase, as indicated by the black diagonal line on the plot. The wider filters (Night Sky H-alpha & XMV660) are predicted to deliver a consistent increase in contrast, one that does not change significantly down to an f-ratio of f/3. The narrow filters deliver a contrast increase that varies significantly with f-ratio, but in general are predicted to always deliver higher performance than the wider filters. In the context of the question I am trying to answer in this report, i.e. how narrow is too narrow, it would seem that there is no limit to the contrast increase that can be realized by using progressively narrower filters. The contrast increase predicted for the three ideal filters (#21 to #23) suggests that contrast continues to increase at the same rate at least down to a FWHM of 0.4nm. This observation should be tempered by the reality that fabrication of filters with the spectra I have assumed for #21 to #23 will be extremely difficult and costly. The contrast increase that is more likely to be achieved with a commercially available filter is somewhere between the ideal filters and the two physical samples I tested (#12 & #13).

Using the measured filter spectra I was also able to predict the SNR that would be achieved when each filter was used to collect image data. My calculation assumes a perfect sensor, so both read noise and dark current noise are set to zero. This leaves only shot noise which scales with the signal, which in turn is the sum of the object luminance and the light pollution luminance. The results of my calculations are presented in Figure 9, again plotted as lines to show how the predicted SNR varies with optics f-ratio. The SNR calculation assumes that sub-exposure time has been kept constant between all the filters being compared.

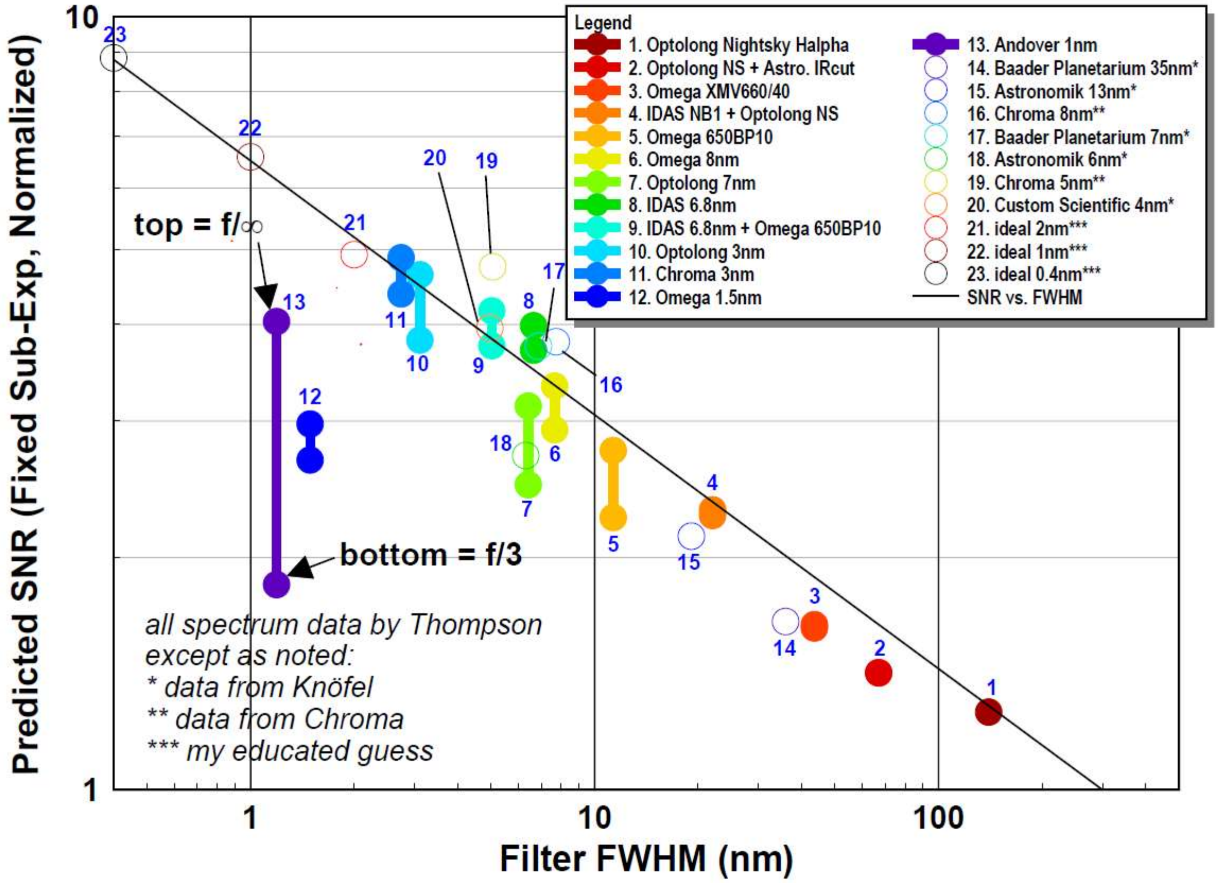


Figure 9 Predicted SNR: Back Illuminated Monochrome CMOS, LP w/LED (NELM+2.9)

As with the contrast increase prediction, the SNR prediction also indicates a clear trend with FWHM. Unlike what was presented in the first revision of this report, there does not seem to be an optimum FWHM. SNR is predicted to increase steadily as the bandwidth decreases, at least down to a bandwidth of 0.4nm. Of note is the fact that SNR is much more sensitive to filter peak transmissivity than contrast increase, as is illustrated by the larger scatter in the data points off of the trendline as well as the magnitude of the delta SNR predicted between f/∞ and f/3 optics. The implication of this observation is that it is not enough for a filter to simply have a narrow bandwidth, it also needs a high peak transmissivity for it to be able to deliver both a large increase in contrast AND a high SNR.

The SNR predictions presented in Figure 9 assume that the same sub-exposure time is used regardless of the filter FWHM. In practice this is not advisable since the signal strength will be proportionally smaller corresponding to the filter's bandwidth. Because there are physical limits introduced by the sensor, such as bit depth and noise limited minimum sensitivity, a more effective approach is to increase the sub-exposure time corresponding to decreasing filter FWHM. Thus the cost of using a narrower filter, other than its purchase price, is an increase in the length of your sub-exposures. As a rough guide, a filter's %LT can be used to estimate how much longer a sub-exposure time should be used compared to no filter. For example: a filter with a %LT of 25% would require a sub-exposure time (100/25) 4x what would be used with no filter. Calculated values of %LT for each of the filters considered in this test are provided in Table 2. When these calculated values are plotted versus bandwidth, a simple relationship is evident (see Figure 10). Using this information the %LT, and thus the recommended sub-exposure time, for any width H-α filter can be estimated.

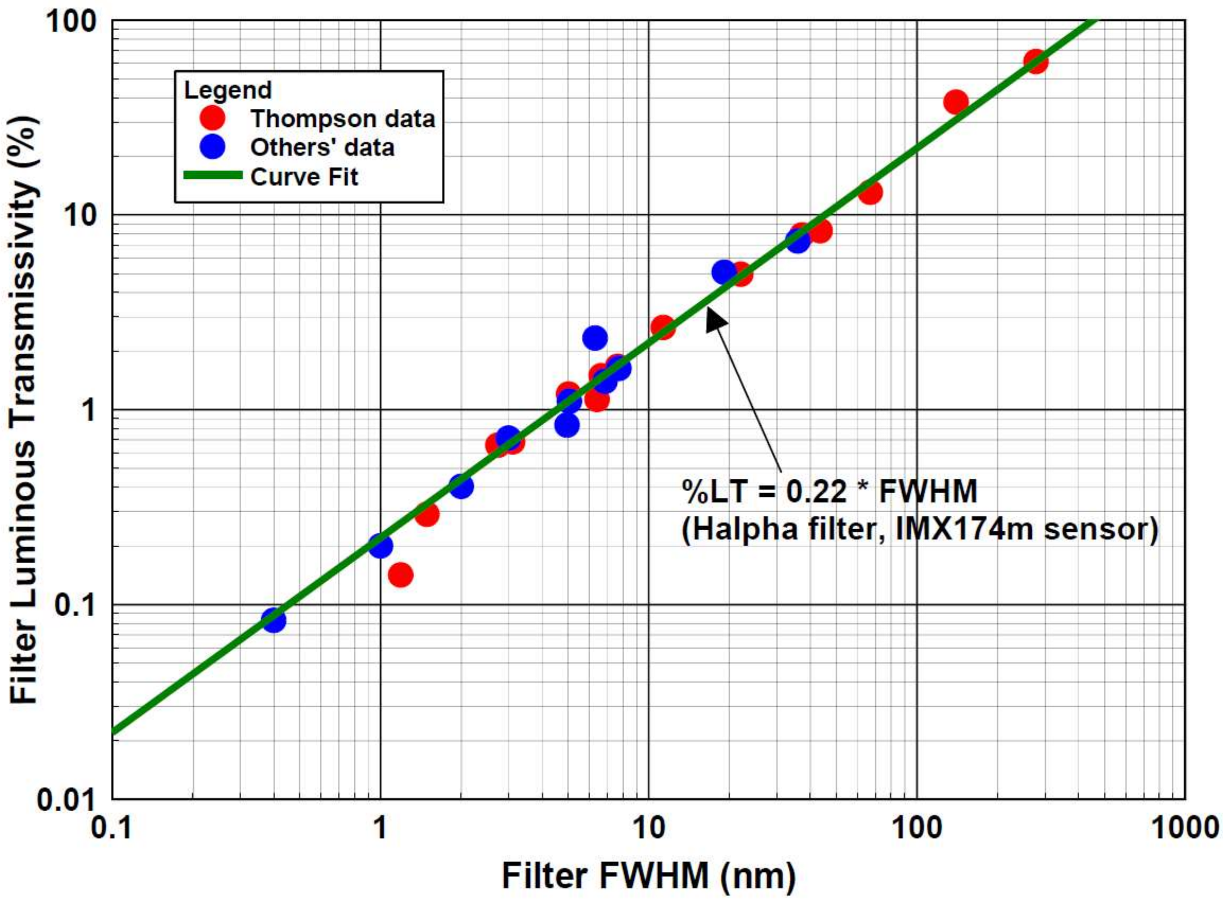


Figure 10 **Calculated %LT vs FWHM for Tested Filters**

Results - Imaging:

As described above in the Method section, image data was captured with each filter using the same scope + camera configuration, with all images collected on the same night within a two-hour time window. Data was collected with the ZWO camera by generating a live stack in Sharpcap, which was then saved as a 16-bit FITS file. For the first imaging session the sub-exposure time was adjusted for each filter in order to achieve an image of generally the same level of overall exposure as the no-filter reference image. This was determined by adjusting exposure according to each filter's %LT, as discussed in the previous section. A sufficient number of frames was stacked in each case to achieve a total exposure time of 350s. For the second imaging session I used fixed sub-exposure times of 120 seconds for all filters, but only collected data for the four narrowest filters in my list. Five frames were stacked to give a total exposure of 10 minutes.

Imaging results from the first imaging session are provided below in Figures 11 and 12, and from the second session in Figure 13. The images presented are of the final stacks, and have had their histograms adjusted in exactly the same way using Fitswork v4.47, a free FITS editing software, so that they provide as fair a visual comparison as possible.

The main thing to note from the images presented in Figures 11 and 12 is that there is a very obvious change in the extent to which the nebulosity is visible, that extent being more so the narrower the pass band of the filter being used. The contrast increase that was observed is consistent for the most part with the predictions made from the spectrometer data. The primary difference between prediction and the images is the extent to which contrast is increased for the narrowest filter, #13 Andover 1nm. Contrast produced by that filter should have been better than all the other filters tested, but it was not. Perhaps this observed lack of performance is due to the Andover filter not having features like edge blackening and anti-reflective coatings which help to improve the contrast produced by filters. Also, both the Andover and Omega filters (#12 & #13) showed issues with vignetting, which was expected due to these two filters having a clear aperture of only 25mm (1").

The images in Figure 13, being taken all at the same exposure time, highlight the impact of each filter on SNR. For roughly the same nebula signal strength, there is progressively less noise in the image as we move from the IDAS filter (#8) to the Optolong filter (#10). Noise starts to increase again for the Omega filter (#12), and finally the Andover filter (#13) has more noise than any of the other three filters tested. This behaviour is consistent with the predictions of SNR made in Figure 9.

Using the captured image data I was able to directly measure the contrast increase delivered by each filter, putting a number to what was already observed qualitatively from the images in Figures 11 to 13. This was accomplished by using AstroImageJ to measure the average luminance from two common areas in the images: a dark background area, and a bright nebulous area. The particular areas used are illustrated in Figure 14, with these same areas used for all the images from the two imaging sessions. Measurements of average luminance were taken from both the raw stacked images as well as a single sub-exposure. Contrast increase was calculated from the measured luminance values using the following equations:

$$\text{Measured Contrast} = \frac{[\text{measured nebula luminance} - \text{measured background luminance}]}{\text{measured background luminance}}$$

$$\text{\% Contrast Increase} = [\text{contrast w/filter} - \text{contrast w/out filter}] \div \text{contrast w/out filter} \times 100$$

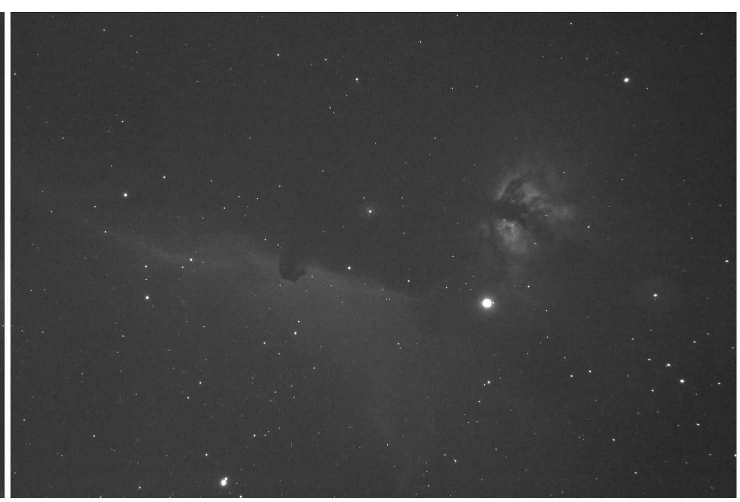
0. No Filter (700 x 0.5s)

1. Optolong Nightsky H-α (265 x 1.3s)

2. Opto. NS H-α + Astro. IR Cut (91 x 3.9s)

3. Omega XMV660/40 (58 x 6.1s)

4. IDAS NB-1 + Opto. NS H-α (35 x 10s)



5. Omega 650BP10 (18 x 19s)

Figure 11 February 6th Imaging Results – Batch 1

8. IDAS 6.8nm (10 x 35s)

9. IDAS 6.8nm + Omega 650BP10 (8 x 44s)

10. Optolong 3nm (5 x 70s)

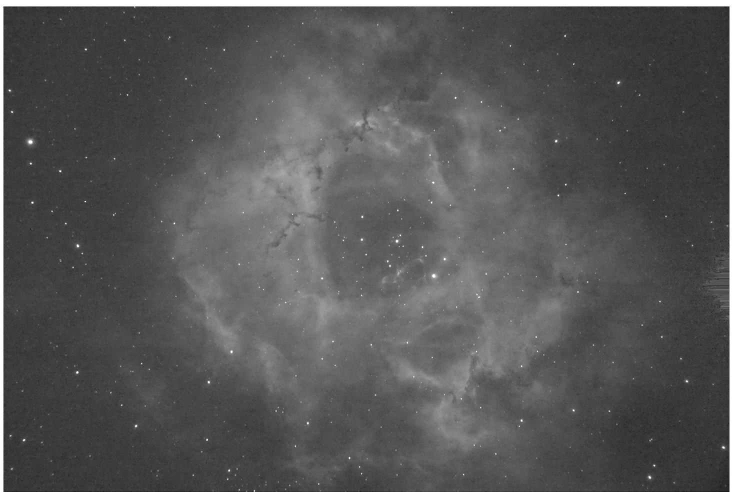
12. Omega 1.5nm (2 x 175s)

13. Andover 1nm (1 x 350s)

Figure 12 **February 6th Imaging Results – Batch 2**

8. IDAS 6.8nm (5 x 120s)

10. Optolong 3nm (5 x 120s)



12. Omega 1.5nm (5 x 120s)

13. Andover 1nm (5 x 120s)

Figure 13 February 8th Imaging Results

The resulting contrast increase measurements are plotted in Figure 15, compared with the corresponding predictions for each filter. The absolute value of the contrast increase measured from my images was consistently lower than predicted because of the brightness of the particular nebulae I was imaging compared to the reference nebula used in my predictions (i.e. NGC7000). Magnitude aside, the trend in contrast increase from one filter to another was found to be consistent between my imaging results and predictions. The one exception, as mentioned earlier, is for the Andover filter (#13) which I had expected to produce a higher contrast increase based on my predictions.

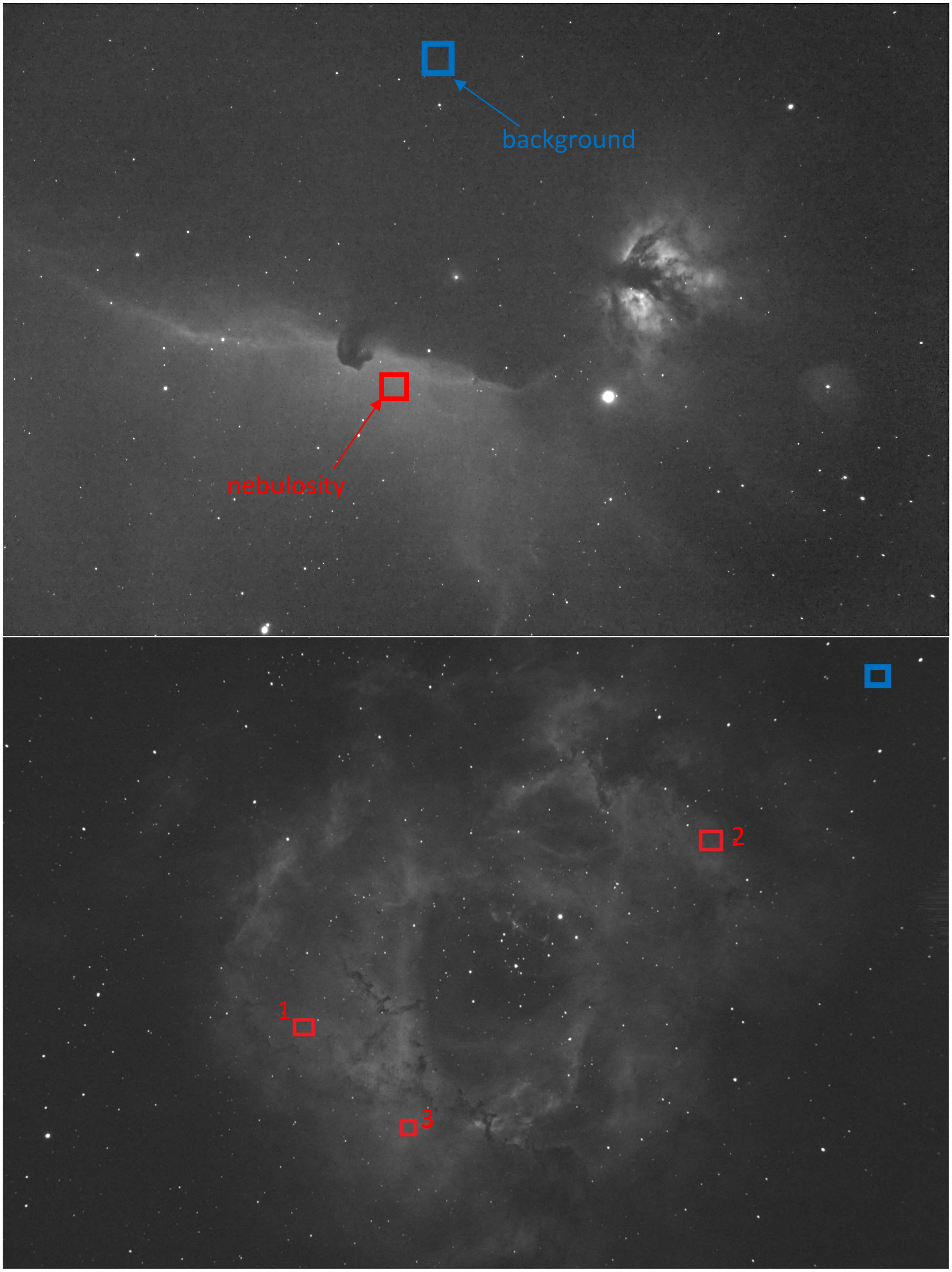


Figure 14 **Areas Used for Image Analyses**

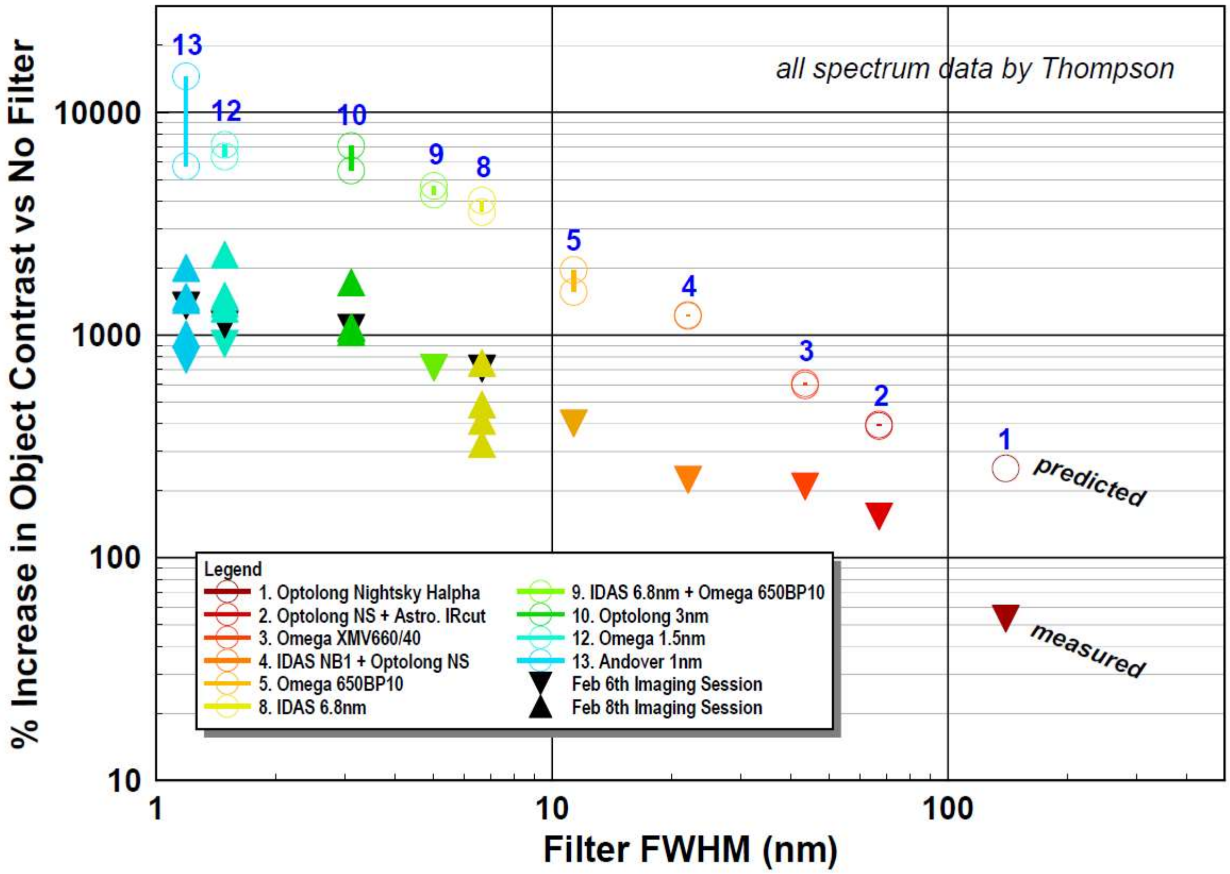


Figure 15 Measured Nebula Contrast Increase

The measurements of luminance from the images also allowed me to evaluate SNR. When I extracted the average luminance values from each image in AstroImageJ, I also recorded the standard deviation (σ). This allowed me to calculate the SNR achieved by each filter using the following equation:

SNR = (measured nebula luminance – measured background luminance) ÷ measured nebula σ

The measured SNR values are plotted in Figure 16, along with the predicted values for each filter. As with the measured contrast increase values, the measured SNR values are consistently less than the predictions, especially for the wider filters. The descrepancy is likely due to a combination of the difference in nebula brightness, measured vs. predicted, and the fact that I have assumed a perfect sensor in my predictions. The presence of read and dark current noise in my images should tend to push measured SNR values down below what is predicted, especially for the wider filters that have lower magnitude nebula signals. Despite the descrepancy in SNR magnitudes, the measured trend in SNR with filter FWHM is consistent with my predictions. The good alignment found between my predictions and measurements serves to validate my prediction method, giving confidence to any other predictions that may be made such as for filters for which I don't have a physical sample or hypothetical filters that don't actually exist.

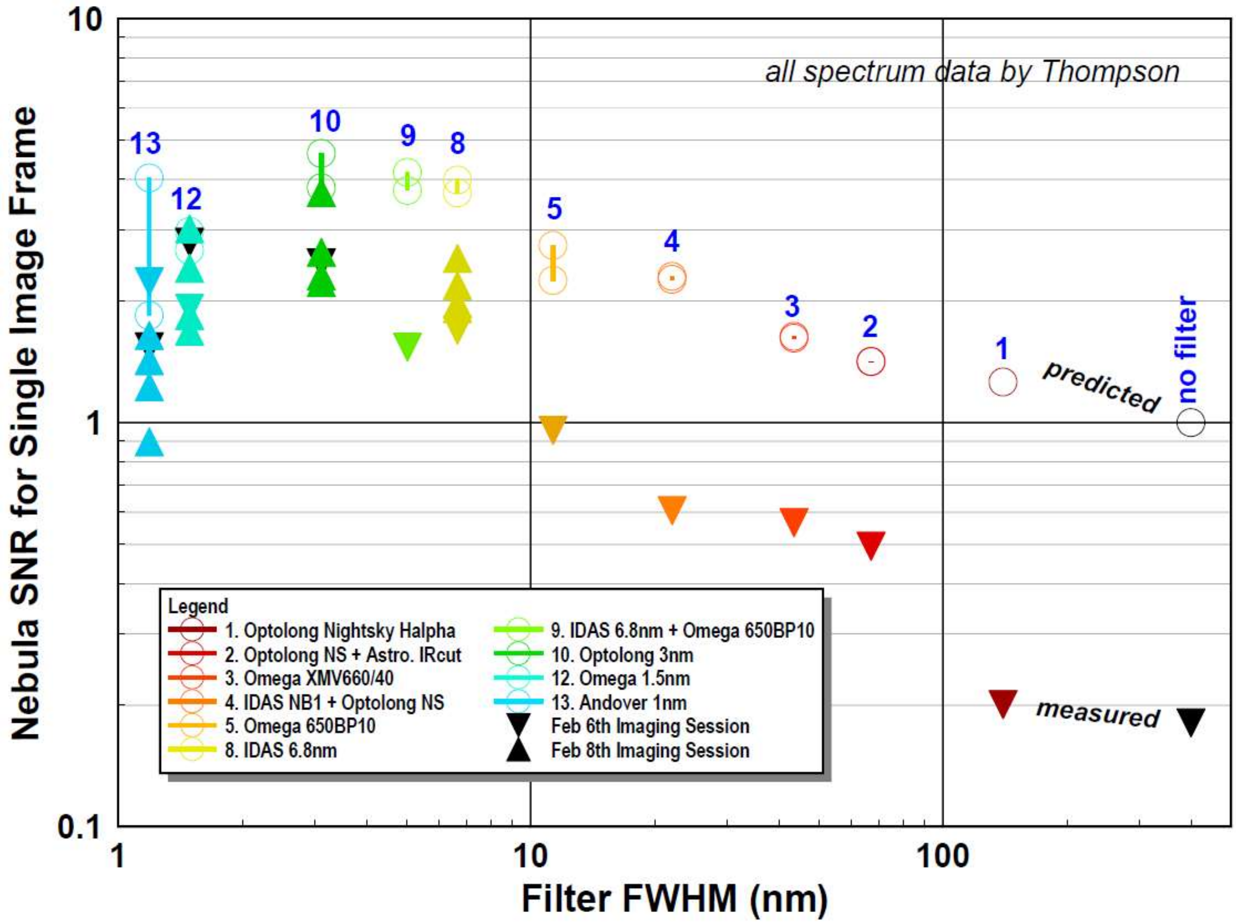


Figure 16 Measured Nebula Signal-to-Noise Ratio

Cost Effectiveness:

In addition to answering the primary question about the practical limits on bandwidth, I also set out in this test to evaluate filter cost effectiveness. Using my predictions of SNR I have assembled a figure that evaluates the cost-benefit of each of the filters tested. Figure 17 presents a plot of $USD per unit predicted SNR versus FWHM. There was a lot of scatter found for the list of filters considered in my test, their cost effectiveness varying widely from $50 per unit SNR to over $300. In general the spread and peak cost of the filters increases with decreasing bandwidth. The data implies however that there are three classes of filter: bargain (<$100/SNR), good value ($100/SNR to $150/SNR), and premium (>$150/SNR). To further refine and populate these three classes I decided to survey all the H-α available today for commercial sale. A list of the resulting 41 filters is provided in Table 3. For all of these filters I calculated a per-frame SNR value, either using the measured spectra as was the case for all the filters considered in my testing, or by simply using the peak %LT and FWHM values quoted by the filter manufacturers. A summary of my filter survey data is available in Appendix A, sorted by increasing FWHM. This allowed me to plot a master cost-benefit graph; price versus SNR for each filter. The resulting graph is presented in Figure 18. The numbers inside each data marker correspond to the filter numbers listed in Table 3. The data marker colour corresponds to the calculated $USD per unit SNR. Figure 18 makes it clear that regardless of the performance level (i.e. SNR) you wish to achieve, there is a filter available for

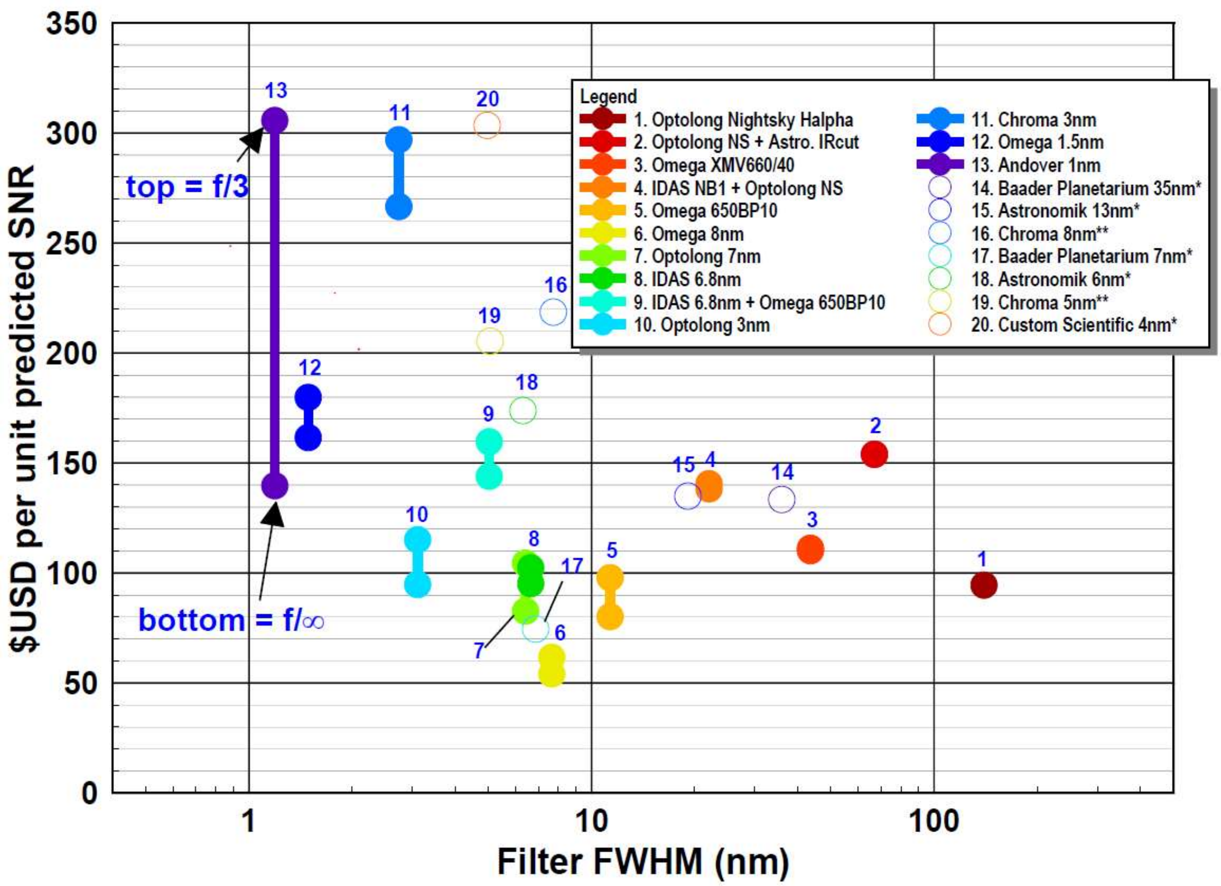


Figure 17 Filter $USD per Unit Predicted SNR

No.	Filter or Filter Combo	No.	Filter or Filter Combo
1	Optolong Nightsky H-α	25	Altair Astro Ultra 3nm H-α
2	Optolong NS H-α + Astronomik UV/IR Blocker	26	Antlia 3nm Pro H-α
3	Omega XMV660/40	27	Antlia 4.5nm Edge H-α
4	IDAS NB-1 + Optolong NS H-α	28	Antlia Ultra-Narrowband H-α
5	Omega 650BP10	29	Askar Color Magic Ultra-Narrowband H-α
6	Omega 8nm H-α	30	Astromania Narrowband NBPF H-α 12nm
7	Optolong 7nm H-α	31	Astromania Nebula Red
8	IDAS 6.8nm H-α	32	Baader Planetarium 20nm H-α
9	IDAS 6.8nm H-α + Omega 650BP10	33	Baader Planetarium 3.5nm H-α
10	Optolong 3nm H-α	34	Baader Planetarium 3.5nm H-α Highspeed
11	Chroma 3nm H-α	35	Baader Planetarium 6.5nm H-α
12	Omega 1.5nm H-α	36	Baader Planetarium 6.5nm H-α Highspeed
13	Andover 1nm H-α	37	Chroma 3nm H-α Fast
14	Baader Planetarium 35nm H-α	38	Explore Scientific 12nm H-α
15	Astronomik 13nm H-α	39	Explore Scientific 7nm H-α
16	Chroma 8nm H-α	40	Omegon Pro 12nm H-α
17	Baader Planetarium 7nm H-α	41	Optec H-α
18	Astronomik 6nm H-α	42	Pegasus Astro 7nm H-α
19	Chroma 5nm H-α	43	Svbony 7nm H-α
20	Custom Scientific 4nm H-α	44	ZWO 7nm H-α
24	Altair Astro Premium 7nm H-α		

Table 3 List of Commercially Available H-α Filters

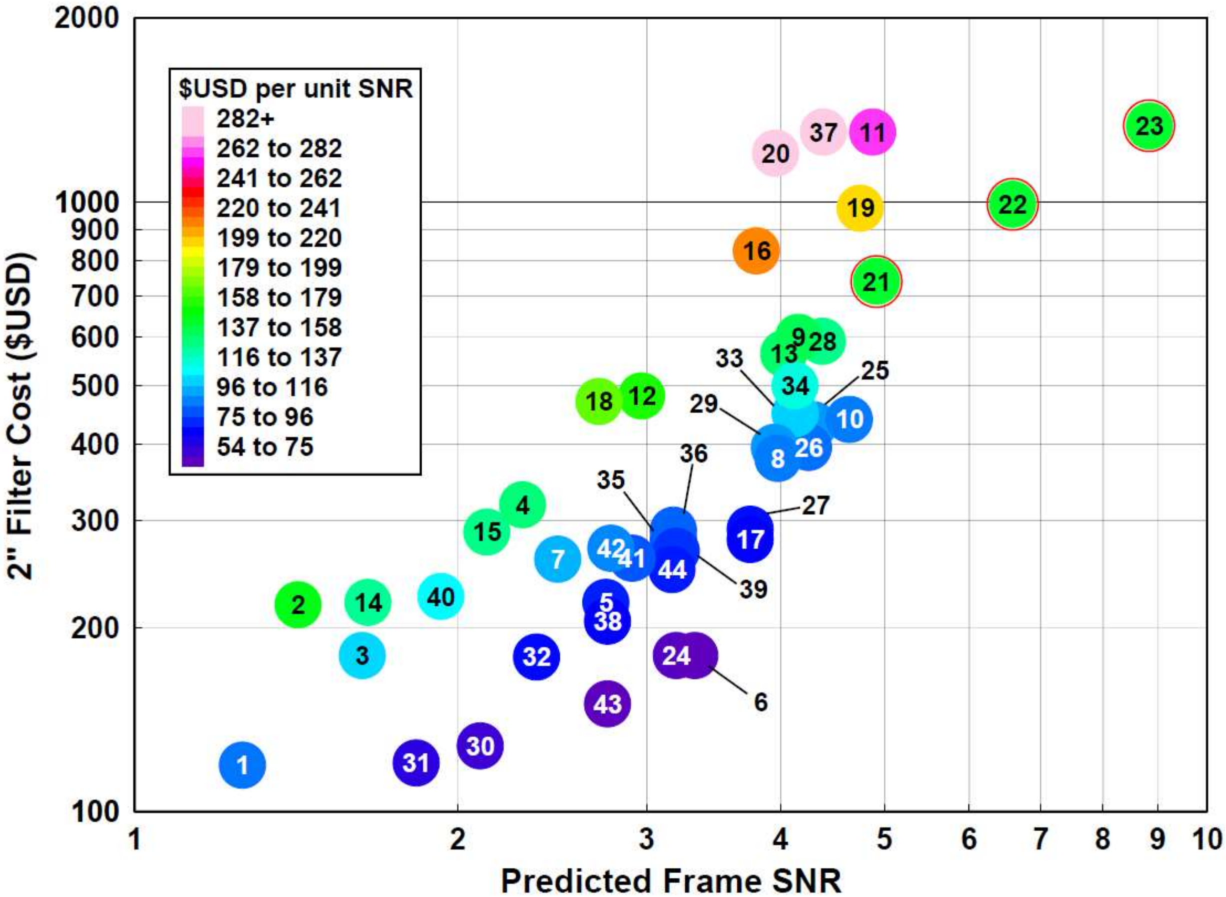


Figure 18 Filter $USD per Unit Predicted SNR

sale in every price class: bargain (purple markers), good value (blue markers), or premium (green/orange/pink markers). Perhaps not surprisingly, the most heavily populated class of filters is good value. In the last couple of years there has been a lot of growth in the number of different filter models and brands available in this class, most notably from Chinese manufacturers. These new brands are providing serious competition against the premium brands, especially since they are offering premium features like: very narrow FWHM, high off-band blocking (>OD4) to eliminate halos, and per-batch measured filter spectra. I have included in Figure 18 my best guess at what the three ideal filters, #21, #22 & #23 (2.0, 1.0, and 0.4nm wide respectively), would/should cost if they were ever brought to market, based on their predicted performance relative to existing filters. Manufacturing such narrow filters with any amount of repeatability will be expensive and require serious quality control, which in my opinion puts them into the premium filter price category.

Conclusions:

Based on the results of the testing described above, I have made the following conclusions:

1. For the range of FWHM considered, there was no limit observed to the increase in nebula contrast increase that could be realized using a progressively narrower bandwidth. This was determined primarily by spectrum analysis. Imaging results were found to be consistent with spectrum analysis predictions, however the two sub-2nm sample filters available for

testing were found to be poor representations of what should be possible with a filter purpose-built for astronomy.

2. For the range of FWHM considered, there was no limit observed to the increase in SNR that could be realized using a progressively narrower bandwidth. This was determined primarily by spectrum analysis. This conclusion is counter to that made in the first version of this report, the discrepancy being a result of using a low-resolution source for the nebula emission spectra in my prediction model. Imaging results were found to be consistent with spectrum analysis predictions, however the two sub-2nm sample filters available for testing were found to be poor representations of what should be possible with a filter purpose-built for astronomy.
3. To be able to fabricate filters with FWHM values below 2nm that are useful for amateur astronomy would be difficult and expensive. Such filters would require %LT values above 80% (preferably >90%), off-band blocking better than OD4, and CWL accuracy better than ±0.2nm. Based on the price-per-performance of existing commercially available filters, the price I would expect for a 2nm and 1nm wide filter would be \$740 and \$990USD respectively.
4. Although there would seem to be no limit on the imaging performance improvements that can be realized with progressively narrower filters (down to 0.4nm wide at least), that does not mean that there isn't a practical limit on what is useful to amateur astronomers. The increase in performance that you get from narrower FWHMs comes at a cost of longer sub-exposure times and higher sensitivity to optics f-ratio. For astrophotographers who image at different f-ratios, it would be very inconvenient if they needed a different filter, optimized for band shift, for each of their telescope setups.
5. Filters are available that can deliver any desired performance (SNR) level, at a wide range of prices. Filters priced in the "good value" class are becoming more and more competitive, delivering performance levels comparable to premium filters.
6. Good agreement was found between my predictions of filter performance and the results of my imaging tests. These results serve to validate my prediction method, allowing for the evaluation of any filter based solely on its measured spectrum.

Cheers!

Jim Thompson (top-jimmy@rogers.com)

Appendix A – H-alpha Filter Cost vs. Performance Summary Table

No.	Filter or Filter Combo	Spectrum Data Source	FWHM [nm]	2" Filter Cost [USD]	Predicted SNR	$USD per unit SNR
23	Ideal 0.4nm H-α	JT	0.4	1330*	8.84	150
22	Ideal 1nm H-α	JT	1.0	990*	6.59	150
13	Andover 1nm H-α (1")	JT	1.2	563	4.03	140
12	Omega 1.5nm H-α (1")	JT	1.5	480	2.97	162
21	Ideal 2nm H-α	JT	2.0	740*	4.92	150
28	Antlia Ultra-Narrowband H-α	OEM1	2.5	590	4.38	135
11	Chroma 3nm H-α	JT	2.7	1300	4.88	267
25	Altair Astro Ultra 3nm H-α	OEM1	3.0	430	4.30	100
26	Antlia 3nm Pro H-α	OEM1	3.0	395	4.25	93
37	Chroma 3nm H-α Fast	OEM1	3.0	1300	4.39	296
10	Optolong 3nm H-α	JT	3.1	439	4.64	95
33	Baader Planetarium 3.5nm H-α	OEM1	3.5	449	4.13	109
34	Baader Planetarium 3.5nm H-α Highspeed	OEM1	3.5	499	4.13	121
29	Askar Color Magic Ultra-Narrowband H-α	OEM2	4.0	395	3.95	100
27	Antlia 4.5nm Edge H-α	OEM1	4.5	290	3.75	77
9	IDAS 6.8nm H-α + Omega 650BP10	JT	5.0	599	4.16	144
20	Custom Scientific 4nm H-α	AK	5.0	1200	3.96	303
19	Chroma 5nm H-α	C	5.1	975	4.75	205
18	Astronomik 6nm H-α	AK	6.3	470	2.71	174
7	Optolong 7nm H-α	JT	6.4	259	2.48	104
35	Baader Planetarium 6.5nm H-α	OEM1	6.5	279	3.18	88
36	Baader Planetarium 6.5nm H-α Highspeed	OEM1	6.5	289	3.18	91
8	IDAS 6.8nm H-α	JT	6.7	379	3.98	95
17	Baader Planetarium 7nm H-α	AK	6.9	279	3.75	74
24	Altair Astro Premium 7nm H-α	OEM1	7.0	180	3.20	56
39	Explore Scientific 7nm H-α	OEM1	7.0	267	3.20	83
44	ZWO 7nm H-α	OEM1	7.0	249	3.17	79
6	Omega 8nm H-α	JT	7.7	180	3.33	54
16	Chroma 8nm H-α	C	7.7	830	3.80	219
43	Svbony 7nm H-α	OEM2	8.0	150	2.76	54
41	Optec H-α	OEM2	9.0	260	2.91	89
42	Pegasus Astro 7nm H-α	OEM2	9.0	270	2.78	97
5	Omega 650BP10	JT	11.3	220	2.75	80
38	Explore Scientific 12nm H-α	OEM1	12.0	205	2.76	74

15	Astronomik 13nm H-α	AK	19.1	287	2.13	135
32	Baader Planetarium 20nm H-α	OEM1	20.0	179	2.37	76
4	IDAS NB-1 + Optolong NS H-α	JT	22.0	318	2.30	138
30	Astromania Narrowband NBPF H-α 12nm	OEM2	23.0	128	2.10	61
40	Omegon Pro 12nm H-α	OEM2	24.0	225	1.93	116
14	Baader Planetarium 35nm H-α	AK	35.9	220	1.65	133
31	Astromania Nebula Red	OEM2	43.0	120	1.83	65
3	Omega XMV660/40	JT	43.6	180	1.63	110
2	Optolong NS H-α + Astronomik UV/IR Blocker	JT	67.0	218	1.42	154
1	Optolong Nightsky H-α	JT	140	119	1.26	94

** My best guess at cost based on $USD/SNR fixed at 150.*

Spectrum Data Sources:

JT measured by Jim Thompson
AK measured by André Knöfel
C measured by Chroma Filters
OEM1 values of FWHM & peak %LT quoted by filter manufacturer were used as-is
OEM2 values of FWHM & peak %LT extracted from spectrum plot issued by manufacturer